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Photonic Network Architecture: Next Generation Internet Applications

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EXECUTIVE SUMMARY

Introduction of fiber optic cable into the global communications infrastructure was the opening move in a transition from electronic communications networks to a new generation of all-optical communications networks. It was hard to imagine the road that lay ahead. Fiber optic cables expanded the available bandwidth, lowered cost, and increased reliability. Like copper, fiber optic cable is a fundamental element of a new, evolving information transfer technology.

Advances in corporate enterprise networks started a trend towards information-based products and services. The Internet took information networks beyond the realm of large corporations and created an information network for everyone, be they individuals, small businesses, or large corporations. The uptake of information services over the Internet can only be described as remarkable.

Internet growth overpowered available fiber and SONET capacity setting the stage for rapid growth in dense wavelength-division multiplexing (DWDM). DWDM has become so popular that it will ultimately displace Synchronous Optical Network (SONET) from wide area and local exchange infrastructure. Advances in DWDM and other optical technologies are doubling optical capacity every nine months. Optical transmission growth is outpacing the growth in electronic switching capacity. In so doing, optical fiber and DWDM are taking the communications market away from electronic devices and passing it to its successor known as “photonics.”

Many photonic devices are in their infancy. Photonic switches are large, relatively slow, and have unproven reliability. Optical filters and amplifiers lack refinement and standardization. Even so, development and refinements in manufacturing will deliver optical devices to the market place and eventually replace SONET, Internet Protocol (IP), and asynchronous transfer mode (ATM) equipment.

There is a general recognition that photonics is the enabling technology for future networks. The International Telecommunication Union (ITU), Internet Engineering Task Force (IETF), and many other organizations are working on standards for everything from submarine cable systems to optical signal routing. Research is underway to create more efficient amplifiers, filters, and switching devices. Recent discoveries give the promise of optical storage, which if fulfilled will solve a fundamental problem impeding optical packet switching and may ultimately lead to optical computing.

It is now possible to build high capacity optical systems with capacities of 10 terabits per second operating on a single fiber strand. High capacity photonic networks will lower cost and provide the bandwidth necessary for widespread video communications. They will extend high-speed access to businesses and residences.

The ultimate shape that optical switching will take is unclear…hidden in the mists of future invention and untested markets. All-optical switching may lead to new signaling protocols unlike ATM or IP. The standards have not been written and experience has not passed verdict upon how all-optical switching will evolve into a mature communication infrastructure. Yet, the trend to all-optical networks is clear.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ADM	Add/Drop Multiplexers
ADSL	Asymmetric Digital Subscriber Line
ANSI	American National Standards Institute
AOTF	Acousto-Optic Tunable Filter
APON	ATM Passive Optical Network
APS	Automatic Protection System
ASIC	Application-Specific Integrated Circuit
ASP	Application Service Provider
AT&T	American Telephone and Telegraph
ATM	Asynchronous Transfer Mode
ATM PON	ATM Passive Optical Network
BER	Bit Error Rate
CATV	Cable Television
CCITT	Consultative Committee on International Telegraphy and Telephony
CLEC	Competitive Local Exchange Carrier
DARPA	Defense Advanced Research Projects Agency
DIFF-SERV	Differentiated Services
DSL	Digital Subscriber Line
DWDM	Dense Wavelength Division Multiplexing
DXC	Digital Cross Connect
EDFA	Erbium-Doped Fiber Amplifier
FBG	Fiber Bragg Grating
FCC	Federal Communications Commission
FEC	Forward Error Correction
FITL	Fiber-in-the-Loop
FSAN	Full Services Access Network
FTTC	Fiber-to-the-Curb
FTTCab	Fiber-to-the-Cabinet
FTTH	Fiber-to-the-Home
IBT	In-Band Terminator
IEEE	Institute of Electrical & Electronics Engineers
IETF	Internet Engineering Task Force
ILEC	Incumbent Local Exchange Carrier
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ISDN	Integrated Services Digital Network
ISP	Internet Service Provider
ITU	International Telecommunications Union
ITU-T	International Telecommunications Union – Telecommunication Standardization Sector
LAN	Local Area Network

LEC	Local Exchange Carrier
MAN	Metropolitan Area Network
MEMS	Micro-Electromechanical Machines
MPλS	Multiprotocol Lambda Switching
MPLS	Multiprotocol Label Switching
NTON	National Transparent Optical Network
OADM	Optical Add-Drop Multiplexer
OAN	Optical Access Network
OBS	Optical Burst Switching
OC-1	Optical Carrier 1
OC-12	Optical Carrier 12
OC-192	Optical Carrier 192
OC-3	Optical Carrier 3
OC-48	Optical Carrier 48
OC-768	Optical Carrier 768
OCC	Optical Connection Controller
ODSI	Optical Domain Service Interconnect
OEO	Optical-Electronic-Optical
OIF	Optical Internetworking Forum
OLT	Optical Line Terminal
O-NNI	Optical Network-to-Network Interface
ONU	Optical Network Unit
OPS	Optical Packet Switching
OSC	Optical Supervisory Channel
OTN	Optical Transport Network
O-UNI	Optical User-to-Network Interface
OXC	Optical Cross Connect
PCM	Pulse Coded Modulation
PDA	Personal Data Assistant
PDH	Plesiochronous Digital Hierarchy
PMD	Polarization Mode Dispersion
PON	Passive Optical Network
POTS	Plain Old Telephone Service
PSTN	Public Switched Telephone Network
QoS	Quality of Service
RBOC	Regional Bell Operating Company
RFD	Reserve-a-Fixed-Duration
SDH	Synchronous Digital Hierarchy
SHWP	Shared Wavelength Path
SIG RR	Signature Resource Record
SLA	Service Level Agreement
SLA	Service Level Agreement
SOA	Semiconductor Optical Amplifier
SONET	Synchronous Optical Network
SS7	Signaling System 7
STM	Synchronous Transfer Mode

TAG	Tell-and-Go
TCP/IP	Transport Control Protocol/Internet Protocol
TDM	Time Division Multiplexed
TPC-5	Trans-Pacific Cable-5
VoDSL	Voice-over-DSL
VoIP	Voice-over-IP
VPN	Virtual Private Network
VT	Virtual Tributary
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WXC	Wavelength Cross Connect
xDSL	Various versions of DSL

1.0 THE EVOLUTION OF OPTICAL COMMUNICATIONS

Optical communications has evolved out of the necessity for a transmission medium with increased bandwidth capacity. The evolution of fiber optic data communications has stemmed from the telecommunications industry's need to multiplex voice channels for interconnecting call distribution centers. In the 1930s communications engineers became aware that the current infrastructure deployment strategy would not support the service demand of future telephone usage. At the time, each concurrent connection required an allocated physical connection.[1] Massive physical networks were implemented and could not possibly have supported future expansions.

The infrastructure problem was not strictly a United States issue. Europeans were also dealing with demand-based expansion problems. Early multiplexing techniques included frequency division multiplexing, which attained little success due to cost issues. In the late 1960s, research into a digitization technique called "Pulse Code Modulation" (PCM) was performed. PCM utilizes 8000 8-bit samples per second, creating a 64 kbps digital channel for carrying voice. Digitizing the audio channel made multiplexing easier. Early multiplexing techniques involved simple bit interleaving which proved ineffective for dense multiplexing operations.[1]

At this time the European and United States telecommunications industries diverged. The United States systems multiplexed 24 64 kbps channels, and added some control overhead, to yield a 1.544 Mbps channel, referred to as a "T1". Europe, on the other hand, multiplexed 30 64 kbps channels and 2 control channels to yield a 2.048 Mbps channel, referred to as an "E1". Table 1 and Table 2 depict the different multiplexed voice services standards. The multiplexing differences between America and Europe laid the framework for critical integration problems that would have to be addressed.

Table 1: United States Voice Service Rates [2]

United States Voice Service	*Speed (Mbps)*	*Description*
DS0	0.064	1 Voice Channel (8000 8-bit samples/sec)
DS1 (T1)	1.544	24 Voice Channels
DS1C (T1C)	3.152	48 Voice Channels
DS2 (T2)	6.312	96 Voice Channels
DS3 (T3)	44.736	672 Voice Channels
DS4 (T4)	274.176	4032 Voice Channels

Interoperability between the two networks became expensive and complicated. As further multiplexing was performed on the trunk lines, distance and vendor differences led to extensive transmission problems. Clock signal skew and distance-related delays caused signal timings to be compromised. To resolve these problems, the Plesiochronous Digital Hierarchy (PDH) standard was adopted by the International Telecommunications Union (ITU) in the 1970s. PDH allowed successful interoperability of these communications networks, but problems with network scalability and the introduction of additional value-added services for fiber optic media made PDH obsolete. To add or remove a data channel at a point along the network, extensive network infrastructure was needed to provide for the de-multiplexing, channel addition or removal, and re-multiplexing of the channels.[1] PDH does not provide for channel addition without demultiplexing down to the channel hierarchy level of the channel to be added.

Table 2: European Voice Service Rates [2]

European Voice Service	***Speed (Mbps)***	***Description***
E1	2.048	30 Voice Channels
E2	8.448	120 Voice Channels
E3	34.368	480 Voice Channels
E4	139.264	1920 Voice Channels
E5	565.148	7680 Voice Channels

The court-ordered breakup of the American Telephone and Telegraph Company (AT&T) at the end of 1983 created the need for a new American National Standards Institute (ANSI) standard for the interoperability of the Regional Bell Operating Companies (RBOCs). Synchronous Optical Network (SONET), which allows for the addition or modification of a channel without extensive demultiplexing, became the United States standard. SONET was designed to be compatible with the United States PDH systems. Having observed SONET's integration benefits, the ITU adopted a Synchronous Digital Hierarchy (SDH) standard. SDH was designed to be interoperable with both the new U.S.-based SONET equipment and the large investment in European PDH equipment.[1] Both SONET and SDH operate by means of Synchronous Transfer Mode (STM) digital transmission. STM is a time division multiplexed technology with consistent framing every 125 microseconds.[1] Table 3 outlines the optical and electrical multiplexing services and rates for SONET and SDH. As shown in the Description column, the SONET/SDH rates were developed to accommodate the existing voice multiplexing hierarchies.

The SONET standard supports synchronous framing for data and overhead octets. Several protocols can be run over SONET, such as Asynchronous Transfer Mode (ATM) or Internet Protocol (IP). When run over the optical transmission medium of single-mode fiber, SONET can be utilized as an interfacing protocol for long distance fiber runs. Typical SONET networks consist of Digital Cross Connects (DXC), Add/Drop Multiplexers (ADM), and Line Terminating Equipment (LTE). DXCs are the interconnecting structures of SONET network rings. These provide the Optical-Electronic-Optical (OEO) conversions, multiplexing and demultiplexing functions, and programmable mapping for network interconnection and switching. The ADMs allow for the direct insertion and removal of individual services onto the same SONET connection.[3] This ability is an improvement over PDH which requires demultiplexing down to the speed of the inserted channel. The Line Terminating Equipment allows users to interface with the SONET network. Such devices could be a telephone switch or network gateway. SONET also provides for network management and fault detection/traffic redirection. Figure 1 depicts a typical SONET network.

Table 3: SONET/SDH Signaling Rates [2][3]

SONET Optical	***SONET Electrical***	***SDH Optical***	***Data Rate (Mbps)***	***Payload Rate (Mbps)***	***Description***
OC-1	**STS-1**	**N/A**	51.84	50.112	28 DS1s or 1 DS3
OC-3	**STS-3**	**STM-1**	155.52	150.336	3 OC-1s
OC-9	**STS-9**	**STM-3**	466.56	451.008	
OC-12	**STS-12**	**STM-4**	622.08	601.344	12 OC-1s or 4 OC-3s
OC-18	**STS-18**	**STM-6**	933.12	902.016	
OC-24	**STS-24**	**STM-8**	1244.16	1202.688	
OC-36	**STS-36**	**STM-12**	1866.24	1804.032	
OC-48	**STS-48**	**STM-16**	2488.32	2405.376	48 OC-1s or 16 OC-3s
OC-192	**STS-192**	**STM-64**	9953.28	9621.504	
OC-768	**STS-768**	**STM-256**	39813.12	38486.016	

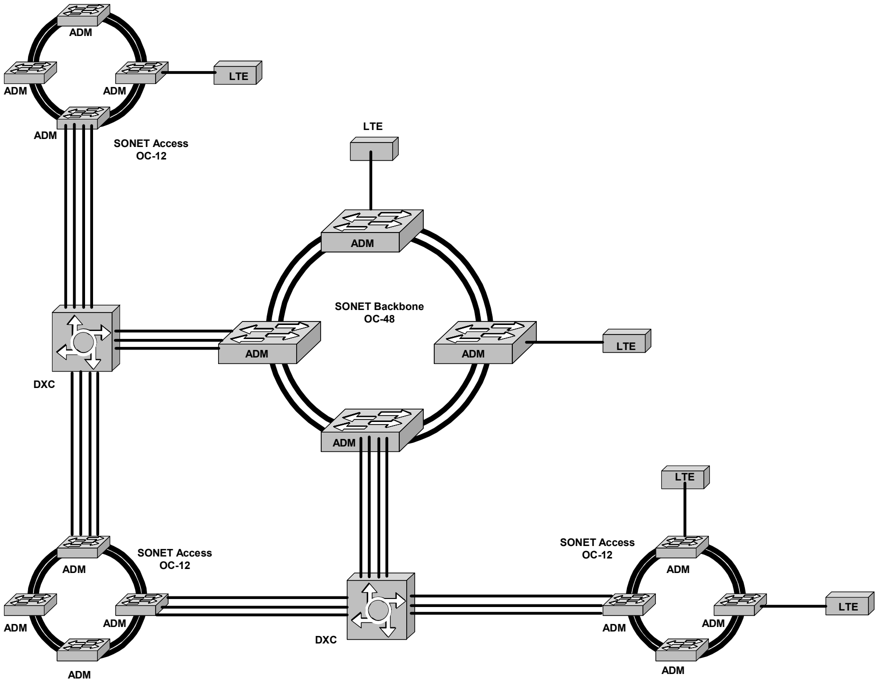


Figure 1: Typical SONET Network

Once a network infrastructure has been deployed, upgrades to increase capacity can be expensive. Cost effective ways of increasing optical network capacity could save corporations substantial capital. Wavelength Division Multiplexing (WDM) entered into the picture and dramatically increased effective fiber optic bandwidth. WDM, and its Dense Wavelength Division Multiplexing (DWDM) counterpart, operate under the premise of multiplexing different optical signals by wavelength on the same physical medium. This allows network engineers to increase network capacity without extensive and expensive infrastructure redesign.

Similar in functionality to SONET's ADMs, but different in method, DWDM's Wavelength Cross Connects (WXCs) populate the DWDM ring topology. WXCs coexist with ADMs and can provide substantial benefit to the infrastructure when implemented together within the backbone. DWDMs provide wavelength conversion to allow for optical routing and cross-wavelength traffic redirection. SONET provides the network management and control protocol to ensure the integrity of the optical transmission. Thus, a hybrid of SONET and DWDM network infrastructures provides an effective, efficient, and dependable backbone architecture.

Missing from the DWDM/SONET hybrid is the concept of high-speed fully optical switching, also known as "photonic switching." Currently, for network layer switching to occur, a conversion must be done from the optical domain to the electrical domain. The necessary routing and switching is performed electrically and the signal is converted back into the optical domain for transport. This process becomes increasingly difficult as the speed disparity of optical transport and electronic switch backplanes increases almost daily. As networks evolve towards all-optical networks, also known as "transparent networks", protocols must be developed to ensure manageability and controllability without inefficient OEO conversions.

2.0 ENABLING TECHNOLOGIES FOR OPTICAL NETWORKS

Optical networks are composed of various enabling technologies, merged in harmony to produce high-speed, reliable, and affordable communications backbones. The benefits of all-optical networks are vast, yet the technologies necessary to render this dream a reality are complex. Advancements in semiconductor research, networking concepts, optical processing techniques, and switching implementations continue to be investigated. Due to all of these research endeavors, the realization of all-optical transport networking is cresting the horizon.

2.1 Optical Infrastructure Components

In an effort to realize all-optical networks and photonic switching, researchers have developed various optical infrastructure components to perform various tasks similar to those performed by existing electrical network elements. Optical cross connects, optical add-drop multiplexers, and optical gateways all perform distinct functions necessary for the successful implementation of an all-optical network. To realize these optical network elements, various technologies and component advancements complement each other by providing physical realizations for optical internetworking concepts.

2.1.1 Optical Signal Modifiers

The proliferation of optical networks, in part, can be attributed to advancements in optical semiconductor research. Advanced optical amplifier design has provided circuit designers with components capable of reducing the size and cost of optical circuit implementations. Tunable lasers have greatly reduced the cost required to operate on various wavelengths within the optical transmission. Special substrate applications have made it possible to filter out the unnecessary components of optical signals to fully realize optical networks. As a result of extensive research in these areas, optical infrastructure development is ahead of projection, laying the foundation for the physical realization of all-optical networks.

2.1.1.1 Optical Amplifiers

Optical amplifiers are critical to high-speed optical networks. Historically, long-distance fiber runs utilized optical amplifiers to boost the spectral power of the transmission. Recently, however, research is underway to use optical amplifiers for additional applications such as wavelength conversion.

Raman amplifiers operate by means of a pump laser. This pump laser operates at a shorter wavelength than the signal laser. As the pump and signal wavelengths proceed down the optical medium, the pump laser starts scattering photons and losing energy. This energy is absorbed by the signal, since it is at a longer wavelength, resulting in amplification of the signal. The pump laser eventually fades due to this loss of energy. Therefore, Raman amplification provides a means of amplifying optical signals of any wavelength within the transmission line, depending on the wavelength separation of the pump and signal. Raman amplification also reduces the need for costly electrical amplifiers along the transmission path. Multiple Raman amplifiers are necessary when amplification of multiple wavelengths in a fiber is needed.

Erbium-Doped Fiber Amplifiers (EDFA) address the scalability problems of Raman amplifiers. An EDFA consists of fiber doped in Erbium, a rare ion. The addition of the Erbium impurity causes amplification across a broad spectrum of wavelengths when excited by a pump laser. Like Raman amplifiers, EDFAs require no OEO conversion to produce this in-line amplification. While EDFAs amplify a larger number of wavelengths along the transmission line than Raman amplifiers, they do have a long delay time that could hinder their inclusion in optical switches.

Historically used for optical transmission amplification, Semiconductor Optical Amplifiers (SOA) were determined to contain nonlinearities that affected the integrity of the optical signal when used across a broad range of wavelengths. These problems, however, did not mark the end of SOAs. Instead, these nonlinearities make SOAs useful for wavelength conversion techniques as described in section 2.2.3. [4][5][6]

Raman amplifiers, EDFAs, and SOAs were all developed for the purpose of amplifying optical signals for long-haul transport. As the technology has matured, these devices have also become key elements in other forms of optical infrastructures. Optical amplifiers play a critical role in the successful proliferation of optical networking.

2.1.1.2 Tunable Lasers and Filter Structures

Optical transmission relies on precise wavelength-sensitive equipment to successfully process and direct optical signals. Lasers are the driving force behind optical communications and operate at various wavelengths. The ability to tune these lasers provides administrators with the ability to replace a failed laser from reserves. Since the tunable lasers can be configured in the field to support any of the wavelengths in a system, only a small number of spare lasers need to be kept in inventory. This feature removes the need to stock spare lasers for each particular wavelength used in the system. Current manually tunable lasers are also the first step towards in-circuit automated tuning. Automated tuning will provide an enabling technology for the development of all-optical networks.

Several different methods for tuning lasers currently exist. Mechanically tuned lasers suffer from long tuning times and are used when the connection is mostly fixed to a particular wavelength. Acousto-optically tuned lasers employ a sound wave to change the refractive index of the laser cavity to modify the wavelength. Acousto-optically tuned lasers have a faster tuning time and are limited only in the number of wavelengths that can be affected. Electro-optically tuned lasers operate by changing the refractive index of the laser cavity by implementing an electric field. Injection current tuned lasers utilize a current-controlled diffraction grating to tune the laser. Injection current tuned lasers provide high tuning speeds that are necessary for photonic networks.[7] The ability to effectively tune lasers will provide optical network designers with the scalability and cost effectiveness to proliferate new optical technologies in their networks.

Tunable filters allow certain wavelengths to be singled out from a multi-wavelength optical signal. Researchers have developed several filter technologies, each with different tuning methods and ranges. A filter common in optical network infrastructures is the Fiber Bragg Grating (FBG). FBGs are, in general, a fixed wavelength filter technology. Slight tuning can be achieved by varying environmental or physical conditions of the filter. These filters modify the index of refraction of a small section of fiber to reflect and filter out a predetermined wavelength, much the same way that a notch filter operates in electronic circuitry. FBGs are useful in the creation of optical add-drop multiplexers as well as to compensate for dispersion. Thin film substrates are another type of optical filter. They consist of a fiber coated with a dielectric material. Thin film substrates pass a single wavelength and block all others, providing the inverse functionality of FBGs.[8] Thin film substrates are equivalent to a narrow band-pass filter in electronic circuits. Additional optical filters include Fabry-Perot filters, mode-coupling filters, and liquid crystal tunable filters.[7] Tunable filters are partially responsible for the advancements of optical multiplexers and are a critical component in optical networks.

2.1.2 Wavelength Division Multiplexing (WDM)

Wavelength division multiplexing (WDM) is the optical equivalent of frequency division multiplexing. Frequency and wavelength are inversely proportional, and the multiplexing schemes associated with both are relatively similar. Wavelength division multiplexing is the multiplexing of different separate wavelengths of light onto a common light channel such as a fiber optic medium. The light is multiplexed by means of a diffraction grating or optical prism. Figure 2 depicts the optical wavelength multiplexing process.

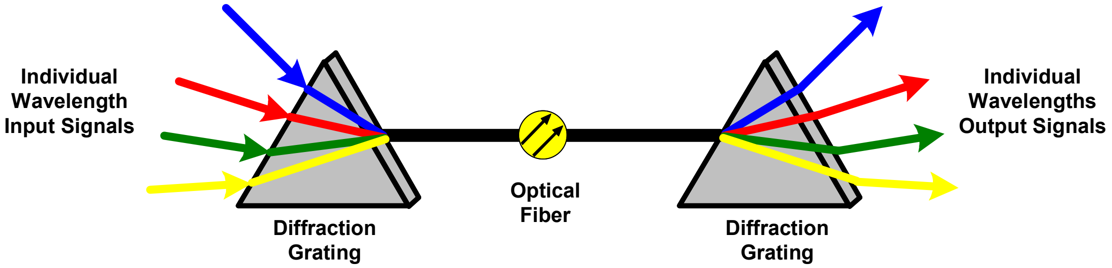


Figure 2: Wavelength Multiplexing and Diffraction Gratings [9]

WDM technology initially multiplexed two wavelengths for multiplexing, 1310 nm and 1550 nm. These wavelengths are common in devices that interface to single mode fiber, since the fiber has lowest optical loss at these wavelengths. As the multiplexing technology has progressed, WDM devices have grown to accommodate greater than two wavelengths. As the number of supported wavelengths per fiber continues to grow, a new name for the technology has emerged: “dense wavelength division multiplexing” (DWDM). DWDM involves the multiplexing of additional wavelengths around the 1310 nm and 1550 nm wavelengths, to yield more optical channels per fiber. DWDM technology's bandwidth expansion is limited only by the resolution of the wavelength division of the optical network elements.[3]

2.1.3 Optical Cross Connects (OXC)

Reliable and affordable optical cross connects (OXC) are essential to the proliferation of all-optical switches. The evolution of OXCs stemmed from advances in micro-electromechanical systems (MEMS). MEMS is a technology that enables the control of miniature mechanical devices such as very small mirrors. In OXCs, MEMS mirrors are used to reflect the optical signal from one input to the chosen output. Early design utilized a binary-controlled two-dimensional mirror array that would either implement a mirror or remove it from the light path. Recently, analog controlled three-dimensional mirror matrices have been designed that allow for finer control of optical signal direction. Three-dimensional optical cross connects utilize three-dimensional mirror matrices to connect any input to any output and reduce cost by utilizing fewer mirrors. Two-dimensional optical cross connects require N^2 mirrors, while three-dimensional optical cross connects require 2N mirrors, where N is the number of inputs or outputs.[5] Figure 3 depicts the two-dimensional OXC structure and Figure 4 depicts the three-dimensional OXC structure.

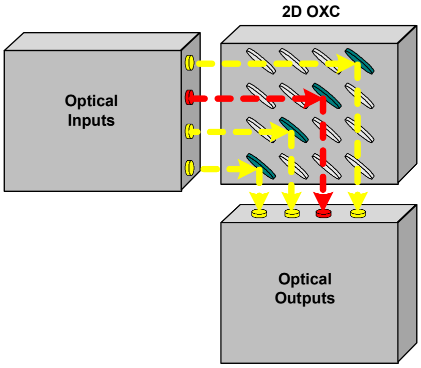


Figure 3: 2D Optical Cross-Connect Structure with N^2 Mirrors [5]

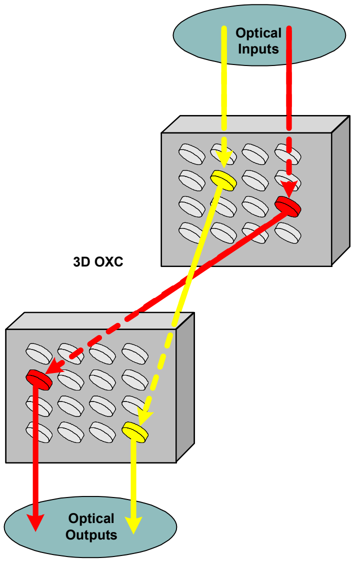


Figure 4: 3D Optical Cross-Connect Structure with 2N Mirrors [5]

2.1.4 Optical Add-Drop Multiplexers (OADM)

Optical Add-Drop Multiplexers (OADM) are responsible for adding or removing individual signals (wavelengths) at individual points along the optical transport channel. OADMs function fully in the optical domain without performing an OEO conversion. OADMs operate as peripherals to the OXCs, providing the OXCs with the appropriate signals to direct. There are two types of OADMs. The first operates with fixed optical filters and is deemed a fixed wavelength OADM. The second operates with tunable optical filters and is referred to as a dynamic OADM.[10] While fixed wavelength OADMs are the more mature variant, researchers are actively pursuing dynamic OADMs with features such as acousto-optic tunable filters (AOTF). The AOTF removes the need for an optical switch typically found in a dynamic OADM and thus reduces cost. Figure 5 illustrates a fixed OADM and Figure 6 illustrates a dynamic OADM.

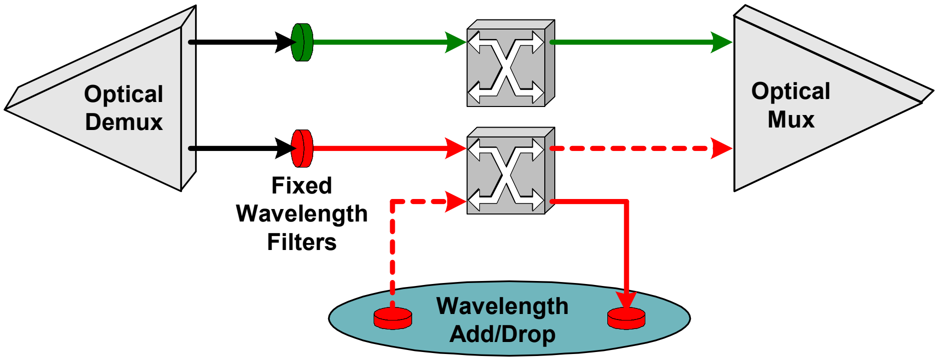


Figure 5: Fixed OADM

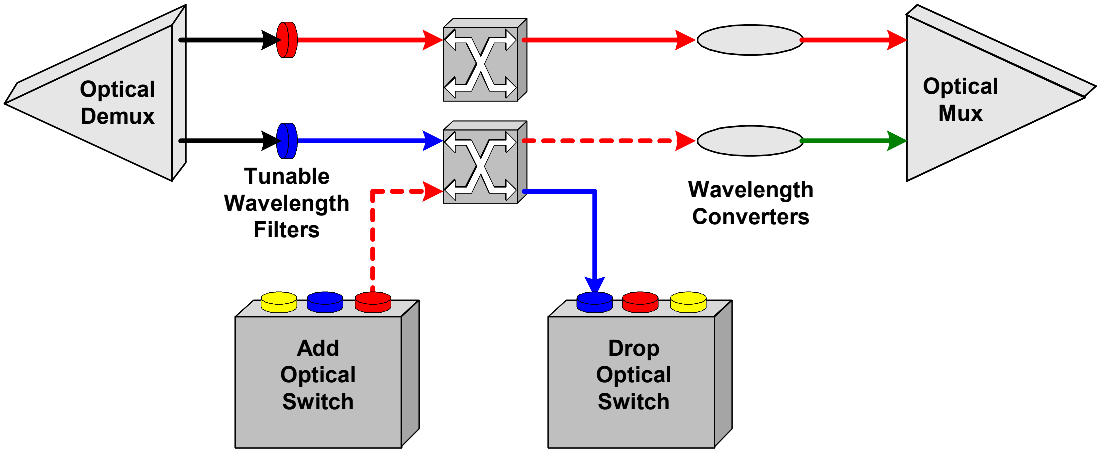


Figure 6: Dynamic OADM

2.1.5 Optical Gateways

Migration towards all-optical networks will begin with the core backbone network elements and expand to the edge devices. Edge devices will be required to perform the electronic-optical conversion to convert the electrical signaling data into optical form for backbone transport. Optical gateways will be responsible for offloading overhead conversion burden. In addition, optical gateways reduce the transport delay time by performing conversions on lower data rate edge traffic as opposed to high-density core flows. These optical gateways will need to interface between many protocols and the optical layer. Figure 7 depicts the interfacing provided by optical gateways. High-speed, reliable, and manageable optical gateways are critical to all-optical network performance, since they are the last-mile node of the all-optical network.

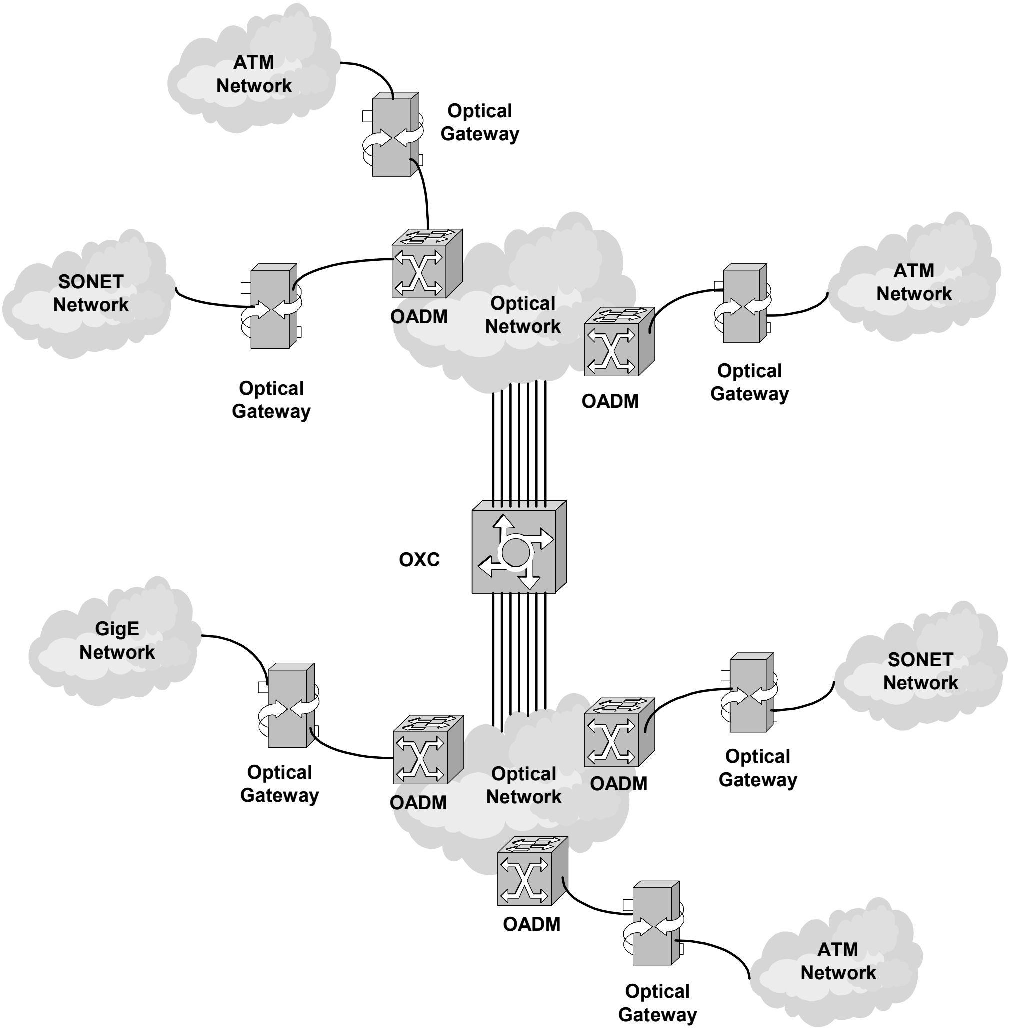


Figure 7: Optical Gateways in All-Optical Networks

2.2 Optical Processing Techniques

As the design of all-optical networks progresses, the ability to modify or manipulate the optical signal will prove critical to the scalability of the network. Techniques for regenerating an optical signal, converting the wavelength to support optical routing, buffering for switching implementations, and encapsulating the optical signal all provide functionality critical to the successful proliferation of all-optical networks.

2.2.1 Optical Regeneration

Optical signals degrade over long distances and due to various impairments. Causes for this degradation are dispersion, loss, crosstalk, and non-linearities of the optical components and the fiber.[11] In order to ensure signal integrity over long distances or high path losses, regeneration techniques are necessary. Historically, regeneration has occurred in the electrical domain, after an optical-electronic conversion. The electrical signal must then be converted back to the optical domain prior to re-transmission. For extremely long fiber runs, optical amplifiers and optical repeaters are necessary. Optical amplifiers boost the power of the optical signals in the fiber. Unfortunately, the noise on the line is also amplified. The answer to this noise problem is optical repeaters. Optical repeaters perform OEO regeneration. This process filters the noise and reconstructs the optical signal for retransmission to ensure signal integrity throughout each transmission segment. Therefore, it is standard practice to implement an optical repeater after every two optical amplifiers.[12]

Optical regeneration can be accomplished in three different ways. The first level of regeneration is referred to as 1R regeneration. This regeneration is standard signal amplification and is performed by optical amplifiers. The second level of regeneration, or 2R regeneration, is performed by semiconductor optical filters, which reshape the signal by filtering the noise. The final regeneration level is 3R. This level provides amplification, reshaping, and re-timing on the optical signal. Recent advances have enabled network equipment to optically recover the pulse clock to, in effect, re-sync the optical signal. These advances are moving optical networks toward total transparency. Figure 8 depicts the three regeneration levels.

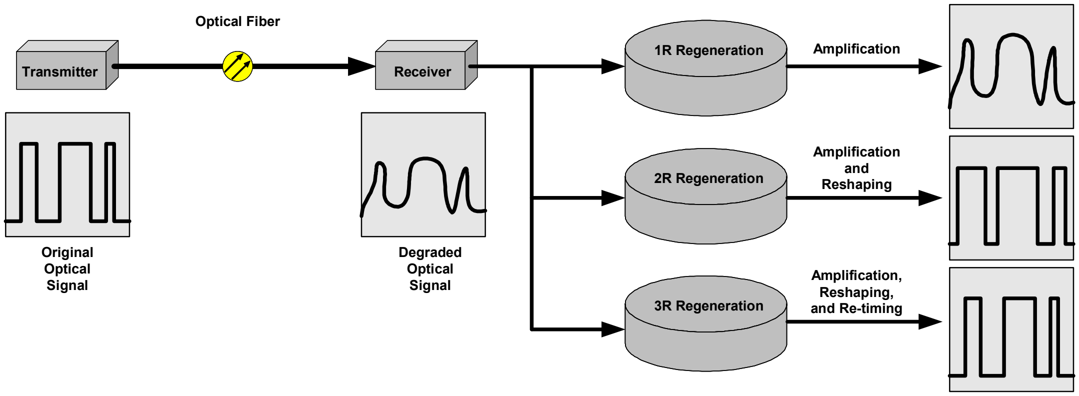


Figure 8: Optical Regeneration Levels

Optical regeneration in the optical domain would eliminate the need for the costly OEO conversions throughout the core network segments. With these conversions eliminated, scalability problems would be lessened due to the elimination of these transport bottlenecks. Further research is necessary to develop multiple simultaneous wavelength optical regeneration to fully integrate with DWDM technology.

2.2.2 Optical Dispersion Compensation

Longer wavelengths tend to propagate faster than shorter wavelengths. As optical signals travel through long fiber runs, a significant time offset proportional to the distance develops between the different wavelengths. Unfortunately, since all real optical pulses contain a small range of wavelengths around the intended wavelength, different components of the optical pulse travel at slightly different speeds. When this occurs, the optical pulse widens, possibly overlapping with other optical pulses and corrupting the optical signal. Known as “dispersion,” this optical side effect limits the maximum transmission rate of the fiber by forcing an increase in the optical pulse separation. Figure 9 depicts the effects of optical dispersion on transmission rate.[6]

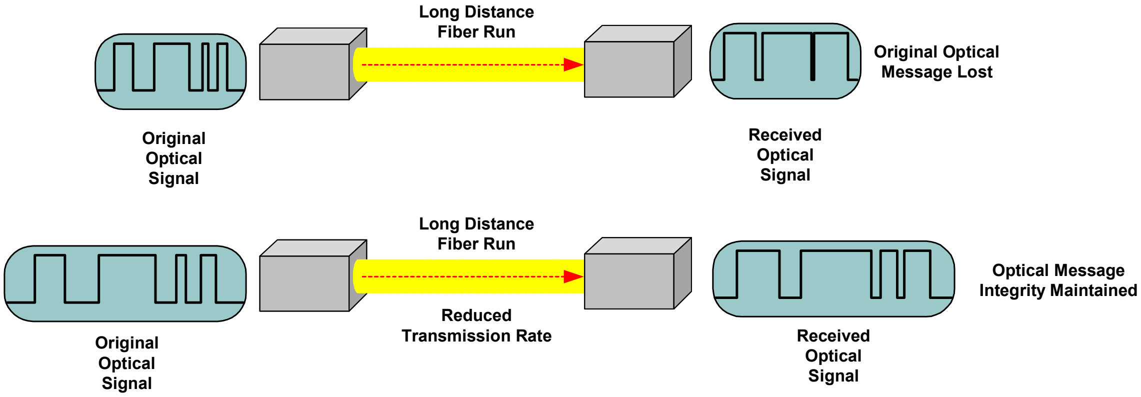


Figure 9: Effect of Optical Dispersion on Transmission Rate

Signals in long fiber runs encounter several forms of dispersion. Chromatic dispersion is caused by the variation in the propagation speed through a fiber as a function of wavelength. Modal dispersion occurs in multi-mode fiber and results from the different distances, or modes, traveled by the optical signals. Polarization Mode Dispersion (PMD) occurs when the orthogonal optical pulses in a fiber arrive at different times due to physical imperfections in the fiber core.

Dispersion effects must be compensated for to extend the bandwidth and range of optical fibers. One technique for dispersion compensation is dispersion-shifted fiber that compensates for the chromatic dispersion by canceling its effect with waveguides. Another compensation technique is the inclusion of opposing dispersive elements within the optical chain to strategically cancel the effects of dispersion. Other methods being developed include dispersion-flattened fiber and dispersion-optimized fiber.

2.2.3 Wavelength Conversion

Wavelength conversion is a critical optical networking component that will allow routing to be achieved entirely within the optical domain. This technology will complement optical switching, by providing additional functionality within high-speed core networks. All-optical wavelength conversion reduces the wavelength contention issue in photonic switching. Optical switching is wavelength dependent; therefore, only one information stream can be transmitted on any given wavelength throughout the network segment at a given time. Wavelength conversion provides a method for translating from one wavelength to another, allowing the optical switch to complete the operations without blocking either source. Having this performed completely in the optical domain provides a speed benefit and minimizes corruption losses due to the elimination of the OEO conversion process. Figure 10 provides an illustration of the contention issue faced by photonic switches.

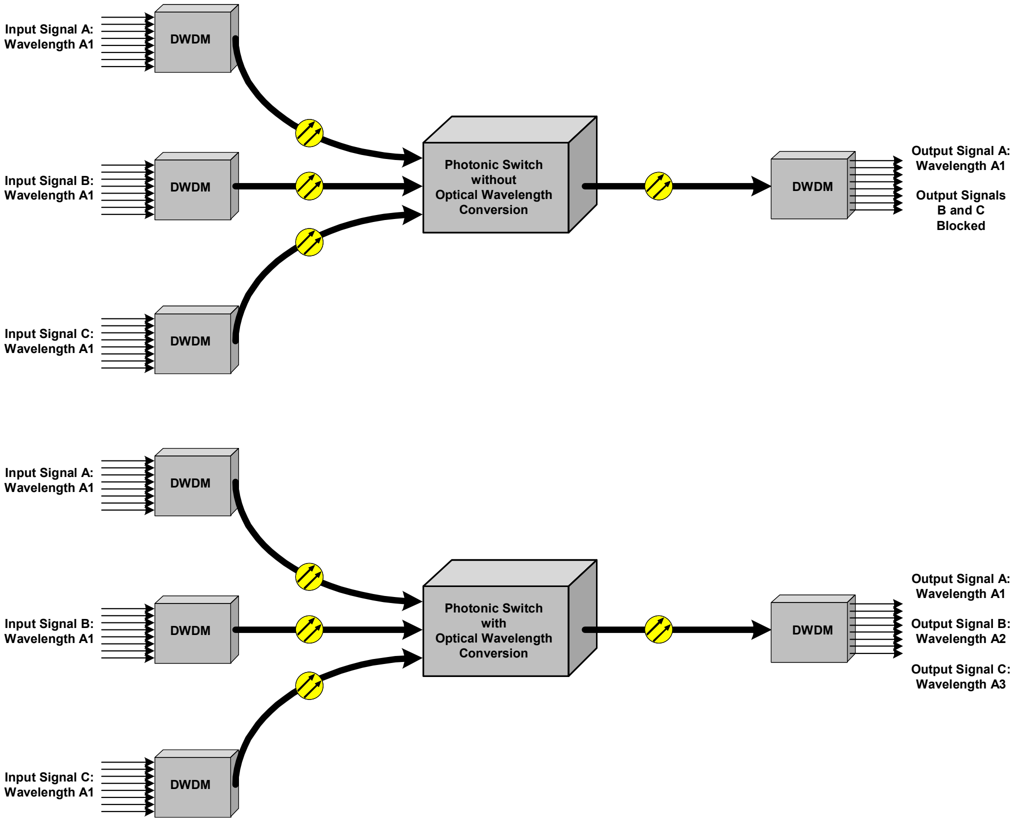


Figure 10: Photonic Switching and Wavelength Conversion

Currently, wavelength conversion is achieved via an OEO conversion process, which adversely affects transmission speed due to conversion. Laser modulation is time consuming and hinders a system's ability to be rapidly reconfigured in the event of optical channel corruption. Work is underway to move the wavelength conversion process to the optical domain in an effort to simplify network design and management. Research for all-optical wavelength conversion focuses on advanced semiconductor design for exploiting substrate nonlinearities and optical properties. Methods include cross-gain modulation, four-wave mixing, and cross-phase modulation.[4]

2.2.4 Optical Buffering

Timing contention surfaces when two input signals simultaneously attempt routing through the same output port. When this occurs, in electrical based networks, time-contention resolution is provided via memory buffering. Lower priority traffic remains buffered until higher priority transmissions are complete. Memory buffering facilitates store-and-forward routing, thereby preventing the loss of information as it traverses the network. The alternative to memory buffering is traffic rejection, or the drop of packets at the congested node. In optical networks the concept of memory buffering is yet unrealized. Optical delay lines currently hold the most promise for fulfilling the optical buffering need. These delay lines consist of different length fibers, tuned to deliver the optical signal after specific delay intervals.

Several methods of optical buffering have been proposed; however, none have been widely implemented at this time. Node architectures can be categorized as single or multi-stage, feed-forward or feedback buffers.[13] Figure 11 depicts the single-stage feed-forward 4-input/4-output optical buffer structure. Single-stage feed-forward optical buffers resolve contention by taking all of the optical signal inputs (①), converting them so that they reside on individual wavelengths (② and ③), multiplexing them together (④), and then distributing them to a set of delay lines, each having a unique delay time (⑤). The individual output port selects a specific delay line to resolve contention. The aggregation is then demultiplexed (⑥ and ⑦). Finally, the individual output port transmits the chosen wavelengths (⑧ and ⑨). Single-stage feed-forward optical buffers provide a costly way to implement contention resolution. The large number of components necessary for implementation is unattractive to large-scale network designers. Also there is no defined way for higher priority packets to supersede lower priority packets.[13]

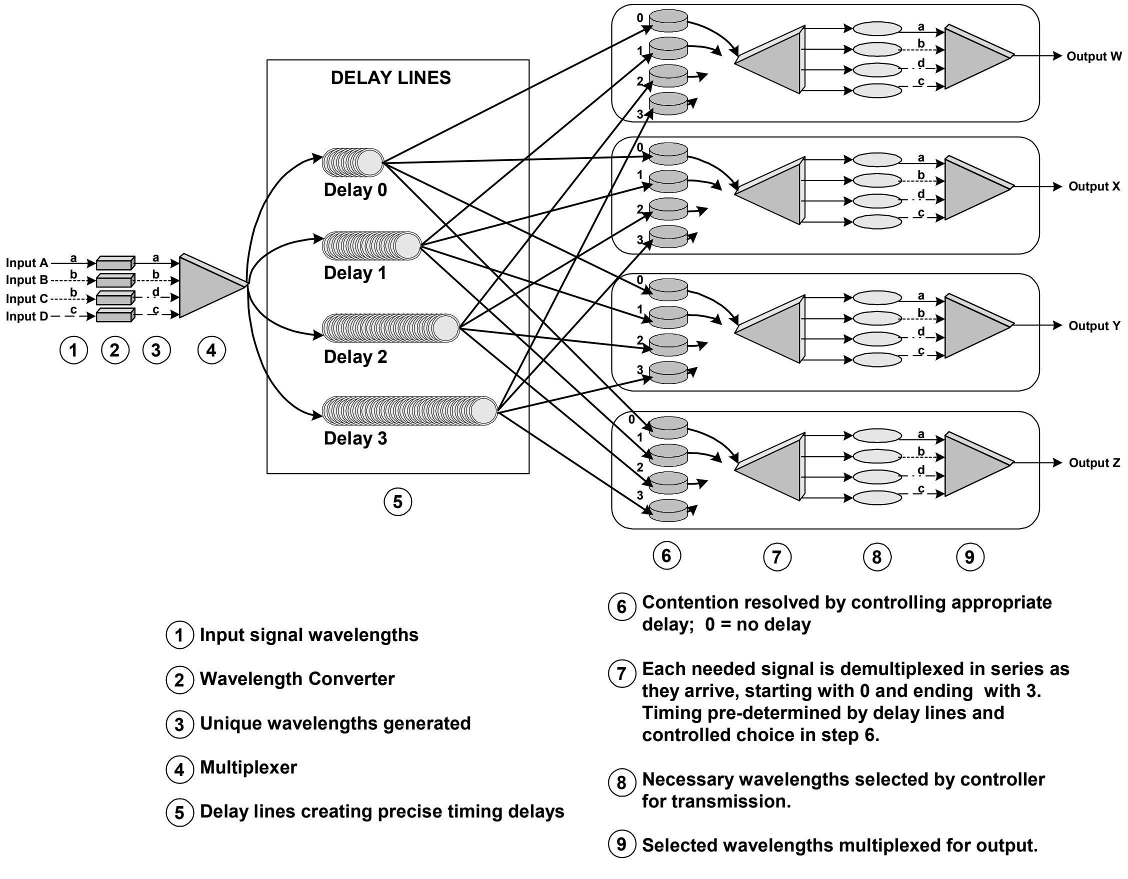


Figure 11: Single-Stage Feed-Forward 4X4 Optical Buffer Structure

Single-stage feedback optical buffers try to reduce the component burden associated with single-stage feed-forward optical buffers. Single-stage feedback optical buffers do not require a wavelength conversion or multiplexing operation prior to delay line allocation. Single-stage feedback buffering differs from single-stage feed-forward buffering in that the single set of delay lines in the buffer are shared by all wavelengths. Wavelengths are directed to a delay line appropriate to resolve the contention, thereby providing the benefit of packet prioritization. If a packet is superceded by one of higher priority, the packet is sent through another delay line and the process continues. Single-stage feedback optical buffers allow for scalability. Unfortunately, some lower priority packets could experience substantial power loss while having to make several delay line iterations. This power loss creates the necessity for optical amplification which can lead to signal degradation.[13]

Multi-stage feed-forward optical buffers are currently being proposed to resolve multiple contentions and should accommodate more efficient, faster buffering. Cascading multi-stage feed-forward buffers could accommodate large switching fabrics by providing the large-scale buffering necessary for operation. Research is in progress to develop practical methods for this form of buffering.

2.2.5 Deflection Routing

Deflection routing is a complement to optical buffering for handling interface/port contention resolution. Also known as “hot potato routing”, deflection routing constrains the network to a bufferless environment by not allowing traffic to enter the network if it cannot be immediately passed from the ingress node. Each inner-node operates under this same premise, thus preventing contention within the network. When a node accepts a packet, it will relay the packet towards its destination on the shortest path available without queuing. Deflection routing removes the need for the expensive infrastructure investment of optical buffering, by reducing the need for optical amplifiers, signal regeneration hardware, and calibrated delay lines.

Advantages of implementing deflection routing in an optical network are a simpler and less expensive infrastructure implementation, network congestion reduction, and adaptability to mesh topologies. Disadvantages of deflection routing consist of network synchronization issues that yield out-of-order packet arrival, no control over maximum number of hops through the network, difficult quality of service (QoS) implementations, and possible localized bandwidth inefficiency.

In the event that the network becomes somewhat asynchronous due to varying switch transmission rates or dramatic changes in switch utilization, congestion may increase and create a packet roaming condition. This condition would cause an increase in the number of hops for each packet in the network. An overall reduction in network throughput and possible network collapse would result. In an optical network, where signal degradation is an issue, this condition could lead to data compromise or the necessity for expensive signal regeneration. Also, if packets are prevented from entering the network because the ingress node is congested, they will be dropped since there is no facility for storing the optical signal. Packets already in the network are given priority over entering packets. Quality of service is difficult to implement because predetermined paths are not allocated and routing is determined at each node. Research is underway to advance deflection routing algorithms to address the issues of packet life and deflection strategies.[14][15]

Understanding the advantages and disadvantages of deflection routing, researchers are investigating the implementation of a hybrid deflection routing and optical buffering scheme. The hope is that this would provide optical networks with a stable time/interface contention resolution solution. For optical networks to proliferate, the balance between infrastructure cost and network speed must be maintained. Deflection routing offers a method to reduce these costs while used in conjunction with optical buffering.

2.2.6 Digital Wrapper Technology

Administration and maintenance functions for optical networks have historically been achieved by means of SONET/SDH encoding. In order to continue to utilize these capabilities, each signal must be formatted for SONET/SDH.[16] This violates the transparency goal of all-optical networks due to the inherent OEO conversion necessary to append the required SONET/SDH maintenance overhead.

Digital wrapper technology, introduced by Lucent in 1999, currently exploits the necessity for the conversion process at the optical signal regeneration nodes by appending overhead bytes to support network management and maintenance.[17] Digital wrapper technology removes the legacy of SONET/SDH from optical networks by treating each wavelength as its own independent optical channel. Each optical channel maintains the structure of packetized information data within its payload, adding the benefit of protocol independence. Header information is used to provide overhead bytes for monitoring and analysis information and wavelength based restoration.[16] The trailer contains forward error correction (FEC) data for the encapsulated payload. Figure 12 illustrates the protocol structure of the digital wrapper.

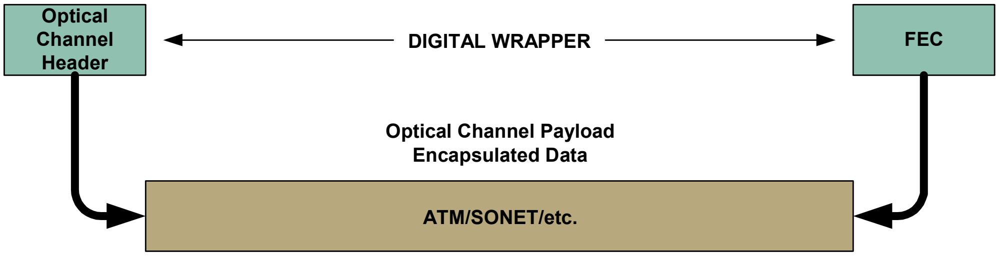


Figure 12: Digital Wrapper Structure

A benefit of digital wrapper technology is that it provides the optical network convenient access to information necessary for determining bit error rate (BER). This, in turn, yields longer distances and reduces the quantity of OEO conversion repeaters on the network. Hence, the effective network speed increases. Another benefit of digital wrapper technology is that it is FEC method independent. Each segment of the network could perform different implementations of FEC, depending upon the characteristics of the link. Digital wrapper technology also provides for a separate optical channel called the Optical Supervisory Channel (OSC). The OSC allows for end-to-end management of the different wavelengths within the optical network. [16] This will allow for QoS characteristics to be developed.

There is a movement to utilize digital wrapper technology in the optical domain without the need for the optical-electronic conversion. Provided that the optical regenerators are able to append overhead onto the optical channel and that equivalent 3R regeneration in the optical domain can be achieved, the goal of an all-optical transparent network could be achieved, at least in the core of transport networks.[16]

2.3 Optical Network Classes

Examination of various optical network classes provides insight into the evolution of various optical switching architectures. Widely implemented are optical link networks and broadcast and select optical networks. Research is underway into wavelength routed networks and photonic packet-switched networks. Progress in optical network design is rapid and will soon yield transparent, infinitely scalable, and robust network architectures which could proliferate throughout industry. The following sections describe these network classes in greater detail.

2.3.1 Optical Link Networks

Optical link networks provide connectivity in a point-to-point fashion across an optical network. Switching for optical link networks is done entirely in the electrical domain. The optical components are all static in nature, and thus, no network reconfiguration is possible without physical intervention.[18] Optical link networks are prevalent throughout industry. Their broad use is a good indication of industry's interest in all-optical networks. There are two distinct types of optical link networks. First, point-to-point links consist of DWDMs interconnecting electronic switches. Figure 13 depicts a common point-to-point optical link network.

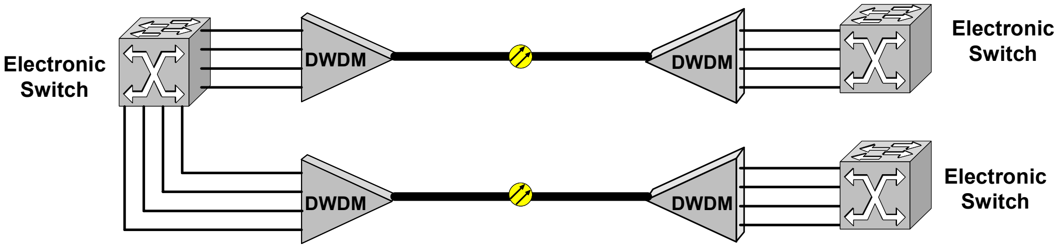


Figure 13: Point-to-Point Optical Link Network

The second type of optical link network is the shared-medium broadcast network. This class of network utilizes the functionality of a DWDM Passive Star Coupler, which distributes a DWDM optical signal to additional network segments. Figure 14 depicts a shared-medium broadcast optical link network.

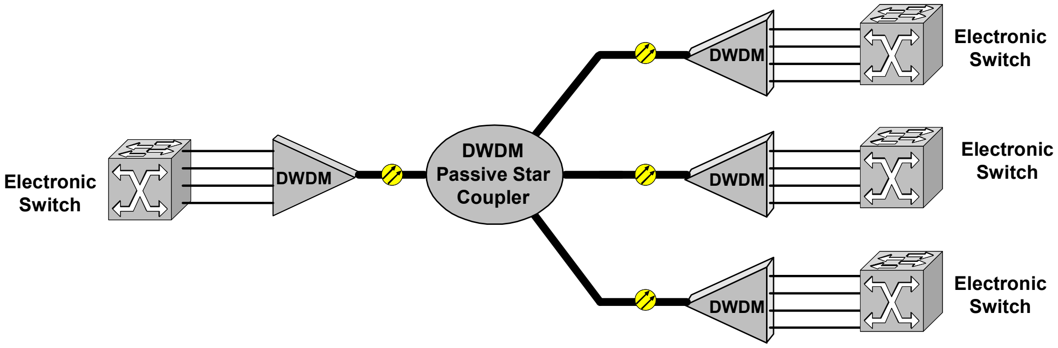


Figure 14: Shared-Medium Broadcast Optical Link Network

2.3.2 Broadcast and Select Optical Networks

Broadcast and select optical networks, as shown in Figure 15, leverage the benefits of tunable optical transmitters and receivers. These networks incorporate wavelength-agile receivers that tune to the appropriate signaling wavelength. Broadcast and select optical networks can be strictly optical or a hybrid with OEO conversion networks between the receivers and the DWDM or DWDM passive star coupler.[18] Tunable receivers add the benefits of scalability to optical link networks.

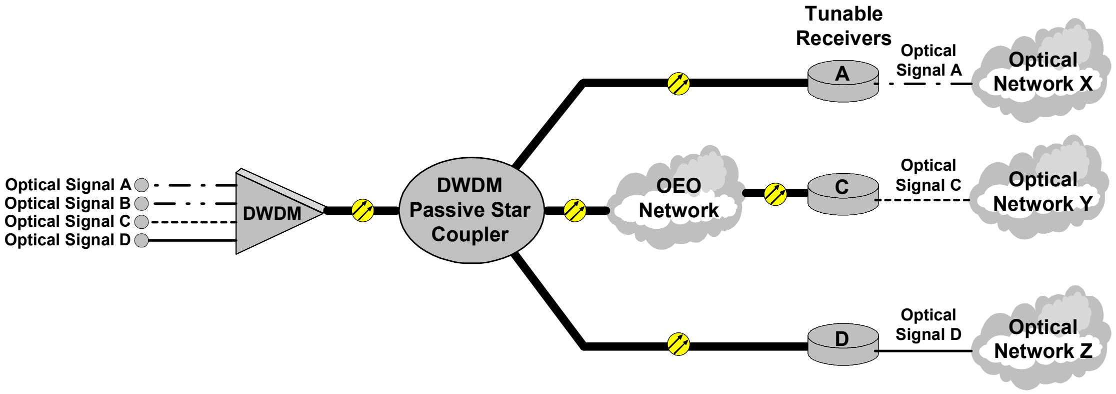


Figure 15: Broadcast and Select Optical Network

2.3.3 Wavelength Routed Optical Networks

Wavelength routed optical networks employ the light path switching functions of OADMs and OXCs. They may optionally use tunable transmitters and receivers to provide routing within a larger-scale network. Wavelength routed optical networks, as depicted in Figure 7, provide the ability to optically add and remove wavelengths from the network with multiplexing/demultiplexing. The implementation of optical cross connects further expands the network's ability to optically pass information between networks. Wavelength routed optical networks can be either circuit switched or packet switched, depending upon the configuration of the OADMs, OXCs, and whether the optical transceivers are wavelength-agile or not.

2.3.4 Photonic Packet-Switched Optical Networks

Photonic packet-switched optical networks are the final step towards completely transparent all-optical networks. Optical packet switches are fully in the optical domain with OEO conversions only performed at the edge of the optical networks. All optical components are implemented to provide necessary functionality for all-optical processes throughout the network. Optical switches provide scalable, high-speed, reliable network performance while minimizing infrastructure costs in the long term. Figure 16 depicts an all-optical photonic packet-switched optical network.

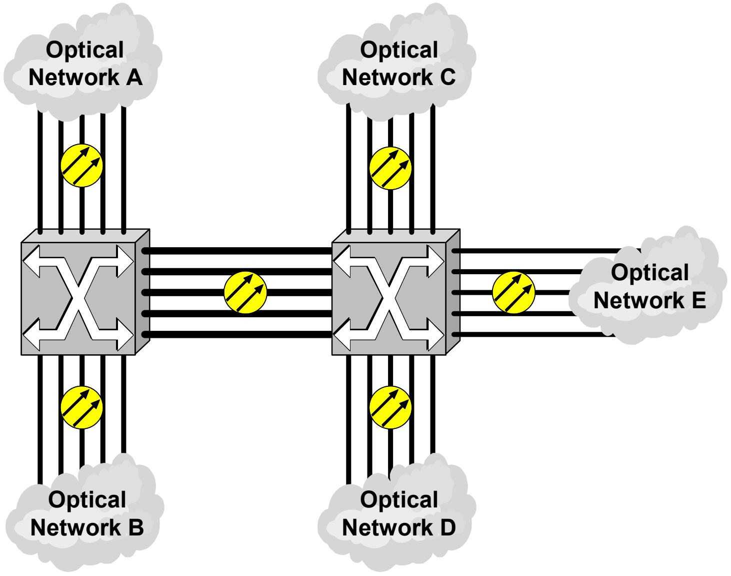


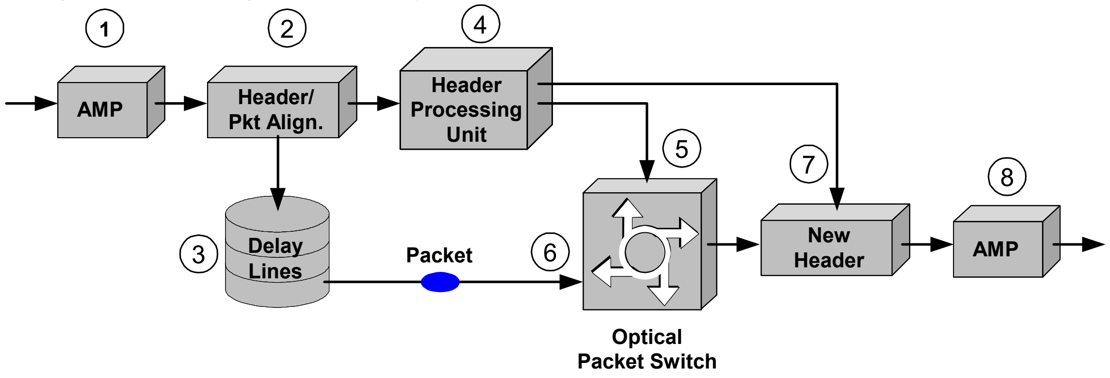
Figure 16: Photonic Packet-Switched Network

2.4 Optical Switching Architectures

Photonic switching architectures have resulted from the marriage of optical networking infrastructures, processing techniques, and creative network interconnection classes. The previous three sections have presented a background understanding of the enabling technologies implemented within photonic switching architectures. Several forms of photonic switching architectures surface from this advanced research. Optical packet switching forms a basis for high-speed all-optical data communications. Optical burst switching is viewed as a modification to the photonic packet switching design. Multiprotocol lambda switching (MPλS) blends multiprotocol label switching (MPLS) with optical communications in an effort to produce a more efficient means of provisioning resources within the optical cross connects (OXCs). MPλS will be analyzed in the context of its implementation within switching architectures.

2.4.1 Optical Packet Switching

Optical Packet Switching (OPS) is an emerging switching technology. Striving for an all-optical switching solution, researchers have experimented with two forms of optical packet switches. First, slotted optical packet switches provide the ability to optically switch fixed length packets. This enables higher speed switching because less direction information has to be determined prior to switched transmission. Slotted optical packet switches also permit the implementation of fiber delay lines, which adds the benefit of optical buffering to the switch. Figure 17 depicts the flow of a slotted optical packet switch. First, the input signal is pre-amplified as necessary (①). Next, the packet header is reviewed and optional packet realignment occurs (②). The packet is then sent through a delay line (③) to allow the header processing unit time to pre-configure the optical switch (④ and ⑤). The optical packet switch allocates the appropriate optical input to the appropriate optical output (⑥), a new header is attached (⑦), and the optical packet is amplified prior to retransmission (⑧).[19] The process repeats and the switch is reconfigured each time. Currently, header processing and switch configuration is done in the electrical domain. Research is underway to append an optical header, based on advanced modulation techniques, to effectively provide all-optical table-referenced routing and switching functionality.[20]



① Preamplification of optical input signal.

② Packet header review and optional packet alignment.

③ Delay on packet to allow for (4).

④ Header processing unit reads packet header.

⑤ Header processing unit pre-configures optical packet switch

⑥ Contention resolution provided by packet switch. Optical inputs sent to appropriate optical outputs.

⑦ New header written.

⑧ Optional power re-amplification.

Figure 17: Slotted Optical Packet Switch Flow

Unslotted optical packet switches perform switching on variable length packets. The architecture of unslotted optical packet switches is simpler than slotted optical packet switches because there is no pre-configuration of the switch itself nor any segmentation and reassembly of the header information. Unfortunately, because the switch is not pre-configured, contention problems arise. This results in higher packet loss.[19]

2.4.2 Optical Burst Switching

Optical Burst Switching (OBS) is a more efficient switching scheme than OPS. The reservation of bandwidth is unidirectional, thereby eliminating the necessity of timely response messages. Aggregating packets in bursts of data allows for less processing overhead and increases the overall speed of the network. By utilizing bursts and unidirectional end-to-end bandwidth reservation techniques, OBS networks eliminate the need to process packets at intermediate network nodes and establish a direct network segment from source to destination. The current trend is for the development of OBS to continue to grow. Once optical buffering techniques mature, OPS should become more prevalent then OBS.

There are three different techniques to achieve OBS. They vary primarily in terms of bandwidth release.[21] In-Band terminator (IBT) optical burst switching operates by detecting an IBT, or empty data set, inserted after the optical data burst, to release reserved bandwidth. Figure 18 depicts the typical IBT OBS frame.

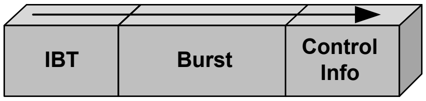


Figure 18: IBT Optical Burst Switch Frame

First, address information is sent in the form of a header or control packet (①), followed by burst data ending with the IBT (②). After some processing delay, the necessary network bandwidth is reserved (③) and the burst data is switched from input to output (④ and ⑤). Once the IBT is detected, the network bandwidth is released (⑥).[21] The process repeats for multiple bursts. Figure 19 illustrates the flow of IBT OBS.

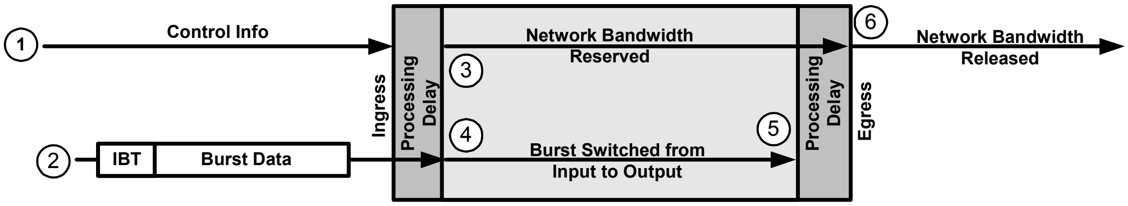


Figure 19: IBT Optical Burst Switch Flow

The second technique for optical burst switching is tell-and-go (TAG). TAG OBS operates the same as IBT OBS except a release packet replaces the in-band terminator. The switch releases the reserved bandwidth when it receives the release packet. An alternative to the use of release packets is refresh packets. Refresh packets are sent periodically to indicate that the connection is still active. If no release packets are received within a timeout period then the bandwidth would be released.[21]

The third technique for optical burst switching is reserve-a-fixed-duration (RFD). RFD OBS operates by including, within the control packet, the duration of the necessary bandwidth reservation. This method eliminates the overhead associated with the IBT and release packet of the previous two techniques. RFD provides a more efficient allocation of bandwidth and buffers.[21] RFD is currently the focus direction of most OBS research.

2.4.3 Multiprotocol Lambda Switching (MPλS)

Multiprotocol Lambda Switching (MPλS) is the optical equivalent of Multiprotocol Label Switching (MPLS). MPLS was designed to provide high-speed packet switching in the electronic domain. Implemented on the core routers within a network as shown in Figure 20, MPLS provides a mapping of Layer 3 traffic to Layer 2 transports, in an effort to reduce the processing overhead of current packet-switched networks.[22] MPLS achieves high-speed switching by adding a fixed-length 4-octet field to the IP packet. High-speed hardware segments the label, reads the QoS flags, and directs the data flow without the need for inspecting the remainder of the packet header or calculating the data flow path. The MPLS label is appended at the edge gateway of the network. Each

MPLS router along the path reads the encapsulation label and immediately forwards the packet towards its destination without further inspection. If necessary, the label could be modified by an inner MPLS router for optimized dataflow redirection. This label is finally removed by the destination gateway to produce the original packet. MPLS is highly scalable, since all of the necessary direction information can be obtained from the label and no reference has to be made to large tables located at each router.

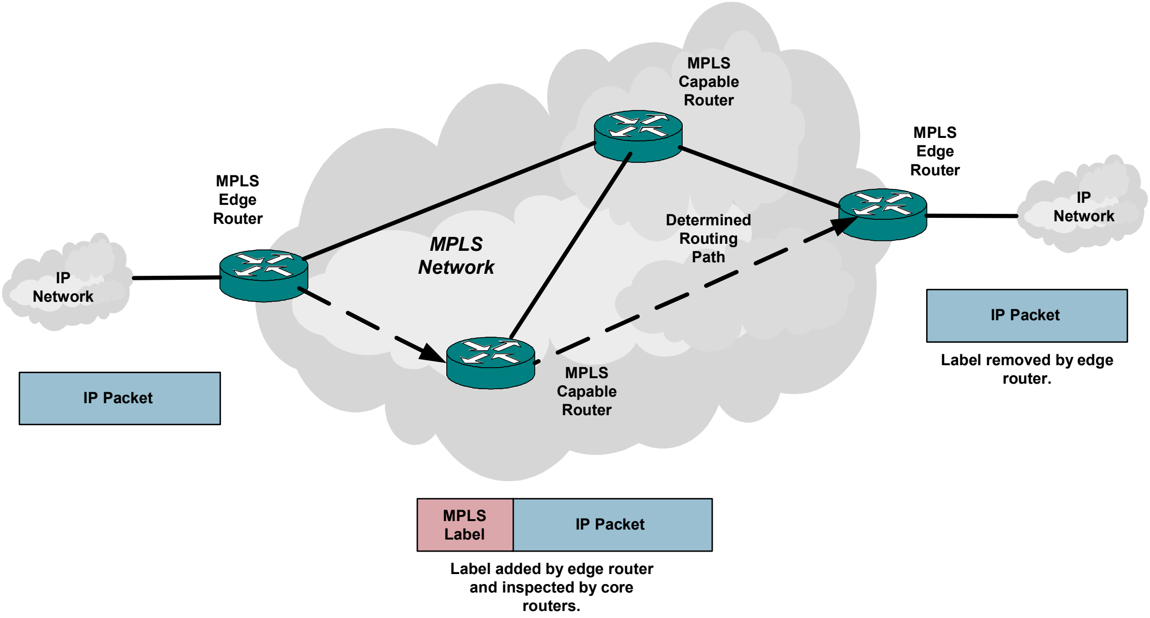


Figure 20: MPLS Functionality

MPλS extends the MPLS concept directly into the optical domain as shown in Figure 21. Optical interconnects can be controlled to route traffic on specific wavelengths, through the optical network core, to the destination edge optical gateway. MPλS operates on specific wavelengths in much the same manner that MPLS operated on packet switched data. Implementation requires the use of a control plane to accomplish the traffic engineering and subsequent traffic redirection. Implemented with either an overlay control plane or peer control plane, MPλS provides control of the optical physical layer providing DWDM-level network provisioning. Adding controllability to the switching of wavelengths provides network engineers with the ability to dynamically allocate the available core bandwidth. The bandwidth provisioning speed is also increased because the QoS is implemented on a per-wavelength basis as opposed to a per-packet basis. Through advanced traffic class segregation and aggregation, core level QoS can be optimized.[23]

MPλS is gaining standards support, but is still several years from widespread implementation. The Internet Engineering Task Force (IETF), International Telecommunication Union – Telecommunication Standardization Sector (ITU-T), Optical Internetworking Forum (OIF), and American National Standards Institute (ANSI) are all investigating dynamically reconfigurable optical networks such as MPλS.[24] Optical networks are on the verge of revolutionizing the way we communicate, and MPλS could be the control mechanism to make it a reality.

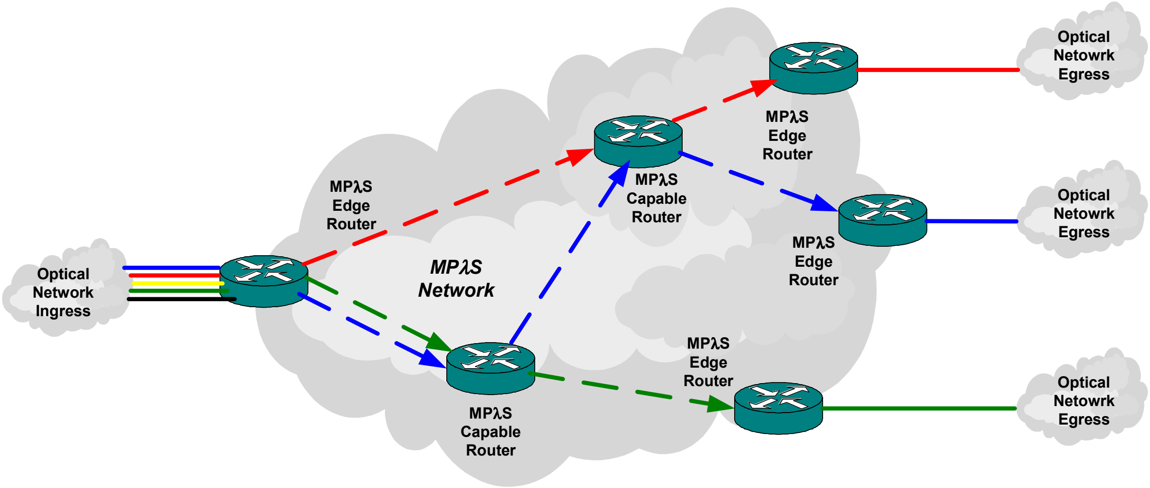


Figure 21: MPλS Functionality

3.0 NETWORK TECHNOLOGY IN TRANSITION

For the past one hundred years, communications technology has evolved along service cycles. A service cycle begins when a new service is introduced. The service progresses through the cycle, gaining popularity and becoming the dominant contributor to new network revenue and capacity demand. At maturity, network operators satisfy demand for the service, network growth subsides, and revenues level off. The next service cycle begins when a new service upstages the mature service by creating new network revenue and dominating network growth. The service cycles for telegraph, telex, and telephone spanned decades. As time passed, the service cycles became progressively shorter. Each cycle saw the market for interpersonal communications move to a new network growth leader. Telex upstaged telegraph, telephony superseded telex, and the Internet overshadowed telephony. Looking ahead in time, multimedia messaging in the form of voice-over-IP, desktop conferencing, and multimedia-on-demand may eventually surpass email and html as the fastest growing method for interpersonal communications.

Each advance in communications and its associated service cycle drives the global communications network to higher levels of speed, switching capacity, and functional sophistication. New services motivate transitions to new network technology within the infrastructure that responds to the prevailing market trends. Telex switches replaced telegraph operators, telephone switches replaced telex switches, and packet switches in the form of ATM switches and IP routers are replacing telephone switches.

Replacement of infrastructure technologies causes some network components to be displaced from the network. The need for backward compatibility with remaining equipment and the need for continuing support of older services force functions previously provided by displaced components to appear as functions within the new equipment that displaced them.

Many times communications standards developed within one service cycle persist in subsequent cycles because the standards provide legacy support for mature services or because the standards continue to perform useful functions within a new service. For example, Signaling System 7 (SS7) first appeared within the telephone network as an enhancement to the telephone routing and voice-oriented service delivery. SS7 continues to grow in scope by providing the control plane for new Internet-related services like Integrated Services Digital Network (ISDN), Digital Subscriber Line (DSL), fiber-in-the-loop, and voice-over-IP services.

Therefore, new service cycles replace obsolete equipment with more sophisticated higher capacity equipment. New equipment often provides legacy support for older services and frequently employs standards adopted during an earlier service cycle.

The rapid growth in data-oriented services defines the prevailing Internet services cycle. Rapid data service growth challenges the capacity of monochromatic fiber and electronic switching. It is tipping the financial scale from telephony-based circuit switching to data-oriented packet switching. Data services growth is driving the introduction of photonic equipment throughout the communications infrastructure.

The Internet services cycle is creating a new set of technology transitions within the infrastructure. Most obvious among the transitions is the rapid conversion from copper to fiber optic cable.

Fiber optic cables are the foundational technology for data service growth. Fiber optic cable provides greater transmission capacity and superior transmission quality at lower cost than the equivalent copper cable. Enterprises frequently create high capacity campus area and metropolitan area networks using only fiber optic cable.

3.1 Emergence of Ethernet Network Access Services

Ethernet, in its many forms, dominates enterprise networks. Enterprise networks consist largely of local area networks (LANs), campus area networks, and metropolitan area networks (MANs). LANs are almost uniformly 10 Mbps or 100 Mbps (10/100) Ethernet systems operating over twisted-pair copper or fiber optic cable. In most cases, enterprises lease the wide area portions of their networks from the public common carriers by subscribing to ATM, frame relay, or dedicated line services (T1, T3, etc.).[25]

Gigabit (1 Gbps) Ethernet is becoming popular as an enterprise communications backbone technology. As mass production lowers the cost, Gigabit Ethernet will eventually trickle down to the desktop. Ten Gigabit (10 Gbps) Ethernet will soon be appearing within the enterprise networks, primarily as a backbone communications protocol. Ethernet will, for the foreseeable future, be popular as a communications protocol operating along the periphery of high capacity wide area networks.

It is only natural that service providers are beginning to offer 10 Mbps and 100 Mbps Ethernet access services, referred to by Qwest Communications as “transparent LAN services.” Transparent LAN services acknowledge the prevalence of Ethernet as the dominant enterprise network technology. Ethernet access services relieve the customer of the complexity of wide-area network (WAN) router management. There have been recent announcements of Gigabit Ethernet wide area services by Qwest Communications, Broadwing, and XO Communications.[26] These offerings are currently available only between major US cities and appear as point-to-point “transparent LAN services.”

Despite recent announcements of Ethernet wide area services, it seems unlikely that Gigabit or Ten Gigabit Ethernet will prevail within the high capacity wide area network infrastructure. Ethernet is by design a local area network protocol. It works best in lightly loaded networks carrying delay insensitive, best effort traffic. Ethernet protocols provide best-effort packet delivery and lack QoS features. Instead, Ethernet relies on collision detection and other contention based techniques to share resources. Ethernet does not provide any QoS mechanisms.

As such, Ethernet is not well suited for carrying traffic along high-density traffic routes where many different types of traffic must contend in a predictable fashion for a common resource. Ethernet lacks recognized standards for network protection and restoration, making it vulnerable to cable cuts and equipment outages. Therefore, Gigabit and Ten-Gigabit Ethernet are unlikely technologies for high capacity photonic networks used in the core of the national infrastructure.

Instead, carriers will make Ethernet one of the network access options along the periphery of a high-speed ATM-over-DWDM, an IP-over-DWDM, or, eventually, an all-optical photonic switching network. Ethernet access speeds will increase to 1 Gbps as Gigabit Ethernet becomes prevalent within the enterprise networks. Provisioning Gigabit Ethernet access will become more attractive to the carriers as their core networks migrate to 10 Tbps DWDM and 10 Gbps OEO electronics.

3.2 DWDM Inroads Within High Capacity Core Networks

Current wide area networks consist mainly of electronic switching systems interconnected by point-to-point optical transmission channels. Figure 22 is a logical representation of an example wide area network that uses only optical cables as transmission links between switches or routers. SONET interfaces embedded within ATM switches and IP routers encapsulate data packets inside SONET frames for transmission across the fiber optic cable. The figure represents a straightforward, logical network design. However, the design does not fully utilize the optical capacity, and thus, it is costly if applied to wide area networks. The addition of SONET multiplexers in Figure 23 consolidates the traffic onto fewer optical fibers and reduces the infrastructure cost. However, even the addition of SONET multiplexers does not fully utilize the vast capacity of a single fiber optic strand.

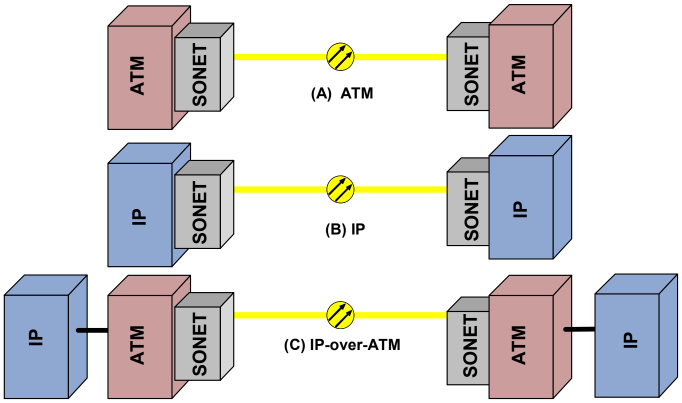


Figure 22: Logical Layout of an Optical Network

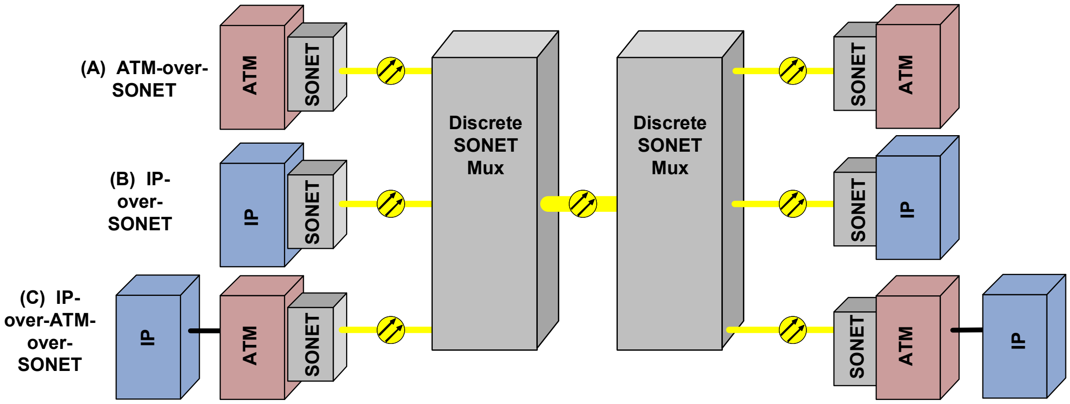


Figure 23: SONET Multiplexed Network Configuration

Note that the SONET multiplexer in Figure 24 combines ATM and IP transmissions at speeds lower than OC-192 into a combined transmission that makes economical use of the fiber optic capacity. Network designers frequently employ SONET multiplexers to combine lower speed traffic originating along the periphery of high capacity networks. The multiplexer's OEO electronics limit the multiplexer's ability to combine traffic onto high capacity fiber optic channels. In the figure, the multiplexer can combine traffic into fiber optic channels of 10 Gbps (OC-192) or less.

Current fiber optic technology provides capacities of at least 10 Tbps over a single fiber optic strand. Practical electronics for OEO conversion have capacity limitation of 10 Gbps (OC-192) today. It is anticipated that advances in OEO electronics will increase the OEO electronic speeds to 40 Gbps (OC-768) within the next four years. Even with 40 Gbps electronics, the SONET multiplexer in Figure 23 uses only a small portion of the 10 Tbps capacity available within a fiber optic strand. Consequently, there will be a great disparity between the fiber optic capacity and the ability to exploit the capacity with available electronics for the foreseeable future.

Data services growth, the cost of new cable deployment, and the need to better exploit the latent capacity of fiber optic cable motivate the introduction of DWDM equipment within the network. DWDM makes it possible to combine several transmissions onto the same fiber strand. For example, the DWDM in Figure 24 combines several high-speed SONET, ATM, and IP transmissions onto the same fiber. The combination makes much greater use of the fiber capacity and avoids costly construction of new fiber routes.

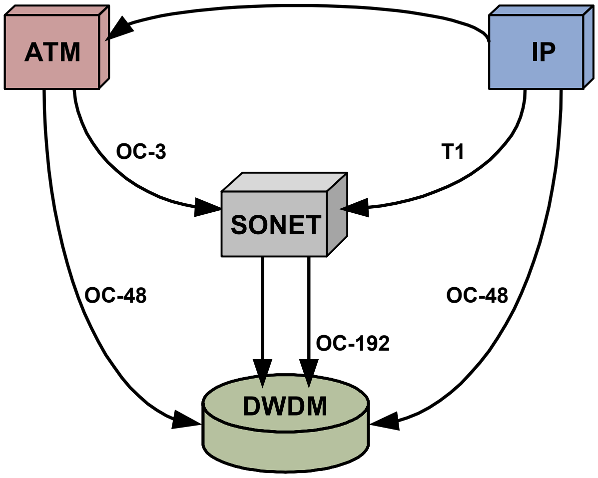


Figure 24: SONET-over-DWDM with Medium Speed ATM and IP Connections

Now, consider a high capacity communication network configured as shown in Figure 25. The ATM switches and IP routers are using the same high speed, OC-192 OEO electronics as the SONET multiplexer. There is no economy gained by passing the OC-192 ATM and IP transmissions through the OC-192 SONET multiplexer. The SONET multiplexer is superfluous. Instead, it is more efficient to connect the ATM and IP equipment directly to the DWDM as shown in Figure 26.

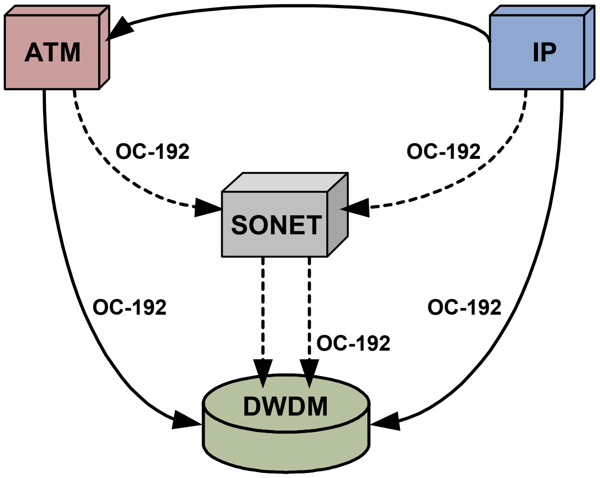


Figure 25: DWDM with High-Speed SONET, ATM, and IP Connections

Figure 26 illustrates the current transitional trend in which DWDMs are displacing SONET multiplexers from the high capacity core network. The DWDM assumes the SONET multiplexing function. Note that the IP routers retain the SONET OC-x signaling interface as a standard for signaling and encapsulating packets across the DWDM channel. Likewise, the ATM switches retain the SONET OC-X signaling interface as a standard for signaling and encapsulating cells across the DWDM channel. Thus, the SONET multiplexers are displaced by the DWDM, but SONET multiplexer functions appear within the DWDM, ATM, and IP equipment.

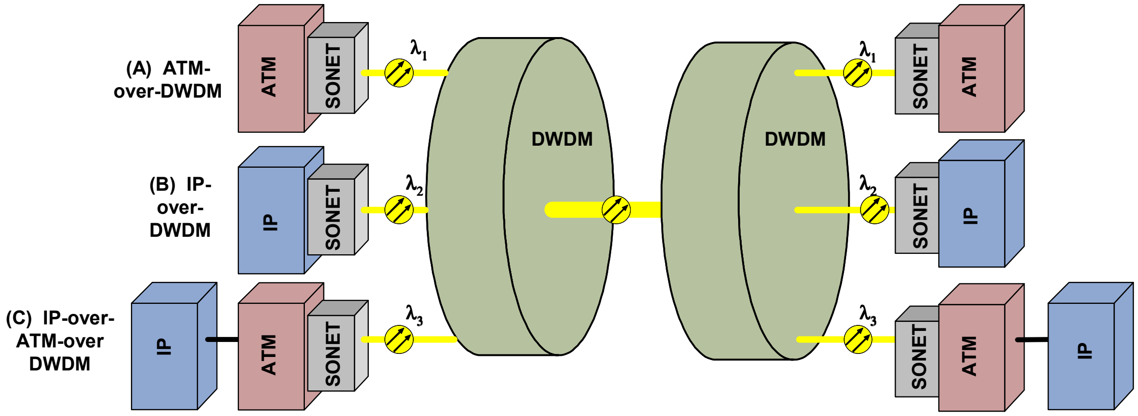


Figure 26: DWDM with High-Speed OC-192 Connections

The dizzying pace of today's service cycles and associated technology transitions is difficult to comprehend and even more difficult to convey to the marketplace. The photonic marketplace has a vernacular for describing the many configurations of the networks as they transition from one network configuration to another. The three SONET-based network configurations previously shown in Figure 23 are frequently referred to as: ATM-over-SONET (Figure 23 A), IP-over-SONET (Figure 23 B), and IP-over-ATM-over-SONET (Figure 23 C). They rely on SONET multiplexers within the network core to consolidate traffic onto fiber optic strands.

Figure 26 shows three alternative configurations to those shown in Figure 23. Networks resembling these are rapidly replacing SONET-multiplexed networks. These DWDM-based configurations are often referred to as: ATM-over-DWDM (Figure 26 A), IP-over-DWDM (Figure 26 B), and IP-over-ATM-over-DWDM (Figure 26 C). Note that all three configurations retain SONET signaling as the standard for the OEO interface between the electronic packet switching and DWDM equipment. Technically speaking, SONET continues to play a role in the network as a standard for signaling across an optical channel. However, SONET no longer exists in the network in the form of a separate piece of equipment. Instead, DWDMs assume the multiplexing role previously provided by SONET multiplexers.

Industrial convention uses the terminology ATM-over-SONET, IP-over-SONET, and IP-over-ATM-over-SONET to denote the presence of discrete SONET equipment within the multiplexing layer of the network. Convention uses the terminology ATM-over-DWDM, IP-over-DWDM, and IP-over-ATM-over-DWDM to denote networks where DWDM equipment takes the place of discrete SONET equipment, even if SONET signaling is used at the OEO interface within the IP and ATM equipment. This report adopts this convention and will use the conventional terminology throughout the remainder of the document when referring to networks comprised of combinations of electronic and optical equipment.

MPλS is gaining standards support, but is still several years from widespread implementation. The Internet Engineering Task Force (IETF), International Telecommunication Union – Telecommunication Standardization Sector (ITU-T), Optical Internetworking Forum (OIF), and American National Standards Institute (ANSI) are all investigating dynamically reconfigurable optical networks such as MPλS.[23] Optical networks are on the verge of revolutionizing the way we communicate, and MPλS could be the control mechanism to make it a reality.

4.0 CURRENT DEPLOYMENT STRATEGIES

There have been many notable advances in photonic networks. Researchers have demonstrated DWDMs over 1000 channels. Optical transmission rates of OC-192 per DWDM channel are common. Total DWDM rates of ten terabits per second (Tbps) and transmission distances of up to 3,000 miles using EDFAs are possible. It is therefore possible in the near term to leverage the installed fiber optic cable base with DWDM, thereby creating 100-fold or even 1000-fold increases in transmission capacity with no new investment in fiber infrastructure.

Photonic network capacity is doubling every nine months.[9] By comparison, electronic data processing and switching electronics are doubling in capacity every two years. There is great incentive to move switching into the optical domain where hopefully switching capacity can scale upward in proportion to transmission capacity. However, advances in photonic components are currently rudimentary in comparison to the state of electronics.

Advances in photonic packet switching have not made a major impact upon commercial network deployments. Photonic packet switching or circuit switching is possible using crude techniques that are slow and have unproven reliability.[27] Optical buffering techniques and optical storage is possible only under specially crafted laboratory conditions. Current light switching techniques are suitable for provisioning, but it will be from five to ten years before commercially viable, high-speed optical switching techniques appear.[9]

Kuwahara et. al. forecast the introduction of photonic products along a time line described in Table 4. As can be seen in the last row of the table, only DWDM and OADM are readily available for use in high capacity core networks. In the absence of OXCs, SONET equipment provides add and drop functions between adjoining DWDM networks. If the predictions of Table 4 hold true, then dynamic OADM and OXC systems will outstrip the bandwidth capacity of SONET equipment and thus displace SONET from core networks.

Optical core networks are evolving along the timeline shown in Table 4. Optical packet switching technology will not make major inroads into networks until issues of speed, reliability, conformance to standards, large-scale integration, and automated manufacturing are addressed by the communications industry. In the meantime, ATM switches and IP routers will provide the primary mechanisms for dynamic routing of traffic through high capacity core networks.

For the next five years or until all-optical packet switching is viable, electronic ATM and IP routers will dominate the switching layer, also called the “data link layer,” of high capacity networks. High capacity electronic switching will bridge adjoining physical layers comprised of reconfigurable optical networks. Figure 27 illustrates that a physical layer consisting of DWDM will carry combinations of ATM, IP, and SONET traffic.

Signaling protocols will route traffic through the data and physical layers, depending upon the application. Computer data traffic will rely on traditional Internet Protocol

Version 4 or 6 (IPv4 or IPv6) for signaling to direct IP-over-DWDM, IP-over-ATM, or IP-over-SONET traffic. Telephony will traverse ATM networks using SS7 out-of-band signaling or traverse IPv4/v6 networks using voice-over-IP in-band signaling. Low quality video may traverse IP-over-DWDM or IP-over-SONET. Video conferencing and high quality video applications will more likely rely on ATM until such time as IP QoS and scaling issues are resolved.[28]

Table 4: Photonic Technology Timeline [9]

	1995 – 1997	1998 – 2000	2000 – 2005	2005 – 2010
Wavelengths per fiber	4 – 16	32 – 128	128 – 512	Greater than 1024
Optical amplification bandwidth	40 nm	80 – 120 nm	200 nm	No prediction
Wavelength spacing	3.2 – 1.6 nm	0.8 – 0.4 nm	0.8 – 0.4 nm	0.2 nm
Capacity per fiber	40 Gbps	320 Gbps	1 Tbps	2 – 5 Tbps
Equipment	DWDM and static OADM	Dynamic OADM	OXC	Optical switching
Optical devices	DWDM and EDFA	Acoustic-optic tunable filter, tunable laser devices	Optical switches	Optical packet routers

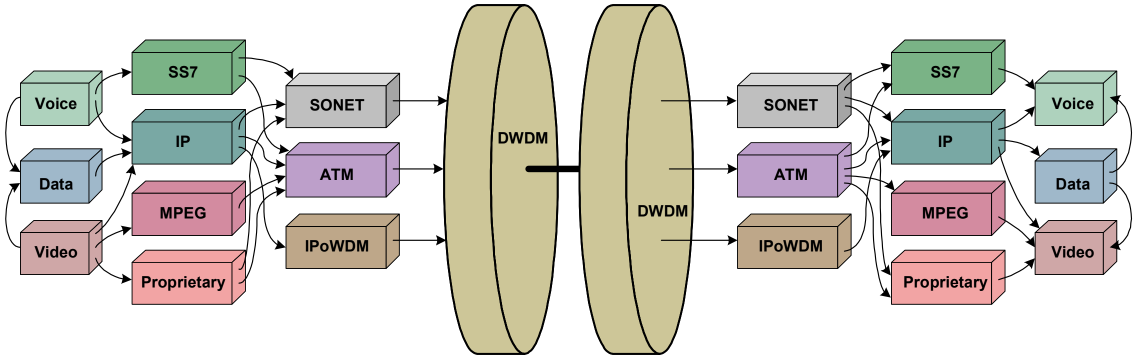


Figure 27: Multiservice DWDM Network

4.1 High-Speed Wide Area Networks

Conservative estimates predict Internet traffic will double every six months for the next few years. By the end of 2002, the United States will need 35 Tbps of network capacity to support Internet traffic. At 35 Tbps, Internet traffic within the US alone will be ten times greater than all of the voice traffic in the world. Every study predicts that data traffic will continue to grow faster than voice traffic. Predominant growth in IP-based traffic will drive new network development to a data-optimized architecture based on combinations of IP and ATM switching technology for the near term.[29][30] Photonic switching will eventually displace ATM and IP from high-speed core networks and will increase the capacity of core networks many times over current electronic switching technology.

Optical fibers and DWDM are proving to be ideal, cost-effective ways of addressing the rapid growth in data traffic. Today, DWDM systems are available that combine up to 40 OC-192 (10 Gbps per channel, 400 Gbps total) channels onto a single fiber. Near term systems will deliver 160 OC-768 (40 Gbps per channel, 6.4 Tbps total) channels per fiber, and laboratories are now demonstrating prototype systems capable of 320 OC-768 channels (12.8 Tbps total) per fiber.[31] Over time, electronics will improve to a point where OEO devices will be capable of driving an OC-768 channel economically.

4.1.1 Switching and Routing Within Photonic Networks

Some network layer technologies are more readily adapted to interface with DWDM channels than others are. ATM standards and interface electronics already exist in forms capable of driving high capacity optical channels. For example, ATM technology readily supports automatic detection of network faults and restoration of traffic along alternate paths. ATM's interfaces map directly from the SONET optical channel structure to the DWDM optical structure provided the optical network contains the necessary wavelength conversion functions. The transition from ATM-over-SONET to ATM-over-DWDM is straightforward. The same statement cannot be said of IP standards and electronic interfaces.

There are problems integrating IP and DWDM directly. DWDM currently lacks the ability to automatically protect, restore, and groom IP traffic in ways that make efficient and reliable use of DWDM channels. SONET/SDH currently provides these functions within DWDM-based networks. However, the advent of OC-192 routers and ATM switches are making SONET multiplexers superfluous in many networks. There is a need to interface ATM switches and IP routers directly to the DWDM optical layer.

Several outstanding issues remain. First, current approaches to IP-over-DWDM do not adequately address the QoS requirements of video and, to a lesser degree, voice. Second, IP routers do not make adequate provision for protection and restoration switching. Consequently, DWDM must provide SONET-like network reliability through sophisticated protection methods and rapid restoration of light paths.

Improvements for IP routing and QoS currently hinge upon the IETF MPLS standard for label switching of IP packets. MPLS provides ATM-like features by providing high speed switching of packets along a defined path for each session. Further development is needed for the proper integration of MPLS and associated standards like Differentiated Services (Diff-Serv) into high capacity IP routers. Advances in MPLS may eventually spill over into the optical domain.

The photonic counterpart to MPLS, MPλS, may be used within all-optical networks. MPλS applies label techniques to wavelength switched optical paths. Each wavelength serves as its own label. Both MPLS and MPλS must perform control functions like addressing, routing, signaling, and survivability. Used in combination, MPLS and MPλS may address the missing elements in today's IP-over-DWDM implementations. However, implementation of MPλS will be quite different from MPLS.

Control functions within MPλS are different than MPLS. The control and data planes must be separate in an all-optical network because of the very limited number of optical switching and signal processing devices currently available. There are three architectures under consideration for controlling the optical layer: router-centric, client-server, and peer-to-peer.[29][30] See Figure 28 for an illustration of these architectures.

Router-centric architecture places all of the switching intelligence in high-speed electronic routers and dedicates DWDM light paths between the router. High capacity routers assume all control of packet movement. Switching within the optical layer is static with optical control functions relegated to long term path provisioning, protection, and restoration.

Router-centric architectures suffer from a lack of scalability as optical channel bandwidths double every nine months, making electronic routers inadequate to the task of managing huge optical bandwidths. Advances in electronics are not increasing IP routing and ATM switching capacity fast enough to keep pace with DWDM capacity growth. Therefore, a router-centric architecture is not a good long-term approach for high-speed core networks.

Client-server, also called "interdomain," architectures keep the electronic routing layer separate from the optical DWDM layer. Client-server networks have separate routing instances within the IP and the optical layers. Routing information is shared between the instances. Routers and optical cross connects (OXCs) have unique IP addresses and a separate control plane for exchanging network, link status, provisioning, and restoration information. There is signaling between the two layers.

Client-server architectures are considered to be the most viable architecture in the short term. Eventually, new more elaborate standards for interfacing IP and DWDM networks will develop, creating a more unified, peer-to-peer architecture.

Peer-to-peer networks resemble the separate control and data planes in the SS7-based telephone network as illustrated in Figure 28. All electronic routing and optical DWDM layers are controlled from a single, unified control plane. All control planes will be electronic until optical computing or other forms of high speed information processing are available to replace electronic computing. A unified control plane provides seamless integration, but requires routing information to be shared between routers and OXCs. Consequently, it may not be practical in the near term. Peer-to-peer networks will be slow to develop because of the time required to formulate the necessary peer-to-peer protocol standards.

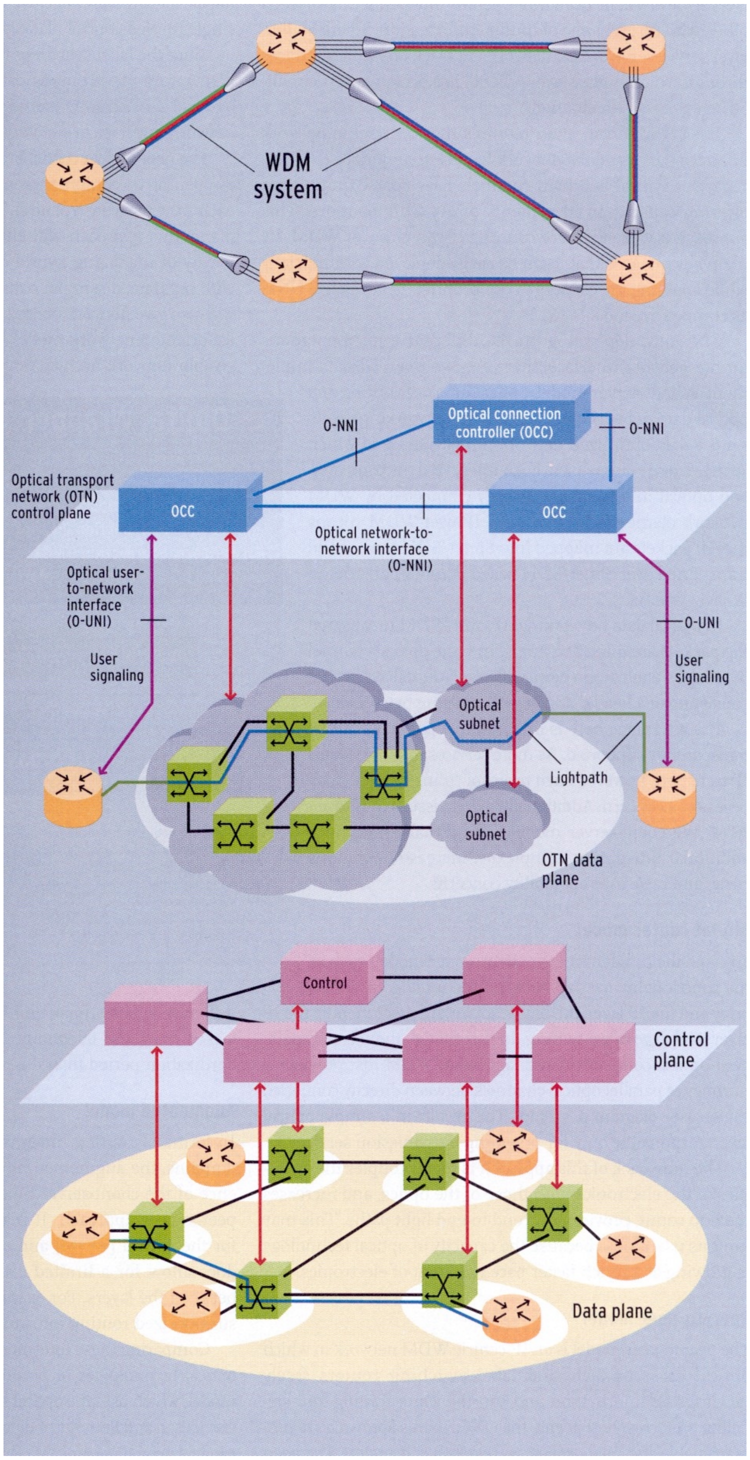


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Figure 28: Router-Centric, Client-Server, and Peer-to-Peer Optical Network Models [29]

4.1.2 Protection and Restoration

Protection and restoration switching are essential in DWDM networks. The prospect of failures in high-speed DWDM networks creates too much risk. DWDM capacity cannot be effectively managed, protected, and restored using IP, SONET, or ATM switching. Therefore, a routing scheme that uses protocols like MPLS or MPλS must provide the intelligence needed within the optical network to perform routing, wavelength assignment, fault detection, protection and restoration switching.

Current switching methods within DWDM networks are slow when compared to SONET or ATM. Therefore, routing and wavelength assignment within DWDM networks must occur much less frequently than in an electronic ATM or IP network. The most likely scenario will be to use static light path establishment with dynamic light path optimization. Static light path establishment employs offline routing schemes to optimally construct the optical network. Dynamic optimization uses automated methods to adjust the static light path configurations in response to changing traffic demands.

DWDM protection could take two forms. Pre-provisioned protection transmits signals over a primary and a backup path. The receiving device chooses between the paths based upon the relative signal quality of each path. Preemptive protection sends high priority traffic along a primary path and low priority traffic along a predetermined protection path. High priority traffic preempts the low priority traffic and seizes the protection path if the primary path fails.

Until high-speed photonic switching devices are available, ATM switches or IP routers will define the primary light path and restoration light paths. The OXCs will establish primary paths and restoration paths by interacting with the routers. Signaling between routers and OXCs will create light paths, delete light paths, modify light paths, and inquire on path status. The control plane requires mechanisms for neighbor discovery, link status updates, route computation, and path establishment. Restoration mechanisms may perform local restoration of links between adjacent OXCs or end-to-end restoration along alternate paths. Restoration paths may be 1+1 reserved capacity (similar to SONET ring protection methods) or shared protection where primary light paths share disjoint protection paths as a means of conserving network capacity and avoiding unnecessary traffic congestion.

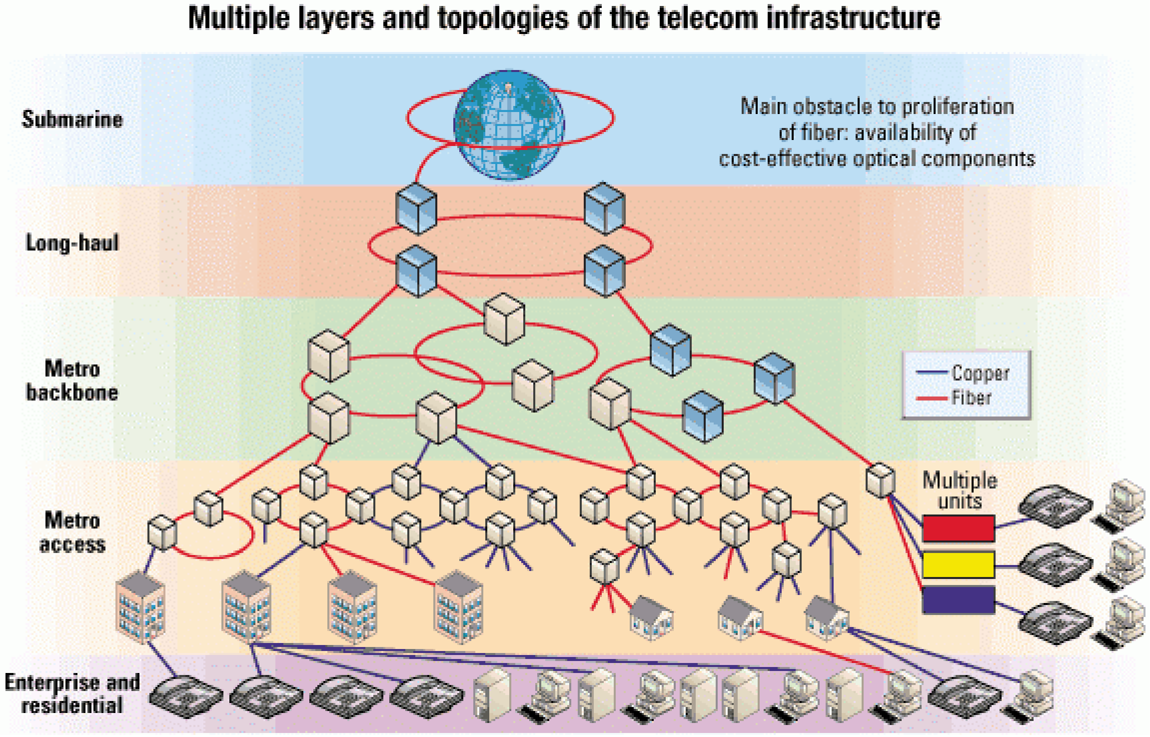
4.1.3 Submarine Networks

Submarine cable networks are an important but little discussed portion of the global communications infrastructure. Yet they provide all-important paths for connecting continents and supporting international commerce. Submarine networks provide services at the top of the global photonic infrastructure hierarchy as depicted in Figure 29.

Submarine cables are built and operated by consortiums of communications carriers from across the globe. A typical undersea cable consortium may involve 30 or more carriers from as many countries in the planning, construction, and management of a single cable system. A carrier consortium will jointly invest from several hundreds of millions to over $1 billion dollars in a single cable spanning the Atlantic or Pacific Ocean.

Introduction of fiber optic submarine cables revolutionized transoceanic communications. Suddenly, a single cable provided 560 Mbps of high quality, intercontinental service. The first undersea cable, called “TAT-8,” provides more voice conversation carrying capacity than all of the copper submarine cables combined. A flurry of undersea cable construction followed on the heels of TAT-8 that now connects the continents like a spider web.

Distinct differences exist between the construction of land-based and submarine cables. Land-based construction costs are heavily weighted by the costs of rights-of-way and trenching. In contrast, an expensive portion of submarine cable construction is the cost of deep-water submersible regenerators. Submarine cables operating at 580 Mbps require digital regenerators every 180 km at a cost of approximately $100,000 per regenerator. Cables spanning the Pacific Ocean from the United States to Japan are over 9600 km in length. The cost of regenerators quickly mounts in such systems. Newer cables like Trans Pacific Cable 5 (TPC-5) use all-optical submersible regenerators and operate at speeds of 1.2 Gbps and higher rates.



Reprinted from the May 2001 issue of Lightwave Magazine.
Source: Mark Sebastyn, Appian Communications Article: "Optical Ethernet: LAN Finally Meets WAN"

Figure 29: Global Photonic Infrastructure Hierarchy [25]

Land-based cables typically house tens or hundreds of fiber strands. Each pair of fiber represents a unique communications channel. Submarine cables rarely contain more than six fiber strands. At any time, only four strands are active, often referred to as "lit strands." Submarine cable designs dedicate two strands as hot standby, protection channels for rapid restoration in case of a regenerator or strand failure. Submarine cables hold the remaining pair as "cold spare" in case manufacturing defects or operational fatigue make one of the primary or protection strands inoperative after the cable is on the sea bottom. The cost of the regenerators and associated power equipment needed to operate more than two primary and two protection strands becomes prohibitive.

Introduction of DWDM and EDFA optical amplifiers to submarine cables increased their capacity immensely. New undersea cable systems operate with high-speed, 10 Gbps electronics, 16-channel DWDM, and SDH add-drop multiplexers. These DWDM submarine cables use EDFA submersible optical amplifiers that create 160 Gbps systems operating over two active strands of single mode fiber.[32] Like their predecessors, these high-speed, transcontinental systems use optical switching in the submersible regenerators and in the DWDM equipment located at the submarine cable-heads to provide rapid restoration to protection strands housed within the same cable.

4.2 Optical Access Networks

Access networks provide the "last mile" link between business and residential subscribers and the high capacity core networks. Access networks have always been an important factor controlling the types of services available to subscribers and the rate at which these services can be provided. They provide access to the services commonly used today (e.g., telephony, Internet Service Provider (ISP), ISDN, cable TV (CATV), dedicated private line, and xDSL services).

There is a broad array of access service providers within the United States. There are the incumbent local exchange carriers (ILECs) represented primarily by the divested regional Bell operating companies (RBOCs), the new generation of competitive local exchange carriers (CLECs), the franchised CATV companies, and the highly specialized building wiring companies, sometimes called "risers." Access service providers, in part, derive services from the high-capacity core network and deliver these services to their subscribers. They must contend with government regulation, long construction lead times, and large up-front investments as they attempt to reach as many customers as possible.

Access networks evolved from discrete copper cable systems, to T1 copper cable systems, and most recently to SONET fiber optic cable systems. Movement to fiber optic access networks is well underway within the United States and most of the industrialized world. Even so, the benefits of optical networks have been slow to reach most businesses and residences.

Gwynne claims that 76% of all businesses are within one mile of a service provider optical cable route.[33] Ninety percent of all interoffice trunks use SONET over single-mode fiber.[30] Clearly, if it were only a matter of being close to fiber optic cable routes, then there would be a large number of subscribers using optical cable services. Yet only 3% of all businesses have connection to fiber-based services. Residential connections to fiber-based services are even more rare. The problem lies in the provisioning of services from a fiber optic cable to many subscribers in an economically attractive manner.

In the past, all cable systems terminated in a carrier office and all derived services emanated from the carrier office to the subscriber. Access carriers distribute their services to their subscribers primarily over copper cable which is part of the "outside plant."

Carrier offices depend heavily upon SONET equipment for the provisioning of services. Extending these services to businesses and residences means placing SONET provisioning equipment and installing fiber optic cable in or very near the subscriber's premises. The cost of upgrading the outside plant to use fiber optic cables is very high, typically as high as $30,000 per mile.[34] The cost of placing SONET equipment and upgrading the outside cable plant to fiber optics limits widespread deployment of many high-speed services. High upgrade costs slowed the introduction of services like ISDN and xDSL. Deployment cost remains a substantial barrier for high-speed access to future all-optical networks. Even so, access carriers continue to invest in fiber optic outside plant. CLECs have 3 million miles of fiber and RBOCs have 14 million miles of fiber installed according to 1998 FCC statistics.[34]

Changing market demands are driving future planning of access networks: [35]

- Application Service Providers (ASPs) need better Service-Level Agreements (SLAs) and QoS from their Virtual Private Networks (VPNs).
- Residential customers want broadband access to the Internet.
- Corporate customers want high-speed bandwidth installed and managed by the carrier from the WAN interface at the customer site. Corporations want to add Web phones and personal digital assistants (PDAs) to their networks.
- Cable TV companies are competing for local exchange carrier residential and corporate clients.
- Data traffic exceeded voice traffic on carrier networks during 2000. It continues to grow much faster than voice.
- Copper cables become a less viable service distribution medium as traffic demand continues to grow.
- Changes in the access traffic mix are forcing carriers to change their networks to accommodate increased Internet holding times and to support heavy video content.

A new breed of optical access networks (OANs), called “asynchronous transfer mode passive optical networks” (ATM PONs) or simply “APONs,” offers a financially viable way of providing high-speed access to a customer’s premises. ATM PONs fall in the class of shared-medium broadcast optical link networks as was generally described by Figure 14. Figure 30 provides a more detailed depiction of an ATM PON. ATM PONs consist of an optical line terminal (OLT) located in the access carrier office and connected by fiber, passive optical splitters, and other passive optical components to several optical network units (ONUs) located on or near the customer homes and offices.[36]

ATM PONs are a major innovation for provisioning customer access to high-bandwidth services. Passive optical networks use few active devices in the access loop, which results in lower operating cost and simplified maintenance.[34] PONs provision access bandwidth incrementally from a single T1 (1.544 Mbps) up to OC-12 (622 Mbps).

ATM is an attractive switching platform in access networks because ATM can handle heterogeneous traffic uniformly and with QoS assurances.[36] An ATM switch within the OLT acts as the gateway between the access network and the high-speed optical backbone network.

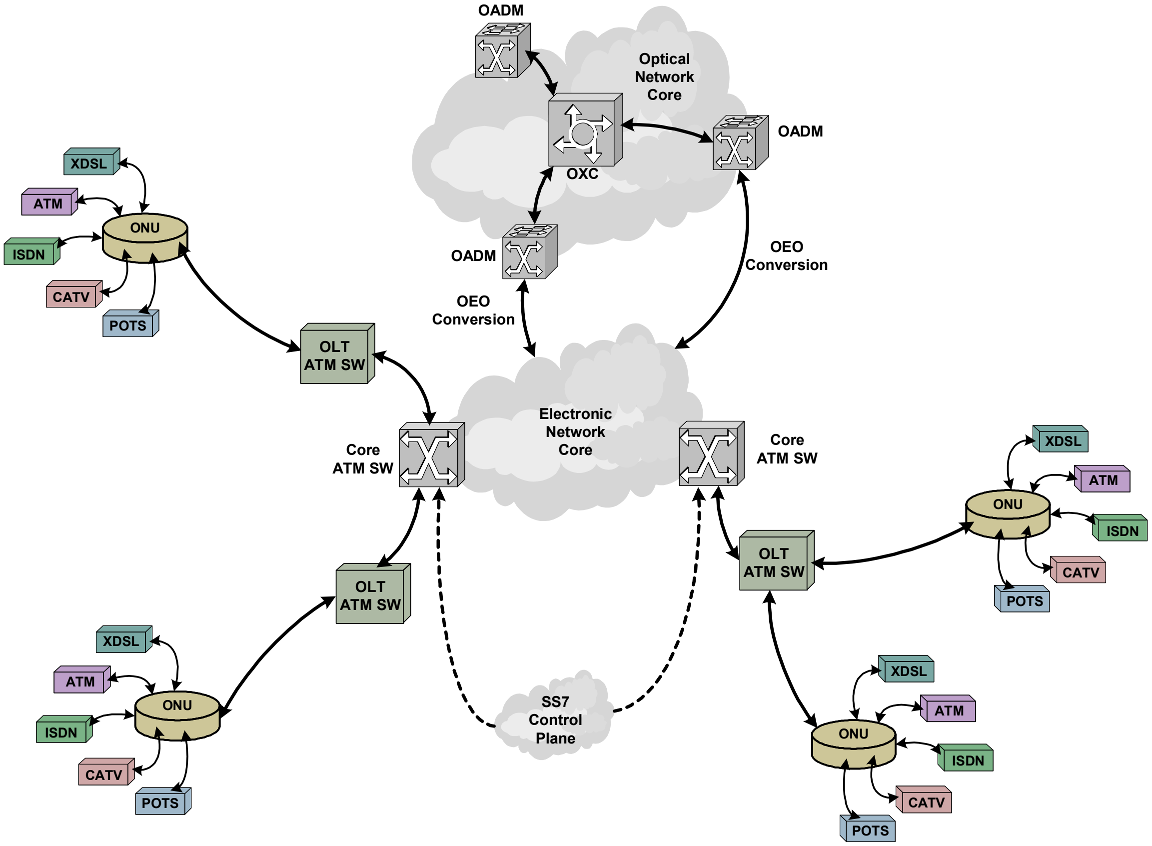


Figure 30: ATM Passive Optical Network [9]

ATM PONs provide many different types of services to each subscriber. Access carriers can configure a typical ONU to supply ATM, xDSL, conventional telephone, voice over DSL (VoDSL), CATV, leased line, and routed Ethernet services to the customer premises. An ATM switch within the OLT provides connection to the carrier's optical backbone network using available SONET or DWDM channels as shown in Figure 30. ATM PON integrates in the carrier's SS7 network control plane. SS7 signaling coordinates switching and routing between the OLT ATM switch and ATM switches located within the optical backbone network.

ITU-T Recommendation G.983.1, October 1998, establishes an approved standard for the ATM PON physical layer. The standard supports a 1310 nm burst time-division multiplexed (TDM) mode uplink to the OLT operating at OC-3 and an OC-3 or OC-12 downlink to the ONU operating in 1550 nm continuous TDM mode.[9]

Each ONU sends its cells on fixed or dynamically allocated time slots within a burst mode TDMA frame. The OLT assigns time slots to each ONU according to the services supported by the ONU. Legacy services like plain old telephone service (POTS) and private lines receive periodically allocated timeslots to ensure constant bit rate and low delay. Bursty traffic like IP packets receive dynamic allocation of timeslots. Each TDMA time slot consists of one PON cell. PON cells consist of a 53-octet ATM cell and a 3-octet PON header.

OLTs communicate downstream to their ONUs and assign upstream time slots using a continuous TDM frame. ONUs receive information the OLT via PON cells contained within OLT-designated downstream time slots.

An ATM PON supports up to 64 ONUs connected over a series of fiber optic branches of a single OLT. Cable lengths from the OLT to any given ONU may be up to 20km. Thus it is possible to deliver high-speed, full duplex services to 64 customer locations over a single strand of passive optical technology.[37]

Access carriers now view ATM PONs as the most economical way to boost service speeds to businesses and residences.[34] ATM PONs are frequently referred to as “fiber in the loop” (FITL) systems, because they currently appear in three cable configurations: Fiber to the home (FTTH), fiber to the curb (FTTC), and fiber to the cabinet (FTTCab). Technical and economic factors currently limit most FITL implementations to the curb or cabinet. Carriers use existing copper cables to extend FTTC and FTTCab networks into homes or small businesses. Eventually, the market demand and economics will extend ATM PONs in the FITL configuration directly into the customer premises.

4.2.1 Business Access Networks

Deployment of FITL in Europe is primarily to businesses in Britain and Germany. Competition between local exchange carriers (LECs) and CATV carriers motivated rapid deployment in Britain. The need for economical methods to rebuild East German infrastructure lead to the rapid construction of optical access networks within Germany. Deployment to businesses has an investment breakeven point for European access carriers at five subscriber lines per business, making FITL practical for many small businesses.[38]

Green predicts optical access networks will grow to 12 million FITL lines in Europe by 2002.[39] Fiber had not reached a cost-effective tradeoff with copper in 1993, but fiber is expected to become more cost effective than copper by 2002. Until then, deployment to residences seems to be limited by the relative cost of copper versus fiber.

4.2.2 Residential Access Networks

Prospects for FITL services are growing within the United States. Several local exchange carriers are adopting ATM PONs for extending services to small businesses and residences. For example, BellSouth began a trial of PONs installed to 400 residential customers during 1999.[3] In December 1999, BellSouth increased its commitment to ATM PONs by awarding Marconi with a $1.0 billion contract for fiber-to-the-curb equipment.[40] Marconi’s ATM PONs equipment delivers FITL voice, video, and data services to within 500 feet of the subscriber. The Marconi contract award brings the total number of FITL subscriber lines installed within the BellSouth service area to 780,000 lines.

BellSouth will offer POTS and asymmetric digital subscriber line (ADSL) services over their FITL systems. The RBOC forecasts that it will deploy between 50,000 and 100,000 FITL access lines per year.[34] If fiber optic costs fall below the cost of new copper installation in 2002 as expected, then the remainder of the decade will see growing emphasis on FITL systems.

5.0 FUTURE OPTICAL NETWORK ARCHITECTURES

Multiplexing is a method widely used within communications networks to combine many low bandwidth channels onto a higher bandwidth transmission medium. The process of combining many communications channels onto a higher capacity transmission medium is often called “capacity grooming.”

During the 1950s, the global communications infrastructure consisted largely of copper cable and analog microwave transmission systems primarily used for carrying Telex and telephone traffic. Bandwidth requirements per communications channel ranged from less than 100 bps for Telex to 3200 Hz for analog voice channels. Grooming during the 1950s and 1960s relied largely on frequency division multiplexing applied to coaxial cables and analog microwave systems.

Market forces drove the deployment of digital multiplexing within the global communications infrastructure. Introduction of digital microwave, digital switching systems, and the increasing popularity of telephone communications during the 1960s and the 1970s created the need for higher capacity, digital multiplexing methods. Widespread introduction of facsimile in the early 1980s compounded telephony growth and made the need for multiplexed transmission capacity through multiplexing more urgent.

Development of plesiochronous digital hierarchy (PDH) multiplexing systems in North America and Europe gave rise to new digital transmission channel formats. North America developed its PDH systems around the 1.544 Mbps, T1 format. The rest of the world adopted the International Telephone and Telegraph Consultative Committee (CCITT) standards (now known as the ITU-T standards) and deployed multiplex systems based upon the 2.048 Mbps E1 format. Both PDH formats were well suited to carrying voice, facsimile, and point-to-point dedicated data lines at 64 kbps or lower speeds. However, their usefulness declined after 64 kbps dedicated lines became too slow to meet market demands.

Advances in data processing, reduced regulation of the communications carriers, and widespread adoption of information as a value enhancing product strategy set the stage for corporate enterprise network development during the 1980s. Corporations built networks to handle airline reservations, coordinate transportation logistics, manage just-in-time inventories, and many other information-intensive tasks. Early successes like the American Airline’s Sabre airline reservation system, the “Wizard of Avis” car rental system, and the Federal Express package tracking system fueled enterprise network development. Corporations and military organizations quickly outgrew 64 kbps channels and demanded higher capacity DS1 and DS3 channels in North America and the equivalent E1 and E3 channels in other settings. The PDH multiplex architecture became economically prohibitive in the face of widespread demand for higher than 64 kbps transmission channels.

5.1 Transitioning the Multiplex Layer from SONET to DWDM

Changing market demand and the widespread introduction of fiber optic cables during the 1980s drove yet another transition within the multiplex layer of the global communications infrastructure. North America and the global communications community adopted nearly identical multiplexing standards referred to as SONET in North America and SDH within the ITU-T. SONET and its global counterpart SDH build upon the 51.84 Mbps, OC-1 multiplex format. Multiples of the OC-1 format create 155.52 Mbps OC-3, 622.08 Mbps OC-12, 1.24 Gbps OC-24, etc., as previously described in section 1.0.[41] The total bandwidth of the multiplexed optical channel depends upon the maximum speed of the electronics used in the SONET OEO subsystem.

Today, electronic technology limits the commercial SONET transmission speed to a 9.95 Gbps, OC-192 multiplexed optical channel. High capacity, OC-192 SONET systems are expensive. Practically speaking, they fail to provide value when combining channel speeds greater than OC-24 onto an OC-192 multiplexed channel.

SONET has its greatest application in combining virtual tributary (VT) channels at VT-1.5 (1.728Mbps), VT-2 (3.456Mbps) and VT-6 (6.912Mbps) onto OC-48 or OC-192 fiber optic channels with efficient add and drop functions. To date, frame relay has been the most successful packet service provided by the carriers. Typical frame relay services fit comfortably within the SONET VTs at rates from 128 kbps to 1.544 Mbps. Rapid growth in Internet data traffic, high-speed ATM networks, and voice-over-packet networks are supplanting frame relay, the virtual tributary architecture, and the voice-centric networks that SONET virtual tributaries were designed to support.

In the early 1990s, the Internet changed network usage patterns, creating an explosion in backbone traffic and a six-fold increase in subscriber line usage. Business requirements grew beyond frame relay and 1.544 Mbps access network transmission speed. Telephone subscriber holding times, the time that a telephone line is in use, were typically within the range of four to five minutes before the Internet became popular. Average Internet subscriber line holding times now fall within a range of 15 to 30 minutes.[42]

Carriers who built single-mode fiber networks during the late 1980s and early 1990s were caught by surprise, having not foreseen rapid growth of corporate LANs and the Internet. They had planned on using SONET to gradually increase the capacity of their established fiber. Rapid Internet traffic growth quickly upstaged plans to use SONET as the primary multiplier of installed fiber capacity.

By the end of 1996, nearly 100 percent of the major carriers were fully lit on all-important routes. On a broader scale, the carriers were 85 percent lit on their overall fiber capacity. Exploding demand put the carriers in a position of turning down customer requests for new service.[43]

By April 1997, the carriers no longer held reserves of dark fiber. Customer demand was growing for OC-3, OC-12, and OC-48 services. AT&T reported in 1999 that demand for OC-48 services was growing rapidly and that SONET equipment was ill suited to meet the demand.[44]

DWDM upstaged SONET as the cost-effective way to increase the capacity of established fiber. Readily available DWDM products multiply the capacity of established fiber by as much as 16 times on 10-year-old, single-mode fiber. A Bellcore study showed that DWDM is 30 percent cheaper than SONET for implementing interoffice trunking mesh. Studies funded by the Defense Advanced Research Projects Agency (DARPA) for the National Transparent Optical Network (NTON) predict that local and interexchange carrier costs will fall by 80 to 90 percent over an eight to fifteen year period starting in 1996. Widespread use of DWDM could reduce current fiber utilization levels from 80% to as low as 2%. Large-scale introduction of DWDM may eventually trickle down to the customer in the form of reduced bandwidth costs.

New, more advanced DWDM technology multiplies the bandwidth capacity of installed fiber by 100 or even 1000 times. It creates large capacity increases and avoids investments in new fiber construction. The economics and capacity advances brought about by DWDM will create growing demand for DWDM equipment at the expense of SONET.

Ryan Hankin Kent (RHK) (South San Francisco, CA) predicts that DWDM sales will grow from $480 million in 1996 to $4.4 billion in 2001.[43] Forecasting is difficult and it is easy to double-count forecasted DWDM requirements. There is always the possibility that carriers are overreacting to the current shortage of fiber and Internet growth. If so, they could be holding massive quantities of excess fiber capacity. For now, all of the participants are betting that traffic demand will grow to match their new fiber and DWDM investments.

DWDM promises many advantages for future networks. Consequently, there is another technology transition ahead for network operators. Technological and economic constraints will moderate the rate of transition.[3]

Network operators began their conversion from PDH to SONET during the 1980s. The communications industry required a decade and $4.5 billion to convert from PDH to SONET. Network operators will require time to amortize their SONET investments. Existing SONET networks will remain in service for a period of time. New high capacity network investments will favor DWDM over SONET.

The rate of SONET replacement by DWDM will be constrained in part by delays in commercially available optical cross connects (OXCs). OXC constraints will subside with time. In the meantime, SONET equipment will act as an electronic add and drop multiplexer between adjoining DWDM networks. Not withstanding the lack of OXC equipment, DWDM is displacing SONET as the primary means for multiplexing subscriber services onto fiber optic cables.

Dell'Oro Group projects that the market for SONET will peak in 2003 and begin a gradual decline afterwards as service providers begin supplanting SONET with DWDM.[45] The DWDM market will increase from $7.4 billion in 2000 to $36.5 billion in 2005. The total optical market for optically based multiplexing (SONET and WDM) will grow from $23.5 billion in 2000 to $57.3 billion in 2005.

WAN router sales will outpace DWDM, growing from $3 billion in 2000 to $26 billion in 2005. Rapid growth in electronic router sales will depend upon the absence of viable photonic packet technology for the next five years.

High-speed WAN routers will see the most rapid growth in the OC-48 line interfaces. Dell'Oro Group expects OC-12 and lower line interface sales to increase seven-fold from $1.9 billion in 2000 to $13.8 billion in 2005. They project that OC-48 and above router interface sales will increase nearly twenty-fold from $0.5 billion in 2000 to $9.1 billion in 2005. Clearly, rapid growth in OC-48 and higher speed interfaces for IP routers and ATM switches spell doom for electronic multiplex technology like SONET. At the same time, high speed routing and switching purchases by their customers will drive network operators to purchase more DWDM equipment.

5.2 Photonic Network Management

Network management is a necessary part of photonic networks. Failures within terabit-per-second optical networks will have devastating impacts on many applications. Therefore, photonic networks must protect against optical node and cable failures in a manner that assures high network reliability. Network management functions must include monitoring, provisioning, and restoration switching. Monitoring must detect changes in signal-to-noise ratios and wavelength deviations. Network management functions must appear within OADM and OXC equipment.[9]

It is possible to configure DWDM networks into as many as eight different types of rings. Automatic protection system (APS) protocols must be added to these ring configurations for reliable protection and restoration functions to exist within the DWDM-based network.

A cohesive network management system will be needed to manage combinations of DWDM, SONET, IP, and ATM networks. Currently, SONET network management systems are proprietary, creating serious problems for the maintenance and operation of SONET rings when multiple suppliers are involved.

SONET benefits from its excellent protection and restoration features. Restoration times of 50 ms make SONET the standard by which all other multiplex technology reliability is judged.[3]

DWDM has relatively long fault detection and restoration times when compared to SONET and ATM. Yet, DWDM lies at a lower layer within the network than ATM and SONET. Reliable restoration requires that DWDM detect and restore faults much more quickly than the SONET and ATM layers. Otherwise, instabilities may develop when higher network layers attempt to restore faults that are subsequently corrected by the DWDM layer. Photonic switching times must be reduced as DWDM takes up larger portions of the physical network.

Optical switching is, therefore, a necessary part of a highly reliable photonic network. However, there are only a few available optical switching technologies (e.g., optical bubble, MEM, and liquid crystal array). Optical switching technologies lag their electronic counterparts by 25 years in terms of speed, fabrication, integration, and sophistication, putting them on the same par with medium-scale integrated electronics. Even so, the optical switching market is approximately $247 million with growth expectations to more than $2 billion by 2004. Service providers are expected to deploy optical cross connects during 2001.[46] Manufacturers of optical switching see demand for their equipment to provide optical add/drop multiplexing and protection switching.

Photonic switching technology must see greater standardization, larger scale integration, and automated fabrication before there will be full displacement of electronics in favor of all-optical networks.[47]

5.3 Emerging Standards

Standards are taking shape for the orderly development of all-optical networks. ITU-T G.709 defines optical channel framing standards for encapsulating SONET, ATM, IP, and other traffic within a DWDM channel.[3] It provides forward error correction and APS functions to improve effective transmission quality, for fault detection, and for restoration switching management.

The ITU-T defined 0.2 nm as the minimum wavelength separation in DWDMs.[9] In so doing, the standard implies that efficient utilization of the DWDM channel bandwidth will require electronic interfaces operating at 10 Gbps (OC-192), which is the commercially practical limit of today's OEO technology.

ATM passive optical networks are the most promising candidates for access networks. Groups including the Full Services Access Network (FSAN), ATM-Forum, and ITU-T are creating standards for ATM-PONs. Most notable of the standards is the ITU-T SG15 standardization designated G.983.1 adopted during October 1998. ITU-T standard G.983.1 specifies the ATM-PON physical layer. G.983.1 ATM-PONs support fiber-to-the-home (FTTH), fiber-to-the-cabinet (FTTCab), and fiber-to-the-curb (FTTC). ITU-T G.983.1 supports a 1310 nm burst mode uplink to a service provider office operating at OC-3 and an OC-3 or OC-12 downlink to a customer premise operating in 1550 nm continuous mode. [9] ITU-T G.983.2 and G.983.3, when published, will add management, control, and new service features to ATM PONs.

ITU-T Recommendations G.971 through G.977 spell out many aspects of all-optical submarine cables. G.975 harmonizes forward error correction methods for submarine cable and G.977 defines the standard requirements for submarine optical amplifiers.

Three groups are focusing on IP-over-DWDM standards. The IETF is working on MPLS and other standards designed to realize the peer-to-peer architectural model. The Optical Internetworking Forum (OIF) is proposing schemes based on both the client-server and the peer-to-peer models. OIF standards rely on MPLS for use in both models. The Optical Domain Service Interconnect (ODSI) proposes user network interfaces for rapid service provisioning based upon modifications to the transport control protocol/internet protocol (TCP/IP) stack.[29]

Fifty vendors including Williams Communications, Siemens, and Sycamore Networks formed the ODSI consortium.[48][49] ODSI seeks a standardized signaling interface between service networks and optical transport networks for the automatic provisioning of optical paths. ODSI-proposed standards assume that services networks consist primarily of electronic IP routers and ATM switches. Optical transport networks consist of DWDM with provisioning capacities of OC-48 or OC-192.

The proposed ODSI protocol adds extensions to the IP and MPLS protocols. If adopted, it would allow customers to provision additional bandwidth within seconds. It would support short-term provisioning of high-definition TV, router, and switched connections to meet immediate demand. The standard is nearing finalization. Sycamore Networks hopes to market equipment based upon the protocol by the end of 2001.

The OIF is working on direct interfaces between IP and DWDM devices. Direct IP-over-DWDM interfaces would bypass ATM and SONET conversions that currently exist in the commercial networks.

The standard setting bodies will create many more standards before all-optical networks become a mature technology. There is a general lack of standards for all-optical management, protection, and restoration. Standards exist for optical cables and are rapidly developing for DWDM. Standards do not exist for optical add/drop multiplexers and optical cross-connect system signaling or management. Optical cell and packet switches are primarily laboratory prototypes and first generation products. Consequently, standardization of optical switching has not begun in earnest.

6.0 CONCLUSIONS

A technological revolution is at hand. Just as the transistor replaced the vacuum tube, and application specific integrated circuit (ASIC) replaced the printed circuit board, photonic devices will replace electronic devices within the global network infrastructure. Today, photonic switching, storage, and filtering devices are either crude laboratory prototypes or first generation production models. Often, they are slow, large, and poorly integrated. Standards for photonic interfaces and protocols are lacking in many areas. Yet, photonic devices are here and they are presently the only long-term solution to the burgeoning Information Age.

It seems that the Information Age is just hitting its full stride. Information now dominates global network planning. Telephony no longer defines network design or new service development. Instead, voice is becoming a component of a data-oriented infrastructure. The conversion of society to an information-based network is ubiquitous and so pervasive that it overshadows telephony and places more demand upon the global networks than telephones.

During the 1990s, the demand for information consumed almost all of the available fiber within the United States and forced the rapid introduction of DWDM. Demand continues to grow at rates that exceed the rate of growth in electronic switching technology. Electronic systems are no longer the leader in communications network evolution.

The communications industry stands upon the threshold of a new era in network design. Copper cables are obsolete. Fiber optic cables already dominate every aspect of submarine, continental, and local exchange transmission. Electronic multiplexing, be it PDH or SONET, will inevitably vanish from high capacity networks, having been replaced by DWDM. Early photonic switching devices are taking the place of electronic protection and restoration switching systems. Inevitably, photonic switching will emerge in the core network as replacements to electronic IP routers and ATM switches.

Photonic technology is setting the pace for growth in the Information Age. Photonic transmission capacity is doubling every nine months, which is more than twice the rate of electronic transmission capacity growth. The disparity between electronic switching and photonic transmission capacities leaves vast amounts of fiber optic capacity unexploited. Electronic switching has become the bottleneck in high capacity networks.

The transition to photonic networks is a clear and inevitable trend. Driven by the exploding demand for information and encouraged by the promise of video communication, the global communications infrastructure will incorporate photonic multiplexing and switching as quickly as the technology matures.

The demand for information will push fiber optics to the curb and ultimately to the home. It will relegate electronics to the periphery of the network where it will operate so long as it is more practical or economical than its photonic counterparts. If the evolution from transistor to computer repeats itself, then there will be an evolution from crude photonic switches and optical amplifiers to photonic routers and ultimately photonic computing.

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