CHAPTER

22

Optical Networking System Design

About This Chapter

Optical networking adds another dimension to the concepts of system design you learned in Chapter 21 for the simple case of a single optical channel per fiber. This chapter covers systems that transmit two or more optical channels per fiber, where signals are managed by wavelength or optical channel. The extra optical channels increase the complexity of system design, and the number of factors that must be considered.

This chapter opens with a review of optical networking concepts. It then explains how optical channels are packed together, contrasting wavelength-division and time-division multiplexing, and dense and coarse channel spacing. Then it covers the properties of optical fibers and optical amplifiers that affect optical networking design. Finally it covers optical switching and channel management, including the importance of wavelength conversion. Optical network design is still a young field, so we will not cover it in as much detail as we did single-channel design in Chapter 21.

Optical Networking Concepts

Optical networking organizes signals by wavelength as well as by the time sequence of digital data. Wavelength-division multiplexing packs a number of optical channels into a transmitting fiber, with each optical channel transmitted at a different wavelength. In an ideal optical network, signals can readily be converted to different wavelengths to rearrange or redistribute them, as cars shift between lanes on a highway. WDM began as a way to squeeze more data through an optical fiber, but is evolving into a new way of managing data by wavelength as well as by digital coding.

There are several key concepts in optical networking.

Granularity is the subdivision of signals in a network.

- *Signal granularity* measures how signals are subdivided within an optical network. The greater the granularity, the more potential ways there are to organize the signals. In general granularity is a good thing because data transmitted over most networks is assembled from many small data streams, not massive flows between two points. Think of the traffic as being like many automobiles, not a few 200-car freight trains.
- *Total transmission capacity* of a system measures how much information a fiber can transmit. It equals the sum of the data rates on all the individual optical channels carried by the system. To maximize transmission capacity, you pack channels as closely together as possible and transmit the highest possible data rate on each channel. Raising the data rate increases the bandwidth required for each optical channel, so trade-offs are inevitable. Cost-performance trade-offs also are inevitable because not all fiber-optic routes require the greatest possible bandwidth, and packing high-speed channels tightly together can be very expensive.
- *Fiber transmission capacity* depends on attenuation and dispersion, which are functions of wavelength. Variations in attenuation and dispersion limit the transmission capacity of certain parts of the spectrum more than others. The degree of limitation depends on overall transmission distance.
- *Amplification capacity* also varies across the spectrum. Good amplifiers are not available at all wavelengths, and amplifiers do not have uniform gain across their operating ranges. Amplification is a must for long-distance optical networks, but may not be required in other types.
- *Switching capacity* for optical networking depends on the ability to manipulate signal wavelength. Wavelength conversion technology is still in development.

Two broadly different families of optical networking technologies have been developed for different types of applications, and further variations may emerge in coming years.

DWDM is used for long-haul systems; CWDM is used for shorter links.

- *Dense-WDM* packs as much transmission capacity as possible into as few fibers as possible. Its main applications are in spanning distances of hundreds of kilometers or more, where infrastructure costs are relatively high. Sharing the capacity over more channels reduces overall costs significantly, even if the cost per channel is high.
- *Coarse-WDM* reduces equipment costs for WDM systems that span moderate distances—tens of kilometers or less. Infrastructure costs over these distances are relatively low, so it's important to limit the cost per channel.

These concepts are the cornerstones of optical network design. Let's look at how they are used.

WDM divides a block of spectrum among optical channels.

Optical Channel Density

A WDM optical network divides a block of spectrum among multiple optical channels. The space required for an optical channel depends on its data rate; the higher the data rate, the broader the bandwidth the channel requires. For example, the signal produced by modulating a single-line light source at 10 Gbit/s occupies four times more bandwidth than does an identical light source modulated at 2.5 Gbit/s. Allocating the spectrum among optical channels is a fundamental step in optical network design.

WDM Compared to High-Speed TDM

Before we slice up the optical spectrum, we should compare WDM to high-speed time-division multiplexing. In principle, a single 160-Gbit/s data stream could carry 16 10-Gbit/s signals or 64 2.5-Gbit/s signals. Why not time-division multiplex the slower signals to higher speeds and avoid the need for so many separate transmitters at different wavelengths?

Fiber transmission distance is limited at high data rates.

Part of the answer is that high data rates impose limitations on fiber transmission. Higher-speed TDM signals run into transmission distance limits; increase the data rate by a factor of four, and the maximum transmission distance drops by a factor of 16 because of chromatic dispersion. The pulse durations are four times shorter, and modulation effects broaden the transmitter spectrum by a factor of four, multiplying pulse spreading caused by chromatic dispersion by a second factor of four. A signal that can travel through 1600 km of fiber at 2.5 Gbit/s can travel only 100 km at 10 Gbit/s, and a mere 6.25 km at 40 Gbit/s. Combine 16 2.5-Gbit/s signals into one signal at 40 Gbit/s and dispersion limits it to 6.25 km; but transmit 16 separate 2.5-Gbit/s signals at different wavelengths and they can all travel 1600 km. Current technology performs well at 10 Gbit/s, but transmission at 40 Gbit/s is difficult, and transmission at 160 Gbit/s is extremely difficult, even in the laboratory.

Another part of the answer is granularity. There's more need for separate 2.5- or 10-Gbit/s channels than for 40-Gbit/s channels. Internet traffic maps mostly show 2.5-Gbit/s links, with 10-Gbit/s transmission only on the highest-traffic routes between the biggest cities. The companies that provide transmission capacity usually subdivide the capacity of their fibers into sizes that their customers want. WDM enables them to split fiber capacity into 2.5- and 10-Gbit/s slices, providing the granularity needed for today's traffic. Customers can transmit independent traffic on each wavelength, and often can choose the transmission format.

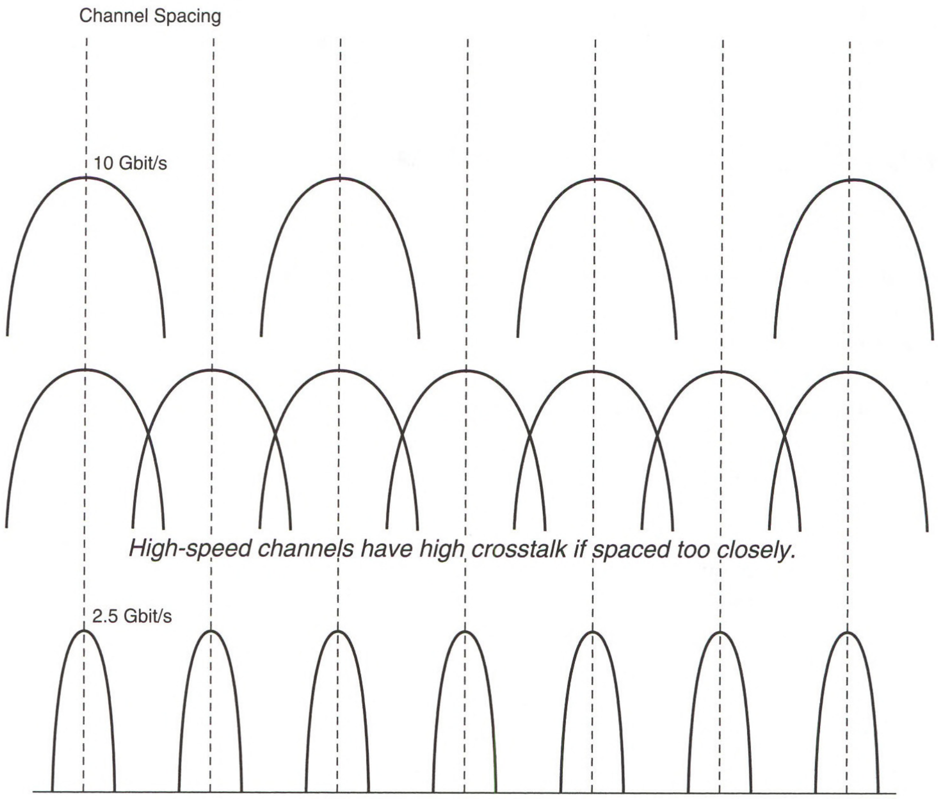
Overall, WDM offers better transmission distance and granularity than high-speed TDM for today's technology and transmission demands.

Spectral Range and Optical Channels

Only a limited spectral range is usable in any fiber system, depending on factors such as attenuation, dispersion, and amplification that will be described later. The available spectrum is divided among multiple optical channel slots, which normally are of an identical width set by international standards. For example, a range of 3200 GHz, corresponding to 1562.42 to 1535.82 nm (192.0 to 195.2 THz), can be divided into 32 100-GHz channels, 64 50-GHz channels, or 16 200-GHz channels.

The space that each channel requires depends on the modulation rate. As shown in Figure 22.1, a 10-Gbit/s signal spreads the modulation spectrum of a carrier signal across a broader range than does a 2.5-Gbit/s signal, so it can't fit in as narrow an optical channel. The degree of separation possible depends on the optics as well as the modulation bandwidth.

FIGURE 22.1
Faster signals spread across more spectrum and require wider slots.



10-Gbit/s signals usually go in 100-GHz channels in practical systems.

Advanced technology can reduce the modulation bandwidth and sharpen the selectivity of the optics to improve channel spacing. However, limits on total transmission capacity are unavoidable. So far the best results obtained in the laboratory without using elaborate polarization schemes have squeezed about 0.8 bit per second into 1 Hz of bandwidth. This figure of merit, called *spectral efficiency*, corresponds to fitting a 40-Gbit/s signal into a 50-GHz optical channel. Spectral efficiencies of practical commercial systems are much lower; they typically assign 10-Gbit/s signals to 100-GHz channels and 2.5-Gbit/s signals to 50-GHz slots.

Populating Channels

Not all wavelength slots are populated.

One confusing dichotomy in optical networking is the often vast difference between the actual operating load of a fiber-optic system and its stated capacity. The difference arises because WDM systems are designed with slots to accommodate a certain number of optical channels, but carriers do not immediately *populate* all these channels with operating transmitters and receivers. Also optical systems often are modular, so only part of the hardware is installed initially, with the remaining optics added as transmitters and receivers are installed on new channels.

Figure 22.2 shows an example of this dichotomy, a WDM system that has potential slots for 40 optical channels. Its *potential capacity* is the number of available slots times the

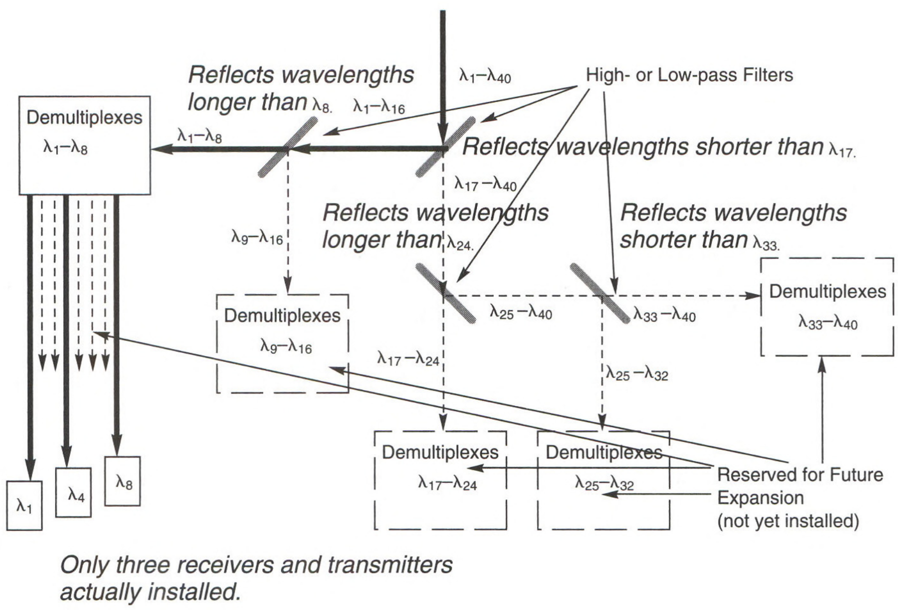


FIGURE 22.2 *Partial provisioning of a 40-channel DWDM system.*

maximum data rate per channel. The carrier operating the system, however, has installed transmitters and receivers on only three of the optical channels; all the others, shown in dashed lines, are reserved for future expansion. In this example, the carrier has bought optics that separate input signals into five groups of optical channels, plus optics that divide one of those five groups of optical channels into eight separate channels. Only three of those eight channels are populated, and the transmitters and receivers may not be operating at the maximum rate. Thus this system could be carrying only 7.5 Gbit/s (2.5 Gbit/s on each of the three populated channels), but have a potential capacity of 400 Gbit/s (10 Gbit/s on each of 40 channels).

This example is typical of the incremental approach that carriers take to installing transmission capacity. Operating companies do not need all the potential capacity immediately, but they do want to have room for future expansion. Transmitters and receivers currently are expensive, but their prices are coming down, so the carrier populates only the channel slots that are needed immediately. If more capacity is needed later, the carrier can populate more slots with cheaper transmitters and receivers, so the carrier buys only the capacity it needs today.

In fact, transmission loads vary, and during the telecommunications bubble many carriers vastly overestimated the maximum transmission capacity they would need. The result was that the actual peak load of a system like the one in Figure 22.2 would fall far short of its 7.5-Gbit/s capacity.

Dense- and Coarse-WDM

Coarse-WDM can reduce transmission costs.

So far we have focused on the practice of packing optical channels closely together to squeeze as much bandwidth as possible through a single optical fiber. This is called *dense-WDM* or *DWDM.* In practice, DWDM systems have channel spacing of 200 GHz or less. They provide huge transmission capacity over long distances, and during the telecommunications bubble they filled the tremendous demand for bandwidth. Today most of these systems are underutilized.

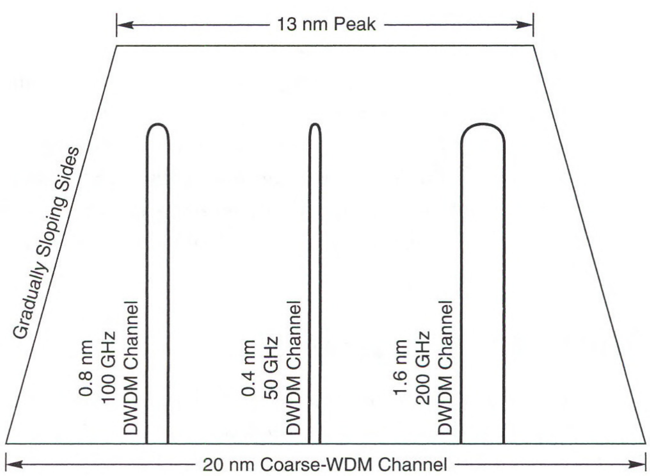
No one seriously disputes the advantages of transmitting signals through one fiber on many separate optical channels. However, they do question the advantages of DWDM, which was developed specifically to provide high-speed, long-distance transmission. Long-haul applications could justify the high costs of precision optics to split the spectrum into narrow slices and of cooled high-speed laser transmitters to provide precise wavelengths that fit into the narrow channel slots. However, those high costs prevented DWDM technology from being used in other applications that could benefit from wavelength-division multiplexing.

An alternative approach, called *coarse-WDM* or *CWDM*, was developed to avoid the high costs associated with precise wavelength control. It divides the spectrum into fewer slices, wide enough to accommodate the wide wavelength variations of much cheaper uncooled diode lasers. Each CWDM channel can carry many DWDM channels, as shown in Figure 22.3. Two variations of CWDM have been developed: one for dividing a single high-speed signal into four slower data streams, and the other for sending up to 18 separate signals through a single fiber without amplification.

10-Gigabit Ethernet uses four-channel CWDM.

The 10-Gigabit Ethernet standard has an option for splitting the data stream into four separate signals transmitted at 2.5 Gbit/s, for a total of 10 Gbit/s. This allows the use of graded-index multimode fibers over longer distances than those possible at 10 Gbit/s and the use of lower-cost 2.5-Gbit/s transmitters with single-mode fiber. The coarse-WDM transmitters use uncooled distributed-feedback lasers emitting at center wavelengths of 1275.7, 1300.2, 1324.7, and 1349.2 nm. The broad range of wavelengths is possible because no optical amplifiers are needed for the distances used in 10-Gigabit Ethernet. Loose wavelength tolerances and using uncooled lasers lower costs. The lasers could operate at temperatures of 0 to 70°C with wavelength drifting no more than 5 nm, which would keep the signals in the proper coarse-WDM slots.

FIGURE 22.3
CWDM and DWDM channel widths.



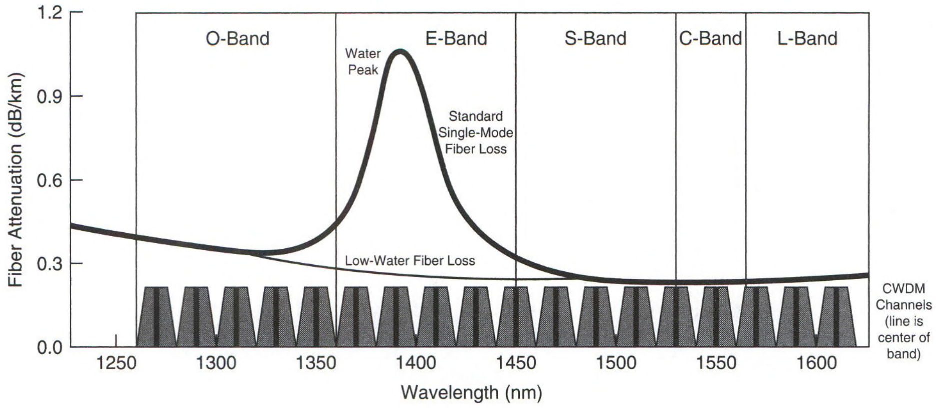


FIGURE 22.4
CWDM channels specified in ITU G694.2 standard.

The ITU G694.2 standard established a grid of 18 CWDM slots with center wavelengths from 1270 to 1610 nm for telecommunications. As shown in Figure 22.4, this range spans the band of lowest attenuation in silica fibers. A few channels lie under the 1.38-µm water peak, but these are easily made available by using low-water fibers. Each of these channels is 20 nm wide. This is broad enough to accommodate the wavelength variations of an uncooled laser transmitter, which drifts about 9 nm when temperature changes by 100°C. The specification allows use of interference filters with central passbands limited to the central 13 nm, which can be made quite inexpensively with insertion loss less than 1 dB. You can see this spectral profile in Figure 22.4.

CWDM has a grid of 18 channels that are each 20 nm wide.

The major applications for CWDM are expected to be in metropolitan networks, which span no more than tens of kilometers and generally do not require amplifiers. Typically these networks operate at data rates to 2.5 Gbit/s, allowing the use of inexpensive directly modulated DFB laser transmitters. All channels except those in the E-band water peak can be transmitted through existing standard step-index single-mode fiber.

The CWDM standard is designed to be used by itself, but blocks of DWDM channels can be slipped into single 20-nm CWDM channels. Up to 16 DWDM channels can fit into a CWDM channel at 1550 nm, and up to 22 into a CWDM channel near 1310 nm. A variety of alternatives are possible, such as using CWDM channels at 1470, 1490, 1590, and 1610 nm to supplement DWDM channels in the 1530–1565-nm erbium-amplifier band.

Overall, CWDM and DWDM each have their own advantages. CWDM is best suited for transmission over moderate distances, where amplification is not required. DWDM is best suited for longer distances, where amplification is needed, because the closely packed wavelengths all fit in the erbium-amplifier range.

Operating Ranges of WDM Systems

Most WDM technologies can span much of the optical and infrared spectrum. WDM systems have been built using visible LEDs and plastic fibers, as well as the infrared sources and silica fibers described above. However, both the properties of the fiber and the amplifier technology used (if any) limit the operating range of any individual WDM system.

Gain Bandwidths of Optical Amplifiers

Optical amplifier gain limits the usable wavelength range.

WDM systems that require optical amplification are inherently limited by the gain bandwidths of the amplifiers. As you learned in Chapter 12, optical amplification depends on stimulated emission, and any material produces stimulated emission over only a limited range of wavelengths. The properties of optical amplifiers vary considerably and are summarized in Table 22.1. In practice, individual amplifiers are limited to usable gain bandwidths of tens of nanometers because WDM systems require uniform gain across their operating ranges; you don't want gain of 5 dB at one band and 35 dB at another.

Doped-fiber amplifiers are limited by the gain bandwidth of the light-emitting elements, praseodymium, thulium, and erbium. Erbium-doped fiber is the most widely used, and has usable gain over the broadest range of wavelengths, from 1530 to 1610 nm. As you learned in Chapter 12, the gain of erbium amplifiers varies widely over that range. They usually are designed specifically for either the C-band at 1530 to 1565 nm or the L-band at about 1570 to 1610 nm. The gain profile can change somewhat with fiber composition, but in general the bandwidth over which gain is reasonably uniform is tens of nanometers.

Raman gain is offset 13 THz from the pump in silica fibers.

Raman gain is offset from the pump wavelength by an amount that depends on the fiber composition. For standard silica fibers, the peak is 13 THz lower in frequency than the pump and has a bandwidth of about 5 THz, as you saw in Figure 12.14. Raman gain can be used to amplify light anywhere in the silica fiber transmission band by picking a pump band offset by the proper amount from the amplified wavelength. Pumping at multiple wavelengths can produce gain across a wide range, but if the range is too large the pumps overlap signal wavelengths, causing interference.

Semiconductor optical amplifiers have a spectral width of a few tens of nanometers, with the peak gain depending on the composition of the active layer. This means it is possible to make optical amplifiers with different central wavelengths by growing active layers with different compositions, but most of these devices are not standard commercial products.

Table 22.1 Optical amplifier properties

Type of Amplifier	Wavelength Range (nm)	Band Limits
Praseodymium-doped	1290–1320	Praseodymium stimulated emission
Thulium-doped	1450–1500	Thulium stimulated emission
Erbium-doped	1530–1610	Erbium stimulated emission
Raman	Broad, offset from pump band by 13 THz	Tens of nm gain band
Semiconductor	Broad, but composition dependent	Tens of nm from one composition

The gain bandwidths of amplifiers are broad enough to accommodate many DWDM channels, but only one or two CWDM channels. For example, the 35-nm wide gain of a C-band erbium fiber amplifier can hold about 40 channels with 100-GHz spacing or about 80 channels with 50-GHz spacing. However, as Figure 22.4 shows, it holds only one CWDM channel, with a second at the edge of the erbium band at 1530 nm. This illustrates why DWDM is used in long high-capacity systems that require optical amplification.

Technically, optical amplifiers are available throughout the 1270 to 1610 nm range of CWDM. However, most of those wavelengths are not widely available from commercial products, and amplification of the whole CWDM range would require several parallel optical amplifiers, a very cumbersome arrangement. In practice, CWDM systems that span the whole possible range are not amplified.

Fiber Bandwidth Limits

Fiber loss is below 0.5 dB/km from 1250 to 1650 nm in low-water fibers.

Fiber attenuation also can limit the wavelengths usable for optical networking, but the limit is much less severe than that imposed by the gain bandwidth of amplifiers. Fiber loss is below about 0.5 dB/km from about 1250 to 1650 nm, except near the 1380-nm water peak in high-water fibers, as shown in Figure 22.4. That entire band is usable in low-water fibers, which are promoted for CWDM applications because they transmit well at 1350 to 1430 nm. Fibers can carry signals at wavelengths outside this band, but large differences in attenuation accumulate over long distances and the resulting differences in power reaching the receiver or optical amplifier can cause problems.

Another fiber issue that can limit usable bandwidth is differences in chromatic dispersion with wavelength. Such differences discourage the use of widely separated wavelengths in long-distance systems. The limitations are much less important for distances under 100 km, where the band usable for CWDM is nearly 400 nm wide. It's possible in principle to pack hundreds of DWDM channels in the same bandwidth, but there's little demand for that much capacity in unamplified systems.

Factors in WDM Design

You learned in Chapter 21 how system characteristics such as fiber attenuation and dispersion affect transmission at a single wavelength. Matters become more complex in WDM optical networking because signals on different optical channels may experience different levels of attenuation, dispersion, and other properties. That makes the properties of the fiber, the amplifier, and other components important factors in WDM system design. We will concentrate on amplified systems because they experience the most severe constraints.

Fiber Attenuation

Figure 5.2 shows that fiber attenuation varies significantly across the low-loss window from 1250 to 1650 nm. Loss in the 1310-nm region is about 0.35 dB/km compared to a minimum below 0.2 dB/km in the erbium amplifier band. This difference means that 100 km of fiber has 35 dB loss at 1310 nm, but only 20 dB loss at 1550 nm, a 15-dB difference at

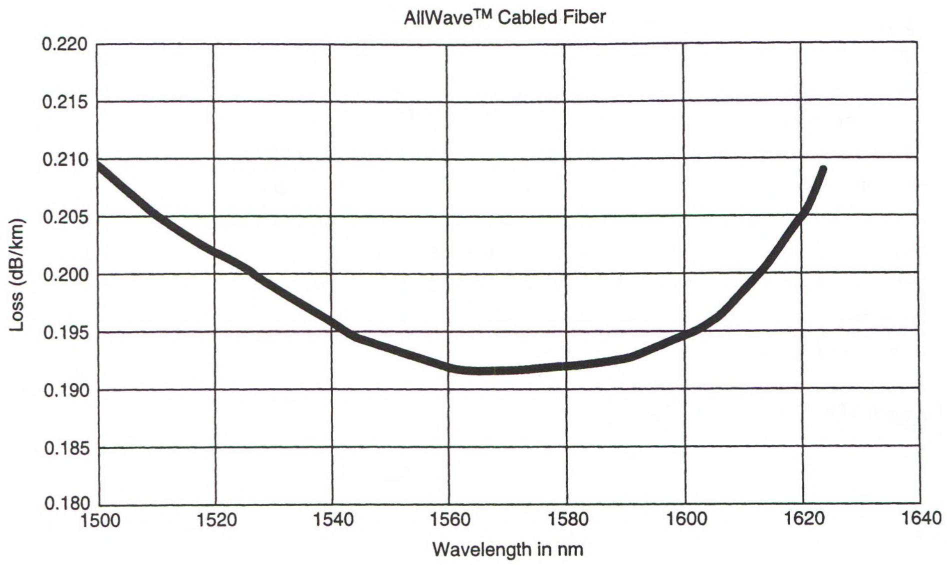


FIGURE 22.5 *Attenuation of low-water AllWave fiber in erbium-fiber window. (Copyright Lucent Technologies Inc.)*

the receiver assuming that input powers were equal. This difference is large enough to impact the design of CWDM systems that span that range.

Fiber loss varies little across the erbium-amplifier band.

The difference is much smaller over the erbium-fiber band used for DWDM, as shown for a low-water fiber in Figure 22.5. For the fiber shown, attenuation ranges between 0.192 and 0.200 dB/km in the 1530- to 1610-nm band, rising to 0.205 dB/km at 1620 nm. In this case, the difference in loss for a 100-km length is small, 19.2 dB at 1570 nm compared to 20.0 dB at 1610 nm. The difference is a mere 0.8 dB, small enough to be smoothed out by techniques used to equalize amplifier gain across the erbium amplifier band.

Dispersion Slope and Compensation

You learned in Chapter 21 that dispersion compensation can reduce the total chromatic dispersion of a fiber link. Dispersion compensation is relatively straightforward at a single wavelength, but recall that chromatic dispersion also varies with wavelength. This makes it necessary to consider the *dispersion slope*—the change in chromatic dispersion as a function of wavelength—in designing WDM systems. As shown in Figure 22.6, the value of the dispersion slope differs between types of fiber. It is largest for large-effective-area fibers, around 0.086 ps/nm^2-km in the C-band erbium-fiber window. Fibers also can be designed with smaller cores and reduced dispersion slopes, about half that value. Conventional nonzero dispersion-shifted fibers have intermediate slopes. This variation of dispersion with wavelength complicates the task of dispersion compensation.

Dispersion compensation can't be perfect across a range of wavelengths.

In a single-wavelength system, chromatic dispersion can be compensated for simply by adding fibers or other components that have dispersion of the same magnitude but the opposite sign, to give net dispersion of zero at the transmission wavelength. However, as Figure 22.7 shows, the curves plotting the dispersions of the transmitting and compensating fibers are not exactly the inverse of each other. At the wavelength λ_2, the dispersion of

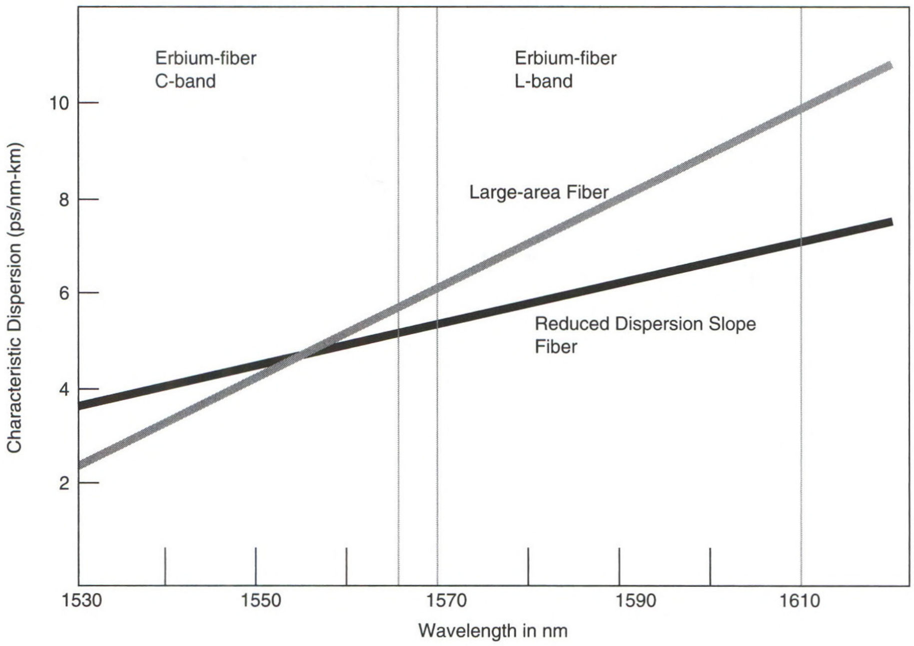


FIGURE 22.6
Chromatic dispersion of reduced-slope and large-effective-area fibers shows difference in dispersion slopes.

1 km of compensating fiber completely offsets the dispersion of 5 km of transmission fiber, leaving a net cumulative chromatic dispersion of zero. However, if you add the curves together at shorter wavelengths the net cumulative dispersion is slightly negative and at longer wavelengths it's slightly positive. Thus the dispersion compensation works perfectly for one wavelength, but not for the other wavelengths λ_1 and λ_3.

These differences accumulate with distance. If you plot the cumulative dispersion along the length of the system, you see the sawtooth pattern shown in Figure 22.8. Dispersion increases gradually as light passes through the transmission fiber, then drops sharply as the signal passes through the compensating fiber, which has negative dispersion. The pattern repeats exactly for λ_3, for which the positive and negative dispersion exactly offset each other. However, the peaks gradually rise for the other two wavelengths, λ_2 and λ_1, where there is a net positive dispersion. This spreading sawtooth pattern betrays the imperfection of dispersion compensation across a range of wavelengths.

Similar effects occur when you compensate for chromatic dispersion by combining lengths of two or more types of transmission fiber. Some submarine cables use two or more types of fiber in each span between optical amplifiers. The bulk of the span is non-zero dispersion-shifted fiber with a slightly negative dispersion—about 2 ps/nm-km at 1550 nm—and a zero-dispersion wavelength longer than about 1600 nm. The negative dispersion is offset by the positive dispersion of about 17 ps/nm-km of the step-index single-mode fiber. (Large-effective-area fiber may be used near optical amplifiers to reduce nonlinear effects, as we will see later.) Although great care is taken to assure the best possible dispersion compensation, the best is not perfect, so dispersion plots along the length of the cable show a spreading sawtooth curve similar to the one shown in Figure 22.8.

FIGURE 22.7
Dispersion compensation in WDM system, showing difference in cumulative dispersion.

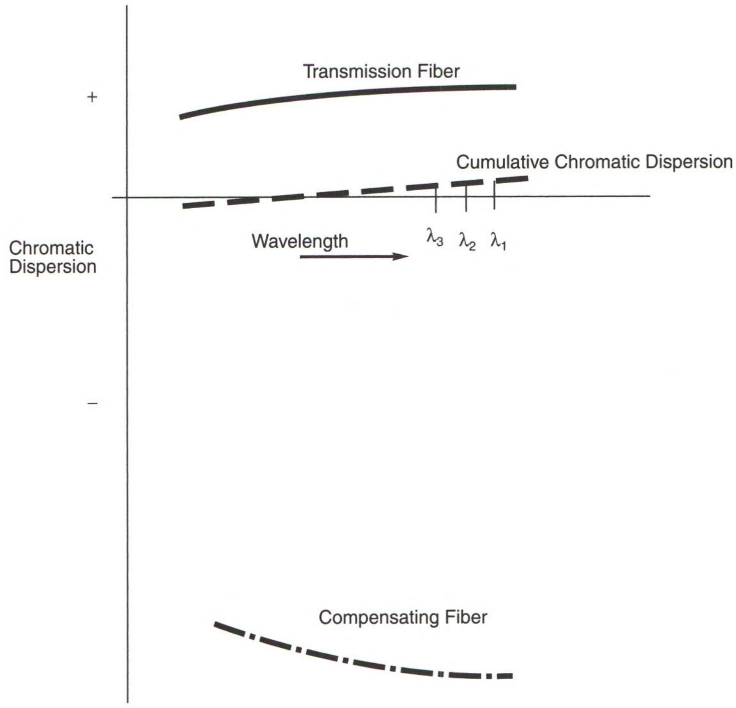
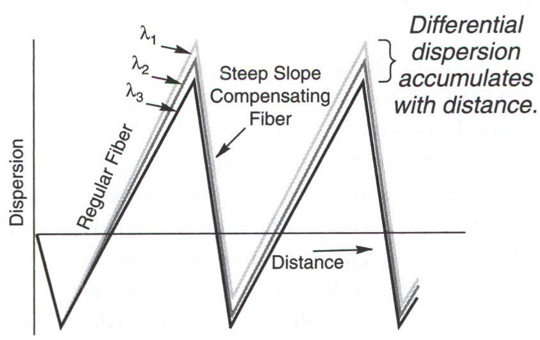


FIGURE 22.8
Cumulative dispersion plotted along a WDM system, which uses short lengths of dispersion-compensating fiber. Total dispersion at the three wavelengths diverges along the length of the fiber because the compensation inevitably is imperfect.



Nonlinear Effects in WDM Systems

Nonlinear effects are proportional to total optical power density and to the distance the light travels through the fiber at high power levels. Long-haul WDM systems are particularly vulnerable because the more optical channels they carry, the higher the total optical power. A single-channel system normally has no trouble transmitting 3 mW, but if a WDM system tries to transmit 80 channels at that power level, the total power reaches 240 mW, which can produce nonlinear effects and interactions among the transmitted channels.

High total power makes WDM systems vulnerable to nonlinear effects.

Nonlinear effects are relatively weak in glass fibers, but their total impact on the signal is proportional to the distance the signal travels in the fiber. In practice, they are not significant in metro systems that run tens of kilometers, but can pose problems in long-haul systems running thousands of kilometers.

Fiber attenuation complicates the picture by reducing the optical power as a signal travels through the fiber, causing nonlinear effects to decline with distance from the light source. As a result, nonlinear effects accumulate over a *maximum effective length*, after an amplifier or transmitter which depends on the fiber attenuation. For a typical single-mode fiber with 0.22 dB/km attenuation at 1550 nm, this is about 20 km per span between optical source and receiver. The value is smaller for fibers with higher attenuation. In long-haul systems, the maximum effective length is multiplied by the number of spans between amplifiers.

Attenuation limits nonlinear effects to a maximum effective length.

Four-wave mixing poses particular problems in DWDM systems. As you learned in Chapter 5, it occurs when signals at three input frequencies combine to generate a mixed signal at a fourth frequency:

$$\nu_1 + \nu_2 - \nu_3 = \nu_4$$

The three input signals need not all be at different frequencies; two of them could be on the same optical channel. The equal spacing of WDM channels means that the new frequency is likely to fall on another optical channel, producing noise and crosstalk.

Four-wave mixing increases if the three input waves remain in phase as they pass through the fiber. That occurs when there is no chromatic dispersion to spread them out along the fiber. If the fiber has some minimum chromatic dispersion in the transmission window—typically at least 1 ps/nm-km—the optical channels do not remain in phase over long distances, and the four-wave mixing signal is reduced, as shown in Figure 22.9. This level of dispersion is too low to limit transmission bandwidth on the individual channels.

Dispersion compensation does not enhance four-wave mixing because it uses lengths of fibers with positive and negative dispersion that combine to produce low dispersion over the entire fiber span. In such systems, the local dispersion is nonzero, so the signal pulses do not stay in phase over long distances. In short, near-zero *cumulative* dispersion over a fiber span is fine, but zero *local* dispersion in a single fiber can keep signals in phase and enhance four-wave mixing.

The dependence of nonlinear effects on power density makes them sensitive to the choice of fiber. Fibers with small effective areas concentrate signal power, making them more vulnerable to four-wave mixing and other nonlinearities. Typically, the effective area is large in step-index single-mode fibers, somewhat smaller in nonzero dispersion-shifted fibers, and smallest in dispersion-compensating fibers. Other trade-offs occur between effective area and reduced dispersion slope; increasing effective area tends to increase dispersion slope, and conversely, reducing the dispersion slope tends to decrease the effective area.

Fiber type affects nonlinear effects.

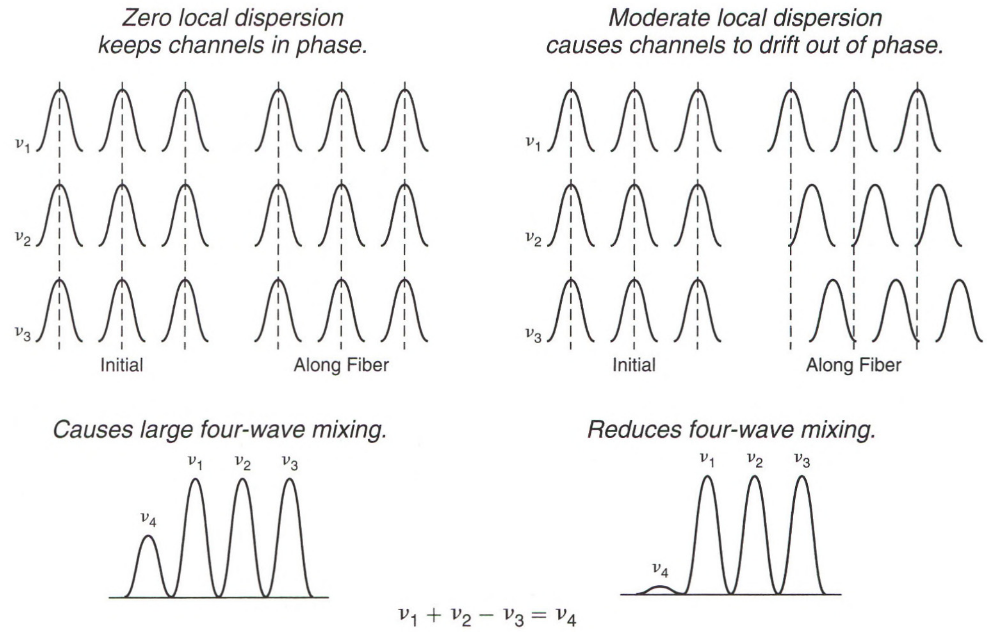


FIGURE 22.9 *Four-wave mixing is high at the zero-dispersion point, where signals stay in phase over long distances. Some local dispersion causes the wavelengths to drift out of phase, reducing four-wave mixing.*

Designers can take advantage of these differences in properties when they select fibers for dispersion compensation. Nonlinear effects can be reduced by placing a large-effective-area fiber close to transmitters or amplifiers, where the optical power is highest. Fibers more vulnerable to nonlinear effects can be placed in parts of the fiber span where power is lower.

Optical Amplification and WDM Design

The role of optical amplifiers is more complex in WDM systems than in single-channel systems. In single-channel systems, the variation of amplifier gain with wavelength limits the usable transmission band. In WDM systems, this variation adds requirements to balance gain across the transmission spectrum. The available optical power must be shared among the transmitted channels, and gain can be saturated when total input power reaches a high level, although power per channel remains modest. Amplified spontaneous emission is a concern because it adds to background noise across the gain spectrum.

These considerations apply to all types of optical amplifiers, but this section will concentrate on erbium-doped fiber amplifiers because they are the most common type in use.

Amplifier Power Levels

Amplifier output is divided among many WDM channels.

Erbium-fiber amplifiers have a maximum output power, typically 17 to 24 dBm for C-band amplifiers. The limit comes from energy transfer, both in exciting the erbium atoms and in stimulating emission, which causes the saturation effects described in Chapter 12. This peak output is concentrated on a single wavelength in a single-channel system, but in a WDM system it is divided among all populated optical channels, limiting the power per channel. As a result, the power per channel in a WDM system decreases with the number of channels. For example, an amplifier operated at its maximum output of 80 mW could deliver 20 mW on each of 4 optical channels, 10 mW on each of 8 channels, or 1 mW on each of 80 channels.

Multichannel operation can limit gain on individual channels to much lower values than are possible with a single channel. If an amplifier saturates at a power level of 15 dBm (30 mW), it can amplify a single –15 dBm input channel by 30 dB. However, if the input were 30 input channels each at –15 dBm (30 μW), the total output power still would be limited to 30 mW, or 1 mW per channel, a gain of only 15 dB. This has important system consequences because it means the fiber span between amplifiers can include only 15 dB of loss—equivalent to 75 km of fiber with 0.2 dB/km attenuation. Adding optical channels without upgrading the amplifiers can downgrade transmission capability. Depending on operational details, doubling the number of optical channels would reduce the power level on each channel by 3 dB, equivalent to 15 km of 0.2 dB/km fiber.

Amplifier power also affects maximum data rate per optical channel. As you learned in Chapter 11, pulse detection requires a minimum number of photons, so average powers must be increased to deliver those photons in shorter pulses. Thus dividing power among more optical channels, which can transmit more data in parallel, reduces the power available to transmit signals at a higher data rate per channel. In short, when operating near system margins, increasing the number of optical channels trades off directly with increasing the data rate per channel.

Gain Flatness and Channel Equalization

Filters can equalize amplifier gain on optical channels.

Erbium amplifier gain typically is flat to within 1 to 3 dB across its operating range. This sounds good until you start cascading amplifiers. That variation is acceptable for a single amplifier, but not in a cascade. A difference of 2 dB between channels becomes 10 dB after five amplifiers, which could lead to the loss of weaker channels. Gain-equalizing filters can compensate for this by reducing the power on the strongest optical channels, as shown in Figure 22.10. The filter's extra attenuation offsets the stronger gain at certain wavelengths, making amplifier gain flat across the spectrum. Some imperfections inevitably remain, but careful engineering can limit channel-to-channel power differences to no more than a few decibels over a chain of more than 100 amplifiers.

Another approach to gain equalization is by adding another amplifier to add power to the system rather than subtract it. Raman amplifiers are an attractive choice because their gain is higher at longer wavelengths than at shorter ones; they complement the spectrum of erbium amplifiers, which peak at shorter wavelengths. *Hybrid amplifiers* combine a Raman amplifier with an erbium-doped fiber amplifier to give more uniform gain across a range of wavelengths. The Raman amplification stage may be in the transmission fiber, but it requires a strong pump beam.

Switching and Optical Networking

Optical networking manages signals as optical channels.

A central concept of optical networking is managing signals by the optical channel, sometimes called a *lambda* after the Greek letter λ used as an abbreviation for wavelength. The idea is to transmit signals in many bit streams at separate wavelengths, such as 40 channels

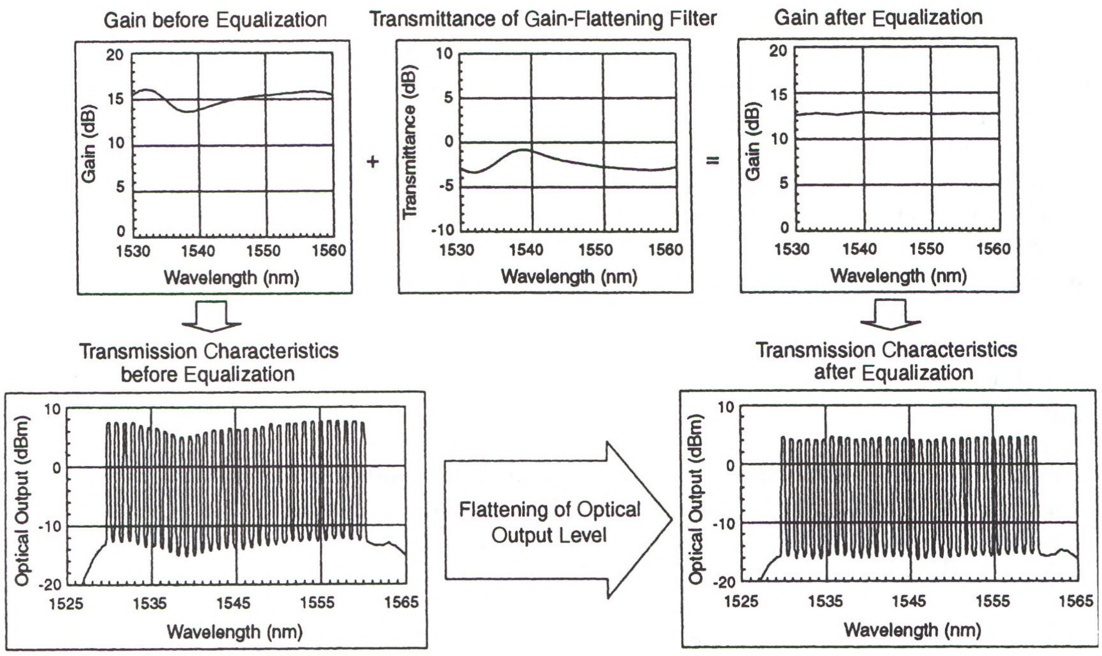


FIGURE 22.10

Effect of gain-flattening filter on an optical amplifier. (Courtesy of Furukawa Ltd.)

at 2.5 Gbit/s rather than a single 100-Gbit/s data stream. Multiple channels offer more *granularity* because each data stream can be detected and processed as an optical channel without disturbing any of the others.

Figure 22.11 shows how a simple optical network switch in Chicago can distribute eight optical channels from Omaha. First the input signal is demultiplexed to its eight component channels. Two wavelengths go to both Detroit and Indianapolis. One wavelength each goes to Minneapolis, Milwaukee, Chicago suburbs, and St. Louis. In this example, the input signals are organized in Omaha, and the Chicago switch directs them on their way without any further processing. The same fiber could carry many other wavelengths going to other destinations, but you couldn't make sense of a drawing with 40 optical channels.

This example looks simple because we've omitted crucial details. The optical switch is just a box; we don't know how it processes the light. The figure doesn't show the conversion of signals from one wavelength to another, although this may sometimes be necessary. To understand how optical networks are designed, let's take a closer look at some key concepts.

Transparent, All-Optical, and Opaque Systems

Both optical switches and networks can be classed into three categories that overlap to some extent.

- *Transparent* systems transmit optical signals without changing their format, as if the light were shining directly through them. They can be amplified, but their wavelength remains unchanged, and the optical signal is never converted into electronic form.

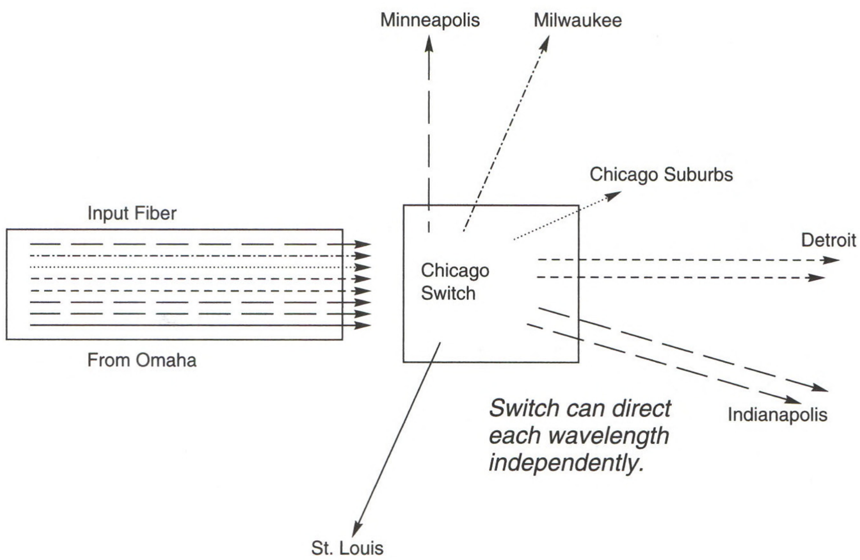


FIGURE 22.11
Granularity of optical channels.

- *All-optical* systems transmit and manipulate only optical signals, which are never converted to electronic form. However, the optical signals may be converted to different wavelengths. All transparent networks are all-optical, but some all-optical systems are not transparent.
- *Opaque* systems convert the input optical signal into electronic form for switching or processing, then convert that signal back into optical form. The output may be at the same wavelength or a different one.

A network does not have to be entirely of one type. An optical network may include "islands" of transparency that transmit signals purely optically, separated by opaque opto-electronic components such as receiver-transmitter pairs or electronic switches.

An optical network may have islands of transparency separated by opaque elements.

Present systems use both all-optical and electro-optical switches. The big switches at network nodes that direct signals among many input and output ports are electronic, converting input optical signals into electronic form for switching, then converting them back into optical form for transmission. Electronic switches take advantage of highly-developed optical techniques for processing signals and directing them among large numbers of possible output ports. All-optical switches generally are simpler devices used to transfer optical signals between fibers without additional processing. One family redirects all signals in the fiber to another fiber; they are used for protection switching. Another selects one or more wavelengths in a WDM signal and redirects only those wavelengths; they can be used as add/drop switches. The signal-distribution switch shown in Figure 22.11 could be implemented with this type of optical switch.

The advantages of transparent and all-optical networks have been much praised, but in practice some electronic components are much more mature than their optical counterparts. For example, wavelength conversion is simplest to implement by converting optical signals into electronic form and using the electronic signal to drive a laser transmitter at a different wavelength. As you learned in Chapter 12, it's also possible to convert wavelengths by purely optical means, but that technology is still in development.

Wavelength Conversion and Routing

Wavelength conversion is needed to manage optical channels.

Wavelength conversion is an important management tool in optical networks. From the network standpoint, the important part of a signal is the information it carries, not the wavelength of the carrier signal. The wavelength is like a lane on the highway, a channel for carrying information. When signals switch from one fiber to another, the wavelength used on the first fiber may not be available on the second, so the signal may have to be converted to a different wavelength. Ideally, the output wavelength should be tunable, so the signal can be switched to any desired wavelength. This ideal isn't easy to implement, but developers are working on it.

Another application for wavelength conversion is in conjunction with a device called a *wavelength router*, which directs input signals to different ports depending on their wavelength. A wavelength router can be viewed as a fixed wavelength-division demultiplexer, which always directs input signals out a particular port according to their wavelength. In the example of Figure 22.11, an input signal at 1542.14 nm might go to Milwaukee, one at 1542.94 nm might go to Minneapolis, and signals at 1543.73 and 1544.53 nm would go to Detroit. By changing the input wavelength, you can change the output port to which the signal is directed.

System Interfaces and Regeneration

The optical network terminates at electronic transmission centers.

The optical network interfaces with electronic signals at input and output ends. The input electronics typically organize the input electronic signals in some way, such as time-division multiplexing to combine signals for high-speed transmission, or regrouping signals from other inputs. Then the signals are converted to optical form, and optical interfaces combine signals at different wavelengths at the input of WDM systems.

Interfaces generally are at transmission centers, nodes, or hubs, where many transmission lines come together. Typically local signals feed into these nodes, which combine them with signals arriving from other points and transmit them on outgoing lines. Big electronic switches regenerate optical signals at major network nodes spaced several hundred kilometers apart.

Optical regeneration has been demonstrated in the laboratory, but has yet to find practical applications. System requirements for optical regeneration are not yet clear.

Design Examples

Designing WDM systems is a complex task that requires considering performance at many wavelengths and the interactions of the multiple signals passing through the system. To demonstrate how it works, we will concentrate on very simple examples that illustrate a few of the considerations.

Amplifier Gain and Power

Suppose we need to transmit 10 optical channels between two switching nodes 200 km apart. We have a single fiber, and space for an optical amplifier at the midpoint. The attenuation of each span is 25 dB, and the transmitter has 3-mW output on each of the 10 channels after the multiplexer. The company warehouse has optical amplifiers with performance similar to that shown in Figure 12.5. Small-signal gain is 30 dB and peak output is 30 mW. The demultiplexer has 5 dB loss per channel, and we haven't picked the receivers yet.

At first glance it looks like there's plenty of margin for operation on a single channel.

Single-channel transmission

Transmitter signal	5 dBm
Attenuation	–25 dB
Amplifier input	–20 dBm
Amplifier gain	27 dB
Amplifier output	7 dBm

Remember, however, that with nine other channels the total amplifier input is –10 dBm, which reduces the gain.

Multichannel transmission (per channel)

Transmitter signal	5 dBm
Attenuation	–25 dB
Amplifier input	–20 dBm
Amplifier gain	22 dB
Amplifier output	2 dBm
Attenuation (span)	–25 dB
Attenuation (demux)	–5 dB
Receiver power	–28 dBm

Receiver sensitivity of –35 dBm is required to achieve a 7-dB system margin.

Adding Optical Channels

Now let's consider what happens if we add another 10 optical channels to the system using the same amplifier and demultiplexer. The amplifier already produces 16 mW (10 channels at 1.6 mW each), so assume the extra input power reduces gain 2 dB.

20-channel transmission (per channel)

Transmitter signal	5 dBm
Attenuation	–25 dB
Amplifier input	–20 dBm
Amplifier gain	20 dB
Amplifier output	0 dBm
Attenuation (span)	–25 dB
Attenuation (demux)	–5 dB
Receiver power	–30 dBm

If we use the same receivers, the system margin is a rather thin 5 dB. This small margin is one reason why adding channels to WDM systems may require more extensive upgrades of optical amplifiers, transmitters, and receivers.

Gain Equalization

Suppose we have a chain of five amplifiers in a WDM system that transmits signals over a span of 600 km on a dozen optical channels. For proper performance, the receivers require signals between –30 dBm and –28 dBm. How much gain variation can be tolerated in each amplification stage, assuming that the variation is the same for each amplifier?

The allowable variation is 2 dB divided by 5 amplifiers, or 0.4 dB for each amplifier. Gain equalization is needed to keep the variation within these limits.

Gain equalization normally uses filters to block the additional power. If the amplifiers normally have 3 dB of gain variation across the spectrum, the filters will reduce the amplifier gain by 3 dB, so the gain budget will have to be increased. This is an example of the many trade-offs involved in WDM design.

What Have You Learned?

1. WDM is a fundamentally different way to organize signals than time-division multiplexing.
2. Granularity is the subdivision of signals in a network.
3. Total transmission capacity is the amount of information that can be transmitted by a network. It depends on data rate per optical channel, the number of channels, and channel spacing. It also depends on the range of wavelengths transmitted.
4. Optical amplifiers are not available for all fiber transmission wavelengths, limiting the bands usable for long-distance transmission. Fiber attenuation and dispersion limit the bands usable for shorter distances.
5. Dense-WDM is used for long-distance transmission. Coarse-WDM is used for tens of kilometers, and is less expensive to implement.
6. Dispersion limits fiber transmission distance at high data rates. WDM provides higher total transmission capacity on multiple channels with lower data rates.
7. Spectral efficiency measures how tightly signals can be packed, dividing the total data rate by the optical bandwidth used. The best rates achieved without elaborate polarization schemes are about 0.8 bit/s/Hz.
8. Network operators do not populate all available channel slots.
9. The ITU G694.2 standard established a grid of 18 CWDM slots with center wavelengths from 1270 to 1610 nm. This grid is used mainly in metro telecommunications networks.
10. Optical amplifiers have gain bandwidths of tens of nanometers; this limits the wavelength ranges available for long-distance DWDM systems.

11. Raman gain is offset from the pump wavelength by an amount that depends on the material; the value is 13 THz in silica. The Raman wavelength is longer (lower in frequency) than the pump wavelength.
12. Fiber loss varies significantly in the 1250 to 1650 nm; it is 0.35 dB/km at 1310 nm and under 0.2 dB/km at 1570 nm. Variation in the erbium amplifier band is much smaller.
13. Dispersion slope measures variation of chromatic dispersion with wavelength.
14. It's impossible to compensate for chromatic dispersion perfectly across a range of wavelengths because the dispersion curves of different fibers don't cancel each other out perfectly. These differences increase over long distances.
15. Nonlinear effects increase with total power and with the distance the light travels at high power. Attenuation reduces nonlinear effects far from the transmitter.
16. Saturation limits total power available from an optical amplifier. Saturation depends on total power, not just power at a single wavelength, so WDM systems can saturate.
17. Opaque systems convert optical signals into electronic form at some point, typically for switching or wavelength conversion.
18. Wavelength conversion is needed to manage optical channels. Wavelength routers direct signals according to their wavelength.

What's Next?

In Chapter 23 you will learn about the structure of the global telecommunications network.

Further Reading

Vivek Alwayn, *Optical Network Design and Implementation,* (Cisco Press, Indianapolis, 2004)

Rajiv Ramaswami and Kumar N. Sivarajan, *Optical Networks: A Practical Perspective,* 2nd ed. (Morgan Kaufmann, San Francisco, 2002)

Questions to Think About

1. Your design packs 2.5-Gbit/s optical channels only 50 GHz apart, but 10-Gbit/s signals require 100 GHz spacing to give adequate performance margins. Which spacing transmits more data if you populate every available slot in the erbium-amplifier C-band? How much is the difference?
2. Wavelengths of 1460 to 1625 nm are available in an unamplified metro WDM system. How many CWDM optical channels can this network transmit with ITU standard 20-nm spacing?
3. You have two types of fiber available for dispersion compensation, step-index single-mode fiber with dispersion of +17 ps/nm-km at 1550 nm, and a reduced-slope non-zero dispersion-shifted fiber with –2 ps/nm-km at the same wavelength.

How much of each do you need for a 95-km span with zero cumulative dispersion at 1550 nm? Which type should you use closer to the transmitter?

4. An erbium-fiber amplifier that has peak output of 20 dBm transmits 40 optical channels. What is the output power on each channel? What happens to the output power if the number of channels is doubled?
5. You need to send 20 optical channels through a series of 50 erbium-doped fiber amplifiers, and the output signals must differ by no more than 6 dB at the end of the amplifier chain. How should you equalize the gain assuming all that difference is due to unequal gain across the range of optical channels?
6. The input to an all-optical switch is a cable containing 48 fibers. Each fiber can transmit up to 40 optical channels. How many optical channels can the switch direct if it has 128 input and 128 output ports?

Chapter Quiz

1. One 40-Gbit/s TDM channel is equivalent to how many 2.5-Gbit/s optical channels?
   a. 1
   b. 4
   c. 16
   d. 40
   e. 100
2. A WDM system has 40 optical channels spaced 100 GHz apart in the 1550-nm region. What is the approximate total spectrum used by the system?
   a. 40 GHz
   b. 100 GHz
   c. 400 GHz
   d. 4 THz
   e. 193.1 THz
3. How is the spacing required between optical channels related to the data rate transmitted on each channel?
   a. The spacing increases with the data rate; the required spacing in gigahertz is larger than the data rate in gigabits.
   b. The spacing equals the signal speed in gigahertz.
   c. The spacing in nanometers is equal to the data rate in gigabits per second.
   d. The spacing decreases with the data rate; it is proportional to the length of the data pulses.
   e. The relationship is impossible to state because data rate is digital and frequency spacing is analog.

4. Which of the following systems can accommodate the most optical channels?

a. coarse-WDM in a system that includes several erbium-doped fiber amplifiers

b. dense-WDM in a system that includes several erbium-doped fiber amplifiers

c. coarse-WDM in a system without optical amplifiers

d. dense-WDM in a system without optical amplifiers

e. not enough information to tell

5. You need to compensate dispersion for a 60-kilometer length of fiber with chromatic dispersion of −3 ps/nm-km. How much fiber with chromatic dispersion of +15 ps/nm-km at the same wavelength (1550 nm) do you need?

a. 5 km

b. 12 km

c. 15 km

d. 25 km

e. 60 km

6. Your fiber has a dispersion slope of 0.08 ps/nm^2-km in the C-band of erbium-fiber amplifiers. Assuming that slope is a straight line, how much does the dispersion change over the width of the C-band?

a. 0.08 ps/nm-km

b. 0.8 ps/nm-km

c. 2.8 ps/nm-km

d. 8 ps/nm-km

e. 28 ps/nm-km

7. A span between two fiber amplifiers includes three types of fiber. Which type should be closest to the output of the first amplifier to reduce four-wave mixing?

a. step-index single-mode fiber with effective area 80 μm^2 and dispersion +15 ps/nm-km

b. reduced-slope single-mode fiber with effective area 50 μm^2 and dispersion –2.5 ps/nm-km

c. large-effective-area single-mode fiber with effective area 68 μm^2 and dispersion –20 ps/nm-km

d. either of the low-dispersion fibers

e. any of the fibers

8. In which fiber is four-wave mixing the largest?

a. step-index single-mode fiber with effective area 80 μm^2 and dispersion +15 ps/nm-km

b. reduced-slope single-mode fiber with effective area 50 μm^2 and dispersion –2.5 ps/nm-km

c. large-effective-area single-mode fiber with effective area 68 μm^2 and dispersion –2.0 ps/nm-km

d. zero dispersion-shifted single-mode fiber with effective area 75 μm^2 and dispersion 0 ps/nm-km

e. 50/125 graded-index multimode fiber

9. An optical amplifier generates 2 mW on each of 40 optical channels. An optical switch downstream diverts half of the optical channels to another cable. If everything else remains constant, what is the power on the remaining channels?

a. 2 mW

b. 3 mW

c. 4 mW

d. 5 mW

e. The amplifier will not work.

10. What is the difference between a transparent and an opaque optical switch?

a. A transparent switch allows light signals to pass through in optical form; an opaque switch converts them to electronic form.

b. A transparent switch is made of clear glass; an opaque switch is made of metal.

c. A transparent switch does not change the data rate of the signal; an opaque switch changes the data rate.

d. A transparent switch transmits a signal; an opaque switch blocks the signal, turning it off.

11. You add eight new optical channels to an optical fiber that already was carrying eight optical channels. The signals must pass through an optical amplifier nearing saturation. All the signals arrive at the amplifier with the same power. What happens to the original eight channels?

a. Output power on all channels after the addition is the same as it was on the original channels because the power per channel is well under saturation.

b. Output power on the original channels is unchanged, but the new channels get less power.

c. Output power per channel drops to a lower level.

d. Output power on the original channels doubles.

e. All channels fail to transmit a signal because they overload the amplifier.

12. Which of the following varies least in the 1550-nm transmission window?

a. chromatic dispersion

b. fiber attenuation

c. erbium-amplifier gain

d. raman amplifier gain