Optical Networking And Dense Wavelength Division Multiplexing (DWDM)

Muralikrishna Gandluru, gandluru@cis.ohio-state.edu

Abstract:

This paper deals with the twin concepts of optical networking and dense wavelength division multiplexing. The paper talks about the various optical network architectures and the various components of an all-optical network like Optical Amplifiers, Optical Add/Drop Multiplexors, Optical Splitters etc. Important optical networking concepts like wavelength routing and wavelength conversion are explained in detail. Finally this paper deals with industry related issues like the gap between research and the industry, current and projected market for optical networking & DWDM equipment and future direction of research in this field.

See Also: IP Over DWDM (Student Report) | Optical DWDM Networks (Lecture by Dr. Jain) | IP over DWDM (Lecture by Dr.Jain) | References on Optical DWDM Networks and IP over DWDM | Books on WDM and Optical Networking
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1. INTRODUCTION

One of the major issues in the networking industry today is tremendous demand for more and more bandwidth. Before the introduction of optical networks, the reduced availability of fibers became a big problem for the network providers. 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. The existing SONET/SDH network architecture is best suited for voice traffic rather than today’s high-speed data traffic. To upgrade the system to handle this kind of traffic is very expensive and hence the need for the development of an intelligent all-optical network. 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, switching and management related products.

1.1 Optical Networking

Optical networks are high-capacity telecommunications networks based on optical technologies and component that provide routing, grooming, and restoration at the wavelength level as well as wavelength-based services. The origin of optical networks is linked to Wavelength Division Multiplexing (WDM) which arose to provide additional capacity on existing fibers. The optical layer whose standards are being developed, will ideally be transparent to the SONET layer, providing restoration, performance monitoring, and provisioning of individual wavelengths instead of electrical SONET signals. So in essence a lot of network elements will be eliminated and there will be a reduction of electrical equipment.

It is possible to classify networks into three generations depending on the physical-level technology employed. First generation networks use copper-based or microwave technologies e.g Ethernet, satellites etc. In second generation networks, these copper links or microwave links with optical fibers. However, these networks still perform the switching of data in the electronic domain though the transmission of data is done in the optical domain. Finally we have the third generation networks that employ Wavelength Division Multiplexing technology. They do both the transmission and the switching of data in the optical domain. This has resulted in the onset of tremendous amount of bandwidth availability. Further the use of non-overlapping channels allows each channel to operate at peak speeds.

1.2 Dense Wavelength Division Multiplexing(DWDM)

Dense Wavelength Division Multiplexing (DWDM) is a fiber-optic transmission technique. It involves the process of multiplexing many different wavelength signals onto a single fiber. So each fiber have a set of parallel optical channels each using slightly different light wavelengths. It employs light wavelengths to transmit data parallel-by-bit or serial-by-character. DWDM is a very crucial component of optical networks that will allow the transmission of data: voice, video-IP, ATM and SONET/SDH respectively, over the optical layer.

Hence with the development of WDM technology, optical layer provides the only means for carriers to integrate the diverse technologies of their existing networks into one physical infrastructure. For example, though a carrier might be operating both ATM and SONET networks, with the use of DWDM it is not necessary for the ATM signal to be multiplexed up to the SONET rate to be carried on the DWDM network. Hence carriers can quickly introduce ATM or IP without having to deploy an overlay network for multiplexing.

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2. DWDM SYSTEM

As mentioned earlier, optical networks use Dense Wavelength Multiplexing as the underlying carrier. The most important components of any DWDM system are transmitters, receivers, *Erbium-doped fiber Amplifiers*, DWDM multiplexors and DWDM demultiplexors. Fig 1 gives the structure of a typical DWDM system.

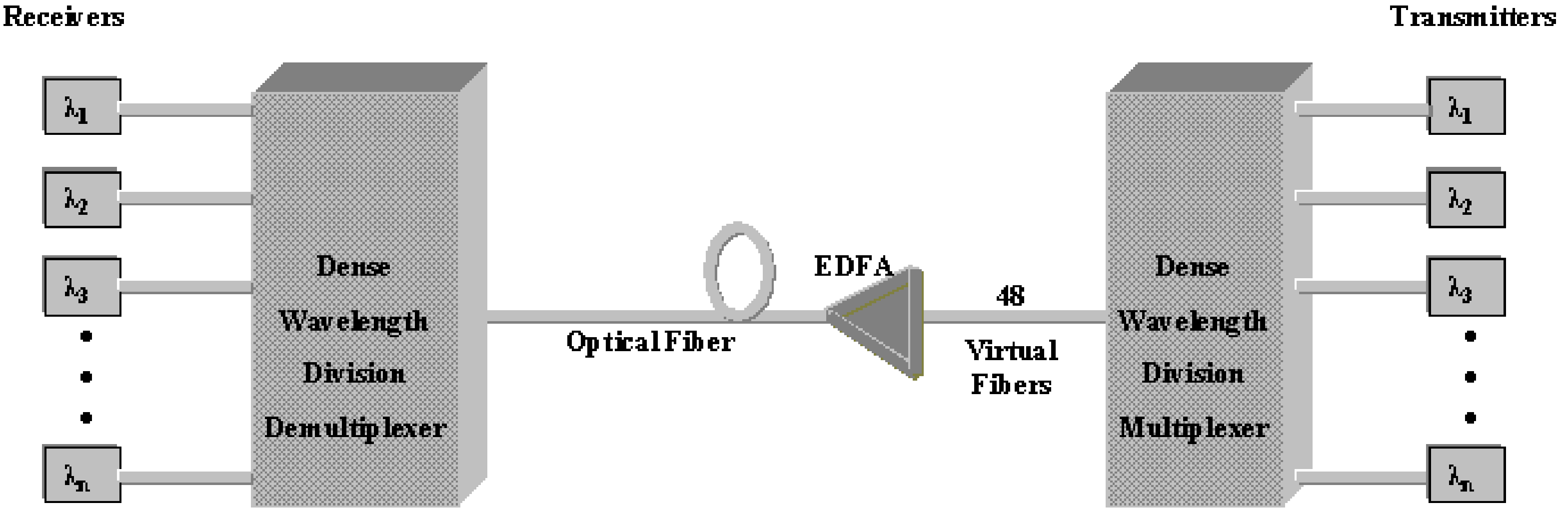

Fig.1 Block Diagram of a DWDM System

The concepts of optical fiber transmission, amplifiers, loss control, all optical header replacement, network topology, synchronization and physical layer security play a major role in deciding the throughput of the network. These factors have been discussed briefly in this sections that follow.

2.1. Optical Transmission Principles

The DWDM system has an important photonic layer, which is responsible for transmission of the optical data through the network. Some basic principles, concerning the optical transmission, are explained in this section. These are necessary for the proper operation of the system.

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. The factors controlling channel spacing are the optical amplifier's bandwidth and the capability of the receiver in identifying two close wavelengths sets the lower bound on the channel spacing. Both factors ultimately restrict the number of unique wavelengths passing through the amplifier.

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***: All wavelengths travel in the same direction within the fiber. It is similar to a simplex case. This calls in for laying one another parallel fiber for supporting transmission on the other side.

  - ***Bi-directional*:** The channels in the DWDM fiber are split into two separate bands, one for each direction. This removes the need for the second fiber, but, in turn reduces the capacity or transmission bandwidth.

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. The receiver the reports the signal trace to the transmitter.

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 less than the rest by atleast 0.1THz.

2.2 Network classification

A network can be physically structured in the form of either 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 can be arbitrary. This is done through the use of different wavelengths to interconnect each node. Until the development of EDFAs the passive star configuration was the most popular configuration due to its superior power budget. However, with the advent of EDFAs, the ring network works out much better after overcoming its power budget problems. What makes the ring network better is its superior resilience. The Optical Cross Connect (OXC) help pass on traffic between each of the rings. A Path-in-Lambda architecture for connecting all-optical networks is under development.

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 (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

Fig.2 Ring Topology Connecting Nodes A & B

Single-Hop Networks vs Multi-hop Networks

Multi-wavelength networks can be also classified as single-hop networks and multi-hop networks. In single-hop networks, the data stream travels from source to destination as a light stream. There is no conversion to electronic form in any of the intermediate nodes. Two examples of a single-hop networks are the *broadcast-and-select* and the *wavelength-routed* architecture.

- **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. Networks are simple and have natural multicasting capabilities. Generally used in high speed LANs or MANs. Other elements in this type of network are tunable receivers and fixed transmitters or fixed receivers and tunable transmitters.
- **Wavelength routed networks:** The key element here is the wavelength-selective switching subsystem. There are again two types of wavelength switching. *Wavelength path switching* involves dynamic signal switching

from one path to another by changing WDM routing while *wavelength conversion the* reuse of the same wavelength in some other part of the network as long as both lightpaths don't use it on the same fiber. Wavelength routing is explained in more detail in section [**6.**]

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 atleast a single wavelength transmitter and a single wavelength receiver tuned to different wavelengths. This type of network requires atleast one intermediate node for a packet to reach the destination. Also, at each intermediate node electronic switching of packets take place. Two examples of actual multihop systems on which packet switching has been implemented experimentally are Starnet (developed by Optical Communication Research Laboratory at Stanford University) and Teranet (developed by Columbia University).

2.3 Optical Amplifiers

Researchers are working on managing traffic optically rather than first converting it to electronic signals. However, it has been noticed that in long-haul networks, the effects of *dispersion* and *attenuation* are significant. What this means is that a signal cannot maintain its integrity over really long distances without having to be amplified. Towards that end, the production of optical amplifiers became important, which would help in amplifying signals at regular intervals. This led to development of the ***Erbium-doped fiber Amplifiers (EDFA)***.

EDFAs are as the name says, are silica based optical fibers that are doped with erbium. It is this doping that achieves the conversion of a passive fiber to an active one. Traditionally it has been used for terrestrial and under-sea purposes. With the development of EDFA we have basically almost rendered 'Wavelength Regenerators' redundant. The element erbium (Er_{68}) boosts the power of wavelengths and eliminates the need for regeneration. It is the optical amplifier that has made WDM economically feasible. 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 typically what happens is that with 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). This results in the Interchannel crosstalk becoming a very important issue at this point.

It became imperative that the amplifier's bandwidth had to be increased while eliminating crosstalk. So this led to the development of ***Silica Erbium fiber-based Dual-band fiber amplifier (DBFA)***. These fibers are similar to the EDFAs and have been able to generate terabit transmission successfully. However, the most important feature of the DBFA is its bandwidth => 1528nm-1610nm. The DBFA has two sub-band amplifiers. The first is in the range of the EDFA and the second one is what is known as ***Extended band fiber amplifier (EBFA)***. 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 upto 100 wavelengh channels as they travel along a single optical fiber and has a usable bandwidth of 80nm. This bandwidth spans the 1530-1565nm channel (C-band) and also the long wavelength channels beyond 1565-1620nm(L-band).

Upto December 1998 industrial capability is such that, wavelength systems were developed that could carry a maximum of 40 wavelengths per fiber. The various stages of this development included 4, 8,16,32 –wavelengths per fiber.

2.4 Synchronization

The SONET networks currently support the multiplexing of lower Time Division Multiplexing (TDM) rates onto higher rates. The Add/Drop Multiplexors (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 quality. The numerous regenerators/transponders and other devices in the path of a 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.

2.5 Security

Optical fibers too facilitate secure connections. Quantum cryptography is one such operation, which exploits the fundamental properties of quantum complementarity (The concept that particle and wave behavior are mutually exclusive, but, are together necessary for the complete description of any phenomena) 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 conventional complexity-based approaches to security, privacy is achieved by posing a difficulty mathematical problem to the interceptor, which is computationally intensive. In contrast, *Quantum Key Distribution (QKD)*, as it is called, provides a new paradigm for the protection of sensitive information in which security is based on fundamental physical laws.

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3. DWDM COMPONENTS

Important components of a DWDM system are the ***Add/Drop Multiplexor (ADM)***, the ***Optical CrossConnect (OXC)***, ***Optical Splitter***. The Add/Drop Multiplexor as the name suggests, selectively adds/drops wavelengths without having to use any SONET/SDH terminal equipment. We require the ADM 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***.

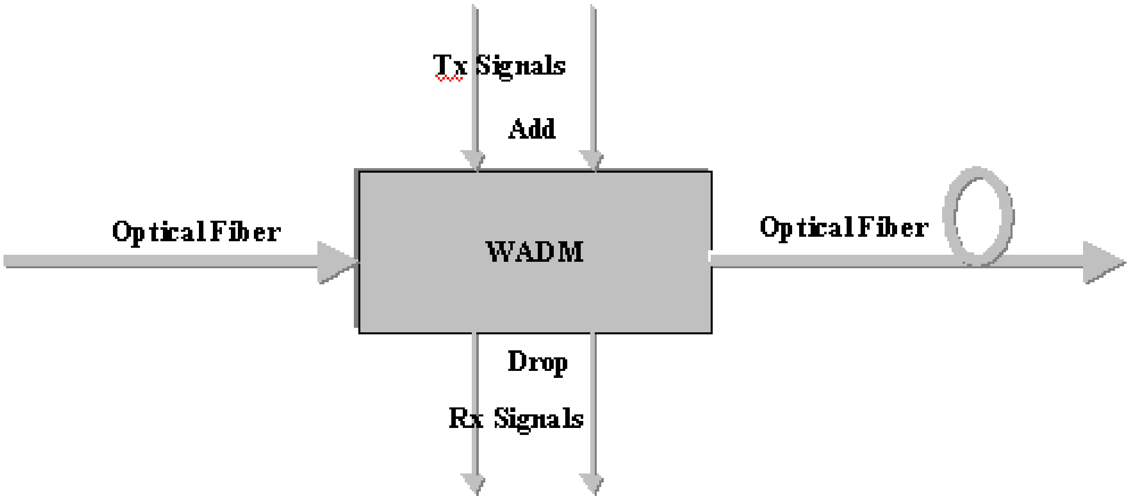

Fig.3 Block Diagram of the WADM

The Optical CrossConnect acts a crossconnect between n-input ports and n-output ports. It allows the efficient network management of wavelengths at the optical layer. The variety of functions that it provides are signal monitoring, restoration, provisioning and grooming.

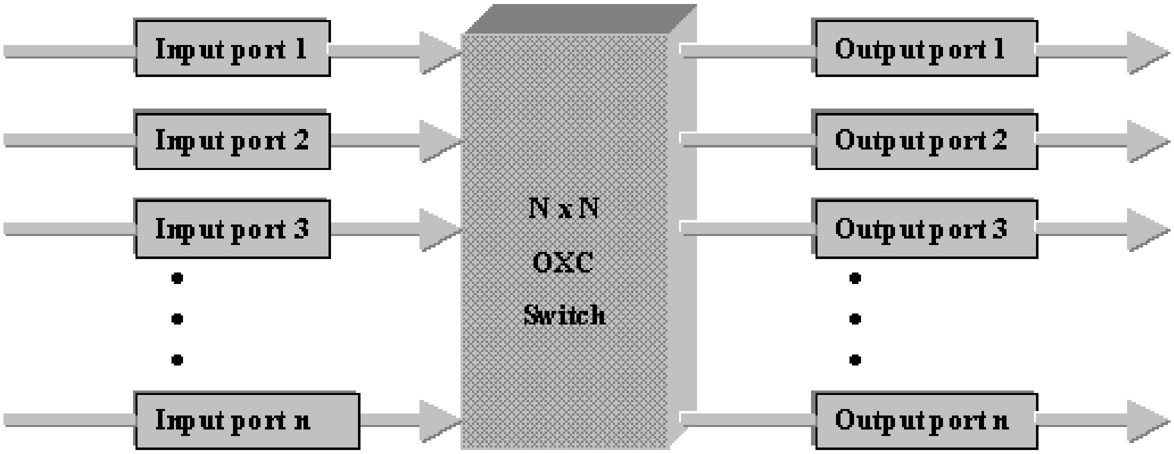

Fig.4 Block Diagram of the OXC

Optical Splitters are being suggested for use in multicast-capable wavelength-routing switches to provide optical multicasting. It is a passive device that will help in replicating optical signals. This is explained in detail in a later section. [**4.2**]

Optical Gateways are devices that will allow the smooth transition of traffic to the optical layer. We can have high-speed ATM networks or a mix of SONET and ATM services with such a gateway. They provide the maximum benefits of optical networks.

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4. OPTICAL NETWORK ARCHITECTURE

Just like every other layer defined in networking, a layer architecture has to be defined for the optical layer. O.Gerstel, P.Green and R.Ramaswami in [**GERSTEL96**] have tried achieving this goal. A multi-wavelength mesh-connected optical network is used to define the architecture of the *optic layer*. A *lightpath* is defined as the path between two nodes and is equivalent to a wavelength on each link on that path. Two aspects of the network topology have been described : physical topology and virtual topology.

The physical topology has WDM cross-connect nodes interconnected by pairs of point-to-point fiber links in an arbitrary mesh topology as shown in the following figure.

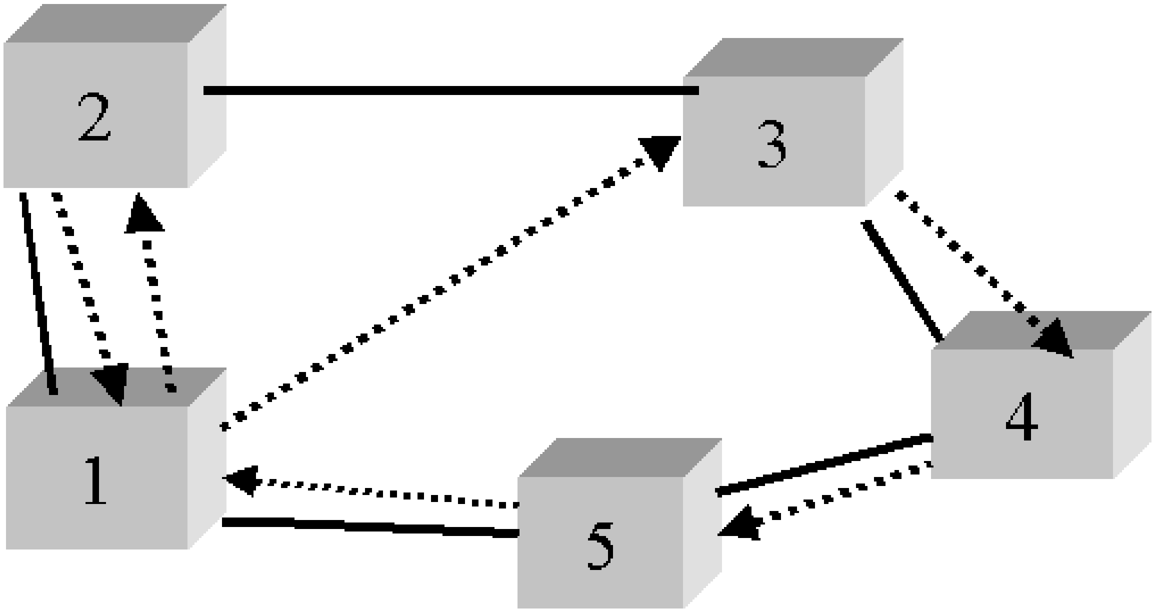

Fig.5 A WDM network consisting of crossconnect nodes interconnected by pairs of point-to-point fiber optic links(i.e physcial topology)

4.1 Virtual Topology

As shown in the below figure, the *virtual topology* of a network is the set of all lightpaths. It is a logical topology and the direction of the arrows actually show the direction of the lightpaths.

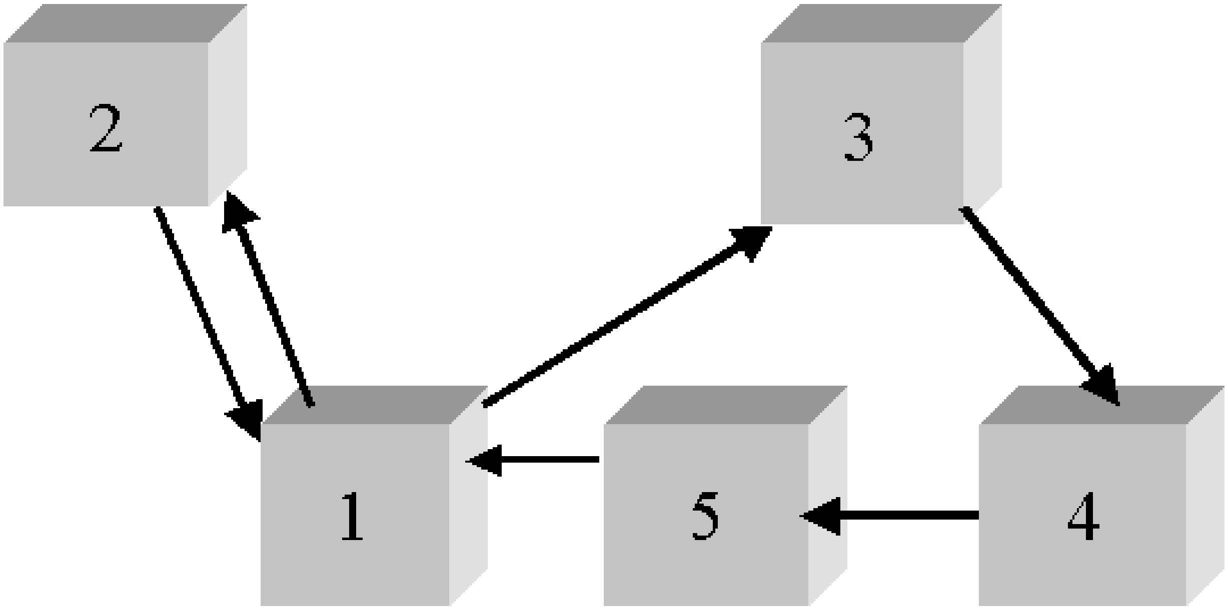

Fig.6 The virtual topology of the WDM network of previous figure

An *optical layer*, also known sometimes as Layer 1, is the layer between the physical layer and the datalink layer or other higher layers for that matter. By using this additional layer in say an ATM network, we would be removing the need of having to convert to optical signal to electric signals and to cells before switching them through ATM switches, if we have wavelength switches in the network. ITU-T SG 15 has defined the optical layer itself as consisting of layers.

The three sublayers of the optical layer are:

- *Optical Channel(OCh) layer*: This corresponds to light paths
- *Optical Multiplex Section(OMSn) layer*: This corresponds to links
- *Optical Amplifier Section(OASn) layer* : This corresponds to link segments between optical amplifiers.

However, in [**GERSTEL96**] more emphasis is laid on the standardization of control and management aspects. The authors make some assumptions about the networks like low setup rate, isolation from physical constraints and routing of bi-directional lightpaths.

4.2 Optical Layer and Higher Layer Interface

Just like every other layer-layer communication, optical layer communicates with the higher layers, both above and below in the protocol stack by means of *Service Data Units (SDUs)*. Besides these guarantees, SDUs also have to be defined to allow for proper exchange between higher layers and the optical layer (in both directions).There are certain services that this new layer must provide to the higher layers.

Addressing

It is obvious that there must be some mechanism for the higher layers to ask for lightpaths from particular nodes in the network. This is done by having an addressing scheme to describe the nodes in the network.

QoS

It is imperative that QoS parameters be provided. Since our eventual goal is to allow an integrated service of transport across networks, this layer must be able to accept any type of layer above it, ATM, SONET, IP etc. Hence this requirement of QoS parameters. The authors [**GERSTEL96**] have given an example of all the parameters that might be needed.

Some research is being done on all differentiated QoS especially with respect to All-Optical WDM Multi-Rings [**MARSAN99**]. Many of the current WDM network architectures require as many wavelengths as there are nodes. This implies a dedicated logical channel for either transmission or reception for each destination. The particular case of multichannel slotted rings has received some attention based on their being attractive solutions for all-optical LANs and MANs. In [**MARSAN99**] the authors assume the following diagrammatic structure with the specific example of the number of nodes (N) = 4.

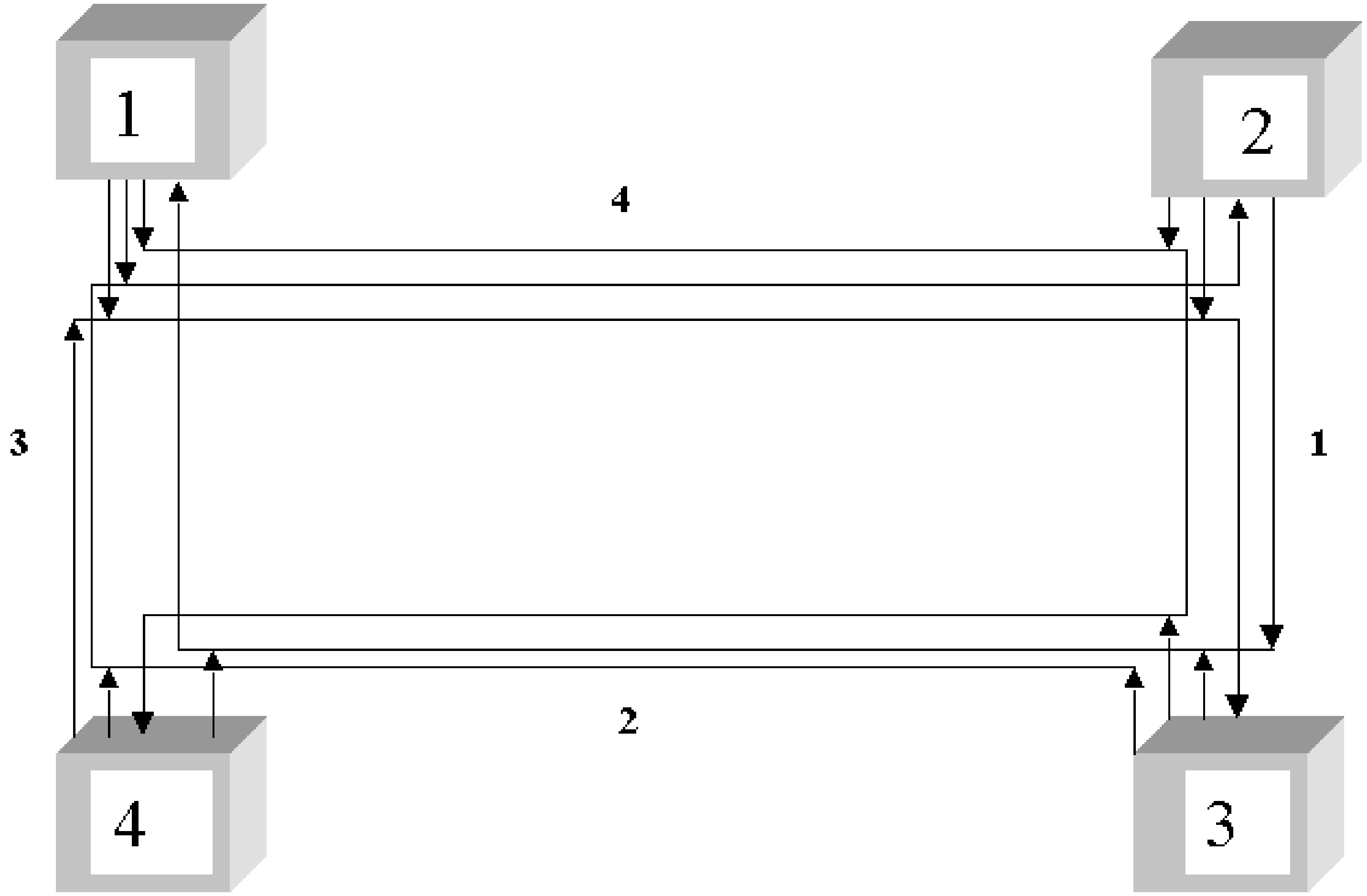

Fig.7 A "roundabout" diagrammatic structure with the number of nodes(N)=4

This structure resembles the "roundabouts" that are there on the roads in many countries. All sources needing to transmit to the same destination must share the corresponding channel. Each node is assumed to have one tunable transmitter and one fixed receiver. Hence, the MAC protocol that has been suggested for this architecture is the *Synchronous Round Robin with Reservation (SR^3)*. It has been divided into 3 heirarchical layers: *access strategy using the **Synchronous Round Robin (SRR)** scheme, the fairness control scheme i.e the **modified MultiMeta Ring (MMR)** scheme and finally a reservation scheme*.

This SR^3 scheme hence provides atleast theoretically, an almost optimal exploitation of the available resources and fair allocation of resources. The reservation scheme allows in controlling queueing delays. The experimental results of [**MARSAN99**] seem to indicate that delay performance is improved for both pure best-effort traffic and also a mixture of guaranteed-quality and best effort traffic. Thus, bandwidth allocation and connection establishment procedures can be easily introduced into systems whose whose traditional mode of operation is connectionless. Since this SR^3 scheme allows reservation of a set of slots by nodes at call setup, it can also be used for applications with QoS requirements.

Multicast capability

This is an optional capability depending on whether multicasting is a feature enabled in the network.

Some research has been done in this area [**SAHASRABUDDHE99**]. Here, the concept of a ***light tree*** is introduced. A light tree is a point-to-multipoint version of a lightpath. Optical multicasting capability at routing nodes has been suggested to increase logical connectivity and thereby further reduce the hop distances that have to be traversed. Optical multicasting is better than electronic multicasting because it is easier to split an optical signal into many identical optical signals rather than copying a packet in an electronic buffer. Using optical splitters does this function of "splitting" an optical signal.

An *n-way* optical splitter is a passive device that does the above defined "splitting" in such a way that atleast one output signal has a power less than or equal to 1/n th times the input power. Optical amplifiers would be needed in the network. The suggested approach is to have a so-called *splitter bank*. This splitter bank will do the optical splitting and also the optical signal amplification. An interesting point is that this splitter bank could have more features such as *wavelength conversion* and *signal regeneration* for "multicast" as well as "unicast" signals in the network.

Now this splitter bank is then used to construct a multicast-capable wavelength-routing switch(MWRS). The basic components of this MWRS are optical switches, splitter bank, multiplexors, demultiplexors. Information coming in through a fiber link is first demultiplexed into separate signals (different wavelengths) and then switched by an optical switch. At this point depending on whether the signal is unicast or multicast, they are sent through different paths. The multicast signals are sent to the splitter bank and the amplified multiple identical signals are then switched by another optical switch. Finally all the signals that are to be sent out on one fiber link are multiplexed together before being sent out.

Mathematic formulation of the light-tree-based virtual topology design problem isthe next step. An optimization problem having any one of the following objective functions is possible:

- Minimization of the network-wide average packet hop distance.
- Minimization of the total number of opto-electronic components.

By solving a mixed-integer linear program for this optimization problem the authors [**SAHASRABUDDHE99**] found that compared to the lightpath-based virtual topology, the light-tree based virtual topology scaled better for both objective functions.

Uni or Bi-directional lightpaths

When all wavelengths travel in the same direction within a fiber, those wavelengths are called unidirectional wavelengths(or lightpaths). The implication here is that another parallel fiber has to be there that supports the opposite direction lightpath

When we have the whole channel split in such a way that for each lightpath in the forward direction there is another lightpath in the opposite direction within the same fiber, such lightpaths are known as bi-directional lightpaths. It is obvious that the transmission bandwidth is reduced. Which one of these lightpaths is chosen depends on the type of traffic.

Since failure recovery is a very important aspect of any network, *network control* has been proposed as a decentralized function though for the early versions a centralized function is also acceptable. *Network management* criteria, interfacing between network control and network management has all been properly defined.

Finally, it is important to realise that there will many such WDM networks belonging to various carriers, organizations etc and for this the authors of [**7**] use a two-level hierarchy. This is similar to the routing protocol of ATM networks: PNNI. The two levels are as follows:

1. The lower level hierarchy is the level of the physical node and the links are physical fibers.
2. The upper level is the level where each node is actually a subnet and the links at this level are nothing but the links between two subnets. The routing protocols that could be used are similar to IGP at this level.

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5. DWDM ARCHITECTURE

Using some of the basic concepts of DWDM systems, it is possible to form an All-Optical layer. Transport of Gigabit Ethernet , ATM, SONET, IP on different channels is feasible. By achieving this, the system becomes more flexible and any signal format can be connected to, without the addition of any extra equipment that acts as a translator between the formats. In this section we will talk about the various types of technologies that can be used over DWDM systems. In particular, we will discuss ***ATM over DWDM*** and ***IP over DWDM.***

5.1 ATM over DWDM

As bandwidth requirements increase, Telcos are faced with huge investments in order to fulfil the capacity demands. Along with this the demand for QoS has increased. There seems to be a general move towards providing QoS while still maintaining the same capacity. ATM over DWDM solves the bandwidth and Quality of Service issues in a cost-effective way. In DWDM networks, if there is a carrier that operates both ATM and SONET networks there is no need for the ATM signal to be multiplexed upto the SONET rate. This is because the optical layer can carry any type of signal without any additional multiplexing. This results in the reduction of a lot of overlay network.

While there are a lot of advantages of running ATM over DWDM, there are certain issues that are of importance that need to be considered. They are channel spacing (four Wave Mixing) and optical attenuation. Hence, we need good wavelength conditioning techniques to solve this problem. The techniques used are Forward Error Correction Technique and the pilot light technique. By using the latter technique network management systems are able to ensure connectivity, signal on each channel and also identify faults. This network management is similar to the way test cells are used on specific Virtual Channels in ATM.

Testing ATM over DWDM

Testing of ATM over DWDM consists of similar concepts to those provided in ATM over SONET. However, with DWDM it is more complex because we now have multiple parallel links on a single fiber. So besides the need of taking into account the connectivity and the conformance to QoS agreements, we need to make sure that these parallel links are all mutually exclusive. Hence, the following parameters need to be measured:

- Signal-to-noise ratio
- Channel power
- Channel center wavelength and spacing
- Crosstalk
- Total Optical Power
- Chromatic dispersion
- Polarization Mode Dispersion

5.2 IP over DWDM (or IP over lambda)

The ultimate solution would be to take IP directly over DWDM. This will bring about scalability and cost-effectiveness. Now we have industry products that actually implement IP over DWDM for example Monterey Networks(bought by Cisco in August '99) have their Monterey 20000 Series Wavelength Router&trade.They claim that by using their product, "service providers can traffic-engineer and rapidly scale up survivable mesh optical cores without introducing intermediate ATM switches or proliferating legacy SONET multiplexers and cross-connects".

In effect we are totally eliminating ATM and SONET layers from the networks. The proponents of IP over DWDM say that SONET’s reliability is due to a lot of redundancy. This overkill prevents the network from using a large portion of its resources. The real test is whether it would be possible to create an end-to-end optical Internet operating from OC-3 to OC-48 and build systems around an optical Internet backbone. Compare that with the news that SONET handles OC-192 smoothly and can touch OC-768. As of March’99, all the IP over DWDM systems that were operational were all SONET frame based.

With the development of erbium-doped fiber amplifiers most systems that use IP over DWDM using SONET frames have removed the SONET multiplexors. GTS Carrier Service in March, launched the first high capacity transport platform in Europe that uses IP over DWDM technology. Further more, major carriers such as AT&T, Sprint, Enron, Frontier, Canarie, have all begun to realize the huge economic potential of IP over DWDM and there is no longer any skepticism about this technology.

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6. WAVELENGTH ROUTING IN OPTICAL NETWORKS

An optical network consists of wavelength routers and end nodes that are connected by links in pairs. The wavelength-routing switches or routing nodes are interconnected by optical fibers. Although each link can support many signals, it is required that the signals be of distinct wavelengths.

Routers transmit signals on the same wavelength on which they are received. An *All-Optical* wavelength –routed network is that wavelength-routed network that carries data across from one access station to another without any O/E (Optical/Electronic) conversions.

Categories of Wavelength Switches (or routers as the authors call them):

Non-reconfigurable switch: These types of switches, for each input port and each wavelength, transmit onto a fixed set of output ports at the same wavelength. These cannot be changed once the switch is built. Networks that contain only such switches are called non-reconfigurable networks.

Wavelength-Independent Reconfigurable switch: These type of switches have input-output pattern that can be dynamically reconfigured. However, the input-output pattern is independent of the wavelength of the signal i.e. there are only fixed sets of output ports onto which an incoming signal can be transmitted.

Wavelength-Selective Reconfigurable Switch: These types of switches combine the features of the first two categories. Also known as *generalized* switch, they basically have both the properties of dynamic reconfiguration and the routing pattern being a function of the wavelength of the incoming signal.

Reconfigurable routers are of bounded degree, while nonreconfigurable routers may not be. That is, the complexity of non-reconfigurable networks can be ignored as it is not of a fixed degree. However, the complexity of reconfigurable networks is strongly dependent on its degree and it is bounded.

6.1 Efficient routing Algorithms

Permutation routing problem

Each end node in a permutation problem is the origin of atmost one session and also the destination of atmost one session at any given time. They introduced a new concept called the *widesense nonblocking criterion*. This criterion effectively insures that at any instant of time, the session present in a network constitute a permutation problem and that no session is every blocked.

A routing scheme is *oblivious* if it always uses the same wavelength to satisfy a given connection request; it is *partially oblivious* if the wavelength must be chosen from a subset of available wavelengths. Bounds on the number of wavelengths needed for oblivious, nonoblivious, and partially oblivious wide-sense nonblocking permutation routing for nonreconfigurable networks were calculated and can be found in the above mentioned paper. For reconfigurable networks, bounds are given on the number of routers needed, with the number of wavelengths as a parameter.

[**PANKAJ95**] focussed on the permutation routing problem in a homogeneous WDMA network, i.e a network having both an input/output port and a switch. A lower bound as well as an upper bound on the number of wavelengths that are necessary for permutation routing as a function of the size and the degree of the network was calculated. Topologies considered were the hypercube, Debruijn and the multistage perfect shuffle.

Lower Bound

By simply counting the number of links in the network , it was concluded that the number of wavelengths must grow atleast as fast as Ω (logN/log d) where N is the number of nodes in the network and d is the degree of the network. "A session requires *h* link-wavelengths if it is routed on an *h* hop path since it uses one wavelength channel on each of the *h* links."

The upper bound is O((logN)^3) and is independent of the degree of the network.

Finally, the problem of determining the number of wavelengths needed to implement any routing scheme for any network, as a function of the congestion and dilation of that network is discussed.The upper and lower bounds together given in [**AGGARWAL96**] and [**PANKAJ95**] for the various kinds of networks suggest that a more heirarchical structure in which switching nodes are separate from input/output nodes may be more promising for all-optical networks"

Research work has been done in solving the problem of routing connections in a reconfigurable optical network using WDM **[RAMA95]**. An upper bound on the carried traffic of connections is derived for any *routing and wavelength assignment(RWA)* algorithm in such a network. A fixed-routing algorithm achieves this bound asymptotically. The RWA problem was formulated as an Integer Linear program (ILP). This bound was found to be good for optical network using dynamic wavelength convertors. Two routing node architectures were presented. In the first structure it was found that as the number of edges increased the reuse factor increased. Also the reuse factor with wavelength convertors was higher than that without one for small values of wavelength systems. Also it is assumed implicitly that in networks without wavelength convertors , two connections can be assigned the same wavelength as long as they don’t share any link in the network.

An important aspect of [RAMA95] was to find the reuse factor for larger networks as a function of the number of nodes, edges and wavelengths via simulation. Based on the results, it was inferred by the authors that it is possible to build all-optical networks without wavelength convertors. However, only a modest number of connections per node with a reasonable number of wavelengths is supported. Using 32 wavelengths it is possible to provide 10 full-duplex connections to each node in a 128-node random network with average degree 4, and 5 full-duplex connections per node in a 1000-node random network with average degree 4.

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7. WAVELENGTH CONVERSION IN OPTICAL NETWORKS

The networks that we have been discussing about until now can be said to be *wavelength-continuity constraint networks*. In such networks, to establish any lightpath, we require that the same wavelength be allocated on all of the links in the path. Suppose we have the following portion of a network. The wavelengths λ_1 and λ_2 that are shown in dotted arrows are the free wavelengths between nodes 1,nodes 2 and node3 respectively. There are 2 wavelength converters , one in node 2 and another in node 3. Here it is not possible to establish a lightpath from 1 to 4 without a wavelength converter because the available wavelengths are different on the link.

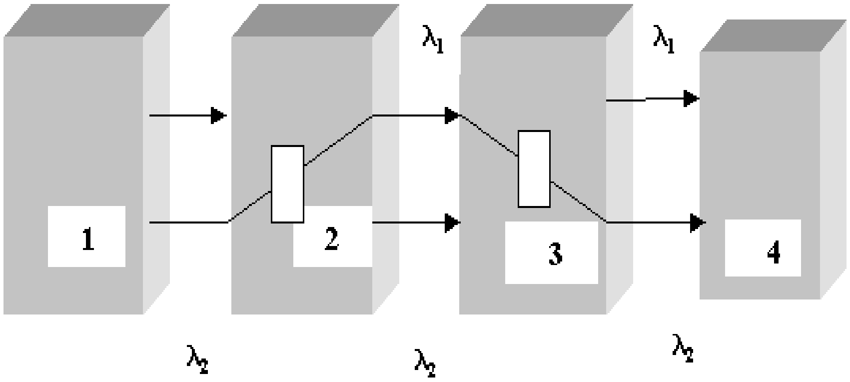

Fig.8 Wavelength Conversion

So, we could eliminate this problem by converting data that is arriving on the link from node 1 to node 2 on λ_1 to λ_2 on the link between node 2 and node 3. Such a technique is called ***wavelength conversion***. Functionally, such a network is similar to a circuit-switched network. For any model of optical routing, we need to make as efficient use of the given optical bandwidth that we have as possible. Wavelength convertors have been proposed as a solution to this problem. ***Wavelength convertors*** have been defined earlier in this report as those devices that convert an incoming signal's wavelength to a different outgoing wavelength thereby increasing the reuse factor. Wavelength convertors offer a 10%-40% increase in reuse values when wavelengths availability is small [RAMA95].

Categories of Wavelength Conversion

No conversion: No wavelength shifting

Full conversion: Any wavelength shifting is possible and so channels can be connected regardless of their wavelengths.

Limited conversion: Wavelength shifting is restricted so that not all combination of channels may be connected.

Fixed conversion: Restricted form of limited conversion that has for each node , each channel maybe connected to exactly one predetermined channel on all other links.

Sparse Wavelength Conversion: Networks are comprised of a mix of nodes having full and no wavelength conversion.

7.1 Wavelength Conversion related Algorithms

We will be comparing the algorithms propounded by [**GERSTEL**], [**RAMA98**], [**WILFONG98**] , [**KLEINBURG99**]. It is obvious that we will always need as many wavelengths as the maximum number of paths sharing a single edge. Also, if we were to use a convertor at every node of a directed graph ***G*** the minimum number of wavelengths required in a valid assignment would be equal to υ (**P**).

υ (**P**) is the natural congestion bound or the maximum number of paths/valid wavelength assignments passing through any single edge. In the absence of convertors we might have the minimum number of valid wavelength assignments to be greater than υ (**P**). This led Wilfong and Winkler [**WILFONG98**] to define a subset ***S*** of the nodes of the graph ***G*** any set **P** of paths has a valid assignment with only υ (**P**) wavelengths. It is an NP-complete problem to find a sufficient set of minimum size for a given graph ***G***. Amit Kumar and Jon Kleinburg in [**KLEINBURG99**] provide a polynomial-time algorithm to find a sufficient set for an arbitrarily directed network whose size is within a factor of 2 of minimum.

In the paper by R. Ramaswami and G.Sasaki [**RAMA98**] the approach used is of a restriction on the number of wavelength conversion at a node. This is contrary to the other papers where we have no restrictions whatsoever on the wavelengths of the channels it can connect but a restriction on the number of wavelength convertors. The authors propose ring and star networks with limited wavelength conversion to support sets of lightpaths efficiently. The amount of wavelength shifting required is very minimal in these networks. Other models considered were the tree and mesh networks.

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8. MARKET SCOPE AND COMPANY PROFILE

Much work is being done in developing optical add/drop multiplexors (OADM) and optical cross-connect switches(OXCS). Metropolitan area networks will be the ones that use these OADMs. However, a lot of work remains to be done for large scale adoption in the industry.

As of today, most networks consist of the physical layer, the SONET layer, ATM layer and the IP layer on top of that. With carriers adding DWDM capabilities to their fiber networks to handle higher volumes of data traffic, SONET technology is fast becoming obsolete. For example, Williams is already rolling out ATM over fiber with its **FLEX-UNI$^{\mathbf{SM}}$**technology. By using non-zero Dispersion Shifted fiber it has OC-192 capacity. Imagine being able to download the whole of "Titanic" movie in less than a second. Using DWDM it is now possible to provide OC-48 channels connected directly to ATM and IP network equipment without extra cost of SONET multiplexors. With the advent of DWDM that is due to R&D labs, providers will now not need to have the expense of laying new fiber to handle bigger load. Companies like WorldCom and its subsidiary Uunet Technologies already have WDM in their networks to multiply capacity. Providers like Qwest Comm., IXC Communications and Level 3 Communications have started using advanced DWDM systems in their fiber laying stage itself.

A lot of companies now have products ranging from fibers to amplifiers to intelligent Optical switches,routers e.g. Lucent(**WaveStar, LazrSPEED fiber, OptiStar**), Ciena(**MultiWave Core Director)**, Monterey Networks(bought by cisco), Alcatel, Nortel Networks, Sycamore Networks, Adva Optical Networking , Williams Network (**FLEX-UNI^{SM}**) etc

8.1 Ciena Corporation (http://www.ciena.com)

Ciena is one of the leading optical networking systems manufacturer in the market today. It has developed a series of products. They have a vision of the so-called "LightWorks" which is a complete, Intelligent Optical Network architecture.

CIENA's LightWorks architecture now offers bandwidth and intelligence in three areas of the telecommunications infrastructure:

Optical transport systems:

- *MultiWave CoreStream*: Capable of handling a capacity of upto 2 Tbps it was designed for global long haul carriers who require scalable capacity, design flexibility and high reliability. http://www.ciena.com/products/corestream/index.html
- *MultiWave Metro*: Allows upto 24 duplex channels over a single fiber pair, enabling the fiber to carry up to 60 Gbps. Its main use is in metropolitan ring applications. Metro can simultaneously support point-to-point, Star, Ring, or Mesh configurations. Its architecture allows easy interfacing with SONET/SDH, ATM, and Fast IP equipment and most embedded network management system

http://www.ciena.com/products/metro/index.html

- *MultiWave Sentry*: Allows throughput of up to 40 Gb/s. This system enables carriers to mix SONET/SDH, ATM, Fast IP, and asynchronous traffic on a common optical network.. This enables the construction of ATM and Fast IP networks without an intervening synchronous layer.

http://www.ciena.com/products/1600-sentry/index.html

- ***Intelligent core switching***: *MultiWave CoreDirector™*:It facilitates scalable, ultra-high density, high-capacity switching(640Gbps). An advanced set of protection and restoration capabilities allows carriers to build mesh, ring or hybrid mesh-ring optical cores without legacy SONET equipment. This product was acquired by Ciena with the purchase of Lightera.

http://www.ciena.com/products/coredirector/index.html

- ***Harnessing core fiber capacity and delivery***: *MultiWave EdgeDirector™ 500*: This product provides an overall solution by allowing the network providers "to offer legacy voice and new high-speed data services across an end-to-end intelligent optical network." CIENA acquired the MultiWave EdgeDirector 500 with the purchase of Omnia Communications on July 1, 1999.

http://www.ciena.com/products/edgedirector/index.html

Considering the fact that a broadband networking system will require high capacity intelligent optical switching and transport systems besides good access systems, ciena seems to be a step ahead in the race to dominate the optical networks market.

8.2 Lucent Corporation (http://www.lucent.com)

Lucent technologies, especially its R&D division Bell Labs are setting new upper limits in the development of serial transmission systems. Bell Labs has more than 2000 patents in the optical technology field. Lucent was the first to market an 80-channel DWDM system at 400 Gigabits per second over a single fiber. Following are some of the news reports that show the pace at which Lucent has been developing new DWDM systems.

- Nov 10. 1999: Scientists at Bell Labs have developed a practical 160-gigabit DWDM system that is able to transmit information at the rate of 160 gigabits/second over 300 km of optical fiber using a single wavelength of light. This single-channel transmission was done over Lucent's **TrueWaveRS™** fiber. It has been developed specifically for high-capacity DWDM systems.
- Oct 11 1999: Bell Labs achieved 10-gigabit serial transmission over ***1.6 km*** of Lucent's new **LazrSPEED** multimode fiber. The error rate was less than one in one trillion.
- Oct 6 1999: Lucent Technologies announces the breakthrough adapter cards and software that will deliver IP over Optics all the way to the server. The product **OptiStar** includes breakthrough network and storage adapter cards and

software that will dramatically increase the amount of data that servers can handle and accelerate the flow of information from a server's hard drive to the end user. **OptiStar**series will replace the 45 MBps WAN connectivity with upto 2.5 GBps fiber link.

- Sept 22 1999 : Lucent announces the addition of the following three new products to the existing **WaveStar** series:

1. **WaveStar MetroPoint OLS**: Point-to-point optical networking system that transmits upto 40 GBps while saving costs upto 60% in costs.
2. **WaveStar AllSpectra OLS**: An optical enterprise system that transmits information using lasers that are 50 % cheaper.
3. **WaveStar OpticGate series**: Network cards that enable data vendors to integrate Lucent's high speed optics with their IP routers and ATM switches.

8.3 Sycamore Networks (http://www.sycamorenet.com)

Sycamore Networks, a Massachusets based 1998 startup is the trailblazer of 1999 in terms of optical networking products. They have the market leading products in intelligent optical networking which integrate the intelligence of SONET/SDH and the capacity of DWDM with state-of-the-art optical networking software to deliver the most flexible and cost-effective solution to public network scaling and service delivery issues. Their products include:

1. **SN 6000 Intelligent Optical Transport Node:** This product allows the use of the so-called "just-in-time" OC-48/STM-16 wave services optimized for private line, high-speed data applications. It provides wavelength conversion and optical multiplexing of the OC-48/STM-16 signals, which are then merged with the OC-192/STM-64 signals for transport over embedded SONET/SDH transport infrastructures. This reduces a lot of expense on SONET/SDH upgrades.
2. **SN 8000 Intelligent Optical Network Node:** This product supports end-to-end provisioning and management of high-speed services across all segments of the optical network. It claims a reach of 1600km without regeneration and is looking to be the preferred network node choice for optical networks. Its strongpoint is the use of the following concepts.
    - "**Optical handoff**" i.e. the transport of optical signals in the optical domain across the backbone and the backbone-access interface (hence there are no O-E-O conversions) and
    - "**Wave sharing**" i.e. an innovative method of combining multiple OC-12/STM-4 and OC-3/STM-1 services into one aggregate OC-48/STM-16 signal.

3. **SILVX Optical Network Management System (ONMS):** It forms the core of Sycamore's software-centric optical architecture. It delivers a scalable management platform to ensure that Sycamore's entire range of Intelligent Optical Networking products can be efficiently introduced into the network.

Sycamore already has a commitment from Williams Communications to use its intelligent optical transport and switching products to provide new long haul services.

8.4 Ericsson (ERION^TM^)(http://www.ericsson.com/US/erion/index.shtml)

Ericsson's ERION group is also in the forefront of today's optical networking and DWDM research. The ERION product family's most publicised product is the **ERION Networker**, the world's first optically protected metro ring. It makes use of the patented **FlexingBus** Technology on top of the Networker DWDM product to provide a ring of circumference 500 kilometres. This distance has stretched the boundaries of the traditional metro environment to what they call a ***Wide Area Metro (WAM)***. This implies that a host of small metropolitan cities come with ambit of this ring. This self-healing optical ring also facilitates the use of ATM over DWDM, IP over DWDM. ERION Networker has been optimized to meet the needs of the emerging metro and WAM markets with an open architecture, manageability and the most scalable DWDM platform. Other products include the GUI software Ericsson Local Manager that mimicks the real life DWDM Network Elements and the Integrated Management Application, an element manager for ERION's DWDM product.

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SUMMARY

In this paper we have discussed various concepts that are integral to the development of the All-Optical Network. Various new technologies available in a DWDM system were introduced. A proposed optical layer was described in much detail. Issues such as Network Control and Network Management was also discussed. Finally the state of the market for optical networking, company profiles and research scope in optical networking and DWDM were discussed.

It is very much possible that a day will come when only two optical layers will exist: WDM layer and IP layer. However, SONET equipment has two features: restoration and trouble-shooting capabilities. For this reason and also for the reason that a lot of investment into SONET has already taken place, SONET will survive. As routers become faster, it will be difficult to convert every wavelength to add or drop off bandwidth. Thus, managing 100+ wavelength systems is probably the next big challenge. Companies like Alcatel have developed OADMs. Standard bodies like ITU-T, ANSI have declared that optical standards will come into picture only after 2000.

Research work is also being done to try and achieve the difficult goal of a high-speed all-optical network. New concepts such as All-optical switching are coming up. 1 Tbps systems are expected in the market by early 2002/2003. Network providers will start leasing out wavelengths (or "lambdas") instead of leasing lines. Cost will be an important issue in widespread deployment of optical systems. A lot of implementation issues, the setting up of standards need to be addressed for an all-optical network to come out at a reasonable cost. How long or for that matter whether we will ever achieve an all-optical network is a moot question.

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LIST OF ACRONYMS

ADM	-Add/Drop Multiplexor
ANSI	-American National Standards Institute
ATM	-Asynchronous Transfer Mode
DBFA	-Erbium Fiber-based Dual-band Fiber Amplifier
DWDM	-Dense Wavelength Division Multiplexing
EBFA	-Extended Band Fiber Amplifier
ERION	-Ericsson Intelligent Optical Network
IP	-Internet Protocol
ITU	-International Telecommunications Union
MMR	-Modified MultiMeta Ring
MPLS	-Multiprotocol Label Switching
MWRS	-Multicast-capable Wavelength-Routing Switch
OA	-Optical Amplifier
OADM	-Optical Add/Drop Multiplexor
OASn	-Optical Amplifier Section layer
OCh	-Optical Channel layer
O-E-O	-Optical to Electronic to Optical
OMSn	-Optical Multiplex Section layer
OXC	-Optical CrossConnects
QKD	-Quantum Key Distribution
UWOA	-Ultra-Wideband Optical Amplifier
RWA	-Routing and Wavelength Assignment
SDH	-Synchronous Digital Hierarchy
SONET	-Synchronous Optical Network
SR^3	-Synchronous Round Robin with Reservation
SRR	-Synchronous Round Robin
TDM	-Time Division Multiplexing
WAM	-Wide Area Metro
WDM	-Wavelength Division Multiplexing

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