Next Move: Evolution Toward All-Optical Transport Networks

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ABSTRACT

Optical transportl networks are growing at an extraordinary rate in order to meet the unprecedented demands for higher bandwidth. Accelerated researches are progressing to develop sophisticated photonoic devices and introduce advanced technologies that can cope with this challenge. All-optical network employing Dense Wave Division Multiplexing (DWDM) offers the required solution, whereby the network can gracefully evolve to meet the indefinite future bandwidth and flexibility requirements. This paper discusses the basic concepts of all-optical networks, the drivers for the evolution of this new network, and the role of DWDM as the enabling technology in this progress. The paper will also present the key technologies and the different components involved in all-optical networks.

INTRODUCTION

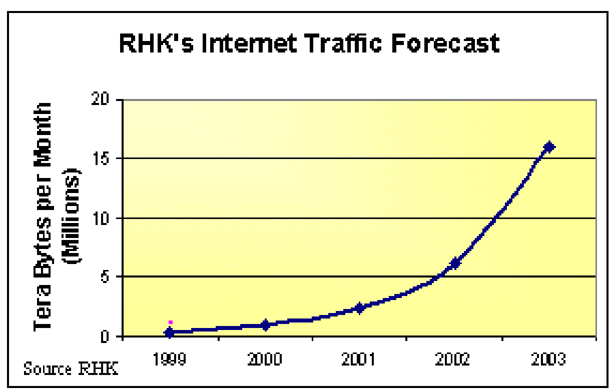
The explosive rate of bandwidth demands driven mainly by the Internet requires a tremendous growth in the transmission capacities. In an all-optical network, time-division multiplexing (TDM) builds aggregate signals transported over optical channels which then can be switched and processed optically. Each optical channel occupies one wavelength on a Wave Division Multiplexed (WDM) system and can be routed through the network. In this way, most of the signal processing functions are moved from the electrical domain to the optical domain, thus providing faster processing and more homogeneous network. This will also allow for the transport of different signals of certain formats and diverse bit rates such as SDH/SONT, ATM, Gigabit Ethernet and IP protocols on individual wavelengths.

SDH/SONET are proven TDM technologies supported by well-established international standards enabling multi-vendor interoperability. These technologies have been widely deployed in the current transport networks providing high degree of flexibility, survivability and are scalable to gigabits per second rates, with good jitter and wander performance figures. To exploit the potentially unlimited bandwidth of the fiber optic and to make use of the rapid advancement in the fabrication of optical devices, the transport networks are evolving from TDM technologies into the WDM all-optical networks.

Optical networking operates predominantly in the optical domain, where the unit of bandwidth (the optical channel) is much larger than in TDM networks [1]. The evolving network needs to be robust to accommodate the variation in requirements between the transported signals in terms of traffic rates, levels of Quality of Service (QoS), reliability and protocols. The network should be also efficient in providing reduction in the capital expenditure and the flexibility of the network management.

TRANSPORT CAPACITY GROWTH

Although the current optical fiber networks have lots of capacity due to implementation of WDM, this bandwidth needs to be optimized to provide quality optical services. The most influencing service driving the capacity requirements is the Internet. A conservative estimate of the Internet traffic growth is that it doubles every six months [2]. This is due to the fact that the number of Internet users is increasing every day and the applications accessed such as image and audio files require high bandwidth. According to a recent study released by telecom market research firm RHK, Internet traffic in North America has reached 350,000 terabytes per month. The following chart summarizes RHK's estimate of current Internet traffic and growth rates [3].



Other factors influencing this growth include data mirroring and backups, optical-based storage technologies, video-based applications, E-commerce and leased lambdas. This exponential growth is pushing the existing transport networks to its limits as the TDM -based systems deployed in the long haul transport networks are currently limited to bandwidth of 10 Gb/s with 40 Gb/s applications to emerge in the near future. Making the required capacity available is a real challenge as optical fibers are being connected to desktops and 64 Kb/s rates to homes will be replaced by 1.5 to 5 Mb/s in the near future through the use of ADSL technology.

LEGACY TRANSPORT NETWORK

Transport networks are presently in the phase of transition from TDM-based SDH/SONET to WDM-based networks. Legacy SDH networks have well defined electrical and optical interfaces ranging from 155 Mb/s (STM-1) to 9.8 Gb/s (STM-64). The three dominant network elements existing in the SDH networks include the low tributary terminal multiplexers, the Add-Drop Multiplexers (ADM) and the Digital Cross-Connect Systems (DXS). The extremely increasing demand for bandwidth has exhausted the available bandwidth in the core networks. To manage this demand, network operators had to find ways to increase the capacity. Traditional solutions included the deployment of additional fiber cable facilities and the upgrade of the existing aggregate speeds to higher ones through the replacement of terminal equipment. An alternative to these two expensive solutions is the deployment of point-to-point WDM systems which provides the required capacity upgrade in a cost effective manner.

In a typical WDM system, separate laser sources generate modulated signals at certain wavelengths (lambdas). Each optical channel is modulated with the information need to be carried. The different signals are then coupled in an optical device called Wave Division Multiplexer which deliver them to the transmitting fiber. At the receiving end, the transmitted signals are decoupled and separated from each other through an optical demultiplexer. This is achieved through the use of wavelength selective optics to direct each wavelength to a separate receiver. In order to support WDM in long-haul operations, amplification of signals is required. The repeater systems used in the typical fiber optic systems are impractical in WDM systems as each wavelength requires a separate repeater. Instead, optical amplifiers are used as they amplify all wavelengths in their operating range.

The most attractive aspect of WDM is its ability to multiply the transmission capacity of a single fiber by the number of optical channels it can multiplex, thus effectively increasing the bandwidth of this fiber to the sum of the bit rates transmitted in all operational wavelengths. Further advancement in WDM technology led to the introduction of *Dense* WDM (DWDM), whereby larger number of wavelengths are coupled into the same fiber. These advancements were possible as a result of the progress made in the production of improved optical fibers, optical amplifiers and integrated solid-state optical filters.

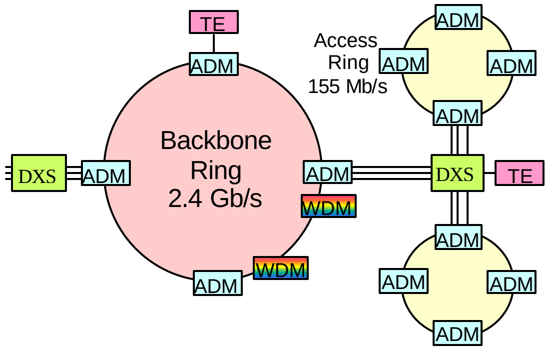


Figure 1. *Existing Transport Network Architecture.*

EVOLUTION OF DWDM

DWDM provides network operators the opportunity to maximize the return on their existing investment by exploiting the embedded capacity of the existing facilities. Technology advances in areas like dispersion-managed fibers and lambda-independent Eropium-Doped fiber amplifiers are accelerating the rate at which this technology is being deployed. Added values resulting from this deployment include savings in the electronic regeneration where in the case of DWDM, a single optical amplifier can be used for N wavelengths. Also, DWDM provides excellent scalability leading to flexible capacity growth and third, the utilization of the existing TDM equipment and present facilities.

In 1996, WDM technology enabled multiplexing of only 16 wavelengths. Advancements in optical technology and in fiber cable manufacturing techniques have resulted in an enormous growth in the available bandwidth. DWDM equipment are now capable of supporting hundreds of wavelengths in one stream. According to Gerry Butters, President of optical networking at Lucent Technologies, researchers at Lucent's Bell Labs have already demonstrated the feasibility of placing more than 1,000 discrete light waves on a single fiber, each carrying as much as 10 Gb/s of data [4].

ALL-OPTICAL NETWORK DEVELOPMENT

In an All-Optical Network (AON), time-division multiplexing builds optical channels which then can be switched and processed optically. Each optical channel occupies one wavelength on a WDM system and can be routed through the network. In this way, most of the signal processing functions are moved from the electrical domain to the optical domain, thus providing faster processing and more homegeneous network.

The deployment of DWDM in point-to-point links represents the first step towards broad optical networking. However, most of the networking functionalities such as cross-connecting, routing, supervision and survivability remained the responsibility of the TDM-based SDH layer. In addition to the above bandwidth growth requirements, other factors are forcing the move into all-optical networking. It is anticipated that the deployment of DWDM point-to-point line system will increase in a large scale. As the required number of wavelengths and span lengths increase, the need to add/drop wavelengths at intermediate sites will grow. As a result, Optical Add-Drop Multiplexers (OADM's) will be introduced in the network. In order to manage this big capacity, Optical Cross-Connect Systems (OXS) will emerge to manage capacity at the optical layer and will be required to operate in a multivendor environment. SDH/SONET will continue to exist in the evolving network basically to serve the networking role for point to point bandwidth demands such as voice traffic.

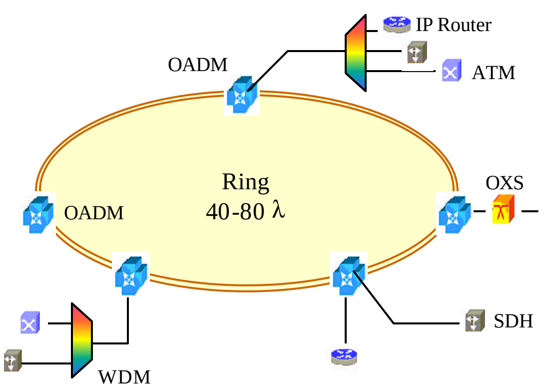


Figure 2. *Future all-optical transport network.*

The evolving optical transport networking will provide the network operators many advantages. First, it will reduce the capital expenditure of the transport network which will be achieved by deleting more SDH add drop multiplexers and some of the old generation cross-connect systems and fiber ring optical line terminals. This will also reflect in reducing the maintenance and administration costs without losing any of the original functionalities. Second, it will improve network failure recovery time as the restoration will be conducted at the optical layer. Third, it will reduce new service provisioning time. This is a result of optical switch ability to direct large amount of traffic in range of STM-16 and STM-64 around the fiber network, thus reducing switching time and service delivery.

ALL-OPTICAL NETWORK ELEMENTS

The architecture of all-optical networks (AON) will resemble that of SDH networks as both are connection-oriented multiplexed networks [5]. The major difference between the two appears in the form of multiplexing technology which is digital (TDM) in SDH versus analog (WDM) in the AON. This plays a major role in the cost versus performance requirements that shall be satisfied by the network design and the optimized deployment of its components. It is worth mentioning that in practice, optical telecommunications networks are not point-to-point but have meshed or ring topologies. Such networks require the capability to drop and add wavelength at certain destinations. This led to the introduction of other optical components such as Optical Add-Drop Multiplexers (OADM) and Optical Cross-Connect Systems (OXS). In the following paragraphs we are going to discuss some of the optical technologies and associated network elements required for the deployment of the AON [6].

OPTICAL SWITCHES

Switches play a number of roles in the optical networks such as directing optical signals to new location or guiding signals between different nodes in complex networks. Optical switches also enable protocol-independent high speed transport of traffic such as IP and ATM in the network core. These tasks require different levels of switch speed, capacity and complexity. Examples of the functions performed by these switches include emergency route restoration, implementation of network configuration changes and the normal traffic add-drop functions.

Several technologies are used in optical switching such as optomechanical and micromechanical switching. Optomechanical switching is a well established technology, in which the gear will redirect optical signals by moving a flexed fiber, a mirror or a lens to transfer the signal to one of the N fibers connected to the switch. MicroMechanical Switches (MEMS) are optomechanical switches smaller than a millimeter in size made by semiconductor processing techniques. Mirrors in optical MEMS are tilted back and forth to reflect beams directed to them from above into output optical ports. Other types of optical switches include Electro-Optical switches, liquid-Crystal Switches and Bubble Waveguide switches [1]. Switching speeds vary from seconds to nanoseconds and are dependent on the switch manufacturing materials. Other parameters that need to be considered in optical switching include optical loss, dispersion, reliability, stability and the switch matrix size. Optical Cross-Connect Systems (OXS) and Optical ADM (OADM) are examples of optical switches and are considered to be constituent of the enabling elements for the evolution of all-optical networks.

OPTICAL ADD-DROP MULTIPLEXERS (OADM)

In transport networks, Add-Drop Multiplexer (ADM) equipment is used to drop the required traffic at a certain node and pass the reminder to the next node. OADM is still evolving and is equivalent to the digital ADM operating in the optical domain to provide grooming and splitting of wavelengths selectively at the different network nodes. Using OADM eliminates for several Optical-Electrical-Optical (OEO) conversions. Many technologies are used in OADM such as Arrayed Waveguide Grating (AWG) and Fiber Bragg Gratings (FBG) [7].

OPTICAL CROSS-CONNECT SYSTEMS (OXS)

One of the main objectives of deploying cross-connect elements in the network is to provide the required resilience that will allow for managing provisioning, protection and restoration. OXS can be realized in two methods. The first is to use the OEO conversion where the optical information is converted into electronic data, cross-connect it, and then convert the electronic data back into optical. This is called *opaque* cross-connects. The second method is to cross-connect the optical channels directly in the optical domain which is known as *transparent switching*. OXS equipment are currently available as commercial products. However, all the first generation OXS are opaque since they utilize electronic switch fabrics. Transparent switching is used in low scale cross-connection. High scale transparent switching is still in the experimental phase.

Optical switches are used to provide scalable optical services that enables fast, low-cost data services. Examples of the optical switches are the TeraMatrix produced by Sorrento, CorWave by Corvis, WaveStar by Lucent Technologies and Aurora switch produced by Tellium [8].

WAVELENGTH CONVERTERS (WC)

Wavelength converter is equipment used in conjunction with OXS systems to convert optical signals from one wavelength to a desired one but maintaining its same digital contents. Such equipment is necessary to provide more routing flexibility in the optical network.

OPTICAL AMPLIFIERS

As the optical signal travels along the fiber optic cable span, it becomes attenuated. To compensate for this loss of power and to allow for expanding the effective fiber span, optical amplifiers are inserted at certain lengths between sources and destinations.

In the opaque regenerator, the incoming wave division multiplexed signal is demultiplexed into its individual wavelengths and each signal goes through OEO conversion, amplified and then multiplexed together again. In all-optical amplifiers, all channels within a window of optical wavelengths are amplified simultaneously without the need for demultiplexing. This shows the advantage of transparent amplifiers over the opaque regenerators in terms of both cost and opeeration.

With the expanding deployment of DWDM in the transport network, the demand of optical amplifiers is increasing as well. This is due mainly to two reasons. First, the span of some fiber rings in these networks are becoming long enough to require amplification. Secondly, amplifiers are used to compensate for the accumulating losses resulting from the different optical components. Emerging technologies such as optical cross-connects and optical add-drop multiplexers are expected to decrease the number of OEO conversions and consequently, resulting in higher signal attenuation as the signal will travel through multiple rings without going through OEO conversions or regeneration.

An example of the optical amplifiers widely used in telecommunications and in particular in DWDM is the Erbium-Doped Fiber Amplifiers (EDFA). The EDFA is a piece of fiber cable heavily doped with eribum and can operate in the C-band (1528-1561 nm) and the L-band (1561-1620 nm). Other types of optical amplifiers include Praseodymium-Doped Fiber Amplifiers (PDFA), Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scatterring (SBS) amplifiers [6].

DISPERSION COMPENSATORS

Increased use of DWDM results in accommodating more wavelengths into the same single fiber. Also, transmission rates from 155 Mb to 2.4 Gb, 10 Gb and soon to 40 Gb/s in each single wavelength have been realized. In addition, most of the existing fibers were installed 10-25 years ago by different vendors resulting in a wide variation in the characteristics of these fibers. All of these factors drive the system designers to pay high attention to the optical chromatic dispersion issue.

To overcome this data-rate and wavelength dependent problem, network designers insert dispersion compensators at certain intervals along the fiber length. Currently, most dispersion compensators are installed at the optical fiber amplifier points, thereby broadening the span between regeneration points. Several techniques exist to tackle the chromatic dispersion problem. The most popular methods are the Dispersion-Compensating Fiber (DCF) and the Chriped Fiber Grating (CFG) [9]. DCF has high levels of dispersion opposite in sign to that one of the transmitting fiber. The disadvantage of this technique is the required length of the DCF. The

CFG is a modular type which makes it more attractive.

TRANSPARENT VERSUS OPAQUE

In transparent networks any optical signal operating at a certain wavelength will travel across the network in the optical domain and will be maintained as an optical signal until it arrives to its destination. During this process no optical to electrical conversion will take place. In opaque Networks, some type of electrical-optical conversion will take place.

Network operators are interested in having a transparent network due to the following advantages: first, lower costs compared to opaque networks which requires additional network elements and many OEO (Optical-Electrical-Optical) conversion componenets including transmitters and receivers. Secondly, protocol-independence, allowing different data rates and signals of different formats to be transported simultaneously. Introduction of transparent networks, however, have many disavantages. The major disadvantage is the signal impairments resulting from accumulation of optical crosstalk due to reductions in the optical signal to noise ratio when crossing from one span to another. This requires that the whole network shall be designed on its entirety, in contrast to opaque networks which can be designed a span by span as it grows. This adds to the design complexity and increases the network engineering costs and complicates future network upgrades. The second disadvantage is the difficulty of monitoring quality of individual signals resulting in more complex network management and fault locating. Third, some functions which are available in opaque networks such as drop and continue and multicast are difficult to implement in the optical domain.

Currently, optical switches still have some electrical components (opaque switching) to complete their functionality. This includes clock recovery, signal equalization, framing and synchronization. However, researches are heading towards presenting switches that will operate entirely in the optical domain (transparent switching). The delay in introducing an entire transparent optical network is due to the following reasons:

- Optical signals need to be regenerated using electrical components to ensure that the signal arrives at its destination with the required intensity and integrity.
- Network management information are still carried over electrical signals.
- Optical switch components are still new and immature with high cost and limited reliability and availability.
- Current carriers huge investment in opaque network elements which requires gradual migration from legacy systems into a transparent all-optical network.

The ultimate goal is to enable an end-to-end photonic network with no OEO conversion. Such a network will ultimately eliminate network bottlenecks, complexity and multi-point of failures.

STANDARD BODIES

A number of committees are working on the standardization of issues related to the migration to all-optical network and the inter-operability between WDM and SDH. Among these are the following:

- Telecommunications Management Forum (TMF)
- Optical Internetworking Forum (OIF)
- Internet Engineering Task Force (IETF)
- ITU-T Study Group 15 (transport networks, systems and equipment)
- SONET Interoperability Forum (SIF)

METRO NETWORKS IN THE OPTICAL DOMAIN

Originally, metro networks are constructed using a hybrid electrical/ optical architecture. Optical signals will travel from one Metropolitan Area Network (MAN) to another through SDH/ SONET transport layer and then converted to electrical signals within the metro network. The emerging advancements in the optical networking is leading into an all-optical MAN. In this approach, ATM, IP and all other data-centric services are delivered directly through optical signals with no OEO conversion. The deployment of hundreds of fiber optic strands each capable of carrying hundreds of separate wavelengths will create a big challenge at the junction between the long-haul and the metro network due to OEO conversion. This problem can be solved by the advent of all-optical solutions.

OPTICAL NETWORK SURVIVABILITY

With a single fiber carrying traffic in excess of a terabit per second, great attention need to be paid to the restoration and protection of the optical network. Today's Internet services such as e-mail, and file transfer are relatively tolerant to delay. In the coming future, however, services requiring higher bandwidth and much smaller transfer delay will become ordinary [10]. Emerging services such as IP-based telephone switches requires in addition, high Quality of Service (QoS) levels.

All-Optical Network (AON) restoration architectures will be deployed in a manner similar to the existing SDH restoration architectures. The restoration could be applied at the optical channel or the optical multiplexer levels and will make use of the existence of optical cross-connection to reroute traffic in case of a failure. Algorithms need to be developed to allow for seamless restoration. AON protection will be also similar to that of the SDH. For point-to-point optical systems, 1+1 and 1:1 protection switching can be applied. While for meshed and ring topology AON networks, Multiplexed section Shared Protection Rings (MSPRings) and SubNetwork Connection Protection Rings (SNCP-Rings) mechanisms can be employed. More information about this topic is available in [5].

CONCLUSION

Evolution of today's legacy systems toward an all-optical network is expected to take place gradually. A massive equipment upgrade is unlikely to occur as current SDH/ SONET equipment is just beginning to pay off for its large investment and the network operators are apparently satisfied with SONET/SDH technology, in terms of survivability capabilities, performance and bandwidth transport of up to 10 Gb/s [7]. All-optical networks will provide network carriers a dramatic flexibility, bit-rate and protocol independence through the ability to segregate the optical channels for different types of services such as TDM, ATM, IP and optical leased lambdas. In the absence of commercially available devices that can clear the accumulated impairments and the support of wavelength switching and conversion in the all-optical domain, some measure of OEO conversion should be expected in the near-term practical optical network architectures.

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BIOGRAPHY

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