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A Review of Dense Wavelength Division Multiplexing and Next Generation Optical Internet

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Abstract*— With the advent of 21st century, the exponential growth of Internet and the revolution in high bandwidth applications have created capacity demands that exceed traditional TDM limits. As a result, the once seemingly inexhaustible bandwidth promised by the deployment of optical fiber is being exhausted. To meet growing demands for bandwidth, a technology called Dense Wavelength Division Multiplexing (DWDM) has been developed that multiplies the capacity of a single fiber. This paper discusses the twin concept of optical networking and DWDM. The paper explains in detail the DWDM system and various components of an all-optical network like Optical Amplifiers, Optical Add/Drop Multiplexers, Optical Splitters etc The traditional IP over SONET architecture as it exists today is reviewed and the concept of transmitting raw IP packets over an optical layer which employs DWDM is put forth. The requirements for creating an all optical networks and issues pertaining such an evolution have been discussed here. This paper shall serve as a guide to the optical transport networks.

Index Terms—**Bandwidth, DWDM, IP, TDM, SONET, Optical Amplifiers, Optical Networks.**

I. INTRODUCTION

In recent years, the explosive growth in Internet activities such as multimedia communications and networking has created an ever-increasing demand on network capacity, bandwidth and transmission rates. With this unprecedented development in telecommunication, many carriers are nearing one hundred percent capacity utilization across significant portions of their networks and finding that their estimates of fiber needs have been highly underestimated. Three methods exist for expanding capacity: 1) installing more cables, 2) increasing system bit rates to multiplex more signals or 3) wavelength division multiplexing (WDM). Installing more cables will prove to be a viable method in metropolitan areas, since fiber has become incredibly inexpensive and installation methods more efficient (like mass fusion splicing.) But this may not be the most cost effective, if conduit space is not available or major construction is required. Increasing system bit rate may not prove economical either. Many systems are already running at SONET OC-48 rates (2.5 GB/s) and upgrading to OC-192 (10 GB/s) is expensive, requires changing out all the electronics in a network, and adds four times the capacity, more than may be necessary. Another major problem is the challenge of deploying and integrating diverse technologies in one physical infrastructure. However, with the development of optical networks and the use of Dense Wavelength Division Multiplexing (DWDM) technology, a new and probably, a very crucial milestone is being reached in network evolution. Such a network will bring intelligence and scalability to the optical domain by combining the intelligence and functional capability of SONET/SDH, the tremendous bandwidth of DWDM and innovative networking software to spawn a variety of optical transport and switching products.

II. OPTICAL NETWORKS

Optical networks are high capacity networks that use light as an electromagnetic carrier wave modulated to transmit information and provide routing, grooming, and restoration at the wavelength level as well as wavelength-based services. It is possible to classify networks into three generations depending on the physical-level technology employed. The first generation networks use copper-based or microwave technologies e.g. Ethernet, satellites etc. The second generation networks use these copper links or microwave links along with optical fibers. Finally we have the third generation networks that employ Wavelength Division Multiplexing technology, which forms the backbone of optical fiber communication.WDM is a technology which multiplexes multiple optical signals onto a single fiber by using different wavelengths, or colors of light. Presently time division multiplexing systems which are widely utilized in optical communication networks use optical-to-electronic conversion, MUX and DMUX in the electronic domain, and electronic-to-optical conversion. Thus, the throughput is limited by the processing speed in the electronic domain. WDM technologies, on the other hand, are based on all-optical multiplexing and de-multiplexing.WDM is further divided into three types: Bi-Directional Wave Division Multiplexing (BWDM), Coarse Wave Division Multiplexing (CWDM), and Dense Wave Division Multiplexing (DWDM).

III. DENSE WAVELENGTH DIVISION MULTIPLEXING

DWDM increases the capacity of the embedded fiber by first assigning incoming optical signals to specific wavelength within a designated frequency band and then resulting signals are multiplexed onto single fiber. The interface is bit-rate and format independent as incoming signals are never terminated in the optical layer. This makes it easy to integrate the DWDM technology with existing equipment in the network while gaining access to the untapped capacity in the embedded fiber. DWDM typically has the capability to transport up to 80 channels (wavelengths) in what is known as the Conventional band or C band spectrum, with all 80 channels in the 1550 nm region. CIENA corporations introduced in April 1996, the first DWDM system in the world to furnish 16 channels over one fiber. A critical advantage of DWDM is its protocol is not related to its transmission speed, thus IP, ATM, SONET/SDH, Ethernet, these protocols could be used and transmission speed between 100Mb/s to 2.5Gb/s. DWDM could transmit different type of data at different speed on the same channel.

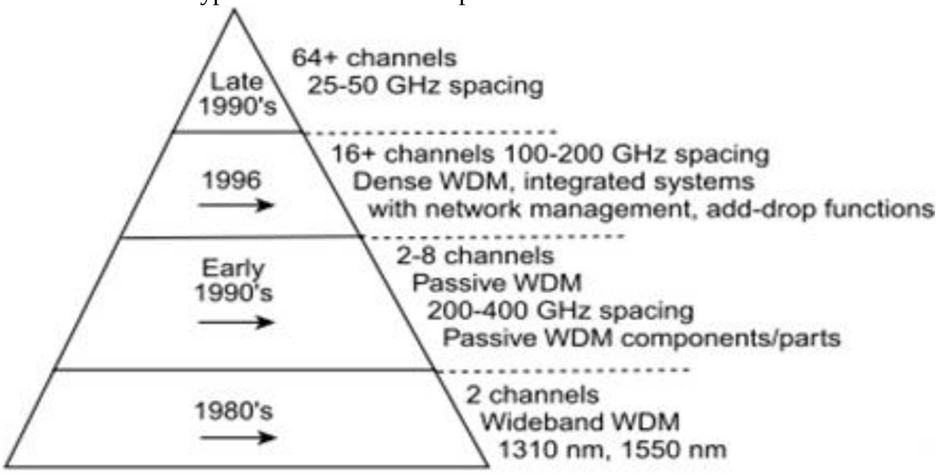

Fig. 1 DWDM Evolution

IV. DWDM SYSTEM

A. DWDM Components

The concepts of optical fiber transmission, amplifiers, loss control, packet switching all optical header replacement, network topology, synchronization and physical layer security play a major role in deciding the throughput of the network.

1. Multiplexer. The multiplexer contains one wavelength converting transponder for each wavelength signal it will carry. It converts the input optical signal into electrical domain, retransmits the signal using a 1550 nm band laser and places multiple band signals onto a single fiber.

2. An intermediate line repeater: It is placed approximately every 80 – 100 km for compensating the loss in optical power, while the signal travels along the fiber. The signal is amplified by an EDFA, which usually consists of several amplifier stages.

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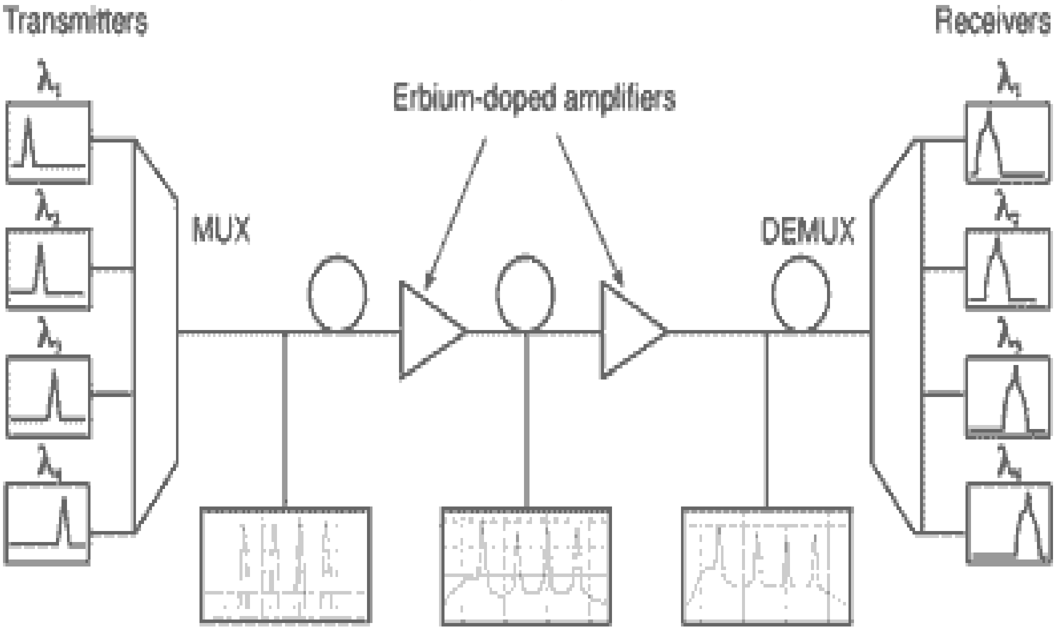

Fig. 2 DWDM System

3.Optical Cross Connect(OXC): OXC switches optical signals from input ports to output ports. These type of elements are usually considered to be wavelength insensitive, i.e., incapable of de-multiplexing different wavelength signals on a given input fiber. OXC is located at nodes cross-connecting a number of fiber pairs and also support add and drop of local traffic providing the interface with the service layer.

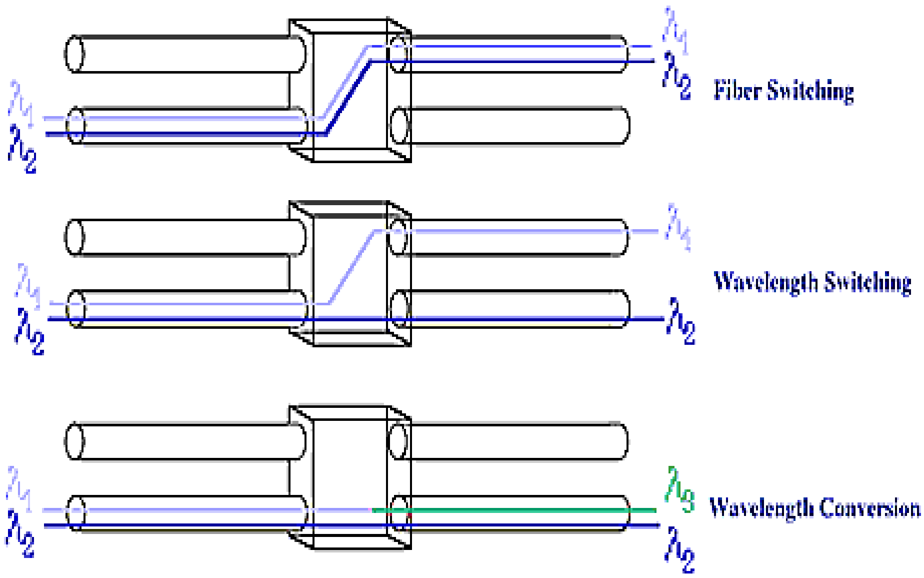

Fig. 3 Switching and conversion with OXC

4. Optical add-drop multiplexer. The Add/Drop Multiplexor as the name suggests, selectively adds/drops wavelengths without having to use any SONET/SDH terminal equipment. 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 The ADM is required to add new wavelengths to the network or to drop some wavelengths at their terminating points. There are two types of implementations of the ADM, the ***Fixed WADM*** and the ***Reconfigurable WDM***. Optical diagnostics and telemetry are often extracted or inserted at such a site, to allow for localization of any fiber breaks or signal impairments. OADM technology introduces asynchronous transponders to allow the optical-network element to interface directly to high revenue generating services.

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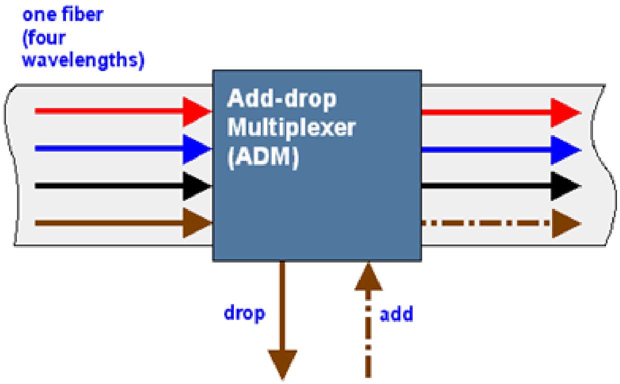

Fig. 4 Basic OADM

5. De-multiplexer: The terminal de-multiplexer breaks the multi-wavelength signal back into individual signals and outputs them on separate fibers for client-layer systems to detect.

B. Optical Transmission Principles

The DWDM system has an important photonic layer, which is responsible for transmission of the optical data through the network and is governed by various parameters like:-

- **Channel Spacing**: The minimum frequency separation between two different signals multiplexed is 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. Channel spacing is controlled by the bandwidth of optical amplifier and the capability of the receiver in identifying two close wavelengths.
- **Signal Direction:** An optical fiber helps transmit signal in both directions. 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 fiber.
- **Signal Trace**: The procedure of detecting if a signal reaches the correct destination at the other end. This helps follow the light signal through the whole network. It can be achieved by plugging in extra information on a wavelength, using an electrical receiver to extract if from the network and inspecting for errors light signal through the whole network. It can be achieved by plugging in extra information on a wavelength, using an electrical receiver to extract if from the network and inspecting for errors.

C. Optical Amplifiers

Erbium-doped fiber Amplifiers (EDFA) are silica based optical fibers that are doped with erbium and amplify the optical signals at regular intervals. It is this doping that achieves the conversion of a passive fiber to an active one. EDFAs have almost rendered 'Wavelength Regenerators' redundant and made WDM economically feasible. Erbium boosts the power of wavelengths and eliminates the need for regeneration. The usable bandwidth by using EDFAs is about 30nm (1530nm-1560nm). However, attenuation is minimum in the range of 1500nm –1600nm. Hence that implies very less utilizations. Also the need to place as many wavelengths (channels) as possible in a single fiber, the distance between two channels is very small (0.8-1.6nm) and Inter channel crosstalk becomes prominent. The need to increase the amplifier's bandwidth while eliminating crosstalk led to the development of Silica Erbium fiber-based Dual-band fiber amplifier (DBFA**)** which can generate terabit transmission successfully and have bandwidth =>1528nm-1610nm. It has been shown that this EBFA has several attractive features compared to the traditional EDFA:

Flat Gain: EBFAs achieve a flat gain over a range of wide range (35nm) as compared to the EDFAs

Slow Saturation: EBFAs reach saturation slower than the EDFAs. Saturation is the state where output remains constant even though input level keeps increasing.

Low Noise: EBFAs exhibit lower noise than EDFAs

Therefore, the 1590-nm EBFA represents a huge leap in meeting the ever-increasing demands of high-capacity fiber-optic transmission systems. A similar product is Lucent's Bell Labs of an "Ultra-Wideband Optical Amplifier (UWOA) that can amplify up to 100 wavelength channels as they travel along a single optical fiber.

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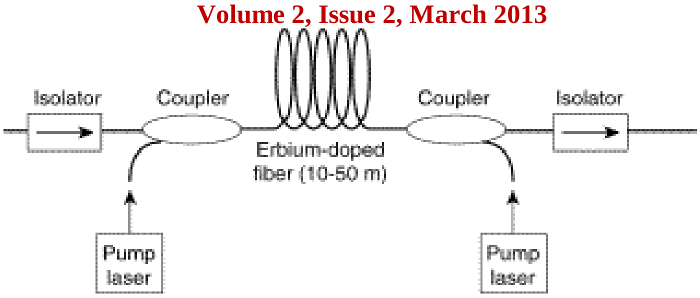

Fig. 5 Optical Amplifier

D. Network Classification

A network can be physically structured in the form of a ring, a mesh, star based or linear bus based on the connection between the various nodes. Although the physical topology of a DWDM system might be that of a ring, the logical traffic distribution topology is arbitrary due to the use of separate wavelengths to connect each node.

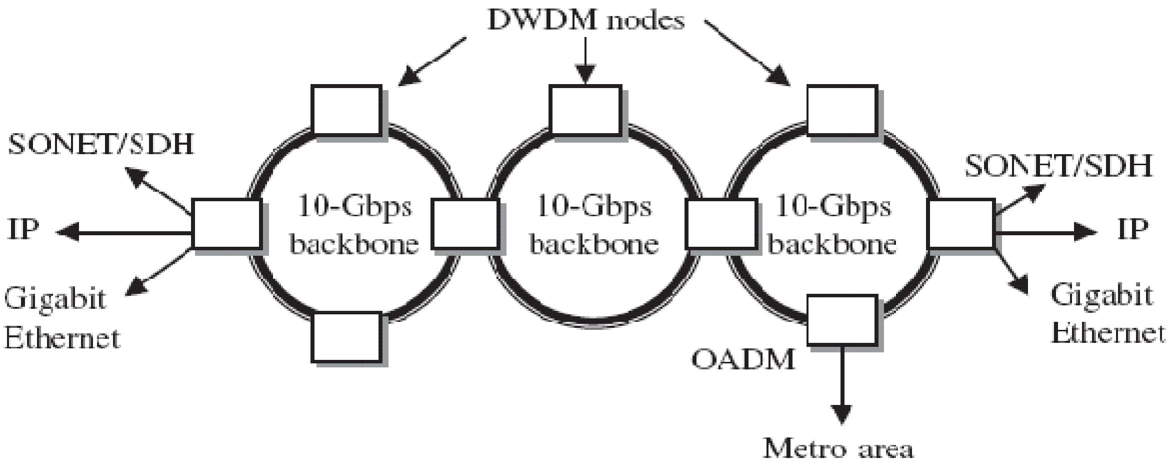

Fig. 6 DWDM network which is configured as a set of large rings

- **Ring Topology vs. Mesh Topology:** A ring topology is preferable 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 rings also have better resilience and restoration than meshes. The ring topology besides serving as a standby link helps share the load. The working segment 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.
- **Single-Hop Networks vs. Multi-hop Networks**: In single-hop networks, the data stream travels from source to destination as a light stream without any conversion to electronic. Two examples of a single-hop networks are :
  Broadcast-and-select networks: It is based on a passive star coupler device connected to several nodes in a star topology. Basically a signal received on one port is split and broadcast to all ports. Generally used in high speed LANs or MANs
  Wavelength routed networks: The key element here is the wavelength-selective switching subsystem which is of two types. 'Wavelength path switching' involves dynamic signal switching from one path to another by In multi-hop networks, each node has access to only a small number of the wavelength channels used in the network. Fixed wavelength transmitters and receivers are used for this purpose with a minimum of at least a single wavelength transmitter and a single wavelength receiver tuned to different wavelengths.

E. Packet Switching

DWDM systems are capable of performing switching in the optical domain without having to convert the signal onto the electrical domain. Switching involves reading in a header from the signal and altering the path of the signal (or packet) appropriately. All optical header replacement is the key to updating information in the

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wavelength-based packets. 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 data packet's own flag and retains the entire packet structure.

F. Synchronization

The Add/Drop Multiplexors (ADM) and transponder en route provide the much-needed synchronization between transmitter and receiver. 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.

G. Security

Optical fibers foster secure connections. Quantum cryptography exploits the fundamental properties of quantum complementarily to allow two remote parties to generate a shared random bit sequence. Users can safely use their shared bit sequence as a key for subsequent encrypted communications. In contrast, Quantum Key Distribution (QKD) provides a new paradigm for the protection of sensitive information in which security is based on fundamental physical laws.

V. IP OVER WDM: NEXT GENERATION OPTICAL INTERNET

A. Need for IP over DWDM

SONET (Synchronous Optical Network) defines interface standards at the physical layer of the OSI model. It 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 SONET layer can be further divided into four layers (Path, Line, Section and Photonic).

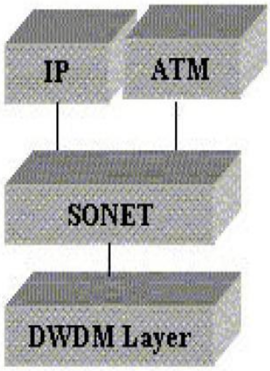

Fig. 7 Primitive Protocol Stack for SONET over DWDM

The 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 leads to function overlap and introduces undesired latency. 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. IP over DWDM system can perform 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.

B. Optical Internet

Bit rate and protocol transparency of DWDM system 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. 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

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provided by the standard SONET architecture.. 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.

Table.1 DWDM Network Model

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

C. IP/DWDM Architecture

The quest for a standard **IP/DWDM Architecture** brought-in two different approaches: SONET-centric (Closed) and Generic (Open). The closed architecture 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.8 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. The segment (B) in Fig.8 denotes the open system. The customer is responsible for providing the actual interface to the end user and for all the protection work.

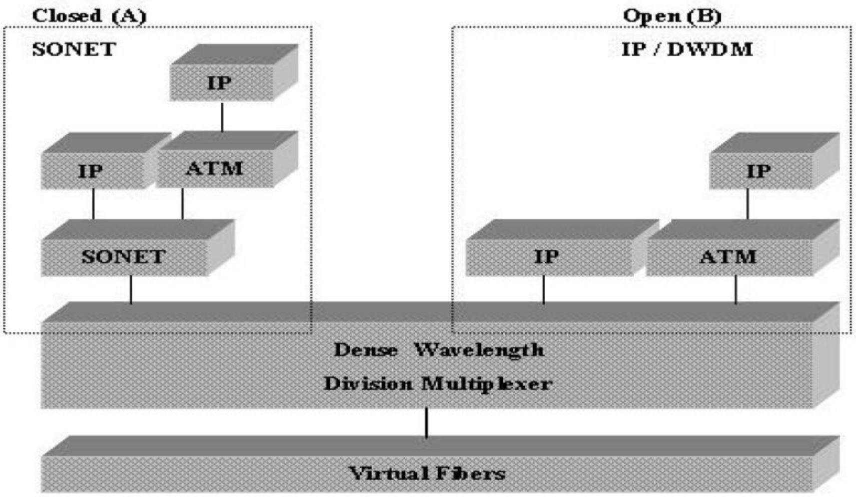

Fig. 8 DWDM Network Architecture

The IP/DWDM system can adopt a variety of architectures and they can be grouped as:

- ***Optical Mesh Transport***

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

- ***Wavelength transport network***

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.

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VI. IP OVER DWDM CHALLENGES

A. Error Detection

The overhead in the frame enables the SONET to detect signal errors and monitor network faults. This error checking can be accomplished at any of the SONET equipment - DWDM transponder, SONET regenerator, or other interface card supporting SONET framing system.
Transporting signals over the DWDM layer directly enhances 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.

B. Network Control and 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

C. 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.

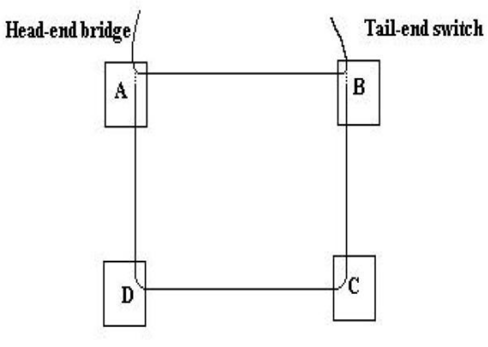

Fig. 9 1+1 protection by OXC

WADMs can accommodate more advanced optical layer protection switching. 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.9 depicts the topology consideration during restoration

D. 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 formats 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.

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E. 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.

VII. CONCLUSION

In this paper we have discussed various concepts that are integral to the development of the All-Optical Network. Various new technologies and principles governing a DWDM system were introduced. The existing system architecture was studied and a proposed optical layer was described in much detail. The basic concepts underlying an IP over DWDM system - like Network Management, Fault Tolerance, Interoperability, Optical Switching - were discussed at depth. . The IP/DWDM systems shall support the Open architecture & provide complete service transparency. The future of all-optical networks is plagued with many challenges. 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. Hence, DWDM acts as the stepping stone towards a true optical networking era

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