

Technology Overview

- 1.1 INTRODUCTION
- 1.2 OPTICAL TRANSMISSION SYSTEMS
 - 1.2.1 Overview
 - 1.2.2 Attenuation
 - 1.2.3 Dispersion
 - 1.2.4 Nonlinear Effects
 - 1.2.5 Optical Fiber
 - 1.2.6 Optical Transmitter and Receivers
 - 1.2.7 Regenerators, Repeaters, and Optical Amplifiers
 - 1.2.8 Characterizing Optical Signals and Performance
 - 1.2.9 DWDM Systems
- 1.3 MULTIPLEXING, GROOMING, AND SWITCHING
 - 1.3.1 Digital Cross-Connects and Add/Drop Multiplexers
 - 1.3.2 OOO Switch Fabrics
 - 1.3.2.1 *Opto-Mechanical*
 - 1.3.2.2 *Electro-Optic Switches*
 - 1.3.2.3 *Acousto-Optic Switches*
 - 1.3.2.4 *Thermo-Optic Switches*
 - 1.3.2.5 *Magneto-Optic Switches*
 - 1.3.2.6 *Liquid Crystal Optical Switches*
- 1.4 SUMMARY

1.1 Introduction

Modern optical transport networks consist primarily of optical switches interconnected using Dense Wavelength Division Multiplexing (DWDM) transmission systems. In this chapter, we review the basic characteristics of optical transmission and switching systems. Specifically, we describe the working principles

that guide the generation and reception of optical signals and its transmission through the optical fiber. We also review the technological foundation behind optical switching, an important element of modern optical transport networks. The discussion in this chapter highlights the physical properties of optical networks, many of which may appear as constraints in the control plane.

1.2 Optical Transmission Systems

1.2.1 Overview

The first step in the development of fiber optic transmission over meaningful distances was to find light sources that were sufficiently powerful and narrow. The light-emitting diode (LED) and the laser diode proved capable of meeting these requirements. Lasers went through several generations in the 1960s, culminating with the semiconductor lasers that are most widely used in fiber optics today.

The next step was to overcome the loss of signal strength, or *attenuation*, seen in glass. In 1970, Corning produced the first communication-grade fibers. With attenuation less than 20 decibels per kilometer (dB/km), this purified glass fiber exceeded the threshold for making fiber optics a viable technology.

Innovation at first proceeded slowly, as the telephone companies—the main users of the technology—were rather cautious. AT&T first standardized transmission at DS3 speed (45 Mbps) for *multimode* fibers. Soon thereafter, *single-mode* fibers were shown to be capable of transmission rates ten times that of the older type, as well as to support spans of up to 32 km (20 miles). In the early 1980s, MCI, followed by Sprint, adopted single-mode fibers for its long-distance network in the United States.

Further developments in fiber optics were closely tied to the use of the specific regions on the optical spectrum where optical attenuation is low. These regions, called *windows*, lie between areas of high absorption. The earliest systems were developed to operate around 850 nm, the first window in silica-based optical fiber. A second window (S band), at 1310 nm, soon proved to be superior because of its lower attenuation, followed by a third window (C band) at 1550 nm with an even lower optical loss. Today, a fourth window (L band) near 1625 nm, is under development and early deployment.

Transmission of light in optical fiber presents several challenges that must be dealt with. These fall into the following three broad categories [Agrawal97]:

1. Attenuation—decay of signal strength, or loss of light power, as the signal propagates through the fiber.
2. Chromatic dispersion—spreading of light pulses as they travel down the fiber.
3. Nonlinear effects—cumulative effects from the interaction of light with the material through which it travels, resulting in changes in the lightwave and interactions between light waves.

These are described in more detail below.

1.2.2 Attenuation

Attenuation in optical fiber is caused by intrinsic factors, primarily scattering and absorption, and by extrinsic factors, including stress from the manufacturing process, the environment, and physical bending. The most common form of scattering, *Rayleigh scattering*, is caused by small variations in the density of glass as it cools. These variations are smaller than the wavelengths used and therefore act as scattering objects. Scattering affects short wavelengths more than long wavelengths and limits the use of wavelengths below 800 nm.

Attenuation due to absorption is caused by a combination of factors, including the intrinsic properties of the material itself, the impurities in the glass, and any atomic defects in the glass. These impurities absorb the optical energy, causing the light to become dimmer. While Rayleigh scattering is important at shorter wavelengths, intrinsic absorption is an issue at longer wavelengths and increases dramatically above 1700 nm. Absorption due to water peaks introduced in the fiber manufacturing process, however, is being eliminated in some new fiber types.

The primary factors affecting attenuation in optical fibers are the length of the fiber and the wavelength of the light. Attenuation in fiber is compensated primarily through the use of optical amplifiers.

1.2.3 Dispersion

Dispersion is the spreading of light pulses as they travel down optical fiber. Dispersion results in distortion of the signal, which limits the bandwidth of the fiber. Two general types of dispersion affect DWDM systems. One of these effects, *chromatic dispersion*, is linear, while the other, *Polarization Mode Dispersion (PMD)*, is nonlinear.

Chromatic dispersion occurs because different wavelengths propagate at different speeds. In single-mode fiber, chromatic dispersion has two components, *material* dispersion and *waveguide* dispersion. Material dispersion occurs when wavelengths travel at different speeds through the material. A light source, no matter how narrow, emits several wavelengths within a range. When these wavelengths travel through a medium, each individual wavelength arrives at the far end at a different time. The second component of chromatic dispersion, waveguide dispersion, occurs because of the different refractive indices of the *core* and the *cladding* of fiber (see section 1.2.5). Although chromatic dispersion is generally not an issue at speeds below 2.5 Gbps, it does increase with higher bit rates.

Most single-mode fibers support two perpendicular polarization modes, vertical and horizontal. Because these polarization states are not maintained, there occurs an interaction between the pulses that results in a smearing of the signal. PMD is generally not a problem at transmission rates below 10 Gbps.

1.2.4 Nonlinear Effects

In addition to PMD, there are other nonlinear effects. Because nonlinear effects tend to manifest themselves when optical power is very high, they become important in DWDM (see section 1.2.9). Linear effects such as attenuation and dispersion can be compensated, but nonlinear effects accumulate. They are the fundamental limiting mechanisms to the amount of data that can be transmitted in optical fiber. The most important types of nonlinear effects are *stimulated Brillouin scattering*, *stimulated Raman scattering*, *self-phase modulation*, and *four-wave mixing* [Agrawal97]. In DWDM, four-wave mixing is the most critical of these types. Four-wave mixing is caused by the nonlinear nature of the *refractive index* (see the next section) of the optical fiber. Nonlinear interactions among different DWDM channels create sidebands that can cause interchannel interference. Three frequencies interact to produce a fourth frequency, resulting in cross talk and signal-to-noise level degradation. Four-wave mixing cannot be filtered out, either optically or electrically, and increases with the length of the fiber. It also limits the channel capacity of a DWDM system.

1.2.5 Optical Fiber

The main requirement on optical fibers is to guide light waves with a minimum of attenuation (loss of signal). Optical fibers are composed of fine threads of glass in layers, called the core and cladding, in which light can be transmitted at about two-thirds its speed in vacuum. Although admittedly an oversimplification, the transmission of light in optical fiber is commonly explained using the principle of *total internal reflection*. With this phenomenon, 100 percent of light that strikes a surface is reflected. By contrast, a mirror reflects about 90 percent of the light that strikes it.

Light is either reflected (it bounces back) or refracted (its angle is altered while passing through a different medium) depending on the angle of incidence (the angle at which light strikes the interface between an optically denser and optically thinner material). Total internal reflection happens when the following conditions are met:

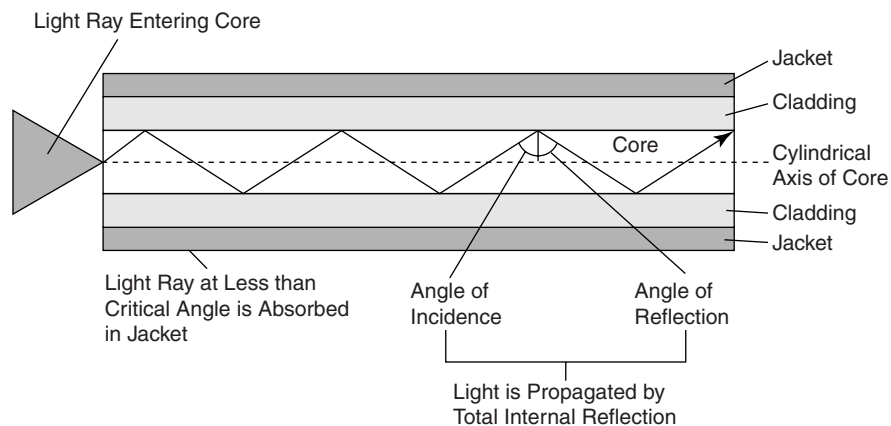
1. Beams pass from a material of higher density to a material of lower density. The difference between the optical density of a given material and a vacuum is the material's refractive index.
2. The incident angle is less than the *critical* angle. The critical angle is the angle of incidence at which light stops being refracted and is instead totally reflected.

An optical fiber consists of two different types of very pure and solid glass (silica): the core and the cladding. These are mixed with specific elements, called *dopants*, to adjust their refractive indices. The difference between the refractive indices of the two materials causes most of the transmitted light to bounce off the cladding and stay within the core. The critical angle requirement is met by controlling the angle at which the light is injected into the fiber (see Figure 1–1). Two or more layers of protective coating around the cladding ensure that the glass can be handled without damage.

There are two general categories of optical fiber in use today, multimode and single-mode. Multimode, the first type of fiber to be commercialized, has a larger core than single-mode fiber. It gets its name from the fact that numerous *modes*, or light rays, can be simultaneously carried by it. The second general type of fiber, single-mode, has a much smaller core that allows only one mode of light at a time through the core. As a result, the fidelity of the signal is better retained over longer distances. This characteristic results in higher bandwidth capacity than achievable using multimode fibers. Due to its large information-carrying capacity and low intrinsic loss, single-mode fibers are preferred for longer distances and higher bandwidth applications, including DWDM.

Designs of single-mode fiber have evolved over several decades. The three principle types are:

1. Non-dispersion-shifted fiber
2. Dispersion-shifted fiber
3. Non-zero dispersion-shifted fiber

**Figure 1-1***Propagation of Light through a Fiber Optic Cable*

As discussed earlier, there are four windows within the optical spectrum that have been exploited for fiber transmission. The first window, near 850 nm, was used almost exclusively for short-range, multimode applications. Non-dispersion-shifted fibers, commonly called standard single-mode (SM) fibers, were designed for use in the second window, near 1310 nm. To optimize the fiber's performance in this window, the fiber was designed so that chromatic dispersion would be close to zero near the 1310-nm wavelength.

The third window, or C band, has much lower attenuation. However, its dispersion characteristics are severely limiting. To alleviate this problem, manufacturers came up with the dispersion-shifted fiber design, which moved the zero-dispersion point to the 1550-nm region. Although this solution meant that the lowest optical attenuation and the zero-dispersion points coincided in the 1550-nm window, it turned out that there were destructive nonlinearities in optical fiber near the zero-dispersion point for which there was no effective compensation. Because of this limitation, these fibers are not suitable for DWDM applications.

The third type, non-zero dispersion-shifted fiber, is designed specifically to meet the needs of DWDM applications. The aim of this design is to make the dispersion low in the 1550-nm region, but not zero. This strategy effectively introduces a controlled amount of dispersion, which counters nonlinear effects such as four-wave mixing that can hinder the performance of DWDM systems [Dutton99].

1.2.6 Optical Transmitter and Receivers

Light emitters and light detectors are active devices at opposite ends of an optical transmission system. Light emitters, are transmit-side devices that convert electrical signals to light pulses. This conversion is accomplished by externally modulating a continuous wave of light based on the input signal, or by using a device that can generate modulated light directly. Light detectors perform the opposite function of light emitters. They are receive-side optoelectronic devices that convert light pulses into electrical signals.

The light source used in the design of a system is an important consideration because it can be one of the most costly elements. Its characteristics are often a strong limiting factor in the final performance of the optical link. Light-emitting devices used in optical transmission must be compact, monochromatic, stable, and long lasting. Two general types of light-emitting devices are used in optical transmission: light-emitting diodes (LEDs) and laser diodes or semiconductor lasers. LEDs are relatively slow devices, suitable for use at speeds of less than 1 Gbps; they exhibit a relatively wide spectrum width, and they transmit light in a relatively wide cone. These inexpensive devices are often used in multimode fiber communications. Semiconductor lasers, on the other hand, have performance characteristics better suited to single-mode fiber applications.

Requirements for lasers include precise wavelength, narrow spectrum width, sufficient power, and control of *chirp* (the change in frequency of a signal over time). Semiconductor lasers satisfy nicely the first three requirements. Chirp, however, can be affected by the means used to modulate the signal. In directly modulated lasers, the modulation of the light to represent the digital data is done internally. With external modulation, the modulation is done by an external device. When semiconductor lasers are directly modulated, chirp can become a limiting factor at high bit rates (above 10 Gbps). External modulation, on the other hand, helps to limit chirp.

Two types of semiconductor lasers are widely used: monolithic *Fabry-Perot* lasers and *Distributed Feedback* (DFB) lasers. The latter type is particularly well suited for DWDM applications for several reasons: it emits a nearly monochromatic light, it is capable of high speeds, it has a favorable signal-to-noise ratio, and it has superior linearity property. DFB lasers also have center frequencies in the region around 1310 nm, and from 1520 to 1565 nm. There are many other types and subtypes of lasers. Narrow spectrum tunable lasers are available, but their tuning range is limited to approximately 100–200 GHz. Wider spectrum tunable lasers, which will be important in dynamically switched optical networks, are under development.

On the receive end, it is necessary to recover the signals transmitted on different wavelengths over the fiber. This is done using a device called the *photodetector*. Two types of photodetectors are widely deployed, the *Positive-Intrinsic-Negative* (PIN) photodiode and the *Avalanche Photodiode* (APD). PIN photodiodes work on principles similar to, but in the reverse of, LEDs. That is, light is absorbed rather than emitted, and photons are converted to electrons in a 1:1 relationship. APDs are similar devices to PIN photodiodes, but provide gain through an amplification process: One photon acting on the device releases many electrons. PIN photodiodes have many advantages, including low cost and reliability, but APDs have higher reception sensitivity and accuracy. APDs, however, are more expensive than PIN photodiodes. They may also have very high current requirements and they are temperature sensitive.

1.2.7 Regenerators, Repeaters, and Optical Amplifiers

Optical signals undergo degradation when traversing optical links due to dispersion, loss, cross talk, and nonlinearity associated with fiber and optical components. Regenerators are devices consisting of both electronic and optical components to provide “3R” regeneration—Reamplification, Reshaping and Retiming. Retiming and reshaping detect the digital signal that is distorted and noisy, and re-create it as a clean signal (see Figure 1–2). In practice, signals can travel for up to 120 km (74 miles) between amplifiers. At longer distances of 600 to 1000 km (372 to 620 miles), the signal must be regener-

“3R” Retime, Reshape and Reamplify the signal—by knowing a lot about the signal, re-create it (e.g. SONET)



“2R” Reshape and Reamplify the signal—ignore timing but, for example, restore pulse shape by finding zero crossings (supports “translucent” digital transport)



“1R” Amplify the signal—restore signal amplitude and also amplify any accumulated noise or signal distortions (supports fully transparent transport including “analog” signals)



Figure 1-2

3R-Regeneration in Optical Networks Explained

ated. This is because an optical amplifier merely amplifies the signals and does not perform the other 3R functions (reshape and retime). Recent advances in transmission technology have increased the distance that can be traversed without amplification and 3R regeneration. It should be noted that amplifiers are purely optical devices whereas regenerators require optical-to-electrical (O/E) conversion and electrical-to-optical (E/O) conversion.

Before the arrival of optical amplifiers (OAs), every signal transmitted had to be individually regenerated or amplified using repeaters. The OA has made it possible to amplify all the wavelengths at once and without optical-electrical-optical (OEO) conversion. Besides being used on optical links, optical amplifiers can also be used to boost signal power after multiplexing or before demultiplexing, both of which can introduce loss in the system. The *Erbium-Doped Fiber Amplifier* (EDFA) is the most commonly deployed OA.

Erbium is a rare-earth element that, when excited, emits light around 1.54 micrometers—the low-loss wavelength for optical fibers used in DWDM.

A weak signal enters the erbium-doped fiber, into which light at 980 nm or 1480 nm is injected using a pump laser. This injected light stimulates the erbium atoms to release their stored energy as additional 1550-nm light. As this process continues down the fiber, the signal grows stronger. The spontaneous emissions in the EDFA also add noise to the signal; this determines the noise figure of an EDFA.

The key performance parameters of optical amplifiers are gain, gain flatness, noise level, and output power. The target parameters when selecting an EDFA, however, are low noise and flat gain. Gain should be flat because all signals must be amplified uniformly. Although the signal gain provided by the EDFA technology is inherently wavelength-dependent, it can be corrected with gain flattening filters. Such filters are often built into modern EDFAs. Low noise is a requirement because noise, along with the signal, is amplified. Because this effect is cumulative and cannot be filtered out, the signal-to-noise ratio is an ultimate limiting factor in the number of amplifiers that can be concatenated. This limits the length of a single fiber link.

1.2.8 Characterizing Optical Signals and Performance

The basic measure of digital signal transmission performance is a probabilistic quantity known as the Bit Error Rate (BER). Given a large sample of received bits, the BER gives the percentage of those received in error. The following basic phenomena affect the bit error rate of a signal:

1. Noise, and in particular, noise per bit.
2. Intersymbol interference, that is, the signal interfering with itself.
3. Interchannel interference, that is, other channels interfering with the signal.
4. Nonlinear effects (see [Ramaswamy+02] for a discussion).

Analysis of 1–4 for general communication systems is highly dependent on the modulation method used and the type of detection employed. In optical systems, the modulation method most frequently used is *On-Off-Keying* (OOK). As its name suggests, it is just like turning on and off the light (albeit very rapidly) according to the bits being sent (that is, “on” if a bit is 1 and “off” if the bit is 0). BER of the OOK modulated signal increases with the increasing bit rate of the signal.

Intersymbol interference takes place when a signal interferes with itself. This can happen in a couple of ways. First, if the channel the signal passes through is bandwidth-limited, then the nice square edges on the signal can get “rounded” so that the various individual bits actually interfere with each other. This *band limiting* may take place at the transmitter, receiver, or within the

channel. Within the fiber, dispersion occurs when the different wavelengths that compose the signal travel at different velocities down the fiber.

Interchannel interference occurs when signals based on different wavelengths interfere with each other, that is, their individual spectrums overlap. Hence, the channel spacing in a Wavelength Division Multiplexing (WDM) system must be wide enough to prevent the signal spectrums from overlapping. For a system with 100 GHz spacing carrying OC-48 signals (2.5Gbps bit rate), this is not a problem. As we shrink the spacing down to 12.5 GHz for OC-192 signals, it is more challenging to prevent interchannel interference.

Thus, both the wavelength of an optical signal and its bandwidth affect interference. Moreover, the BER is dependent on the signal modulation method and the bit rate. Thus, impairments such as line noise, loss, dispersion, and nonlinear effects must be taken into consideration when selecting a route to achieve the required performance criteria.

1.2.9 DWDM Systems

WDM [Green92, Agrawal97, Saleh+91] is an analog multiplexing technique where the original signals are “frequency shifted” to occupy different portions of the frequency spectrum of the transmission media. For example, commercial broadcast radio stations take a base audio signal (typically with a frequency between 20 and 20,000 Hz), use this to modulate a higher frequency *carrier* signal, and then broadcast this new signal into free space. This signal does not interfere with other signals if there is sufficient “spacing” between the carriers of the different radio stations. The required spacing is a function of both the spectral characteristics, spectrum, of the original signal and the modulation method.

In optical networking, the transmission medium is an optical fiber rather than free space. The signals of interest, rather than being analog audio content, are typically digital signals of various types. The carrier, rather than being an electromagnetic signal in the KHz or MHz range, is an electromagnetic signal with a frequency around 193 THz, that is, 1.93×10^{14} Hz! And like the radio case, there are a variety of different modulation methods that can be used to apply the digital signal to this carrier for transmission. As we go from radio to optical signals, the technologies change completely, for example, from electronic oscillators to lasers for generating the carrier signal.

The commercial U.S. AM radio broadcasts have carrier frequencies in the range of 560–1600 KHz with a spacing of 10 KHz, that is, signals may exist at 560 KHz, 570 KHz, 580 KHz, and so on. The spectral content of the audio signal is restricted to be between approximately 100–5000 Hz. Early WDM began in the late 1980s using the two widely spaced wavelengths in the 1310 nm and 1550 nm (or 850 nm and 1310 nm) regions, sometimes called *wideband* WDM. The early 1990s saw a second generation of WDM, sometimes called *narrowband* WDM, in which two to eight channels were used. These channels

were spaced at an interval of about 400 GHz in the 1550 nm window. By the mid-1990s, *dense* WDM (DWDM) systems were emerging with sixteen to forty channels and spacing from 100 to 200 GHz. By the late 1990s, DWDM systems had evolved to the point where they were capable of sixty-four to 160 parallel channels, densely packed at 50 or even 25 GHz intervals.

In the WDM case, there has been some initial standardization of frequencies and spacing. In particular, ITU-T has specified the frequencies in terms of offsets from the reference frequency of 193.1 THz [ITU-T98c]. The standard offsets are 200 GHz, 100 GHz, and 50 GHz. It should be noted that there are deployed WDM systems operating with grid spacing as narrow as 25 GHz and even narrower spacing is in the works. The ITU-T specification [ITU-T98c] does not preclude these systems.

Unfortunately, even with a standard set of frequencies, WDM systems from different vendors currently do not interoperate. To understand why this is so, consider a WDM system as shown in Figure 1-3. The current trend in the long haul market place has three aspects: (1) longer distances between regenerators, (2) denser spacing between channels, and (3) higher data rates carried per channel. These trends push the capabilities of the fiber and the systems so that linear and nonlinear effects rather than just signal attenuation must be compensated for or otherwise taken into consideration. Vendors use proprietary techniques to address these issues leading to lack of interoperability. Please refer to [Ramaswamy+02] for more information on transmission impairments in optical networks.

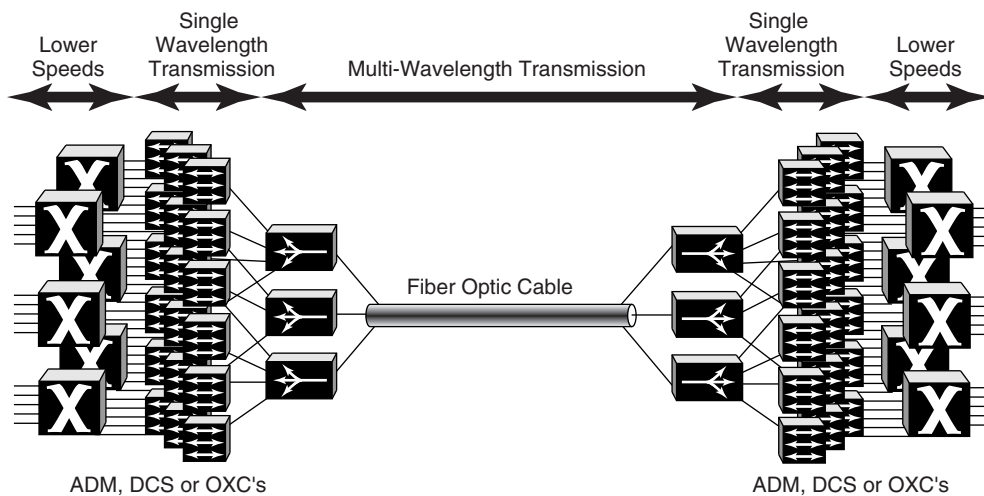


Figure 1-3

A Point-to-Point WDM System (Courtesy Ciena Corporation)

At its core, DWDM involves a small number of physical-layer functions. A typical DWDM system performs the following main functions:

- *Generating the signal:* The source, a solid-state laser, must provide stable light within a specific, narrow bandwidth that carries the digital data, modulated as an analog signal.
- *Combining the signals:* Modern DWDM systems employ multiplexers to combine the signals. There is some inherent loss associated with multiplexing and demultiplexing. This loss is dependent on the number of channels but can be mitigated with optical amplifiers, which boost all the wavelengths at once without electrical conversion.
- *Transmitting the signals:* The effects of cross talk and optical signal degradation or loss must be dealt with in fiber optic transmission. These effects can be minimized by controlling channel spacing, wavelength tolerance, and laser power levels. The signal may need to be optically amplified over a transmission link.
- *Separating the received signals:* At the receiving end, the multiplexed signals must be separated out. Although this task would appear to be simply the opposite of combining the signals, it is actually more difficult.
- *Receiving the signals:* The de-multiplexed signal is received by a photodetector.

In addition to these functions, a DWDM system must also be equipped with client-side interfaces to receive the input signal. This function is performed by *transponders*. Interfaces to the optical fiber that links DWDM systems are on the other side.

1.3 Multiplexing, Grooming, and Switching

Transmission systems alone are not enough to build an optical network. Optical signals need to be multiplexed and demultiplexed at the end points. They also need to be *groomed* and *switched* at intermediate nodes. Grooming is the function of dropping a lower rate signal from one rate speed signal and adding it to another. Switching allows a signal received on one input port and channel to be transmitted on a different output port and channel.

Based on the switch fabric technology, optical switches can be broadly classified into two categories—opaque (or OEO) and transparent (or OOO) [Mouftah+98, Hinton93]. Opaque optical switches, also called *optical cross-connects* or *OXC*s, convert optical signals received at the input to electric signal, switch the electrical signals using an electronic switching fabric, and finally convert the electrical signal back to optical signal at the output. The

name OEO captures the operational principle of the switch in the sense that it converts the incoming optical signal into electrical signal and then converts it back to optical signal. Transparent switches, also called *photonic cross-connects* or *PXCs*, on the other hand, do not perform this optical to electrical translation; they switch the incoming optical signal from the input port to the output port in the optical form (hence, OOO). Optically transparent switches operate over a range of wavelengths called the passband. For any given steady state, optical transparency allows a device to function independent of the type (e.g., analog, digital), format (e.g., SCM, SONET, GbE), or rate (e.g., 155 Mbps, 10 Gbps, 10 GHz) of the information on the optical signal being conveyed.

One of the problems with the OEO switches is that they need to perform multiple opto-electrical translations that can be both complex and expensive. On the positive side, as a by-product of opto-electrical translation, the optical signal undergoes regeneration and wavelength translation comes for free. OOO switches on the other hand, do not perform opto-electrical translation. As a result, they have the potential of being cheaper. OOO switches, however, are incapable of signal regeneration and wavelength translation. They also lack some of the performance monitoring and fault management capabilities that OEO switches offer. In the following we discuss different types of OEO and OOO switching elements.

1.3.1 Digital Cross-Connects and Add/Drop Multiplexers

Digital cross-connects, although not purely optical elements, play an important role in today's optical networks [Ramaswamy+02, Stern+99, Mukherjee97]. They can operate on either optical or electrical signals. Their switching fabric, however, is purely electrical.

Digital cross-connects are used for sub-wavelength level grooming and switching, that is, they work on time division multiplexed signals that may be carried as a wavelength in a WDM signal. Depending on switching granularity, they can be categorized as *wideband*, *broadband*, or *ultraband* cross-connects. Wideband cross-connects switch signals at the granularity of 1.5Mbps (DS1) while broadband cross-connects operate at 50 Mbps (STS-1) granularity. Ultraband is the latest addition to the digital cross-connect family. This type of cross-connect operates on optical signals and uses a 2.5Gbps (STS-48) electrical switching fabric. It is similar in functionality to an optical wavelength switch except that it is an OEO switch as opposed to an OOO switch. Advances in integrated circuit technology have allowed the creation of "ultra high" capacity broadband cross-connects with raw switching capacity similar to that of Ultraband cross-connects but with 50 Mbps switching granularity.

Digital cross-connects are typically located in Telco Central Offices, as shown in Figure 1–4. Wideband cross-connects are used for grooming, multiplexing, and interconnecting traffic between access and collector rings. Broadband cross-connects are used for the same function, but typically in metro-core and wide-area rings. The ultraband cross-connects are primarily concerned with interconnecting DWDM systems in wide area mesh and ring structured optical transport networks.

Today's optical networks also use add-drop multiplexers (ADM) quite extensively. ADMs are typically arranged in a ring topology connecting multiple service provider PoPs (points-of-presence). As the name suggests, they are used to add/drop traffic at a PoP to/from the ring. ADM rings operate at different speeds, and traffic can be added/dropped at different granularities. For example, metro-access rings typically operate at 150 Mbps (OC-3) and 622 Mbps (OC-12), and ADMs in these rings can add/drop traffic at 1.5 Mbps (DS1) or higher granularity. Interoffice metro rings and wide-area rings operate at 2.5Gbps (OC-48) and 10 Gbps (OC-192) speeds and typically traffic is added/dropped at 50Mbps (DS3) or higher speeds.

Standards currently exist that specify the exact characteristics and structure of various signals that digital cross-connects and ADMs operate on (see

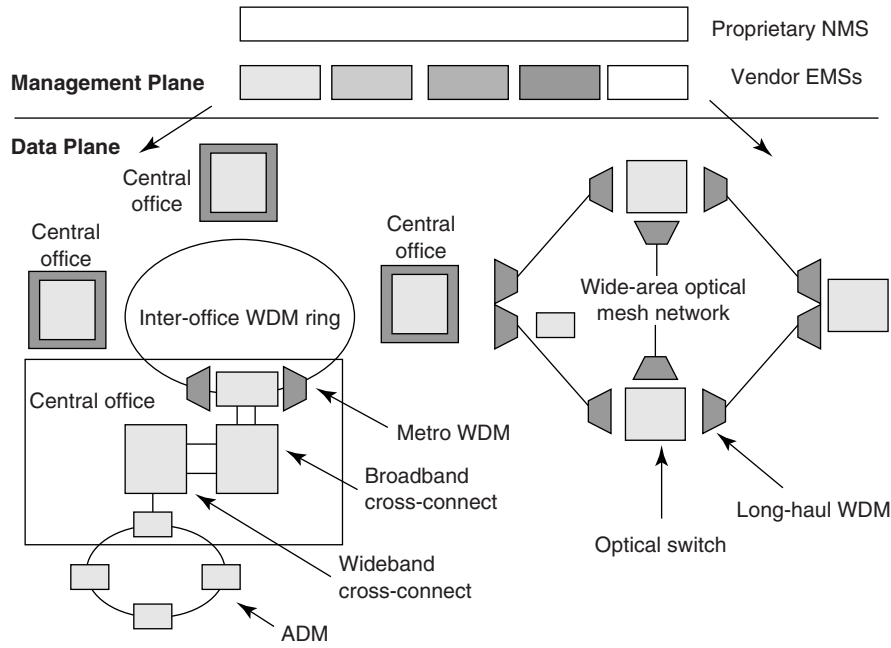


Figure 1–4 Optical Network Architecture

Chapters 2 and 3). This is in sharp contrast to the OOO case where few standards yet exist and intervendor interoperability is very uncommon.

1.3.2 OOO Switch Fabrics

Research, development, and commercialization of OOO (photonic) switches encompasses a variety of switching technologies, including opto-mechanical, electro-optic, acousto-optic, thermal, micro-mechanical, liquid crystal, and semiconductor switch technologies [Mouftah+98, Hinton93]. The performance characteristics and hence possible application of photonic switches may depend on the technology used. It is difficult to predict breakthroughs, but should they occur, they may well revolutionize switching in telecommunications networks. Some technologies utilized in commercially available photonic switches are described in this section.

In order to appreciate the relative merits and shortcomings of different switching technologies, it is important to understand the different metrics used to characterize the performance of a photonic switch fabric. With an *ideal* photonic switch, all the optical power applied at any input port can be completely transferred to any output port, that is, the switch has zero *insertion loss*. Also, the optical power does not leak from any input port to any other input port or any undesired output port, that is, it has infinite *directivity* and zero cross talk. In addition, switch connections can be reconfigured instantaneously, that is, the *switching time* is zero, and any new connection can be made without rearranging existing connections, that is, the switch is *non-blocking*. Unfortunately, no switch is ideal.

In practice, the following characteristics of photonic switch elements and fabrics affect their performance:

- Switching speed: The switching speed of photonic switches ranges from sub-nanosecond to hundreds of milliseconds. Depending on the application, any of these can be acceptable, but some applications require higher speed than others.
- Switching efficiency: In an ideal switch, all the power is transferred from a given input port to the desired output port, and no power is transferred to any other port, in either forward or backward direction. How a switch performs these functions is measured using four primary metrics: insertion loss, cross talk, return, and directivity. Insertion loss is the power lost due to the presence of the switching device: the ratio of output power to input power. The cross talk of a switch is defined in terms of worst case power transfer from the input port into an unintended output port. The return of a switch is defined in terms of power transferred from the input port back into the same fiber. The directivity of a switch is defined in terms of the power transferred from the input port to a different input port.

Insertion loss and cross talk should be as low as possible. Return loss and directivity should be as high as possible, indicating very little reflection back into the input.

- Wavelength dependence: Ideally, the performance of a photonic switch should be independent of the specific wavelength being switched. In practice, certain types of switches, such as opto-mechanical switches, are nearly wavelength independent. Waveguide based switches, on the other hand, are frequently optimized for narrower wavelength region. All the properties of the photonic switch must meet optical specifications across the wavelength range over which the switch is intended to be used. The main wavelength bands of interest for optical communication are those centered on the fiber loss minima at 1310 nm and 1550 nm.
- Polarization dependence: Switches need to have low polarization dependent loss (PDL), low polarization mode dispersion (PMD), and low polarization dependence in switching efficiency. If the signal passes through many switches, PDL can accumulate and lead to large variations in power levels. PMD is a problem primarily at high data rates. PMD in switches can be corrected, since it is a constant, unlike time-varying PMD in optical fiber. Polarization dependent switching efficiency can be problem if it leads to unacceptable cross talk for one of the polarizations.

In the following we discuss different switching technologies. Specifically, we describe the basic principle of switching under different technologies and discuss the intrinsic performance limitations and possible reliability concerns.

1.3.2.1 OPTO-MECHANICAL

This broad category of optical switching technology can be identified based on the use of motion to realize optical switching. They typically have very low loss, and extremely low cross talk. Switching speed of these switches vary from tens of milliseconds to hundreds of milliseconds. Opto-mechanical switches are the most commonly used optical switches today. This broad category can be further divided based on implementation specifics.

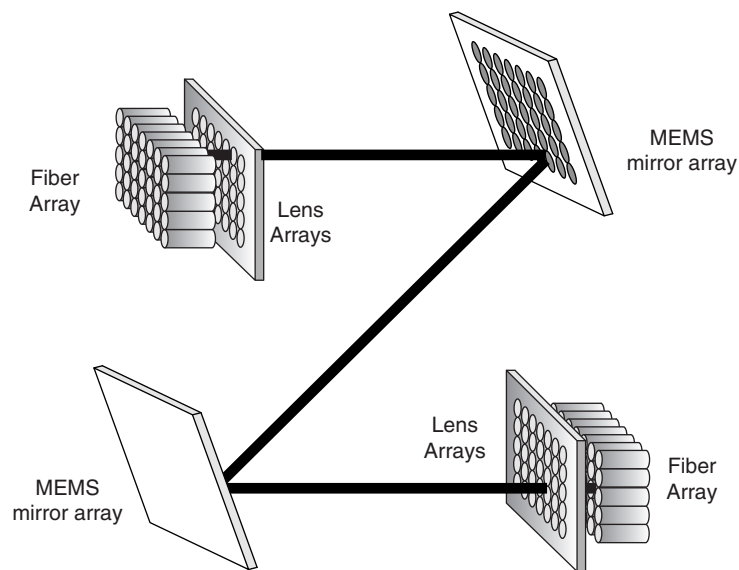
There are two types of opto-mechanical switches: moving fiber type and moving deflector type. Moving fiber technology uses direct moving fiber-to-fiber, or collimator-to-collimator alignment to reconfigure optical connections.¹ Moving deflector technology uses a moving mirror or prism that moves in and out of the optical path of fixed collimators to reconfigure optical connections.

¹A collimator is a device to which a fiber is attached. The collimator then outputs a fixed beam of limited cross-section.

Fiber or deflector motion may be created with a relay, a solenoid, or a stepper motor.

The most popular opto-mechanical switches are based on Micro-Electro-Mechanical Systems (MEMS). A MEMS is a small device that has both electrical and mechanical components. It is fabricated using the tools of the semiconductor manufacturing industry: thin film deposition, photolithography, and selective etching. Frequently, MEMS devices involve the use of semiconductor materials, such as silicon wafers, as well. MEMS devices offer the possibility of reducing the size, cost, and switching time of optical switches, and the ability to manufacture large arrays and complex networks of switching elements.

The switching element in a MEMS optical switch can be a moving fiber, or a moving optical component such as a mirror, lens, prism, or waveguide. The actuation principle for moving the switching element is typically electromagnetism, electrostatic attraction, or thermal expansion. One of the most popular forms of MEMS switches is based on arrays of tiny tilting mirrors, which are either two-dimensional (2D) or three-dimensional (3D). In a typical 2D array, the mirrors simply flap up and down in the optical equivalent of a crossbar switch. When they are down, light beams pass over them. When they are up, they deflect the beam to a different output port. With 3D arrays (see Figure 1-5), the mirrors can be tilted in any direction. The arrays are typically arranged in pairs, facing each other and at an angle of 90 degrees to each

**Figure 1-5***3D MEMS Switch Fabric*

other. Incoming light is directed onto a mirror in the first array that deflects it onto a predetermined mirror in the second array. This in turn deflects the light to the predetermined output port. The position of the mirrors has to be controlled very precisely, for example, to millionths of degrees.

1.3.2.2 ELECTRO-OPTIC SWITCHES

Electro-optic switches are based on directional couplers. A 2×2 coupler consists of two input ports and two output ports, as shown in Figure 1–6. It takes a fraction of the power, α , from input 1 and places it on output 1. The remaining power, $1-\alpha$, is placed on output 2. Similarly, a fraction, $1-\alpha$ of the power from input 2 is distributed to output 1 and the remaining power to output 2. A 2×2 coupler can be used as a 2×2 switch by changing the coupling ratio α . In electro-optic switches, the coupling ratio is changed by changing the refractive index of the material in the coupling region. One commonly used material for this purpose is lithium niobate (LiNbO_3). Switching is performed by applying the appropriate voltage to the electrodes. Electro-optic switches tend to be fast with switching times in the nanosecond range. Since the electro-optic effect is sensitive to *polarization*, electro-optic switches are inherently polarization sensitive, and tend to have relatively high loss.

1.3.2.3 ACOUSTO-OPTIC SWITCHES

In an acousto-optic device, a light beam interacts with traveling acoustic waves in a transparent material such as glass. Acoustic waves are generated with a transducer that converts electromagnetic signals into mechanical vibrations. The spatially periodic density variations in the material, corresponding to compressions and rarefactions of the traveling acoustic wave, are accompanied by corresponding changes in the medium's index of refraction. These

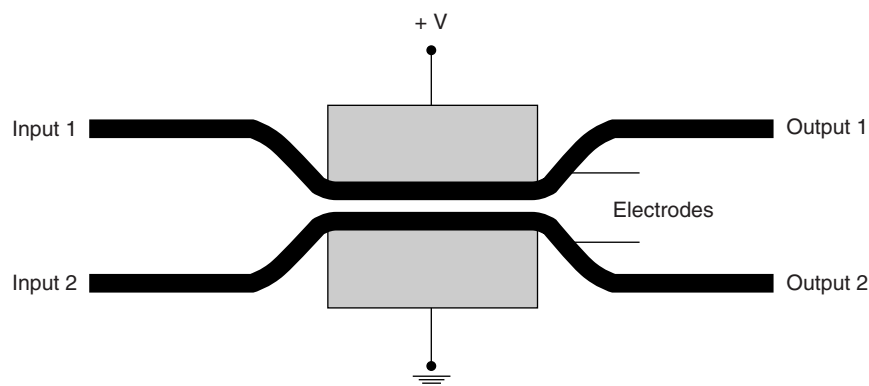


Figure 1–6

Electro-Optic Directional Coupler

periodic refractive index variations diffract light. Sufficiently powerful acoustic waves can diffract most of the incident light and therefore deflect it from its incident direction, thus creating an optical switching device. Acousto-optic switches are wavelength dependent and are more suitable for wavelength selective switches.

1.3.2.4 THERMO-OPTIC SWITCHES

These switches are based on *Mach-Zehnder interferometers* [Green92, Ramaswamy+02]. A Mach-Zehnder interferometer is constructed out of two directional couplers interconnected through two paths of differing lengths as shown in Figure 1–7. By varying the refractive index in one arm of the interferometer, the relative phase difference between two arms can be changed, resulting in switching an input signal from one input port to another. These switches are called thermo-optic switches because the change in the refractive index is thermally induced. Thermo-optic switches suffer from poor cross talk performance and are relatively slow in terms of switching speed.

1.3.2.5 MAGNETO-OPTIC SWITCHES

The magneto-optic effect refers to a phenomenon in which an electromagnetic wave interacts with a magnetic field. The Faraday effect is an important magneto-optic effect whereby the plane of polarization of an optical signal is rotated under the influence of a magnetic field. Magneto-optic switches use Faraday effect to switch optical signal. These switches are typically characterized with low loss and slow switching speed. They are somewhat wavelength dependent.

1.3.2.6 LIQUID CRYSTAL OPTICAL SWITCHES

A liquid crystal is a phase between solid and liquid. Liquid crystal-based optical switches also utilize polarization diversity and polarization rotation to achieve optical switching. Switches of this type are typically quite wavelength

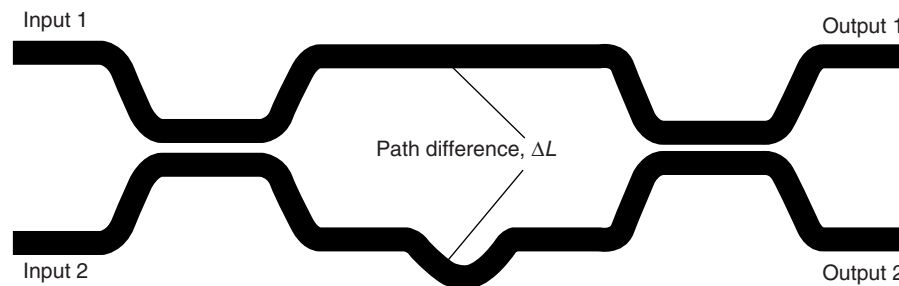


Figure 1–7

Mach-Zehnder Interferometer

dependent, since the amount of polarization rotation depends on wavelength. Liquid crystal polarization rotation is also intrinsically temperature dependent. Switching speed is relatively slow, usually between 10–30 ms range, since the switching mechanism requires reorientation of rather large molecules.

1.4 Summary

In this chapter, we gave an overview of the key elements of modern optical networking. Although the theoretical underpinnings are rather specialized [Ramaswamy+02], it is useful to have a high-level understanding of the technology to appreciate the networking and control plane concepts that follow in later chapters. Our review in this chapter is by no means exhaustive. Readers may refer to [Ramaswamy+02, Stern+99, Mukherjee97] for in-depth treatment of optical network architecture. For a thorough treatment of optical transmission systems including DWDM, please refer to [Agrawal97, Green92]. For a detailed discussion on optical switching, please refer to [Mouftah+98, Hinton93].