Electrical power is usually given as the product of the voltage (V) times the current (I):

$$P = VI$$

or, power (in watts) = volts × amperes. The relationship can take other forms if you use Ohm's law, $V = IR$ (voltage = current × resistance):

$$\text{Power} = \frac{V^2}{R} = I^2R$$

Recall that voltage across a resistance is the strength of the electric field, and you can see that electrical power looks like optical power. It's easy to measure the voltage or current in electronics, but it's not easy to measure the amplitude of the electric field in light waves. Thus in electronics you may measure the voltage and current and multiply them to get power, but in optics you measure power directly.

A closer comparison of optical power and electronic power shows more about their differences and similarities. The energy carried by an electron depends on the voltage or electric field that accelerates it. Earlier, I mentioned the electron volt as a unit of energy. One *electron volt* is the energy an electron carries after it is accelerated through a potential of one volt. The total power is thus the number of electrons passing through a point times the voltage that accelerated them.

Energy per photon depends on the photon wavelength.

Each photon has a characteristic energy, which depends on its wavelength or frequency. If the light is at a steady level, the amplitude of the light wave measures the number of photons per unit time. Thus the total energy delivered by the light is the energy per photon times the number of photons (the wave amplitude).

This makes the two types of power look the same, and that stands to reason. Electrical power is the energy per unit time delivered by electrons, where the electron energy depends on the voltage that accelerated the electrons. Optical power is the energy per unit time delivered by photons, each of which has a fixed energy that depends on its wavelength. The total power measures the rate at which these photons are arriving.

There is a complication to this picture. Normally, a constant voltage accelerates all electrons to the same energy. However, all photons arriving at a given point do not have the same energy unless they all have the same wavelength. Lasers can deliver monochromatic light, with all photons having almost the same energy, but optical measurements were developed long before lasers, when there was no easy way to account for differences in photon energy. Instead of trying to count photons, optical power measurements usually average out the differences and give the results in watts.

Peak and Average Power

Power is an instantaneous measurement; it varies with time.

Power is an instantaneous measurement of the flux of energy at a given moment. This means that it can vary with time. In general, two types of power are measured in optical systems: *peak power* and *average power.*

The peak power is the highest power level reached in an optical pulse, as shown in Figure 17.2. This power may not be sustained long. In a fiber-optic system, this is the highest level reached while a signal is being transmitted.

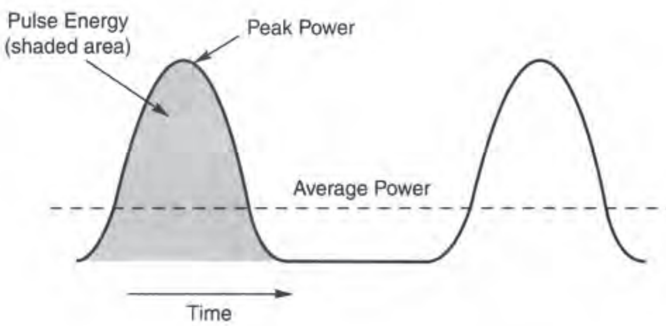


FIGURE 17.2
Peak and average power, and total pulse energy.

The average power measures the average power received over a comparatively long period, often a second. In a communication system, this is the average over many pulses and quiet intervals. For a digital fiber-optic system in which the transmitter is sending "on" pulses half the time (a 50% duty cycle), the average power is half the peak power because the power is either fully on or fully off. In the example of Figure 17.2, the average power is less than half the peak power because the power is lower than the peak during most of the pulse, and because no power is delivered between pulses.

Peak power is the highest level in an optical pulse; average power is the average over an interval.

The average power of an ideal digital transmitter also depends on the modulation scheme. Some modulation patterns and data streams do not keep the transmitter emitting light half the time.

In practice, fiber-optic measurements average power levels over many pulses to give average power rather than peak power. However, transmitter output may be specified as peak power, so it pays to check.

Pulse energy is another measurement that can be valuable. An example is trying to calculate how many photons arrive per pulse in high-speed systems, because that number drops with data rate. Suppose the average power in two signals is 10 μW. If one signal carries 2.5 Gbit/s and the second carries 10 Gbit/s, the pulses in the faster system will be only one-fourth the duration, and during that interval they will deliver only one-fourth the total energy carried by a pulse lasting four times as long. If you delve deeply into communication theory, you will find that the ultimate limits on communications often are stated as the minimum pulse energy needed to deliver a bit of information.

The ultimate limits on communications come from pulse energy.

Pulse energy measures the total energy received during a pulse, as shown in the shaded area in Figure 17.2. If the power is uniform during the length of the pulse, as in a series of square digital pulses, the pulse energy Q is the product of the power P times the time t:

$$Q = P \times t$$

If the instantaneous power varies over the length of the pulse, you need to integrate power over the pulse duration, which is mathematically expressed as:

$$Q = \int P(t)\,dt$$

As long as the power remains level during the pulse, multiplication works fine.

Optical Power Measurement Quirks

The definition of decibels looks different for power and voltage.

Before I go deeper into measuring various forms of optical power, I'll warn you about a few potentially confusing measurement quirks. In electrical measurements, the decibel power ratio is often defined in terms of voltage or current. These are in the form

$$\text{Power ratio (dB)} = 20 \log\left(\frac{V_1}{V_2}\right) = 20 \log\left(\frac{I_1}{I_2}\right)$$

where V and I are voltage and current, respectively.

Fiber-optic measurements usually give a different-looking equation in terms of powers P_1 and P_2:

$$\text{Power ratio (dB)} = 10 \log\left(\frac{P_1}{P_2}\right)$$

Why the different factor preceding the log of the power ratio? Because electrical power is proportional to the square of voltage or current. If you measure the ratio of voltage or current, you have to square it to get the power ratio, which is the same as multiplying the log of the ratio by 2. You don't have to do that if you measure power directly, either optically or electrically. Electrical measurements are usually in voltage or current, but optical measurements are in power, so it may seem that the difference is between optical and electrical. However, the real difference is between measuring power directly or indirectly. Both formulas are correct, but be careful to use the proper one.

Optical power can be measured in decibels relative to 1 mW (dBm) or 1 μW (dBμ).

A second potentially confusing point is measurement of optical power in some peculiar-seeming units. Normally, power is measured in watts or one of the metric subdivisions of the watt—milliwatts, microwatts, or nanowatts. Sometimes, however, it is convenient to measure power in decibels to simplify calculations of power level using attenuation measured in decibels. The decibel is a dimensionless ratio, so it can't measure power directly. However, power can be measured in decibels relative to a defined power level. In fiber optics, the usual choices are decibels relative to 1 mW (dBm) or to 1 μW (dBμ). Negative numbers mean powers below the reference level; positive numbers mean higher powers. Thus, +10 dBm means 10 mW, but −10 dBm means 0.1 mW. Zero means there is no difference from the reference level, so 0 dBm is 1 mW.

Such measurements come in very handy in describing system design. Suppose, for instance, that you start with a 1-mW source, lose 3 dB coupling its output into a fiber, lose another 10 dB in the fiber, and lose 1 dB in each of three connectors. You can calculate that simply by converting 1 mW to 0 dBm and subtracting the losses:

Initial power	0 dBm
Fiber coupling loss	−3 dB
Fiber loss	−10 dB
Connector loss	−3 dB
Final Power	−16 dB

Convert the −16 dBm back to power, and you find that the signal is 0.025 mW; however, that often isn't necessary because many specifications are given in dBm. This ease of calculation and comparison is a major virtue of the decibel-based units.

Types of Power Measurement

As Table 17.1 indicates, optical power measurements may include the distribution of power per unit area or angle. The main concern of fiber-optic measurements is with total optical power within a fiber, or reaching a detector; but the distribution of optical power can be vital for other applications, such as illuminating and imaging. You should understand the differences because the terminology can be confusing and it's important to understand what you're measuring.

LIGHT DETECTORS

Light detectors measure total incident power.

Light detectors measure total power incident on their active (light-sensitive) areas—a value often given on data sheets. Fortunately, the light-carrying cores of most fibers are smaller than the active areas of most detectors. As long as the fiber is close enough to the detector, and the detector's active area is large enough, virtually all the light will reach the active region and generate an electrical output signal.

The response of light detectors depends on wavelength. As you learned in Chapter 11, silicon detectors respond strongly at 650 and 850 nm but not at the 1300 to 1700 nm wavelengths used in long-distance systems. On the other hand, InGaAs detectors respond strongly at 1300 to 1700 nm but not to the shorter wavelengths. In addition, detector response is not perfectly uniform across their entire operating region. You have to consider the wavelength response of detectors to obtain accurate measurements.

Recall also that detectors cannot distinguish between different wavelengths within their operating regions. If eight WDM channels all reach the same detector, its electrical output will measure their total power, not the power of one channel.

In addition, individual detectors give linear response over only a limited range. Powers in fiber-optic systems can range from over 100 mW near powerful transmitters used to drive many terminals to below 1 μW at the receiver ends of other systems. Special detectors are needed for accurate measurements at the high end of the power range.

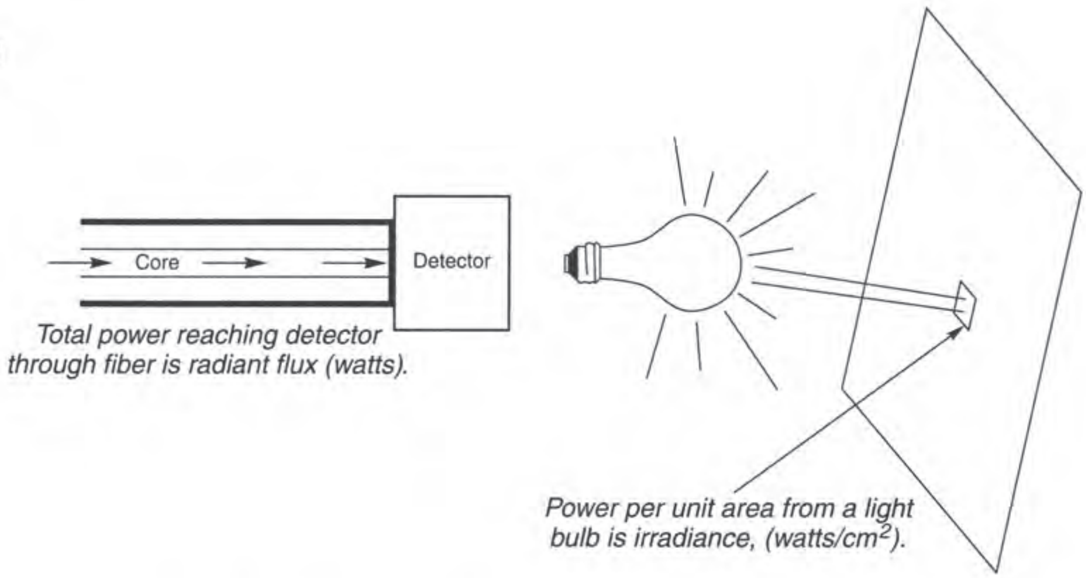
IRRADIANCE AND INTENSITY

Irradiance (E) is power per unit area. Intensity (I) is power per unit solid angle.

Things are more complicated when measuring the distribution of optical power over a large area. For this case, another parameter becomes important, called *irradiance* (usually denoted E in optics), the power density per unit area (e.g., watts per square centimeter). Figure 17.3 compares the irradiance on a surface with the total power a detector collects from an optical fiber.

You cannot assume irradiance is evenly distributed over the surface unless the light comes from a "point" source (i.e., one that is very distant or looks like a point), and the entire surface is at the same angle to the source. A book lying flat on the ground is uniformly illuminated by the sun, but the entire earth is not, because its surface is curved. Total power

FIGURE 17.3
Total power and irradiance.



(P) from a light source is the irradiance (E) collected over the entire illuminated area (A). For the simple example of the book in the sun, the total power is

$$P = E \times A$$

If the surface is not uniformly illuminated, the total power is integrated over the entire surface:

$$P = \int EA$$

The E for irradiance could be confused with the E more widely used for energy. Fortunately, irradiance is rarely used in fiber optics, and when the symbol E is used its meaning should be clear.

The term *intensity* (I) also has a specific meaning in light measurement—the power per unit solid angle (steradian), with the light source at the center of the solid angle. This measures how rapidly light is spreading out from the source.

Irradiance and intensity are often confused, and the power per unit area is often called intensity. This mistake is understandable because both units measure the distribution of power, one over a surface area, the other over a range of angles. The easiest way to tell is to look at the units; if someone measures "intensity" in watts per square centimeter, they're really talking about irradiance. There are fewer situations where power is measured per steradian.

Most fiber-optic measurements concern total power. However, irradiance and intensity may be important when measuring the concentration of power inside a fiber core, or when beams are directed through free space.

Radiometry measures all wavelengths. Photometry measures only visible light.

RADIOMETRY AND PHOTOMETRY

Optical measurements are divided into two broad categories, *radiometry* and *photometry*, which are sometimes confused. Photometry is limited to measuring light visible to the human eye, at wavelengths of 400 to 700 nm; invisible light doesn't count for photometry.

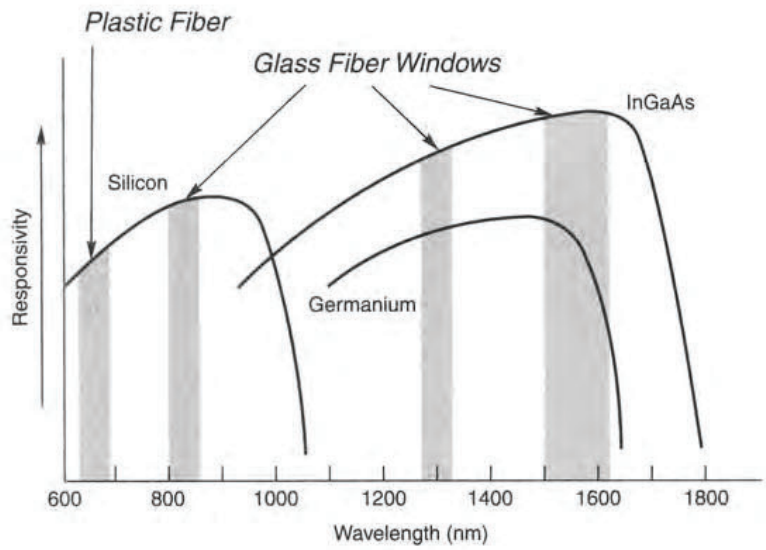


FIGURE 17.4
Detector response at different wavelengths.

Radiometry measures the total power of both visible and invisible light in watts, and it's radiometry that is used for fiber-optic measurements.

Photometry has its own measurement units, *lumens,* which are used to measure the visible light from bulbs. Lumens are not directly convertible to watts because lumens are weighted to account for how the eye's sensitivity varies with wavelength. Light at 550 nm, where the eye is most sensitive, counts more on a photometric scale than 450 or 650 nm, where the eye is less sensitive. Photometry ignores the infrared wavelengths used in fiber-optic communications. You should know what photometry is because many optical power meters are calibrated in both radiometric and photometric units, but you should use the radiometric units.

An ideal *radiometer* would be sensitive across the entire visible, ultraviolet, and infrared spectrum, but real detectors don't work that way. As you learned in Chapter 11, each type of detector responds to a different range of wavelengths, and is not equally sensitive across its entire range. Figure 17.4 shows the variations over the ranges of important detectors compared to the windows for fiber transmission. Power meters are calibrated to reflect detector response.

In practice, fiber-optic power meters are calibrated for measurements at the major fiber system windows, 650, 850, 1300, and 1550 nm. They may not be calibrated at intermediate wavelengths, and as you can see in Figure 17.4, at some wavelengths they may not even respond. All power meters measure average power. They respond much more slowly than signal speeds, so they can't track instantaneous power fluctuations.

Fiber-optic power meters are calibrated for standard transmission windows.

Wavelength and Frequency Measurements

Wavelength-measurement requirements vary widely, depending on the application. Precise knowledge of source wavelengths is critical in dense-WDM systems, where the transmission channels are closely spaced and must be matched to the transmission of demultiplexing components. Knowledge of the spectral response of system components also is vital in WDM systems, particularly for filters used in demultiplexing signals. On the other hand, wavelength need not be known precisely in systems carrying only one wavelength.

Wavelength is critically important in WDM systems.

Wavelength and Frequency Precision

So far, I have usually described wavelengths in round numbers, such as 1550 nm. That's common in optics; engineers who work with light think in terms of wavelength. However, wavelength is not as fundamental a characteristic of a light wave as its frequency. The wavelength depends on the refractive index of the medium transmitting the light; the frequency is constant. This is why standard channels and spacing for DWDM systems are specified in terms of frequency.

Earlier, you learned that the wavelength in a vacuum equals the speed of light divided by frequency, ν:

$$\lambda = \frac{c}{\nu}$$

However, this equation holds only in a vacuum. When the light is passing through a medium with refractive index n, the equation becomes

$$\lambda = \frac{c}{n\nu}$$

which means the wavelength decreases by a factor $1/n$.

Precise measurements and calculations are vital with WDM systems.

I have used round numbers in much of this book because they're usually good enough. Why punch 10 digits into your calculator when you can learn the same concept by punching only 2 or 3? Those approximations don't work for dense-WDM systems. You have to use exact numbers or you get into trouble. To understand why, run through a set of calculations first using the approximation of 300,000 km/s for the speed of light; then use the real value. Let's calculate the vacuum wavelength corresponding to the base of the ITU standard for WDM systems, 193.1 THz.

Using round numbers,

$$\lambda = \frac{3 \times 10^8}{(193.1 \times 10^{12})} = 1553.60 \text{ nm}$$

Using the exact value for c, the wavelength is

$$\lambda = \frac{2.997925 \times 10^8}{(193.1 \times 10^{12})} = 1552.52 \text{ nm}$$

The difference is less than 0.1%, but that's enough to shift the wavelength by more than one whole 100-GHz frequency slot. In short, the wavelength tolerances in dense-WDM systems are too tight to get away with approximations. You have to be precise.

Because of the importance of precision, frequency units may be used in measurements rather than the more familiar wavelength units. You should be ready to convert between the two when necessary, always using the precise formulas.

The wavelengths assigned to optical channels are the values in vacuum, not in air.

If you've been watching carefully, you will note that the wavelengths given so far are for light in a vacuum, where the refractive index is exactly 1. Why don't we use the wavelengths in air, which has a refractive index of 1.000273? It's primarily a matter of convention and simplicity. Physicists have long used vacuum wavelengths, and adjusted them slightly—when necessary—for transmission through air. If you wanted to convert frequency to wavelength in air, you would have to add a factor of *n* to all your equations, which could introduce errors. In addition, light often goes through other media, such as the glass in an optical fiber, and the refractive index of air varies with pressure and temperature.

From a physical standpoint, frequency is a more fundamental quantity. A light wave with a frequency of 193.1 THz oscillates at the same frequency in a vacuum, air, or glass. Yet the wavelengths differ because the refractive index differs among the three media. This is a major reason that the standards for DWDM optical channels are stated in frequency rather than wavelength.

Ways of Measuring Wavelength

It is not easy to measure wavelength precisely; it takes sophisticated instruments and carefully controlled conditions. Precise measurements became essential as DWDM systems packed channels close together, making it critical to separate and identify optical channels precisely. A few basic concepts are critical to understanding these measurements and the specific instruments covered in the next chapter.

Wavelength measurements can be absolute or relative.

Wavelength measurements can be absolute or relative. *Absolute measurements* tell you the precise wavelength (or frequency) of a light source. *Relative measurements* tell you the difference between the wavelengths of two light sources, often in frequency units. In general, relative comparisons are easier to make.

In practice, absolute measurements are made by comparing the wavelength with some well-defined standards of length or frequency. One way is to monitor changes in interference in two arms of an interferometer as the length of one is changed; another is to measure the difference in frequency between the unknown source and a standard, such as a laser with precisely defined wavelength.

The accuracy of both absolute and relative measurements depends critically on calibration of the instruments, accuracy of the standards, and the comparison process. For example, precise measurements require accounting for the fact that air has a refractive index of 1.000273 at room temperature near 1550 nm. Although that number is only slightly higher than the refractive index of a vacuum, the small wavelength shift corresponds to a frequency difference of about 50 GHz in the 1550 nm window. That's significant for DWDM systems.

Linewidth Measurements

In addition to measuring the central wavelength of a laser source, you often need to measure the range of wavelengths in the signal, called the *linewidth* or *spectral width*. Where fiber dispersion is an issue or where a DWDM system carries closely spaced wavelengths, the linewidth should be small and often is measured in frequency units—for example, 150 MHz for a temperature-stabilized DFB laser emitting continuously. On this scale, frequency units are more convenient than wavelength; at 1550 nm, 100 GHz is about 0.8 nm, so 150 MHz is about 0.0012 nm. (External modulation adds to that linewidth.)

At lower speeds, where dispersion is not a critical concern, such as where a simple diode laser is modulated directly, the linewidth is much larger and is generally measured in wavelength units. In this case, wavelength units are more convenient.

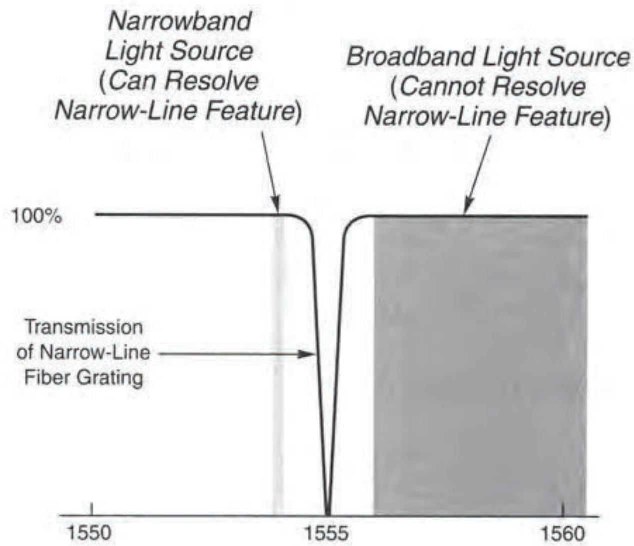


FIGURE 17.5
Only a narrowband source can measure transmission of a narrow-line demultiplexer.

Spectral Response Measurements

Spectral response measures how systems and components respond to different wavelengths.

In addition to knowing the wavelength of the transmitter, you need to know how a fiber-optic system and its components respond to different wavelengths. This is called *spectral response.* For most components, the most important response is loss or attenuation as a function of wavelength. In the case of filters, multiplexers, and demultiplexers, you need to know how light is divided as a function of wavelength. That is, you need to know how much light is routed in different directions at various wavelengths. For optical amplifiers, the important feature is gain as a function of wavelength.

Spectral response measurements require a properly calibrated light source that emits a suitably narrow range of wavelengths. Figure 17.5 illustrates the problem by comparing two light sources with the transmission of a fiber Bragg grating that selectively reflects at 1555 nm for wavelength-division demultiplexing. A narrow-line source such as a tunable laser can accurately measure the response of the fiber grating, but a broadband source cannot, because its light contains a range of wavelengths much broader than the range of wavelengths the grating reflects.

Phase and Interference Measurements

Phase measures a light wave's progress in its oscillation cycle.

In Chapter 2 you learned that light waves have a property called *phase.* Recall that a light wave consists of an electric field and a magnetic field, each of which periodically rise and fall in amplitude, as shown in Figure 17.6. The amplitude varies in a sine-wave pattern, so the position in that cycle is measured as an angle, in degrees or radians. One wavelength is a complete cycle of 360° or 2π radians. Normally the phase is measured from the point where the amplitude begins increasing from zero. Amplitude peaks at 90°, returns to zero at 180°, has a negative peak at 270°, then returns to zero at 360°.

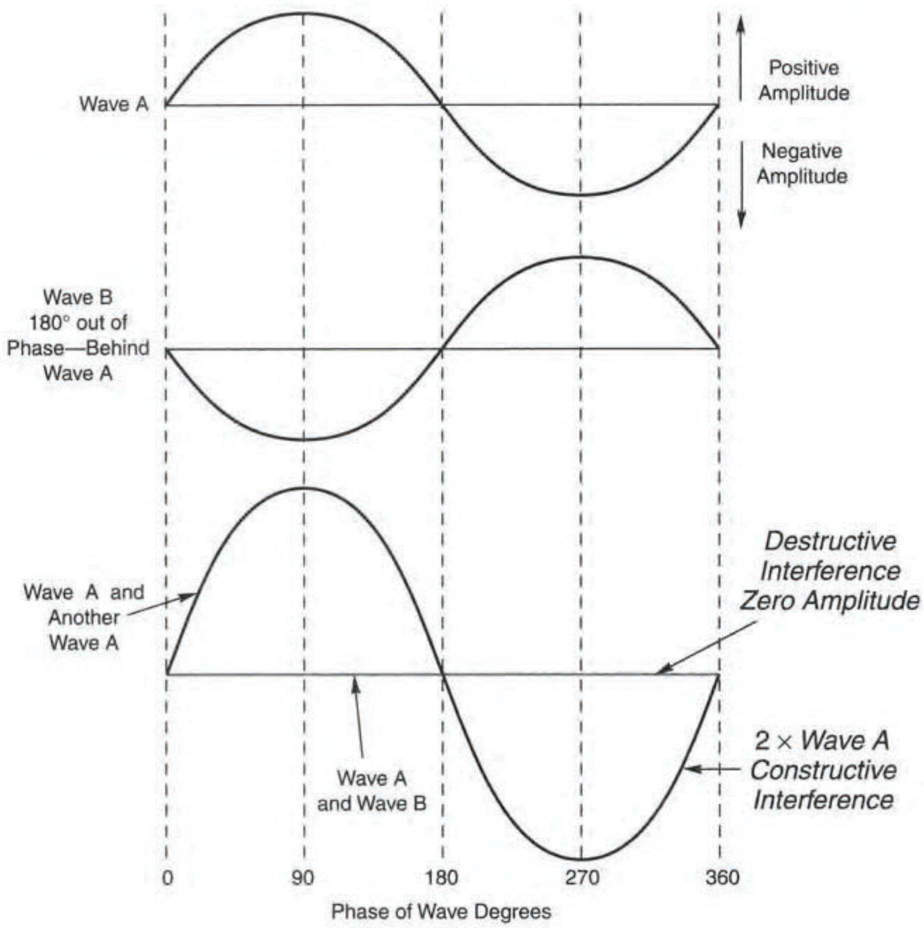


FIGURE 17.6

Phase and interference of light waves.

The absolute phase of a light wave is difficult to measure, but the relative phase can be measured simply by interferometry if the light is coherent. In Chapter 16, you learned that the operation of many fiber-optic modulators and switches depends on phase shifts between light traveling through two parallel arms. The same principle is used to measure phase shift. A laser beam is split, then recombined and the power is measured. If the light beams add constructively, the relative phase shift is 0°. If the beams add destructively, the phase shift is 180°. Other values can be interpolated.

In practice, the phase shift usually is measured relatively, as an angle between 0° and 360° (a whole wave), although the actual shift in phase may be a number of wavelengths plus an angle between 0° and 360°. That's a matter of convenience. Relative phase shift is easier to measure, and usually the relative shift is more important for device operation. The absolute phase shift between two waves can be measured using devices that count the number of interference peaks, but it's rarely necessary for fiber optics.

Actual phase measurements are messier than our simple example. Two beams must be equal in amplitude and precisely 180° out of phase to cancel each other completely by destructive interference. They also must be perfectly coherent, with exactly the same wavelength.

Those conditions are virtually impossible to obtain, so in practice phase shift measurements are made by looking for the maximum and minimum.

Polarization Measurements

Polarization is the alignment of the electric field in a light wave.

The polarization direction of a light wave is defined as the orientation of the electric field, which automatically sets the direction of the magnetic field that is perpendicular to it. Light waves with their electric fields in the same linear plane are *linearly polarized.* If the field direction rotates along the light wave, the light is *elliptically* or *circularly polarized.* If the fields are not aligned with each other in any way, the light is *unpolarized.*

Several polarization characteristics significant in fiber-optic systems may require measurements. The simplest in concept is the direction of the polarization. This can be measured by passing the light through a polarizer and rotating the polarizer to see at what angles the transmitted light is brightest and faintest.

Polarization dependence arises when the loss or gain of a component depends on the polarization of the light passing through it. This can create a problem by modulating the light signal according to its polarization, which introduces noise into the system.

Loss or gain may depend on polarization.

Polarization-dependent loss measures the maximum differences in attenuation for light of various degrees of polarization. For example, if an optical component has 3-dB attenuation when transferring horizontally polarized light and 6 dB for vertically polarized light, it has a polarization-dependent loss of 3 dB—if those are the maximum and minimum values for attenuation. Polarization-dependent loss can be measured by adding polarization analyzers to conventional loss measurement instruments.

Polarization-dependent gain is a variation in gain for light of different polarizations passing through an optical amplifier, the inverse of polarization-dependent loss. It is particularly important for semiconductor optical amplifiers.

Polarization-mode dispersion (PMD) is the spreading of pulses arising from the dispersion of light between the two orthogonal polarization modes, as described in Chapter 5. The degree of PMD is not constant for a fiber; it varies statistically with time, depending on environmental conditions. This means that measurements of PMD have to be made over a period of time. Specialized instruments can measure the instantaneous polarization direction, the instantaneous PMD, and the differential group delay or pulse spreading caused by PMD.

Time and Bandwidth Measurements

Bandwidth and time measurements indicate transmission capacity.

As you learned in Chapter 5, system bandwidth is limited by the spreading or dispersion of pulses in the fiber, transmitter, and receiver. This means that time and bandwidth measurements in fiber-optic systems are related. You can think of them as different ways to measure the information transmission capacity of the system. Time measurements directly measure how fast the system can respond to a pulse. Bandwidth depends on this time response, but it also can be measured directly.

Pulse Timing

Figure 17.7 shows the key parameters in measuring pulse timing.

- *Rise time* is the time the signal takes to rise from 10% to 90% of the peak power.
- *Pulse duration* normally is the time from when the signal reaches half its maximum strength to when it drops below that value at the end of a pulse. This is called *full width at half maximum*, abbreviated FWHM.
- *Fall time* is the interval the signal takes to drop from 90% to 10% of peak power.
- *Pulse spacing* or *pulse interval* is the interval between the start of one pulse and the point where the next should start. If the signal is on for 1 ns and there is a 1-ns delay before the next pulse can start, the pulse spacing is 2 ns. The pulse spacing means the interval between transmitting one data bit and transmitting the next, whether the bits are "0s" or "1s."
- *Repetition rate* is the number of pulses or data bits transmitted per second, which in practice is the pulse spacing divided into 1:

$$\text{Repetition rate} = \frac{1}{\text{pulse spacing}}$$

Thus if the pulse spacing is 1 ns, the repetition rate is 1 Gbit/s.

- *Jitter* is the uncertainty in the timing of pulses, typically measured from the point at which they should start.

Measurements are made by feeding the optical signal to a detector, which generates an electronic output that instruments measure. This means that time response measured for the light pulse also includes the time response of the detector and the instrument. This effect can be significant at high data rates and must be considered in making fast measurements.

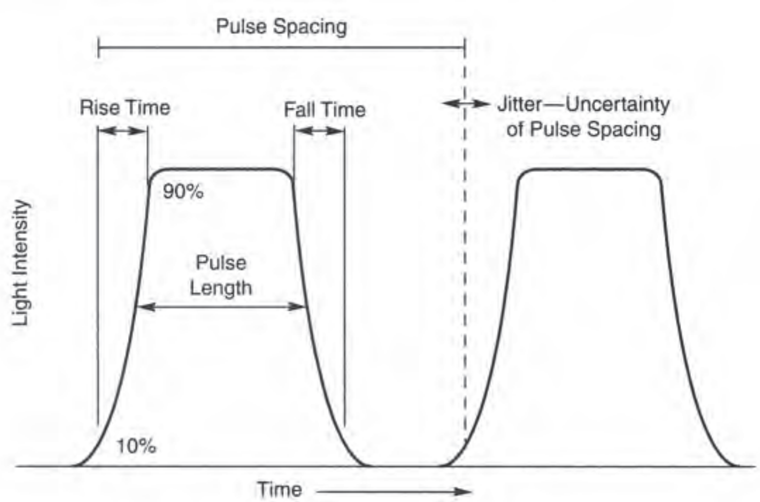


FIGURE 17.7
Pulse timing.

Repetition rates in even the slowest fiber-optic systems are extremely fast on a human scale—a million or more pulses per second—so you cannot see signal-level variations in real time. They are recorded on an oscilloscope or other display, which allows you to see events that are too fast for your eyes to perceive.

Bandwidth and Data Rate

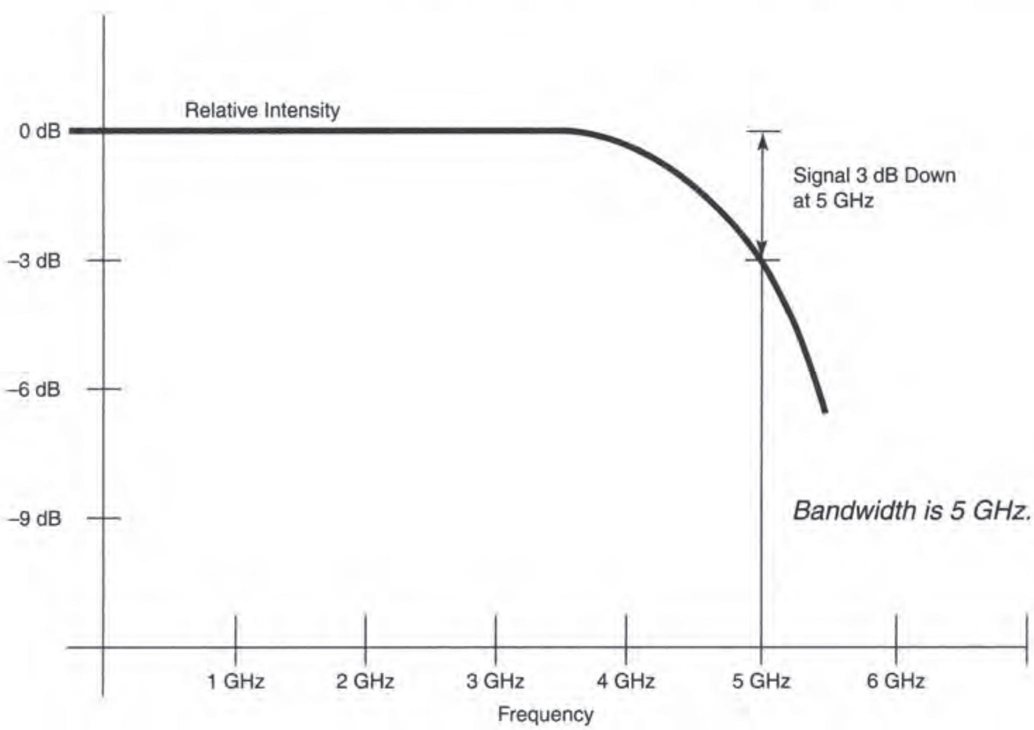
Bandwidth and data rate of communication systems differ in subtle but important ways. *Bandwidth* usually is an analog measurement of the highest signal frequency the system can carry. *Data rate* or *bit rate* is a digital measurement of the maximum number of bits per second actually transmitted. (*Baud* strictly speaking refers to the number of signal transitions per second, which may not equal data rate.) Both bandwidth and data rate deserve a bit more explanation.

Signal bandwidth measures analog transmission capacity.

The carrier frequency in an analog system is modulated with an analog signal spanning a range of frequencies. Typically it cuts off at some low minimum frequency, but the most important limit is the upper frequency cutoff, which arises from dispersion effects in fiber-optic systems. The attenuation increases with signal frequency, and the bandwidth limit normally is defined as the point where signal amplitude is reduced 3 dB, as shown in Figure 17.8. As you can see in the figure, higher frequencies suffer more attenuation.

Note that the signal bandwidth is distinct from the range of wavelengths transmitted by the fiber. You should think of the range of wavelengths as the optical bandwidth, distinct from the signal bandwidth. Optical attenuation is not the same as signal attenuation. An optical amplifier can compensate for optical attenuation by increasing the optical power,

FIGURE 17.8
Frequency response of an analog fiber-optic system.



THINGS TO THINK ABOUT

Types of Bandwidth

We've used the word "bandwidth" to describe fiber-optic systems in a few different ways. Fibers transmit light, and have an optical bandwidth of roughly 800 to 1600 nm. They don't transmit microwaves at all. Yet Figure 17.8 shows what looks like the attenuation of microwave signals passing through fibers. What's going on?

The microwave signals modulate the beam of light by varying the light intensity at microwave frequencies. That is, the microwaves are encoded as variations in the light intensity, just as sound waves are encoded as variations in electricity passing through phone wires. The fibers don't actually transmit microwaves, just as phone wires don't actually transmit sound waves.

The microwave attenuation shown in Figure 17.8 arises from dispersion, not light attenuation. It's easiest to visualize for digital pulses, which dispersion spreads out as they pass through the fiber. Eventually the pulses blur together, which means the microwave-frequency signal has faded away. The light is still there, but the microwave signal has been attenuated to the point where it can't be distinguished from noise.

Recall that square digital pulses actually are the sum of a series of sine waves at harmonics of the square-wave frequency:

$$f(t) = C(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + ...)$$

The highest frequencies give the square wave its sharp edges. Dispersion attenuates those high frequencies the most, rounding the edges of the signal until eventually they are humps that look more like sine waves at the base frequency. Good discrimination circuits can identify those rounded pulses, so you don't need to receive the higher harmonics, only the base frequency (e.g., 1 GHz for a 1-Gbit/s signal).

---

but it can't make up for signal attenuation, which is caused by dispersion. Dispersion doesn't reduce the optical power, but it does blur the signal together, reducing the signal intensity that can be detected above the background noise.

The bit rate or data rate in bits per second is the speed limit of digital systems. The upper limit of the bit rate is determined by the maximum error rate that is considered acceptable. The desired error rate depends on the application. Typically it's one bit in a billion (10^{-9}) or one in a trillion (10^{-12}) for data and voice transmission, but it may be lower for music or video transmission.

Analog bandwidth does not equal digital data rate.

Analog bandwidth and digital data rate are related, but not equivalent. Communications theory shows that a digital signal can be considered as the sum of signals at many different frequencies (called *harmonic frequencies*) that are integral multiples of the fundamental frequency—the signal bit rate. An ideal square wave is made up of a series of analog harmonics of the fundamental frequency:

$$f(t) = C(\sin \omega t + \frac{1}{3} \sin 3\omega t + \frac{1}{5} \sin 5\omega t + ...)$$

The highest frequencies give the square wave its sharp edges. They suffer the most attenuation when the signal is transmitted, so digital pulses first lose their sharp corners, then gradually become more like sine-wave humps. The discrimination circuits described in Chapter 11 are used to tell the humps of attenuated signals from the bumps of noise.

An analog transmission system can carry signals at a range of frequencies. That is, it responds to a certain range, analogous to the nominal 20 to 20,000 Hz response of the human ear. Normally, the bandwidth of fiber-optic systems is limited only at high frequencies. If you measure the signal received as a function of frequency, it drops at high frequencies, as shown in Figure 17.7. Typically the bandwidth is defined as the point where response has dropped by one-half or 3 dB—about 5 GHz in Figure 17.7.

As you can see from Figure 17.7, the system does transmit higher frequencies, but it attenuates them more strongly, so their intensity at the output is much weaker. Thus signals at 5.5 GHz are attenuated about 3 dB more than those at 5 GHz, and 6 dB more than those at 3 GHz. In practice, the higher attenuation means you can't count on the signals reaching the receiver in usable form. The usability of an analog signal is measured by the signal-to-noise ratio, described later in this chapter.

Data rate measures the speed of digital systems.

The speed limit of digital systems is measured as a *data rate* or *bit rate*, that is, how many bits can be transmitted through the system per second. The data rate response is not as easy to plot as the frequency response. In practice, the quality of a digital signal is measured as a *bit error rate*, also described later in this chapter. The poorer the signal quality, the more bits are received incorrectly. The maximum data rate is the highest transmission speed that meets error-rate specifications.

Signal Quality Measurements

Transmission quality of telecommunication systems can be assessed by comparing the output signal to the input. Different measurements are used for analog and digital systems.

Signal-to-Noise Ratio

Signal-to-noise ratio measures analog transmission quality.

Quality of an analog communication system is measured by the ratio of signal power to noise. The higher the *signal-to-noise ratio* (often written S/N), the higher the quality of the signal. What is an acceptable signal-to-noise ratio depends on the application and the user. The background hiss on analog audio cassette tapes is a good example; you notice it more in quiet passages of classical music in a quiet room than you would listening to loud rock music in a speeding car with the windows down. Users of analog transmission systems may set standards that define acceptable signal-to-noise levels. That is done by the cable television industry, the main user of analog fiber-optic systems.

Signal-to-noise ratio also can assess the performance of individual analog components. Optical amplifiers are important examples, where the ratio of the output signal to the background noise determines performance. The concept is fairly intuitive; the more signal and the less noise, the better. Typically signal-to-noise ratios are measured in decibels.

Bit Error Rate

The fraction of incorrect bits is the bit error rate.

Bit error rate (or ratio) measurements compare digital input and output signals to assess what fraction of the bits are received incorrectly. They offer a quantitative measurement of signal quality.

In practice, a special instrument generates a randomized bit pattern, which is transmitted through the system. The total number of bits transmitted are counted. So are errors that occur when the signal bit interpreted by the receiver does not match the transmitted signal. The more wrong bits, the worse the transmission quality.

As you would expect, the bit error rate increases as received power drops, as well as when the system approaches other performance limits such as maximum data rate. The increase in error rate is quite steep, and can be more than a factor of 100 when the input signal drops by 1 dB, if the system is operating near its performance limits. Other factors may set a minimum bit error rate when input power is adequate, and excess power can cause errors by overloading the receiver.

Users set standards for acceptable bit error rates. A typical target for telecommunications and data transmission is 10^{-12} (one error in a trillion bits). Higher error rates may be acceptable in other applications, such as video transmission.

Eye-Pattern Analysis

One popular way to assess performance of digital fiber-optic links is to superimpose a series of pulses on an oscilloscope display. This is called *eye-pattern analysis* because it produces the eye-shaped pattern shown in Figure 17.9.

An *eye pattern* superimposes waveforms of successive bits to assess signal quality.

The oscilloscope traces each received pulse on the screen. If there was no noise, each trace would follow exactly the same line, overlaying other pulses. Adding noise to the signal causes the intensity to vary randomly during the signal pulse, blurring the trace vertically. Likewise, jitter that varies the time when pulses arrive at the receiver spreads the lines horizontally.

What the eye pattern really measures is the repeatability of pulses reaching the instrument. The better the transmission quality and the more uniform the received pulses, the more open the eye will appear. If the eye starts to close—leaving less clear space in the center—it indicates that transmission errors are likely because it's becoming hard to tell the high points of the signal (the top of the eye) from the low points (the bottom of the eye).

The eye pattern measures pulse repeatability.

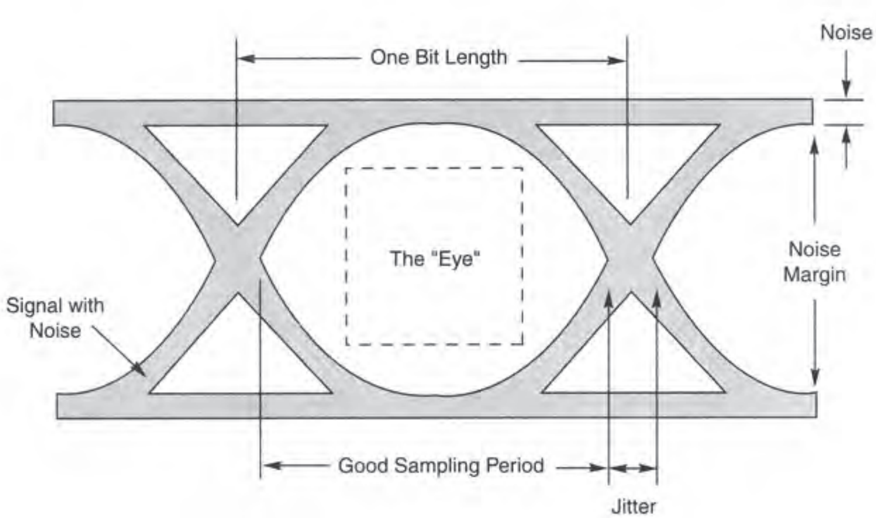


FIGURE 17.9
An eye pattern.

Careful interpretation of the eye pattern can yield important information on fiber-link performance. Some important points for interpreting eye patterns include:

- Height of the central eye opening measures noise margin in the received signal.
- Width of the signal band at the corner of the eye measures the jitter.
- Thickness of the signal line at the top and bottom of the eye is proportional to noise and distortion in the receiver output.
- Transitions between the top and bottom of the eye show the rise and fall times of the signal.

Fiber-Specific Measurements

So far I have described two broad classes of measurements: optical quantities that apply to fiber optics and communications system performance.

Another broad class of measurements is specific to optical fibers and fiber-optic systems. It's impossible to cover them comprehensively in a general introduction to fiber optics, so I will concentrate on a few key fiber parameters, such as attenuation and power in fibers. I will begin with general measurement concepts, then turn to important fiber-optic procedures. Chapter 18 describes important types of test equipment and outlines simple troubleshooting procedures.

Calibration

Calibration is essential for verifying the accuracy of measurements.

Calibration is an essential element of any measurement procedure. You calibrate the bathroom scale when you check that it reads zero before you stand on it to weigh yourself. When you make electrical measurements, you check that the current meter reads zero when the current probes are not in contact with the circuit.

For more precise measurements, you want to make sure the readings are accurate at more points on the scale. To double-check your bathroom scale, you could place a hundred-pound weight on it. To check a current meter, you could connect it to a standard current source designed to deliver one milliampere.

To be really exacting, you might want to go a step further and check the source of your calibrations. Instead of borrowing weights from your neighbor's barbells to test your bathroom scale, you might borrow a set of weights from the local university, which have been compared against precise standard masses. Then you could compare the university's weights against the barbells and find, for example, that the barbell weights weigh 97.5 pounds instead of the 100 pounds stated on the box.

This sort of calibration and comparison is done for precision measurements. Check a good set of test instruments, and you will find dates on which they were calibrated, and you may find that the calibrations are "traceable" to an organization like the National Institute of Standards and Technology, which provides measurement standards in the United States. You don't need this sort of exacting precision for every fiber-optic measurement, but it's essential for precision work. For example, in a short data link you might only need to know optical power to within 20%. However, in a state-of-the-art DWDM system with 50-GHz channel spacing, you may need to measure wavelength of individual light sources with accuracy better than 0.01% to make sure channels are properly spaced.

Fiber Measurement Standards

Measurement standards assure that results are compatible.

Serious fiber-optic measurements often refer to cryptic-seeming codes, such as EIA/TIA-455A. These codes identify standards written by industry and professional organizations, which specify how to make the measurements so the results are comparable to those made by other groups.

Standards often go into excruciating details in specifying the techniques and equipment used for particular measurements. However, those details can be as important in getting the right answer as not leaning against the sink can while standing on your bathroom scale. The essential point is to make sure that everyone's measurements are comparable and repeatable. Fiber specialists have found out the hard way that results can differ depending on whether the labs are or are not air-conditioned.

Chapter 20 talks more about fiber-optic standards, but the details are beyond the scope of this book. The number of standards is expanding, with scope ranging from the fiber itself to details of physical packages and signal formats. Table 17.2 lists some major groups that issue multiple standards. A number of other organizations have formed to produce standards for specific applications or types of devices, such as 10-Gigabit Ethernet or Xenpak transceivers, but the resulting standards usually are administered by one of the groups listed in the table.

Table 17.2 Standards organizations

ANSI	American National Standards Institute	*www.ansi.org*
ASTM	American Society for Testing & Materials	*www.astm.org*
ATIS	Alliance for Telecommunications Industry Solutions	*www.atis.org*
EIA	Electronics Industries Alliance	*www.eia.org*
ICEA	Insulated Cable Engineers Association	*www.icea.net*
IEC	International Electrotechnical Commission	*www.iec.ch*
IEEE	Institute of Electrical and Electronics Engineers	*www.ieee.org*
ITU	International Telecommunications Union	*www.itu.int*
NEC or NFPA	National Electrical Code (administered by National Fire Protection Association)	*www.nfpa.org*
NIST	National Institute for Standards and Technology	*www.nist.gov*
Telcordia	Telcordia Technologies (formerly Bellcore)	*www.telcordia.com*
TIA	Telecommunications Industry Association	*www.tiaonline.org*
UL	Underwriters Laboratories	*www.ul.com*

Measurement Assumptions

One reason that standards describe procedures in so much detail is to limit the number of assumptions made in making measurements. We inevitably make implicit and explicit assumptions, and sometimes those assumptions can lead to the wrong results.

If you check that your bathroom scale reads zero when nothing is on it, and 100 pounds with calibrated weights, you still make an assumption when you weigh yourself. You assume that the rest of the scale is accurate, and that if you go 50 steps up from 100 pounds, the scale is accurately measuring you at 150 pounds. However, it's possible that the scale might be a few pounds off, so what reads 150 pounds is actually 145 or 155 pounds.

We also make many assumptions in fiber optics, and some of them also may be wrong. It's reasonable to assume that light is distributed the same way along the length of a single-mode fiber, but not in a multimode fiber. Light may have to travel through a kilometer of graded-index fiber before distributing itself evenly among all the possible transmission modes. Differences between the real and the assumed mode distribution can affect measurements of the fiber's light-acceptance angle and numerical aperture. Likewise, we might assume that connector loss is identical in both directions, but be fooled because the core of one fiber is slightly smaller than that of the other, so the loss is 0.3 dB higher in one direction than in the other.

Careful adherence to standards can avoid pitfalls, which can be subtle in more sophisticated measurements.

Fiber Continuity

Fiber continuity checks can verify system function. The simplest test is to see if light can pass through the fiber.

A major concern in installing and maintaining fiber-optic cables is system continuity. If something has gone wrong with the system, you need to check if the cable can transmit signals. If it can, you know you have another problem. If it can't, you need to find the break or discontinuity. In some cases, the break may be obvious—a cable snapped by a falling tree limb or a hole dug by a careless contractor. However, such damage is not always obvious, and the cable route may not be readily accessible.

Early fiber technicians developed a quick-and-dirty test of fiber continuity. One shined a flashlight into the fiber, and a second on the other end looked to see if any light emerged. That is far from ideal because flashlight beams do not couple efficiently into optical fibers. It also requires people at each end of the fiber—one to send the light and the other to look for the transmitted light—and those people must be able to communicate with each other.

Now specialized instruments can do a much better job, often without requiring people on both ends. You will learn more about them and troubleshooting techniques in Chapter 18. Optical time-domain reflectometers (OTDRs) and optical fault indicators send pulses of light down the fiber and look for reflections that indicate a fault. Optical test sets measure power transmission. Fiber identifiers can tell if exposed fibers are carrying signals (they work by bending the fiber and observing light that leaks out at the bend). Visible fault identifiers send visible red light through the fiber, and visual inspections show if any is leaking out.

Optical Power

Measurements of optical power require knowing the wavelength and duty cycle.

Optical power is the quantity most often measured in fiber-optic systems. I described the basic principles earlier. The power may be output from a transmitter or optical amplifier, power emerging from a length of optical fiber, or power in some part of a system. The wavelength must be known so that the detector can be calibrated for that wavelength. Duty cycle—the fraction of the time the light source is on—should also be known to interpret properly measurements of average power. The usual assumption is 50% (half on, half off) for digital modulation, but under certain circumstances that may be far off (e.g., if a series of 1s is being transmitted in NRZ code).

Normally, power is measured where the light emerges from a light source or fiber. Fiber-optic power meters collect the light from the fiber through an optical connector, which directs the light to a detector. Electronics process the detector output and drive a digital display that shows the power level in linear units (nanowatts to milliwatts) or in dB referenced to either 1 mW or 1 μW. Measurement ranges are automatically switched across the dynamic range, which is typically a factor of one million. Typical measurement accuracy is ±5%.

Measuring optical power stops the beam, because it's absorbed by the detector. If you want to sample the power level in a transmitted signal, you need a coupler to divert a calibrated fraction of the light to a detector and transmit the rest.

It is important to keep input power within the dynamic range of the power meter. Excessive powers won't be measured correctly, and in extreme cases, excess power can damage some detectors.

Attenuation

Attenuation is the most important property of passive optical components, because it determines what part of an optical signal is lost within the component and how much passes through. It is always a function of wavelength, although the wavelength sensitivity varies widely. In fibers, the variation with wavelength is significant; in some other components, it is negligibly small.

Optical test sets measure cable loss.

As you learned earlier, attenuation is measured by comparing input and output powers. Figure 17.10 shows a standard way to measure cable loss using an optical test set—which includes a light source and transmitter. First the light source is connected to the power

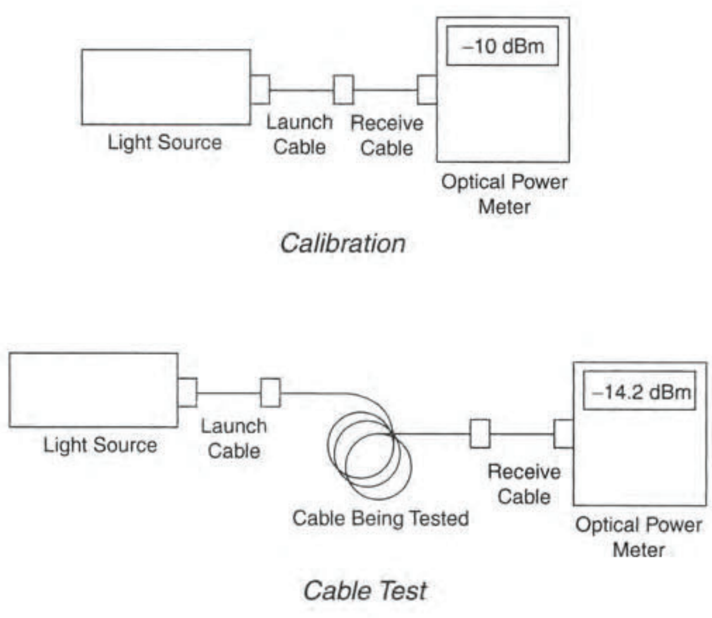


FIGURE 17.10
Cable loss measurement.

meter through a short launch cable, and the power is adjusted to a convenient level (−10 dBm in this case). Then a short receive cable is added between the launch cable and the power meter; a power change no more than 0.5 dB verifies the receive cable is good. The meter is again adjusted to the desired level. Then the cable to be tested is connected between launch and receive cables and the power it transmits is read (−14.2 dBm in this case). The difference, 4.2 dBm, is taken as the total attenuation of the cable being tested, including fiber, connectors, and splices. For more precise measurements, the loss should be measured in both directions through the test cable, because connector attenuation may differ slightly in the two directions.

The same principles can be used to measure the attenuation of other components, such as couplers, or of segments of cable installed in a system. If cable ends are located at different places, the tests can be performed by technicians working at both ends, one with a light source and the other with a power meter, or by temporarily installing a "loop-back" cable to send the signal back to the origination point through a second fiber. Inevitably, small losses are measured less accurately than large ones.

Precise measurements of fiber attenuation rely on cutting back fibers to compare power emerging from short and long lengths.

This simple comparison technique is adequate for most purposes, but it does not precisely measure pure fiber loss, because it includes loss within the connectors at each end. More precise measurements of fiber loss alone require the cut-back technique. First, power transmission is measured through the desired length of fiber. Then the fiber is cut to a short length (about a meter) and the power emerging from that segment is measured with the same light source and power meter. Taking the ratio of those power measurements eliminates input coupling losses (which occur in both measurements), while leaving the intrinsic fiber transmission loss (which is present only in the long-fiber measurement).

The *cut-back* method is more accurate for single-mode fibers than for multimode fibers, because of the way mode distribution changes along the fiber. Accurate measurement of long-distance attenuation of multimode fibers requires use of a mode filter to remove the higher-order modes that gradually leak out of the fiber. However, this won't accurately measure the loss of short multimode fibers, which depends on propagation of the high-order modes.

One special problem with single-mode fibers is that light can propagate short distances in the cladding, throwing off measurement results by systematically underestimating input coupling losses. To measure true single-mode transmission and coupling, fiber lengths should be at least 20 or 30 m.

Mode-Field and Core Diameter

Mode-field diameter is the region occupied by light in a single-mode fiber.

As you learned earlier, fiber core diameter can vary because of manufacturing tolerances. In addition, mode-field diameter—the diameter of the region occupied by light propagating in a single-mode fiber—is somewhat larger than the core diameter. These quantities can be measured.

Practical interest in the mode-field and core diameters depends on the distribution of light, and measurements are, therefore, based on light distribution. One approach is to scan across the end of the fiber with another fiber of known small core diameter, observing variations in light power collected by the scanning fiber. Other approaches rely on observing the spatial distribution of light near to or far from the fiber—the near-field and far-field intensity patterns. Those distributions of optical power can be used to calculate the core diameter.

A related quantity important for both single- and multimode fibers is the *refractive-index profile*, the change in refractive index with distance from the center of the fiber. This also is measured by examining the light distribution across the fiber.

Numerical Aperture and Acceptance Angle

The numerical aperture measures how light is collected by an optical fiber and how it spreads out after leaving the fiber. It measures angles, but not directly in degrees or radians. Although NA is widely used to characterize fiber, it isn't NA that is measured, but the fiber acceptance angle, from which NA can be deduced.

Numerical aperture is not measured directly; it is calculated from the acceptance angle.

Numerical aperture and acceptance angle are most important for multimode fibers. As mentioned earlier, measured numerical aperture depends on how far light has traveled through the fiber, because high-order modes gradually leak out as light passes through a fiber. The measured numerical aperture can be larger for shorter fibers, which carry a larger complement of high-order modes, than it will be for long fiber segments. Measurements are made by observing the spread of light emerging from the fiber.

Cutoff Wavelength

Cutoff wavelength, the wavelength at which the fiber begins to carry a second waveguide mode, is an important feature of single-mode fibers. The measured effective cutoff wavelength differs slightly from the theoretical cutoff wavelength calculated from the core diameter and refractive-index profile. As with core and mode-field diameter, cutoff wavelength is a laboratory rather than a field measurement.

Cutoff wavelength is measured by observing where stripping out the second-order mode causes an increase in loss.

Normally, the cutoff wavelength is measured by arranging the fiber in a test bed that bends the fiber a standard amount. Fiber attenuation as a function of wavelength is measured twice. First, the fiber is bent in a manner that causes the second-order mode to leak out almost completely. Second, the fiber is arranged so it transmits both first- and second-order modes. These two measurements are compared, giving a curve such as the one in Figure 17.11, which shows

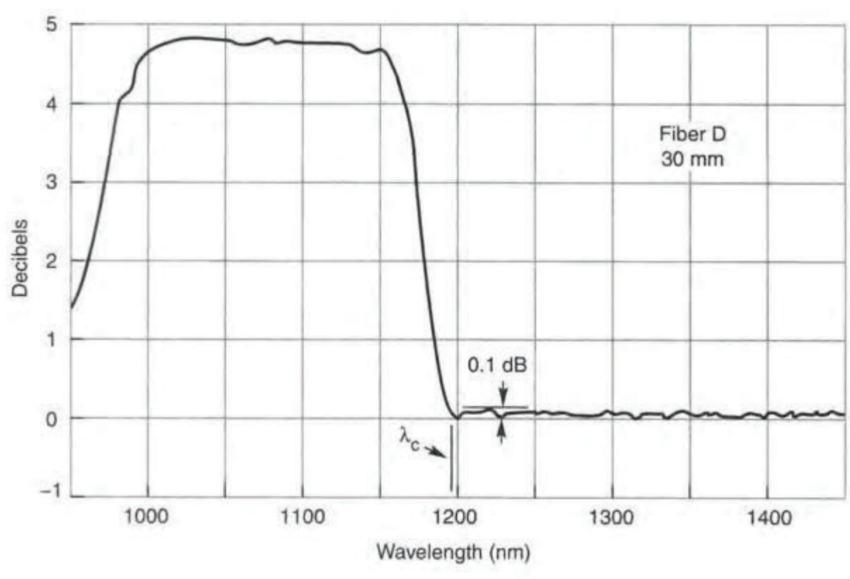


FIGURE 17.11
Measurement of effective cutoff wavelength. (Courtesy of Douglas Franzen, National Institute of Standards and Technology)

excess loss as a function of wavelength. In this case, λ_c is the effective cut-off wavelength, which is defined as the wavelength above which second-order mode power is at least a certain amount below the power in the fundamental mode. The measurement finds this value by locating the point where excess loss caused by stripping out the second-order mode is no more than 0.1 dB.

What Have You Learned?

1. Each photon has a characteristic energy, defined as Planck's constant (h) times the frequency (v). Photon energy also equals hc/λ, where c is the speed of light and λ is the wavelength.
2. Optical power measures the transfer of light energy, and is defined as the change in energy with time. Power is proportional to the number of photons passing a given point per unit time.
3. Optical power is proportional to the square of the light wave amplitude.
4. Optical power can be measured in decibels relative to a power level. The units dBm are powers relative to 1 mW; dBμ measures power relative to 1 μmW.
5. Peak power is the highest level in an optical pulse; average power is the average over a longer interval, typically a second or more.
6. Pulse energy can limit communications because detectors must receive a minimum amount of energy to recognize a pulse.
7. Fiber-optic power meters are calibrated for wavelengths used in fiber systems; they measure average power.
8. Accurate conversions between wavelength and frequency are critical in DWDM systems, where the channels are based on *frequencies*, not wavelengths. Always use the exact value for the speed of light in a vacuum in conversions, 2.997925×10^8 m/s, and remember that wavelengths conventionally used are those in a vacuum, not in air or glass.
9. Wavelengths can be measured absolutely, or relative to another wavelength.
10. Phase measures a light wave's progress in its 360° oscillation cycle. It is measured relative to the phase of other light waves.
11. Polarization measures the alignment of electric fields in light waves. Polarization-dependent loss can affect system performance.
12. Bandwidth measures the highest analog frequency a system can transmit. The speed of digital systems is measured by the maximum data rate that can be transmitted.
13. Signal-to-noise ratio measures analog transmission quality. Bit error rate measures the quality of digital transmission.
14. An eye pattern superimposes waveforms of successive bits to assess signal quality. The more "open" the eye, the more similar the successive pulses are, and the better the transmission quality.

15. Measurement standards assure that results are compatible. Calibration verifies measurement accuracy.
16. Precise procedures are needed to measure fiber or cable attenuation accurately.

What's Next?

Chapter 18 covers test equipment and troubleshooting techniques.

Further Reading

Dennis Derickson, ed., *Fiber Optic Test and Measurement* (Prentice Hall PTR, Upper Saddle River, NJ, 1998)

Edward F. Zalewski, "Radiometry and Photometry," section 24 in Michael Bass, ed., *Handbook of Optics,* 2nd ed., Vol. 2 (McGraw-Hill, New York, 1995)

Catalogs of test equipment manufacturers typically include tutorials on fiber-optic test and measurement. Two good ones are:

Agilent Technologies, *Lightwave Test and Measurement Catalog* (see *www.agilent.com*)

Exfo Electro-Optical Engineering, *Lightwave Test & Measurement Reference Guide* (see *www.exfo.com*)

Questions to Think About

1. A 1-Gbit/s signal has an average power of 1 μW at the receiver. What is the average energy in each pulse?
2. A 10-Gbit/s signal has an average power of 1 μW at the receiver. What is the average energy in each pulse?
3. The wavelength being transmitted in Questions 1 and 2 is 1550 nm. How many photons does each pulse contain?
4. Suppose these systems were operating at a wavelength of 850 nm. How many photons would be in each pulse at average power of 1 μW and data rates of 1 and 10 Gbit/s? Assuming that noise levels are constant relative to photons per bit, how would that affect signal-to-noise ratios?
5. The air pressure at the Keck Telescope on the top of Mauna Kea in Hawaii, 4.2 km above sea level, is about 60% of that at sea level. The refractive index of air is 1.000273 at standard temperature and pressure. Assume that the refractive index of air is proportional to density. What are the wavelengths of light with a frequency of 193.1 THz in a vacuum, in air at sea level (standard temperature and pressure), and at the top of Mauna Kea? Be sure to use the exact value of the speed of light, 299,792.5 km/s. How does this compare

with the shift in wavelength between optical channels at 50 GHz spacing at the same frequency?

6. What is a frequency difference of 100 GHz equivalent to at the 850 nm wavelength of gallium arsenide lasers?

Chapter Quiz

1. Optical power is
   a. light intensity per square centimeter.
   b. the flow of light energy past a point.
   c. a unique form of energy.
   d. a constant quantity for each light source.
2. What measures power per unit area?
   a. irradiance
   b. intensity
   c. average power
   d. radiant flux
   e. energy
3. A digitally modulated light source is on 25% of the time and off 75% of the time. Its rise and fall times are instantaneous. If its average power is 0.2 mW, what is the peak power?
   a. 0.2 mW
   b. 0.4 mW
   c. 0.8 mW
   d. 1.0 mW
   e. impossible to calculate with the information given
4. The light source in Problem 3 is left on for 10 s. How much energy does it deliver over that period?
   a. 0.2 mW
   b. 0.2 mJ
   c. 0.8 mJ
   d. 2 mJ
   e. 8 mJ
5. Light input to a 10-km long fiber is 1 mW. Light output at the end of the fiber is 0.5 mW. What is the fiber attenuation in dB/km?
   a. 0.3 dB/km
   b. 0.5 dB/km
   c. 1 dB/km
   d. 3 dB/km
   e. 5 dB/km

6. Optical power is proportional to the

a. square of the optical intensity.

b. square of the optical energy.

c. wavelength times the speed of light.

d. square of the voltage applied to the detector.

e. square of the electric-field amplitude.

7. An old meter with its labels worn off measures the output of a 1550-nm laser transmitter at zero lumens even when you turn it to peak sensitivity. What's wrong?

a. The laser is burned out.

b. The meter is reading in radiometric units, which only measure power at 1300 nm.

c. The meter is calibrated in photometric units, which only measure light visible to the eye.

d. You are using a dead optical energy meter.

e. You are using an electrical power meter.

8. Optical channels are spaced 50 GHz apart in a DWDM system. What wavelength difference does this correspond to at 1550 nm?

a. 0.2 nm

b. 0.4 nm

c. 0.5 nm

d. 0.8 nm

e. 50 nm

9. A continuous 1-mW beam delivers light at 193.1 THz for one second. About how many photons is this equivalent to? Use a value of 6.626×10^{-34} J/Hz for Planck's constant h.

a. 10^9 photons

b. 193.1×10^9 photons

c. 7.82×10^{12} photons

d. 193.1×10^{12} photons

e. 7.82×10^{15} photons

10. Pulse duration is

a. the interval between the time the rising pulse reaches half its maximum height to the time the falling pulse drops below that height.

b. the interval between successive peaks of the pulse.

c. the time it takes the pulse to rise from 10% to 90% of its maximum value.

d. half the cycle of a periodic sine wave.

e. the time from the start of one pulse to the start of the next.

11. System bandwidth is measured as the

a. number of bits per second transmitted with no errors.

b. number of bits per second transmitted with a bit error rate of 10^{-12}.

c. maximum frequency transmitted with no decline in power from lower frequencies.

d. frequency at which power has dropped 3 dB from the power at lower frequencies.

e. wavelength at which power has dropped 3 dB from the power at lower wavelengths.

12. What is the standard measure for transmission quality in digital systems?

a. signal-to-noise ratio

b. bit error rate

c. attenuation from transmitter to receiver

d. 3-dB bandwidth

e. pulse interval

13. Jitter measures

a. rise time of a digital pulse.

b. duration of a digital pulse.

c. shaking of your test instruments caused by people walking through your lab.

d. uncertainty in bit error rate.

e. uncertainty in pulse timing.

14. What does an open eye pattern indicate?

a. good-quality transmission because a series of digital pulses are nearly identical

b. good-quality transmission because an analog carrier signal is at peak intensity

c. that a signal of at least one milliwatt is reaching the instrument

d. that the fiber is broken so it cannot transmit noise

e. that you have managed to stay awake through the whole chapter

15. What do you need to measure accurately the loss of a length of cable with connectors on each end?

a. an optical power meter

b. a light source and an optical power meter

c. a light source, an optical power meter, and a launch cable

d. a light source, an optical power meter, a launch cable, and a receive cable

e. a light source, an optical power meter, a launch cable, a receive cable, and a bit error rate test set

CHAPTER

18

Troubleshooting and Test Equipment

About This Chapter

Fiber-optic troubleshooting usually involves checking for damaged or incorrectly installed equipment, or for components that have failed or malfunctioned in some way. Sometimes the problems are simple, but usually they require specialized test equipment to analyze and identify the problem.

This chapter opens by summarizing common problems likely to be encountered in fiber-optic systems. Then it describes important test equipment and its operation, drawing on measurement concepts you learned in Chapter 17. Finally it reviews some simple procedures to track down problems. The techniques covered are specific to fiber optics, not general to communications. That means you will learn ways to spot a broken cable, but not how to diagnose the hardware or software in an electronic switching system.

This chapter is an introduction to basic concepts and the most important equipment, not a step-by-step description of everything you will need to know on the job. That's a book or a course in itself. Think of it as a quick introduction to fiber-optic first aid. It won't teach you how to perform delicate surgery on the network, but it will help you respond intelligently if the system goes down.

Fiber-Optic Troubleshooting

The goal of troubleshooting is to diagnose and correct problems. This chapter, like the rest of this book, focuses on fiber-optic equipment, but that still leaves a wide range of potential problems. Fiber-optic systems generally are reliable, but they are not perfect. As Murphy said, "If anything can go wrong, it will."

Not all failures have obvious causes like cable breaks.

Our first thought when something fails is usually of a dramatic problem. When your telephone service goes out, you suspect a wire has snapped somewhere. Likewise, it's logical to suspect that a broken cable is behind the sudden failure of a fiber transmission line. Often it is, with culprits ranging from careless backhoe operators to gophers. But cable breaks are not always obvious; construction workers may not notice if their equipment doesn't expose broken cable ends, and gophers don't drag the gnawed cables out to show you. You may need special equipment to spot the damaged cable. In fact, it's much more efficient to use test equipment to spot damaged cable from a convenient point than to drive along a cable route looking for a suspicious construction site.

In practice, many other things can cause complete failures. Fibers may be bent too tightly at junction boxes and snap in response to a small strain. Strain, crushing, or contamination may have damaged the fibers inside a cable without visible impact on the outside of the cable itself. Dirt may have gotten into a connector and blocked light transmission. A laser may have failed in the transmitter, or a component may have failed in the receiver power supply. WDM components may have gradually drifted out of tolerance until signals no longer fall at their assigned wavelengths.

Many failures occur when something changes, so a good starting point is to ask if users changed the system in any way just before it failed.

Some failures are complete; others merely degrade transmission.

All problems are not complete failures. Noise on your phone line can make it impossible to use a dial-up modem, transmit faxes, or carry on a conversation, but you may still get a dial tone. Likewise, a defective connector or an electronic malfunction in the transmitter or receiver might make a fiber line noisy, or attenuate the signal and increase the bit error rate (or, in analog systems, decrease the signal-to-noise ratio).

Fiber-optic troubleshooting also involves installing new services or changing existing ones. Typically new services are added to cables that already carry some traffic, either on other fibers in the same cable sheath, or on other wavelengths in the same fiber. You can't assume the fibers are ready to handle the intended traffic. You may need to measure fiber attenuation, chromatic dispersion, and other properties in order to verify that they can transmit signals at the required data rate over the intended distance. You may need to adjust transmitter power or add (or remove) attenuators to deliver the proper power level to the receiver.

You also may need to verify that the fibers go to the proper destination. One common cause of installation failures is that the fibers don't make the proper connections. Someone may have plugged a connector into the wrong socket, and the fiber may go to a dead line.

In short, troubleshooting is a complex task, and the more complex the system, the more complex it is to troubleshoot. Although manual inspection can spot some problems, test equipment generally can help you diagnose and locate problems faster and more accurately. Thus you will spend most of this chapter learning about test equipment and how it can help you. First, however, you should consider what types of measurements you need for what jobs.

Testing, installation, and troubleshooting are distinct but related tasks.

Testing, Installation, and Troubleshooting

We can divide measurement and troubleshooting tasks into three broad classes, which sometimes overlap.

- *Testing* evaluates equipment in the laboratory, factory, or field. Research engineers test new systems they have assembled on the laboratory bench to see how well they operate. Quality control technicians test new equipment before shipping it to customers. Field engineers test equipment in the field to check that it meets specifications, both after installation and during routine maintenance.
- *Installation* requires testing to verify that equipment works as intended. This may be done both before and after actual installation. If you're installing cable in a difficult site, you spend a few minutes checking that it arrived with all the fibers intact before spending a week laying it. Before adding a transmitter at a new wavelength to a WDM system, you may verify that the system will transmit that wavelength properly. In some cases, you may need to trace the route of a fiber through a system, as you would do in installing an extra home phone line.
- *Troubleshooting* occurs after problems happen with a fiber-optic system, when you try to find the source of the problem and then repair it. Unlike testing and installation, you know there is a problem, but you have to find it. Troubleshooting can require checking many points of possible failure.

The overlaps are many. Installation becomes troubleshooting when you try to turn on the system and it doesn't work. The problem may be a fiber connector plugged into the wrong socket, or it may arise from the interaction of two or more components that are slightly out of specification.

Typically, similar test equipment is used in testing, installation, and troubleshooting. You are likely to use different versions of an instrument on a factory floor and in an all-wheel drive van loaded with troubleshooting equipment for field work, but the measurement principles are the same.

Measurement and Signal Transmission

One important practical consideration in all measurements is whether or not they interrupt communication signals.

Some measurements can be made without interrupting traffic.

Interrupting traffic is not a major concern if the system is not operating because it is being installed or has failed. Interruptions *are* an issue if a system is partly operational, such as when new wavelengths are being added to a WDM system. In that case, you need to be certain that tests on one wavelength channel do not disrupt the operation of others. Avoiding interruption is particularly important for preventative maintenance and testing, when your goal is to verify correct system operation.

One way to avoid interruptions is to make measurements with a wavelength not used in the fiber system. Fiber transmission can be tested with a signal at 1625 nm, which is outside the operating range of normal fiber systems. This is called *out-of-band testing*, and can spot problems such as damaged fibers or bad connectors without disrupting service. However, it obviously can't verify operation of transmitters at other wavelengths. Another approach is to include taps along the system, which divert a small fraction of light to test equipment or an optical performance monitor, as shown in Figure 18.1.

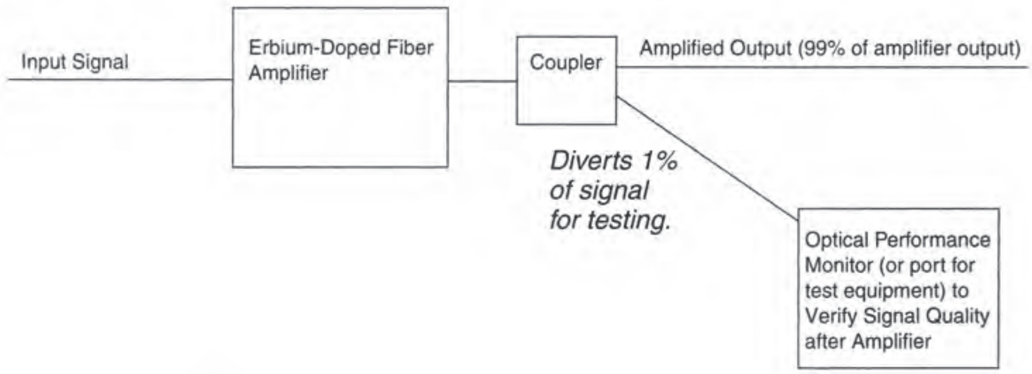


FIGURE 18.1 *Splitting off a small fraction of light for measurement or optical performance monitoring.*

Test and Measurement Instruments

Catalogs from major equipment makers list many types of equipment designed for fiber-optic test and measurement. Trying to cover them all would take a book in itself, so I will focus on the equipment you are most likely to encounter, particularly in general field service, installation and operation. Other equipment is used in manufacturing or in research and development, but much of it is specialized for such tasks as evaluating performance of erbium-doped fiber amplifiers.

Power, attenuation, wavelength, and signal quality are key measurements for troubleshooting.

The basic measurements are those you learned in the last chapter, including power, energy, attenuation, wavelength, and signal quality. We will concentrate on a few major areas (some of which may be measured together, such as optical power and wavelength in an optical spectrum analyzer):

- Fiber continuity and attenuation (usually measured by comparing power levels)
- Optical power
- Wavelength
- Signal quality
- Polarization

Different instruments measure these quantities differently, and may be used for different applications. During an installation, you may need to check continuity between transmitter and receiver; other times you may want to know attenuation of the fiber between them.

Optical Power Meters

Optical power meters are calibrated for specific wavelengths.

Optical power meters are among the simplest optical measurement instruments. Their basic functional elements include a fiber connector, a calibrated detector or detectors, electronics that amplify the signal, controls that set the range and measurement, and a digital display. The display usually is autoranging, and shows measurements on watt or dBm scales selected by the user. The most widely used designs are compact handheld devices like the

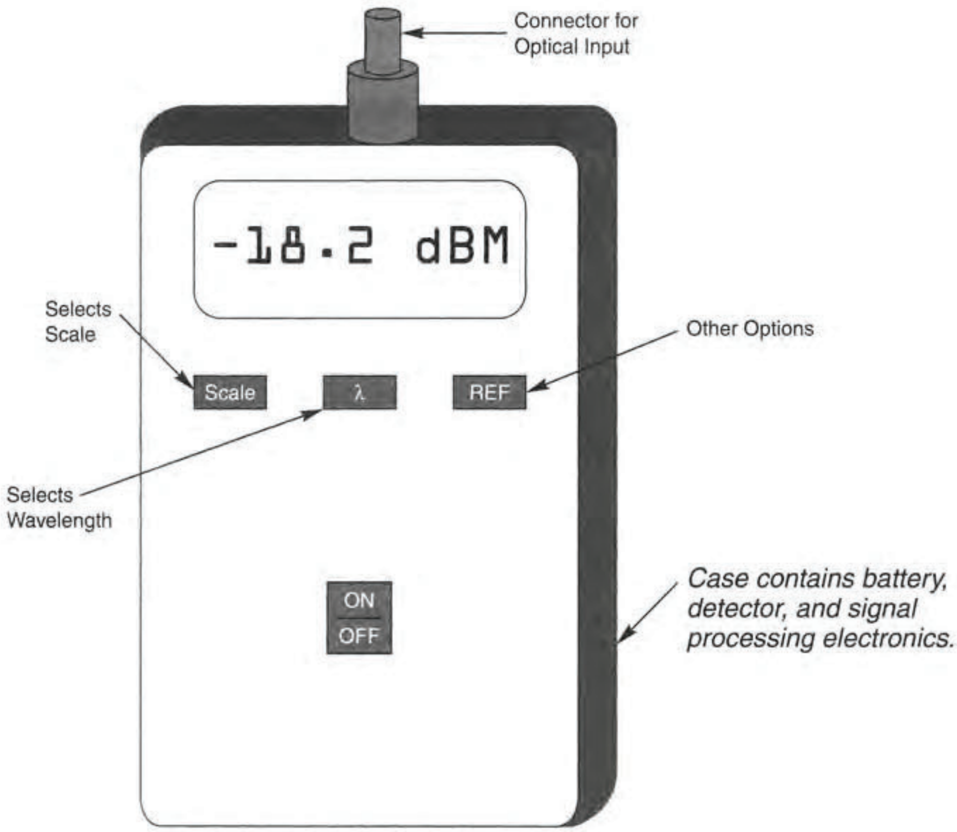


FIGURE 18.2
Handheld optical power meter.

one shown in Figure 18.2, and they are invaluable tools for many measurements. Most instruments can store measurements and have computer interfaces.

Power meters typically use germanium or InGaAs detectors, which are calibrated for selected wavelengths in the standard fiber windows. A bare-bones model may be calibrated for only 850, 1300, and 1550 nm, but more sophisticated models are calibrated at many wavelengths through the range, including 780, 820, 840, 850, 860, 910, 980, 1060, 1200, 1280, 1290, 1300, 1310, 1320, 1330, 1530, 1540, 1550, 1560, and 1600 nm. Special versions are made for high-power measurements of pump laser wavelengths near 980 and 1480 nm. Some switch between long- and short-wavelength detectors, and may be calibrated for the 660-nm plastic fiber window. Because detector response varies with wavelength, care must be taken to match the instrument's range to the wavelength being measured.

Light Sources for Testing

To measure attenuation and other characteristics of fiber systems, you need a light source as well as an optical power meter. A variety of fiber-optic test sources are available, designed for different applications, and you must match the source to the measurement task. In simple light sources the wavelength is fixed, but in more sophisticated (and expensive) instruments the output wavelength is tunable with various degrees of precision.

Test sources supply light at fiber system wavelengths.

Test sources deliver a continuous, calibrated power level for measurements of power and loss. They also may have a separate output mode that modulates signals at an audio frequency to aid in identifying the fiber under test. Some have two outputs. Important types include:

Broadband light sources include tungsten lamps, fiber amplifiers, and edge-emitting LEDs.

- *Broadband sources* normally emit a broad range of near-infrared wavelengths; a familiar example is a tungsten lamp. Typically the entire range of wavelengths is passed through whatever is being measured, with output power measured by a wavelength-selective instrument (an *optical spectrum analyzer*, described later in the chapter). Although the total amount of light is high, the amount of light per unit wavelength is relatively low. Table 18.1 summarizes the key features of the most important types, tungsten lamps, edge-emitting LEDs, and fiber amplifiers operating with no input signal so they generate only amplified spontaneous emission. They generally are not used in the field.
- *Monochromators* are laboratory sources long used in nonfiber measurements. They differ from other types in that their broadband emission is tuned internally by selecting a narrow range of wavelengths with a prism or diffraction grating. Only that narrow range is used for measurements.
- *LED sources* are also used in small portable field instruments. Typically these have center wavelengths of 850, 1300, or 1550 nm and spectral bandwidths of 50 to 100 nm for testing the major glass-fiber windows. They launch microwatts to tens of microwatts into a fiber.
- *Fixed diode laser sources* may emit on one band in a fiber window, or may include many separate lasers to simulate signal transmission in a WDM system. Sources that emit on one wavelength in the 850, 1300, or 1550 nm band typically have linewidth

Table 18.1 Broadband sources and their characteristics

	Tungsten Lamp	Edge-Emitting LED	Amplified Spontaneous Emission from Erbium-Fiber Amplifier
Wavelength range (nm)	Broadband across infrared	Depends on composition	1500–1600 nm
Spectral width	Whole near-infrared	50–100 nm per LED, multiple LEDs can be used	Peak amplitude 30–40 nm
Total power into single-mode fiber	1 μW	100 μW	1 to 10 mW
Peak power per nm into single-mode fiber	−63 dBm/nm	−25 dBm/nm	−10 dBm/nm

of a few nanometers and deliver more than 100 mW into a fiber. Like LED-based light sources, they normally are used in portable field devices. WDM laser sources include one laser per optical channel, spaced the same as in a transmission system, and are specifically designed for testing WDM system performance.

- *Tunable laser sources* can tune their output wavelength, as described in Chapter 9. Some are erbium-doped fiber lasers, tunable across the entire C- and L-bands. Others are tunable across narrower ranges, but can be combined to give a wider range. They generate very precise wavelengths for tests of DWDM components and systems.

Typically, test sources emit continuous beams for measurements, but their output can be modulated for special purposes and to identify the signal or the transmitting fiber.

Field test sources normally come with a selection of connectors and adapters to allow their use with a variety of equipment.

Optical Loss Test Sets

An *optical loss test set* combines a light source with an optical power meter calibrated to work with it. The amount of power emitted by the light source is known, so the power meter measurement indicates how much the received signal has been attenuated. Optical loss test sets also can measure attenuation by comparing power levels with and without the component being tested, as you saw for a cable in Figure 17.10. Optical loss test sets are offered as distinct instruments, but you can think of them as a light source packaged with a power meter.

An optical loss test set includes a light source and power meter calibrated to work together.

Optical return loss test sets are different in that they measure light reflected back toward the source rather than transmitted through the system. Reflections are very important because they can cause noise in edge-emitting semiconductor lasers, degrading system operation. Reflection measurements, sometimes called *reflectometry*, can check for potential problems.

Fiber-Optic Talk Sets

Many types of measurements require two technicians working at different locations to test a system running between the two points. Fiber-optic talk sets were developed to allow them to communicate with each other and coordinate their tasks. Similar equipment is used on copper telephone wires. Fiber-optic talk sets include a simple transmitter and receiver that can send and receive voice signals through optical fibers. In a sense, they turn any available fiber into a telephone line. They generally have headsets attached.

Typical talk sets also can generate a 2-kHz signal for fiber identification. Multifunction talk sets also can generate a continuous signal to measure fiber attenuation.

Visual Fault Locators

A visual fault locator is a hand-held troubleshooting instrument that sends red light from a semiconductor laser down a fiber to check for faults such as cracked fibers or defective splices. The visible light travels along the core until it reaches a fault, where it leaks out. Light leaking through the fault can be seen through plastic coatings and jackets under suitable illumination. Infrared light in the signal leaks out at the same point, but your eyes can't see it.

A visual fault locator spots faults by sending red light down a fiber.

Attenuation of glass fibers is much higher at the 630 to 670 nm wavelengths of red light than in the 1300 to 1650 nm transmission window, but the red light can still travel up to 5 km through standard fibers. Note that the fibers must be exposed to use visual fault location effectively. If the red light leaks out inside a thick cable wrapped in black plastic, you can't see it. The technique is particularly valuable in equipment bays and other places inside buildings where fibers are exposed.

Shining a flashlight beam down a multimode fiber can serve the same function, and has long been used to trace fiber continuity as well. However, the flashlight couples little light into a single-mode fiber.

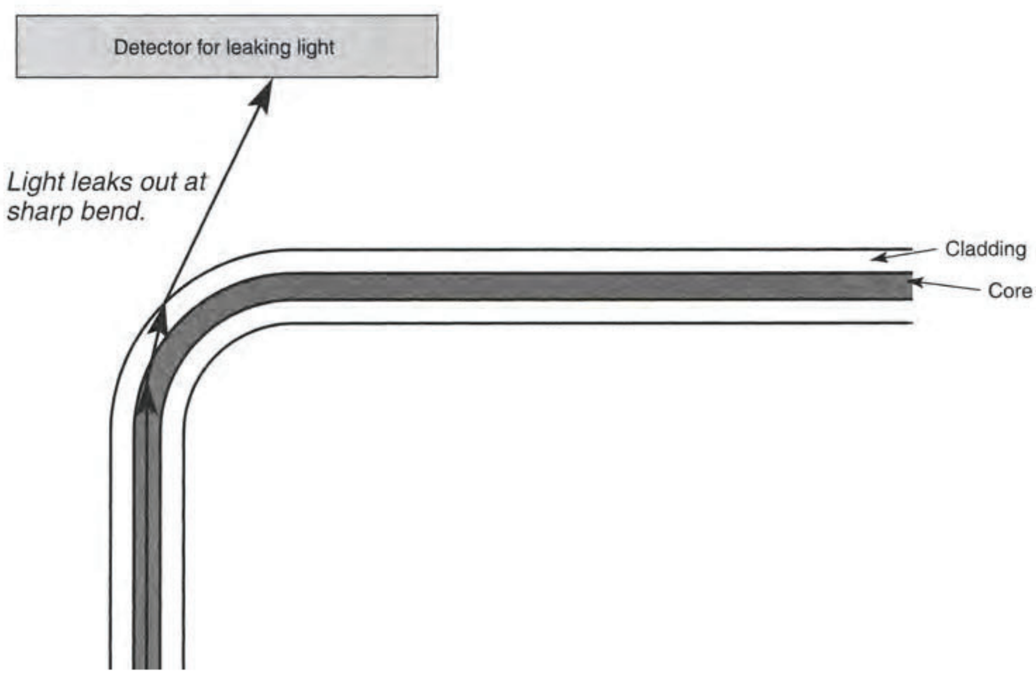
Live Fiber Detectors

A little signal light leaks out when fibers are bent.

The ability to locate fibers carrying live traffic also is important in troubleshooting. This isn't easy because, as you learned earlier, light passing through a fiber does not generate electromagnetic fields or other external signs of its passage. However, traffic can be detected by bending the fiber, as shown in Figure 18.3. The bend causes light in the core to exceed the critical angle for total internal reflection when it hits the core-cladding boundary, so it leaks out.

Detection of live traffic can be invaluable, but the technique requires care. Sensitive detectors are needed because only a small fraction of the signal leaks out. (Recall that you can't see the invisible infrared signal wavelength.) Bending the fiber too tightly can weaken or break it. Thus you use special instruments that can sense the signal wavelengths after they pass through plastic fiber coating and jackets. Sensitivity of the technique depends on the type of fiber.

FIGURE 18.3
Live fiber detector: If light leaks out at a bend, a signal is passing through the fiber.



Optical Time-Domain Reflectometers

The *optical time-domain reflectometer (OTDR)* is a powerful and versatile instrument for fiber-optic measurements. It's essentially an optical radar that shoots a short light pulse down the fiber. Glass atoms scatter a small fraction of the light back toward the instrument because of the Rayleigh scattering that you learned about in Chapter 5. Irregularities such as splices, connectors, and defects in the fiber reflect and scatter additional light.

An OTDR is an optical radar that analyzes fiber properties.

An OTDR plots intensity of the light scattered back to the instrument as a function of time after the pulse is fired down the fiber. This is interpreted as the light intensity along the length of the fiber, as shown in Figure 18.4, with the distance along the fiber calculated from the round-trip time for the light pulse.

To a first approximation, the plot indicates two things: the attenuation of the fiber, and locations of any discontinuities. The attenuation is indicated by the slope of the decline in power along the fiber. The peaks on the plot are reflections from discontinuities, analogous to blips on a radar screen. Sharp drops indicate points where light leaks out of the fiber. Like interpreting radar signals, interpreting OTDR data isn't quite that simple, but let's look at the most important features before we look at the complications.

Figure 18.4 shows a sharp peak at the very left end of the plot, at the start of the fiber. This is a region where an OTDR can't accurately measure the properties of the fiber because the instrument is too close. It's called the *dead zone* and typically is a few meters to 20 meters from the instrument.

OTDRs cannot analyze the near end of the fiber well.

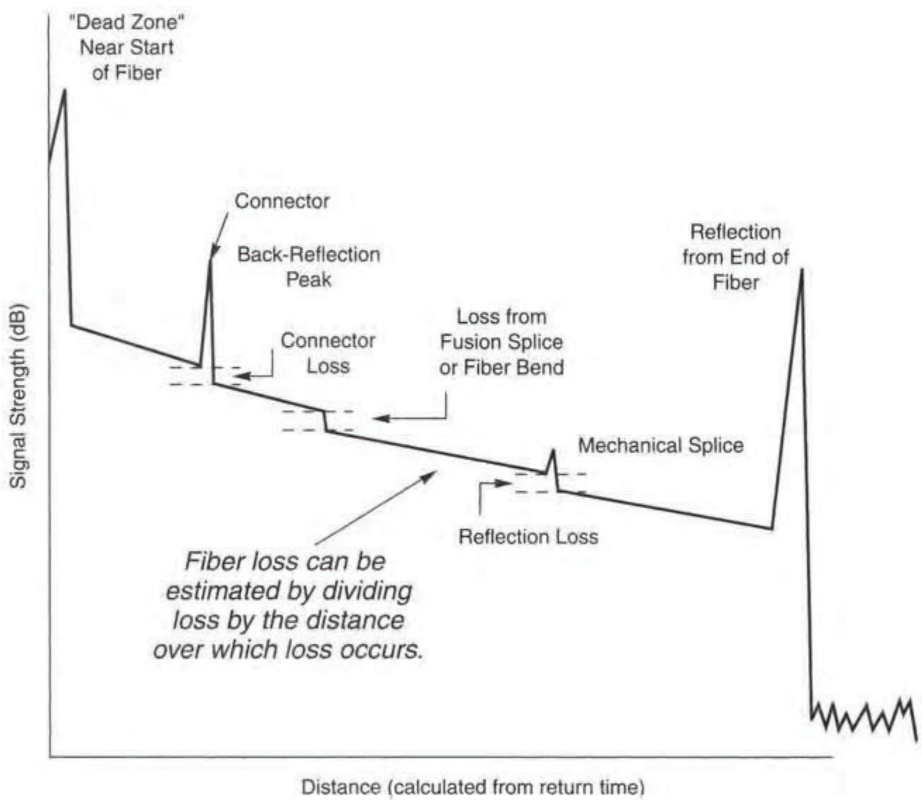


FIGURE 18.4
Features of an OTDR plot.

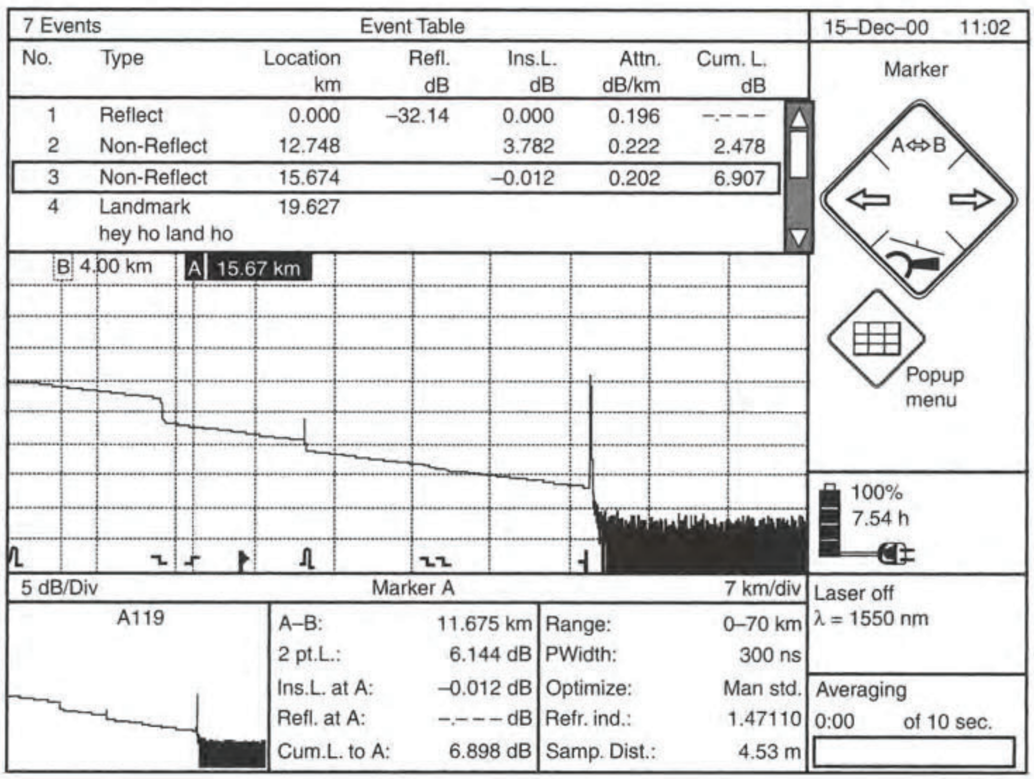
The largest peak in Figure 18.4 is at the end of the fiber, where light is reflected back toward the instrument. If the fiber is broken, that point is the end of the fiber, with peak reflection. The jagged spikes to the right of the end of the fiber are meaningless noise. The next largest peak is reflection from a connector where the fiber ends are not perfectly butted together. Look carefully and you can see that the light intensity just on the right of the connector is below that just to the left; this drop is the connector loss. A mechanical splice also reflects a little light back to the instrument and has a measurable loss, but in this case both loss and reflection are lower in the mechanical splice. A sudden drop in reflected light, without a reflective peak, may come from the loss within a fusion splice (which should have negligible reflection) or from light leaking from the fiber at a bend.

Early OTDRs simply plotted the returned light for a skilled operator to interpret. Modern instruments analyze the raw data and provide their own interpretation, giving values for quantities such as fiber attenuation, length, and the locations of reflections. They also tabulate points where the plot has peaks or dips as "events," as shown in an actual OTDR display in Figure 18.5. The instruments can expand the scale to study selected parts of the cable in detail, and include options for computer output or printouts.

OTDRs can quickly locate damage to a cabled fiber in the field.

These features make the OTDR a very useful instrument in the field, where it can spot faults up to tens of kilometers away. A single technician can locate the point where a fiber is damaged to within a matter of meters by using an OTDR at one end of the cable. That saves a lot of costly labor searching for damage along the length of a cable, and makes the OTDR a standard tool for repair crews working in the field.

FIGURE 18.5
OTDR display includes log of locations checked, potential anomalies, and loss between points on cable. Spike at right is end of the fiber; reflections beyond that point are noise. (Courtesy of Agilent Technologies)



Yet it's vital to remember that OTDR plots are only approximations. Direct measurements of attenuation are more accurate than calculations from OTDR plots. Accuracy depends on the fraction of light scattered, which differs between types of fiber. Junctions of fibers with different mode-field diameters can cause peculiar effects, such as "gainers," splices where the power appears to be higher on the far side of the fiber than on the near side. This effect occurs when the more distant fiber scatters more light than the near one. Gain is measured in only one direction; the light experiences a loss in the other direction. To get more accurate values, you should take the average of splice loss in both directions. These limitations can be significant in assessing splice quality, but are rarely critical in tasks like locating cable breaks.

Oscilloscopes, Analyzers, and Eye Patterns

As you learned in Chapter 17, eye-pattern analysis is based on superimposing a series of received signal pulses on top of each other to show how precisely they replicate each other and verify a clear distinction between on and off states. Originally that was done by aligning pulses on an oscilloscope, and this can still be done where necessary.

Oscilloscopes and analyzers perform eye-pattern analysis.

Modern oscilloscopes or "communications analyzers" are programmed to perform functions automatically, such as eye-pattern analysis. Optional plug-in modules can provide other functions. Normally oscilloscopes are test instruments used in the laboratory or factory, but they also can be used at terminal points and switching centers to diagnose system performance when needed.

Special Test Sets

Some fiber parameters such as chromatic dispersion and polarization-mode dispersion require complex measurements. They are best performed by test sets designed to measure the raw parameters and process the data internally, yielding the desired measurement results. Typically test sets are used in the lab, factory, or switching center.

Chromatic dispersion testers are large and complex systems that make measurements and calculate results.

Polarization-mode dispersion and *polarization-dependent loss* require measurements with a *polarization analyzer*, that separates light into its two polarized components and measures their transmission through fibers and other components. Polarization characteristics can be important for high-performance fiber systems, so some polarization analysis systems have been developed for field use.

Bit error rate testers transmit a random bit sequence and compare it to the received signal, measuring the number of bits incorrectly received.

Optical Spectrum Analyzers

An *optical spectrum analyzer* records optical power as a function of wavelength by scanning the spectrum. It can plot power levels on all WDM channels for performance assessments.

Optical spectrum analyzers measure power as a function of wavelength.

Figure 18.6 shows the basic idea of an optical spectrum analyzer. Input optics collect light, generally from an optical fiber, and focus it onto a diffraction grating. As

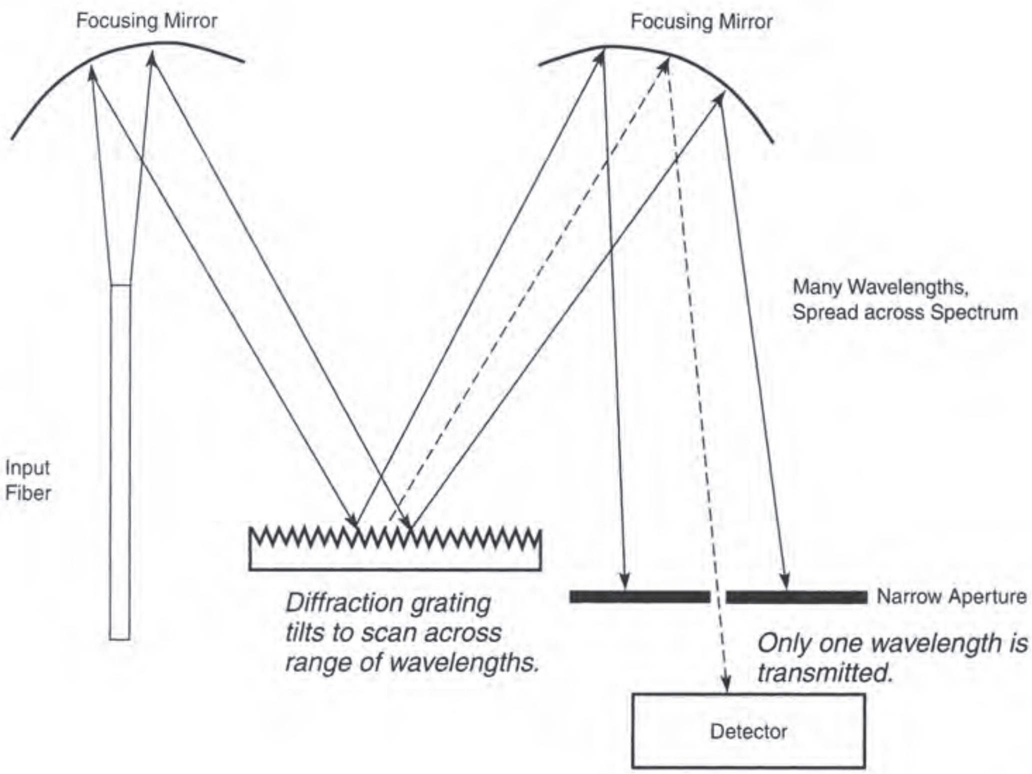


FIGURE 18.6
Optical spectrum analyzer.

you learned earlier, a diffraction grating spreads out a *spectrum* of wavelengths. This spectrum is then focused onto a flat surface, where a narrow aperture or slit transmits a narrow band of wavelengths to a detector. The detector measures the power at that wavelength.

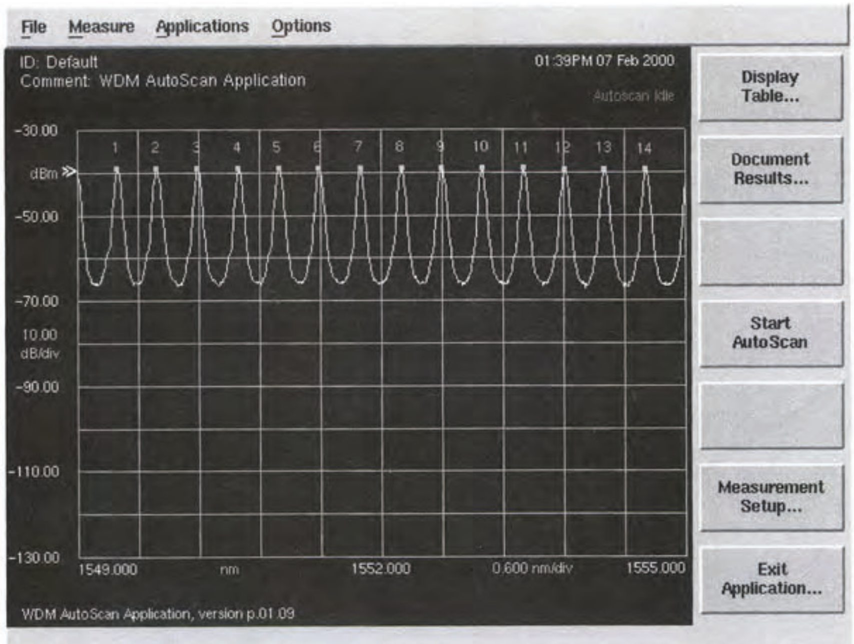
In this design, tilting the diffraction grating moves the spectrum, so a different wavelength passes through the slit. Tilting the grating slowly and continuously scans the entire spectrum across the slit. With proper calibration, the power measured at a certain time is correlated with the wavelength passing through the slit at that instant. This makes it possible to plot power against wavelength, and assess the power levels on different optical channels in a WDM system, as shown in Figure 18.7.

Other designs are possible. The slit and detector can move instead of the grating, scanning across the plane where the spectrum is spread out. Alternatively, the spectrum can be spread across an array of detectors, with each one detecting a separate wavelength, an approach used in optical performance monitors, described below.

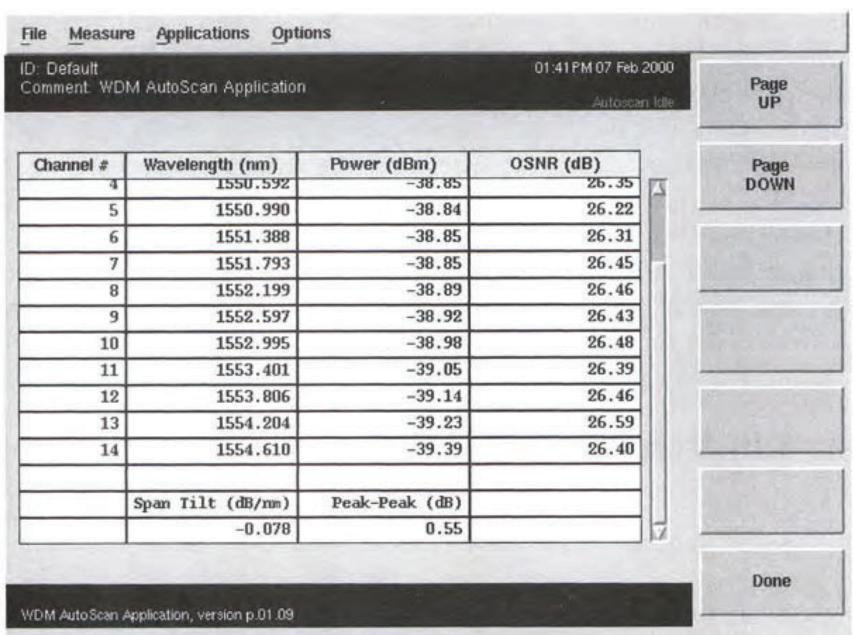
Optical spectrum analyzers average power over long intervals.

Note that optical spectrum analyzers measure power over long intervals of time relative to bits, so they show average power on each optical channel.

Optical spectrum analyzers began as high-performance laboratory instruments. As wavelength-division multiplexing spread through the telecommunication network, optical spectrum analyzers were adapted for use in the field and in switching centers. They are important instruments in verifying the proper function of WDM systems and in troubleshooting if problems should arise.



a



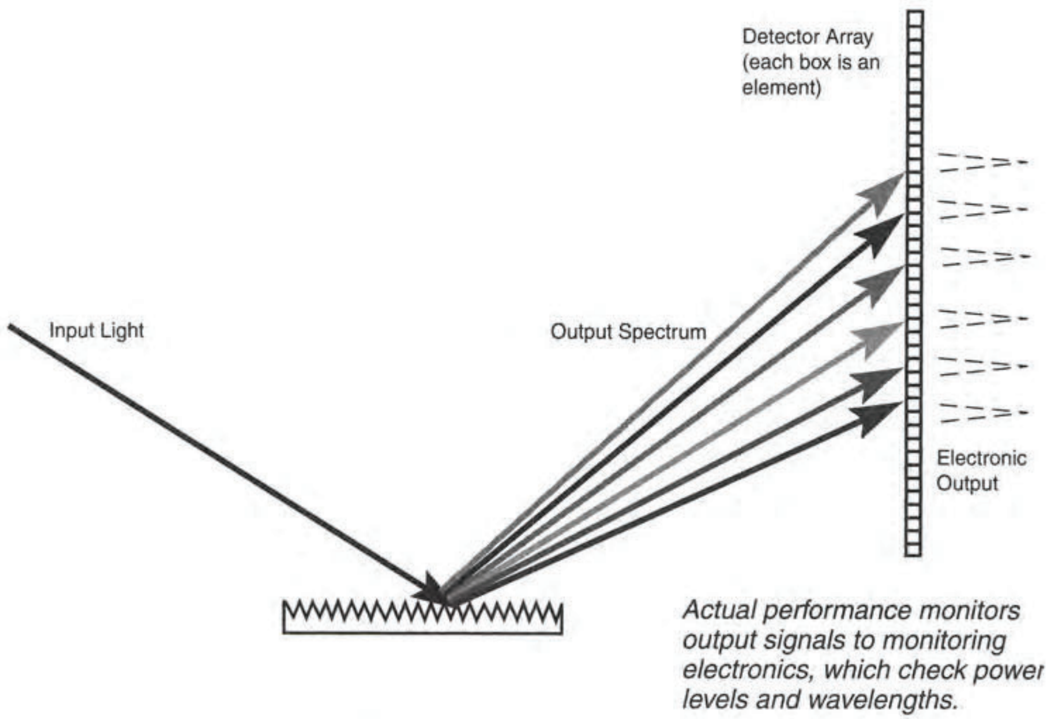
Channel #	Wavelength (nm)	Power (dBm)	OSNR (dB)
4	1550.592	-38.85	26.35
5	1550.990	-38.84	26.22
6	1551.388	-38.85	26.31
7	1551.793	-38.85	26.45
8	1552.199	-38.89	26.46
9	1552.597	-38.92	26.43
10	1552.995	-38.98	26.48
11	1553.401	-39.05	26.39
12	1553.806	-39.14	26.46
13	1554.204	-39.23	26.59
14	1554.610	-39.39	26.40
	Span Tilt (dB/nm)	Peak-Peak (dB)	
	-0.078	0.55	

b

FIGURE 18.7

Optical spectrum analyzer measures wavelength, power, and signal-to-noise ratio of channels in a WDM system. A graphic plot (above) displays the channels; a numerical display (below) gives measurements. (Courtesy of Agilent Technologies)

FIGURE 18.8
Optical performance monitor.



Optical Performance Monitors

Optical performance monitors are simple versions of spectrum analyzers.

An *optical performance monitor* is a simple version of an optical spectrum analyzer that can be installed at critical locations in a WDM system. One common version of an optical performance monitor, shown in Figure 18.8, spreads a spectrum across a linear array of photodetectors, so each element measures the power on a particular optical channel. The detector array output goes to monitoring systems that verify the signals are at the proper wavelengths and at the proper intensity. Alternatively, a tunable filter can scan the spectrum, which is measured by a single detector. The variation of the detector array output during the scan measures the power delivered at each wavelength. The detectors don't monitor the bits transmitted, only the signal power and wavelength.

Optical performance monitoring was much discussed during the build-out of long-haul WDM systems, but has not been widely implemented. Although optical performance monitors measure the same quantities as some measurement instruments, they are part of network equipment, not separate instruments.

Wavelength Meters

Accurate wavelength measurements are essential for building and operating WDM systems. Optical spectrum analyzers give approximate values, but wavelength meters can give more precise values.

A wavelength meter is based on the Michelson interferometer.

Wavelength meters are built around a device called the *Michelson interferometer.* It consists of a beamsplitter and a pair of mirrors, as shown in Figure 18.9. The beamsplitter divides input light into equal portions, with one-half transmitted through the beamsplitter and the other half reflected to the other *arm* of the interferometer at the bottom.

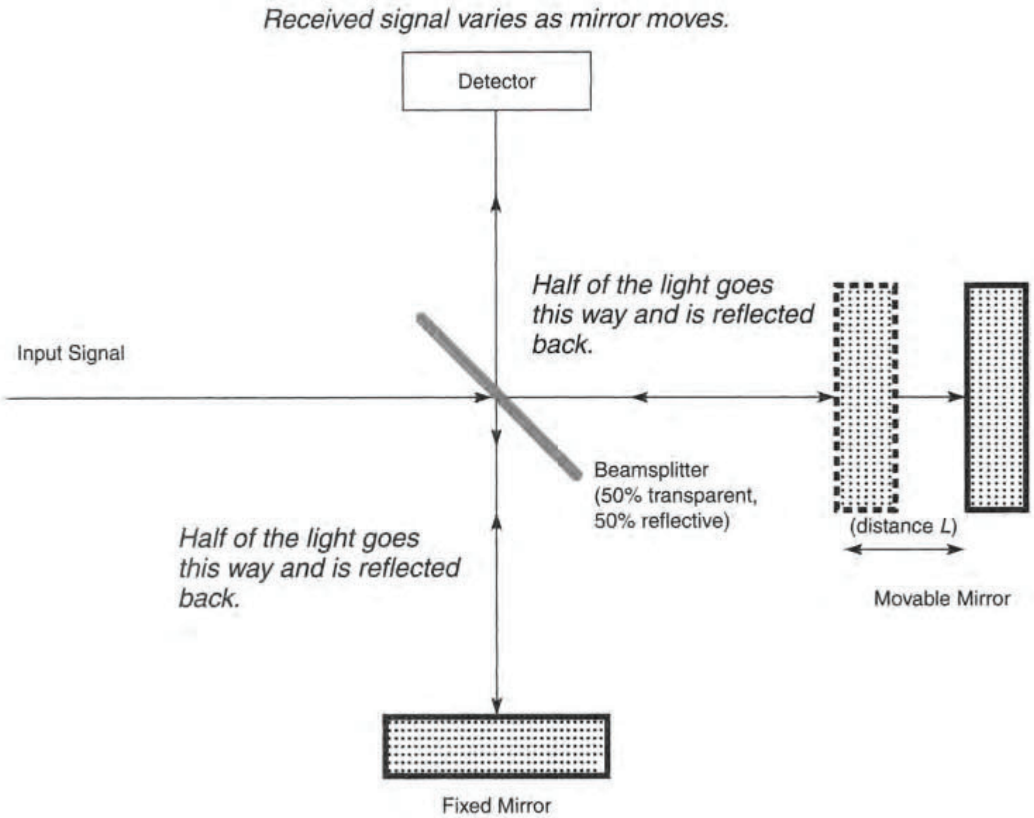


FIGURE 18.9
Wavelength meter counts interference fringes as mirror moves over a known distance.

In Figure 18.9, the bottom arm is a fixed length; a mirror at the end reflects light back toward the beamsplitter. Half the reflected light passes through the beamsplitter to the detector at top; the other half is reflected back toward the light source. The mirror at the end of the horizontal arm is moved back and forth, so its length varies. That mirror also reflects light back toward the beamsplitter, with half the light passing through and the other half reflected toward the detector.

The amplitudes of the beams reaching the detector from each arm are identical. Because the light came from the same source, the waves from the two arms are nominally identical, so they can interfere constructively or destructively. Suppose you initially adjust the moving mirror so the light amplitudes cancel out at the detector. Then you move the mirror a known distance, counting each time the light reaching the detector goes through a light-dark-light cycle. If you know the distance L precisely and find that the light goes through N cycles as the mirror moves that distance, you can calculate wavelength from the equation

$$\lambda = \frac{2L}{N}$$

(The factor of 2 comes from the fact that the light makes a round trip through the arm, so the light travels twice the distance of the arm.)

Precise measurements of wavelength require accounting for the refractive index of dry air, 1.000273 at 1550 nm. Extremely precise measurements require considering air pressure, temperature, and humidity as well, which change the refractive index of air slightly.

Wavelength meters give digital measurements of both wavelength and power at that wavelength for use in the factory or at operating sites. They can be calibrated by measuring known wavelengths.

Troubleshooting Procedures

Fiber-optic systems are far too diverse to give a single, all-purpose guide to troubleshooting. Because this book concentrates on principles of the technology, this section covers basic concepts rather than details. Specific procedures depend on the nature of the system, and often require looking at the electronic parts of the network to isolate the problems.

Troubleshooting systematically analyzes problems.

Troubleshooting is a systematic way of performing tests to isolate problems. You may perform it in different ways depending on the tools you have at hand and your starting location. If you are testing a faulty point-to-point transmission line, your first task is to isolate whether the fault is in the transmitter, the cable, the receiver, or an attached connector. Figure 18.10 gives two alternative approaches for a single technician, starting at either the transmitter or receiver end. The basic idea is to test what you have easy access to first, before traveling to a remote site. A pair of technicians working at each end and able to communicate with each other would follow a different procedure.

The OTDR's ability to spot problems remotely makes it invaluable for troubleshooting point-to-point systems from a single location, although the distance measurements may not be exact. Cables usually include "storage loops"—extra lengths of cable that allow room

FIGURE 18.10 *Troubleshooting procedures for point-to-point link.*

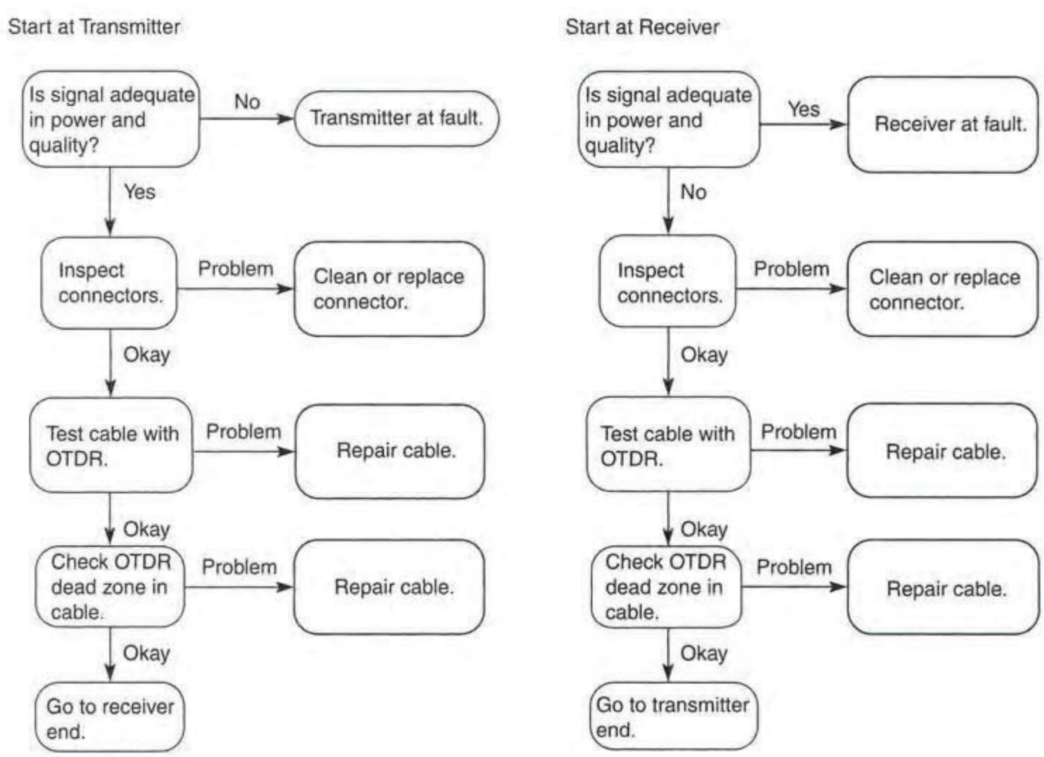


Table 18.2 Typical problems in point-to-point fiber systems

Problem	Origin	Diagnostic Equipment	Repair
Excess connector loss	Dirt or damage	Inspection microscope	Clean, reinstall, replace
Excess loss localized in fiber or cable	Excess bending	Visual fault locator or OTDR	Straighten fiber or cable
Excess splice loss	Aging, stress, or contamination	OTDR or visual fault locator	Reinstall
Fiber break	Physical damage to cable	OTDR, visual fault locator	Splice or replace cable

to replace damaged cable. Nonetheless, if you can pinpoint a break in a 100-km cable to the nearest 20 m, you have an excellent head start in finding the damage.

Other equipment also assists in diagnosing faults in cable systems. Table 18.2 lists some typical cable problems, their causes, and ways to identify and fix them.

Office local-area networks offer other types of problems in equipment such as patch panels and entry boxes. Cables in office buildings also face different menaces than outdoor cables. People can snap fibers by tripping over loose cables or tugging on equipment attached to the cable. Breaks are most likely near connectors. Cables hidden in walls or suspended ceilings can be cut accidentally. The more equipment connected, the more things can go wrong.

The majority of cable runs in local-area networks generally are too short for OTDRs to be useful, but LANs usually cover small areas, making on-site service easier. Table 18.3 lists a number of steps you can take to check system function. They are divided into tests that don't disrupt system operation and those that interrupt service.

Failure versus System Degradation

One useful way of sorting problems is to determine whether they result in permanent and total system failure or merely degrade system operation. (Degradation includes those maddening intermittent problems that often go away temporarily when you try to diagnose them.) Always check for any changes in system or terminal configuration. If the network worked fine until you moved your workstation to clean the desk, check for damage to the attached cable or dirt in the connector. If a user just installed new communications software, testing the receiver and fiber output may show it's not a hardware problem at all.

Failures may be total or merely degrade system operation.

Typically—but not always—total failures mean some key component has failed or power is down to an essential part of the system. Any obvious changes in the environment are the leading suspects. If a construction crew is digging a hole in the street where your cable runs and that part of the system goes down, they're your number one suspect. Likewise, check for recent changes in junction boxes; somebody may have replaced a cable incorrectly and plugged the connector into the wrong adapter.

Table 18.3 Local-area network troubleshooting

Equipment to Check	Tasks
Does not interrupt network operation	
Patch cords and panels	Trace cabling to verify proper connections are made; correct if needed.
Patch cables and fibers	Check bend radius; correct if too small.
Transmission cables	Inspect for damage or tight bends. Check for signs of recent construction near cable.
Powered equipment	Check power is on and monitors show normal operation. Verify configuration.
Cable connections	Verify connections are secure.
Outdoor plant	Inspect for signs of damage or evidence of recent construction or other disruption.
May interrupt network operation	
Cable connections	Wiggle connectors to hunt for intermittent connections.
Interrupts network operation	
Patch cables and cable connections	Disconnect, test cables, and inspect and clean connectors at all termination points.
Transmission cables	Measure attenuation and compare to specified values.
Long cables	Test with OTDR and compare to records, looking for changes.
All cables with laser transmitters	Check for back reflection toward transmitter, which could disrupt laser operation.
Transmitters	Measure output power level and compare to records and specifications.
Receivers	Measure power arriving through fiber and compare to records. Verify it equals transmitter output minus cable loss.

Intermittent problems suggest loose connectors or partial damage to connectors. A simple check is to wiggle cables and connectors while monitoring for changes in operation.

Degraded operation, such as reduced data transmission speed, may indicate noise in the system. You can rule out a cable break, but not damage to the fiber or bends that cause large light losses. The transmitter or receiver may be generating excess noise, or producing weak signals. Dirt in a connector may be the problem. System degradation also may be a warning of imminent failure of a component or subsystem. Generally such degraded operation is likely to require test equipment to track down the problem.

WDM Troubleshooting

Other challenges arise in systems transmitting multiple wavelengths through the same fiber. So far we've assumed that each fiber carries only one signal. WDM systems carry multiple signals, which means more potential problems to track down.

WDM troubleshooting requires special techniques and instruments.

A total failure of a WDM system—where all channels are out and no light comes through the system—can be treated much like total failure of a single-channel system. No individual laser failure would knock out an entire WDM link, but a power failure could. Cable breaks also could disable an entire WDM system. An obvious first test is to see if power is reaching the receiver end.

Table 18.4 lists some potential failure modes and what parameters to check first as the most likely causes. Optical spectrum analyzers can check the power level on each optical channel. Wavelength meters may be needed for precise measurements of optical wavelengths.

Table 18.4 WDM system failures and likely causes

Type of Failure	Check First
All channels down, no power reaching receiver	Cable break, power failure at transmitter site.
All channels down, power reaching receiver	Optical channels at proper wavelengths using optical spectrum analyzer. Verify power at receiver, performance of demultiplexer. Measure noise levels.
One channel down; all others operating	Failure of transmitter or receiver on that channel. Failure of multiplexer or demultiplexer on that channel. Noise on that channel.
Some channels down, others operating	Drift of some optical channels from assigned wavelengths. Performance of optical amplifiers. Noise on affected channels. Problems in multiplexer or demultiplexer. Look for patterns in failures.
Degradation of one channel only	Degradation of transmitter or receiver on that channel, possibly including wavelength drift. Misalignment of that channel in multiplexer or demultiplexer. Background noise.
Degradation of multiple channels	Problems in multiplexer or demultiplexer. Problems in optical amplifiers. Broad background noise (e.g., amplified spontaneous emission).
Degradation of all channels	Entire multiplexer or demultiplexer. Problems in optical amplifier. Damage to cable or connectors causing noise.

What Have You Learned?

1. The goal of troubleshooting is to diagnose and correct problems.
2. Some failures are complete; others merely degrade transmission. Not all failures have obvious causes.
3. Testing evaluates equipment in the laboratory, field, or factory. Installation requires testing to verify equipment works as intended. Troubleshooting responds to problems.
4. Some instruments directly measure power, attenuation, wavelength, and signal quality; others interpret raw data to analyze system performance.
5. Optical power meters are calibrated for the standard wavelengths used in fiber-optic systems.
6. Test sources include LEDs, fixed diode lasers, broadband sources, and tunable lasers, which operate at fiber system wavelengths.
7. An optical loss test set includes a light source and power meter calibrated to work together to measure attenuation. Optical return loss test sets measure light reflected back to the source.
8. A visual fault locator spots faults by sending red light down a fiber, so you can look for scattered red light.
9. Bending a fiber allows a little signal light to leak out; detecting this light is a simple test for live fibers.
10. An optical time-domain reflectometer (OTDR) analyzes fiber properties by sending a short light pulse down a fiber and measuring light scattered back to the instrument. It allows a technician at one end of a cable to spot distant flaws.
11. Oscilloscopes and communications analyzers perform eye-pattern analysis.
12. Optical spectrum analyzers spread a multiwavelength signal into a spectrum of light and measure the power at each wavelength. They are valuable for testing WDM systems.
13. A wavelength meter uses a Michelson interferometer to measure the wavelength of light.
14. Preferred troubleshooting techniques depend on the tools you have at hand, your starting location, and the type of system you are analyzing.
15. One way to classify problems is to determine whether they cause permanent and total system failures or merely degrade operation.
16. WDM troubleshooting requires special instruments such as optical spectrum analyzers and wavelength meters.
17. Some tests can be performed without disrupting system operation; others interrupt service.

What's Next?

In Chapter 19, we will turn to the basic concepts behind fiber-optic communication systems and optical networking.

Further Reading

Bob Chomycz, *Fiber Optic Installer's Field Manual* (McGraw-Hill, 2000)

Dennis Derickson, ed., *Fiber Optic Test and Measurement* (Prentice Hall, 1998)

Jim Hayes, ed., *Fiber Optics Technician's Manual* (Delmar Publishers, 1996). See Larry Johnson, "Fiber optic restoration" (Chapter 16) and Jim Hayes, "Fiber optic testing," (Chapter 17).

Catalogs:

Agilent Technologies, *Lightwave Test and Measurement Catalog* (*www.agilent.com*)

Exfo Electro-Optical Engineering, *Lightwave Test & Measurement Reference Guide* (*www.exfo.com*)

Questions to Think About

1. Devise a troubleshooting procedure for testing your ability to connect to the Internet using a personal computer, an external modem, and a standard telephone line.
2. Which is more likely to fail: an old fiber-optic cable left undisturbed in an underground duct, or a new office cable that was plugged into a new computer?
3. What is the advantage of measuring fiber attenuation at 1625 nm?
4. You want to test a WDM system by transmitting signals through it one wavelength at a time at the same power generated by the standard transmitters. What sort of light source should you use?
5. You test a 50-km cable with an OTDR and find a sharp peak at 25 km and no signal returning from greater distances. What does this tell you about the cable?
6. When the moving arm in a wavelength meter moves 7 mm, the instrument counts 9,000 fringes. What's the difference between the wavelength in a vacuum and the wavelength in air ($n = 1.000273$)?

Chapter Quiz

1. An optical power meter would be least likely to be calibrated for measurements at

   a. 850 nm.
   b. 1300 nm.
   c. 1400 nm.
   d. 1550 nm.

2. An optical loss test set includes a(n)
   a. wavelength meter and power meter.
   b. optical spectrum analyzer and power meter calibrated across the same range of wavelengths.
   c. power meter and a length of fiber calibrated to work together.
   d. light source and a power meter calibrated to work together.
   e. power meter, light source, wavelength meter, and optical spectrum analyzer.
3. A visual fault indicator does what?
   a. It shines red light down the core of a fiber to make visible any flawed points where light leaks from flaws.
   b. It illuminates the plastic coating of a fiber with red light to spot any uneven spots on the surface.
   c. It shines light through the hollow zone of a loose tube cable to search for any fiber fragments in the cable.
   d. It illuminates the outside of a fiber with ultraviolet light to cause fluorescence where light leaks from the fiber.
   e. None of the above
4. You can test a fiber to see if it's carrying an optical signal by
   a. pointing the end at a white piece of paper and looking for fluorescence.
   b. scraping away the cladding and monitoring for light leaking out.
   c. bending the fiber and monitoring with an infrared sensor for light leaking out.
   d. removing the plastic coating and looking for light in the fiber.
   e. all of the above
5. You use an optical time-domain reflectometer to analyze a fiber with an 10-μm air gap at a connector. What would you expect the OTDR to show at the point where the connector is installed?
   a. nothing
   b. a strong reflection accompanied by a loss
   c. a strong reflection accompanied by a gain
   d. a flat region across the gap
   e. a sharp drop in scattering in the air gap, followed by higher scattering in the glass
6. What type of test equipment can best identify a fiber that has been moved and connected to the wrong point in a patch panel?
   a. an OTDR
   b. an optical loss test set

   c. an optical power meter
   d. an optical spectrum analyzer
   e. manual inspection and comparison with records

7. What type of instrument can display an eye pattern?
   a. oscilloscope
   b. optical loss test set
   c. optical power meter
   d. OTDR
   e. optical spectrum analyzer

8. An optical spectrum analyzer can record
   a. the spectrum of a light source.
   b. all the wavelengths transmitted by a WDM system.
   c. the optical channels amplified in an erbium-doped fiber amplifier.
   d. the wavelengths transmitted by an optical multiplexer.
   e. all of the above

9. A wavelength meter is based on what optical system?
   a. Mach-Zehnder interferometer
   b. optical spectrum analyzer
   c. Michelson interferometer
   d. Fabry-Perot interferometer
   e. Ross-Perot interferometer

10. What is the easiest way to locate a break in an aerial cable?
   a. drive along the line and look for fallen cables
   b. measure cable loss with an optical return loss meter
   c. measure the cable with an OTDR
   d. measure power level at the receiver
   e. listen to police radio for reports of drunk drivers hitting utility poles

11. The bit error rate of the fiber-optic system connecting your building to the Internet has reached 10^{-3}. What possibility can you rule out when you start troubleshooting?
   a. A backhoe broke the cable.
   b. The laser transmitter has gotten too warm and drifted off wavelength.
   c. dirt in a connector
   d. Moisture has contaminated an outdoor splice.
   e. a kink in the cable at a junction box

12. An optical spectrum analyzer shows that your WDM system delivers no signal at all at one wavelength but other channels are working fine. Which of the following could have caused the problem?

a. A gopher gnawed one fiber in the cable.

b. The laser for that channel failed.

c. Dirt has gotten into a connector.

d. The cable is kinked at the junction box.

e. failure of an optical amplifier

CHAPTER

19

System and Optical Networking Concepts

About This Chapter

The fiber-optic components described in earlier chapters are assembled into systems to provide communication services. This chapter takes a closer look at basic system concepts that were introduced in Chapter 3. To understand telecommunications systems and the emerging optical network, you need to learn both the specifics of how fiber-optic systems transmit signals and the tasks these systems perform. This chapter is the first of several that will teach you about optical networks and the services they provide.

An Evolving Network

The telecommunications industry is in transition. Signal transmission technology, services offered, and the structure of the industry are all changing. This book is about technology, so it concentrates on transmission and services, but business considerations also affect the choice of technology and the selection of services offered.

We'll start with a brief introduction to a few key concepts, then study system concepts in more detail.

Telecommunication Systems

Chapter 3 introduced the concept of telecommunication systems. Telecommunication networks deliver voice, video, and data services around the globe. Extensive interconnections among global, national, and local systems allow you to send electronic mail to Japan, to fax a document to Africa, or to phone someone in England.

The term *telecommunications* does not specify what technology delivers signals. Today's global network is a blend of three fundamental technologies. Electrical current

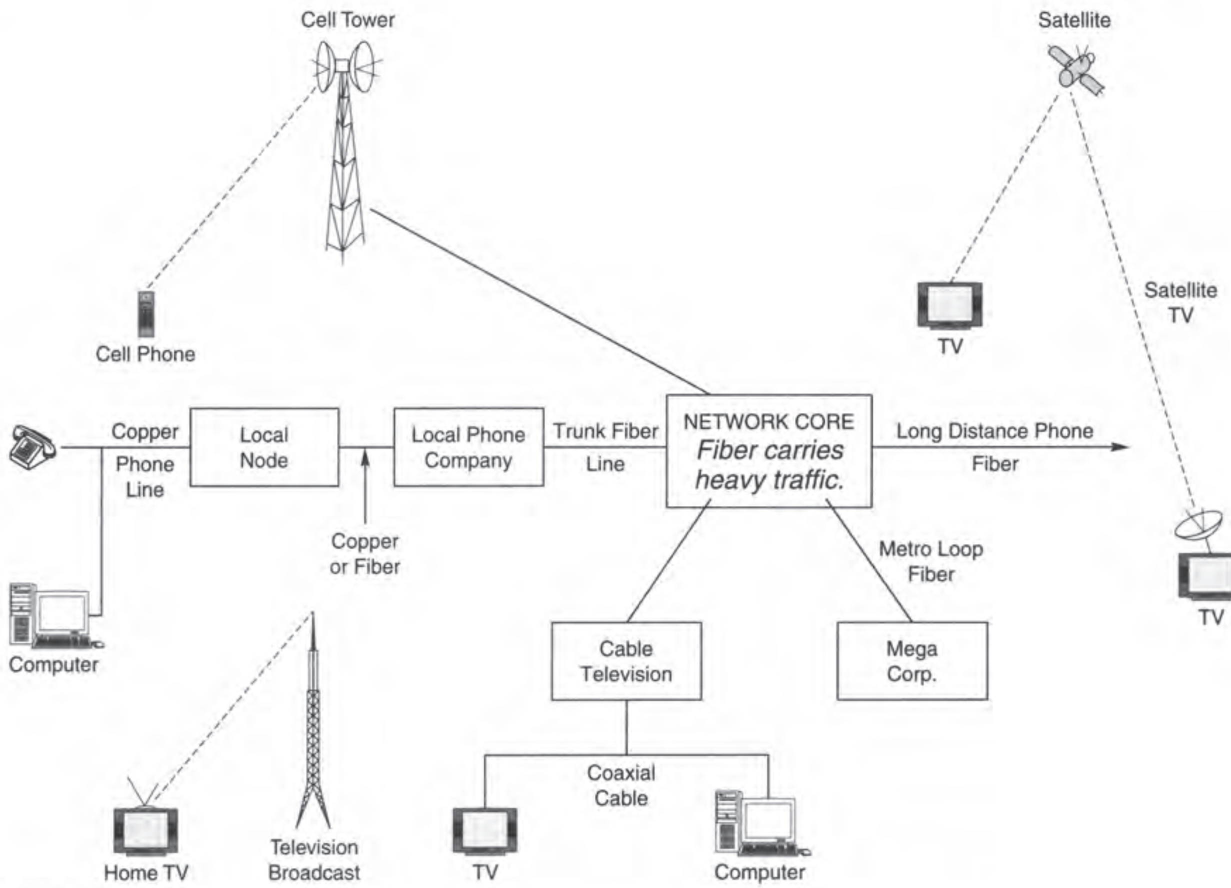


FIGURE 19.1
Technologies used for different types of telecommunications.

carries signals through copper wires, including both coaxial cables and the plain "twisted pair" used in telephone systems. Radio waves carry signals through air and space, between satellites, ground antennas, and mobile devices. Light waves convey signals through glass optical fibers.

Copper, wireless, and fiber play different roles in the global network.

These three technologies usually play different roles in the global network. In general, copper wires distribute signals to fixed devices, such as wired phones, television sets, and homes. Wireless (radio) signals travel to mobile devices, such as cell phones, laptops and pagers, and also broadcast video and audio programs to many points over wide areas. Fiber typically provides the superhighway, transmitting large volumes of information. Figure 19.1 shows the general layout.

This picture is a simplified one, and there are many cases in which the roles of these technologies overlap. For example, you may use a wireless network to link fixed computers in your house to avoid drilling holes in the wall. Signals often may be distributed partway over fiber and the rest of the way over copper. In some cases, optical fibers may run direct to people's homes. Satellites may provide some backbone transmission. But in general the categories of fixed distribution, mobile distribution, and backbone or "superhighway" transmission can be useful in understanding how networks operate.

Optical Networking

The term *optical networking* refers to networks in which signals are managed as well as transmitted in the form of light. This is a significant distinction. As you learned earlier, a network is built of "pipes" and "switches." Originally optical signals were transmitted only through pipes, and converted to electronic form by switches. The development of optical switches has made it possible to manage signals in optical form, without converting them to light.

Optical networking manages signals as light.

Optical networking so far has involved more marketing type than practical application technology. An *all-optical network*, in which signals remain in optical form out to the edges where they are converted into other forms, has theoretical advantages. However, true optical networking also has practical problems, so its applications have been limited.

Changing Business Models

Both telephone and cable television began as local monopolies that delivered only specific services, which regulators rigidly divided. Competition became the rule during the past two decades, first in long-distance telephone service, and later in local telephone service. Cable and phone companies, once rigidly separated, now compete head-to-head in Internet service. Cellular telephones are taking traffic away from "land lines." Many new companies emerged to offer a variety of services, and many of them fell, sometimes spectacularly, in the turbulent marketplace. Many survivors are now struggling to find ways to turn a steady profit.

The telecommunications business is undergoing rapid change.

As the business has changed, the global telecommunications network has grown and expanded, but many elements remain the same. The network still includes an inner core that processes signals and transmits them close to their destination, and an outer distribution network that collects signals from their origins, delivers them to the core, and picks them up as they emerge from the core and distributes them to their destinations. Phone service via the Internet is new, but a phone call is still fundamentally a phone call, even if it now can be routed over the Internet.

Telecommunication Network Structure

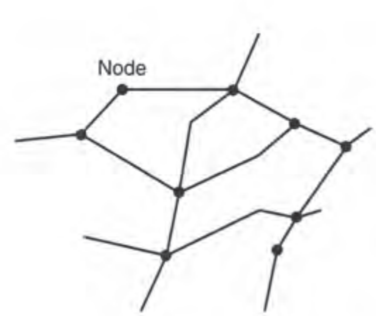
Today's global telecommunication network carries a mixture of voice, video, and data signals. Its structure is far more complex and fluid than in the days when it carried only long-distance telephone calls for national telephone monopolies. Let's look briefly at the overall topology before turning to the structural elements that build up the network.

Nodes and Connection Points

Telecommunication networks consist of links running between nodes, as shown in Figure 19.2. Typically there are multiple routes between pairs of nodes, both to handle traffic flow and provide backup in case of cable failures. The nodes direct signals to the next node, or distribute them locally.

Telecommunications networks are made of links between nodes.

FIGURE 19.2
Network connects nodes.



Each node is a point that serves many users—it could be a neighborhood distribution center, a telephone switching center in a small town, or a major switching center in a big city. These nodes, in turn, distribute signals farther to other nodes or to individual customers. Small nodes connect to larger ones and customers; larger nodes connect to smaller ones and to high-capacity *backbone systems*. The traffic is highest on the backbone routes between major population centers. Although individuals make more local calls, the signals are spread through many local cables, while long-distance calls are carried by a few high-capacity cables.

Types of Services

Telecommunications includes voice, video, and data signals.

We generally think of telecommunications as including voice, video, and data signals. Thanks to the Internet, digital data accounts for the largest share of traffic volume in the United States.

These services are distinct and have different transmission requirements. *Voice* requires little bandwidth per channel, but is highly sensitive to delays and requires two-way connections. Video requires much more capacity, and is also sensitive to delays, but its delivery requires only a one-way connection. Internet data comes in bursts, so transmission rates vary greatly with time, but the signal can tolerate delays.

Traditionally voice and video were transmitted on separate networks, each designed specifically for that type of traffic. Facsimile transmissions and computer data can travel over phone lines in the form of signals coded as a series of tones, but their speed is limited. High-speed Internet traffic is transmitted on dedicated lines using a protocol developed specifically for data. Dedicated networks are optimized for a specific type of traffic, but separate networks are expensive, so new techniques have been developed that convert signals into formats suitable for transmission on other networks. Voice signals can be converted for transmission on both cable television networks and the Internet, although Internet transmission uses a different type of switching, which imposes some limitations.

Circuit and Packet Switching

The telephone system is circuit-switched. The Internet is packet-switched.

The crucial operating difference between voice telephone transmission and the Internet is how signals are packaged.

Since the telephone was invented in the nineteenth century, voice calls have been made over dedicated circuits. Originally calls went over pairs of wires strung between phones;

now they are assigned a reserved slot in a stream of other data, called a *virtual circuit.* This reserved capacity means that once a connection is made, the phone responds the instant you start talking, and the person at the other end hears you immediately.

The Internet was designed around *packet switching,* which groups data together into packets for transmission. Each packet has an address header, which is read by network elements called *routers,* that direct the packet to its destination. Packets can fill the distribution pipeline much more efficiently because they don't have to reserve particular capacity, and they can be delayed. That's fine for electronic mail or for downloading pages from the Web, but annoying when it makes streaming video flow unevenly, or introduces delays into conversations over the Internet.

Circuit- and packet-switched signals are transmitted separately. Packet-switched signals can be repackaged for transmission over a circuit-switched network, and vice versa, but usually at added expense or with loss in quality. *Voice over Internet Protocol (VoIP),* for example, converts voice signals for transmission on the Internet and is more efficient than ordinary phone lines, but does not provide the same guarantee of prompt signal delivery. You'll learn more about VoIP later.

Standards and Protocols

Telecommunications systems follow standards so that all parts of the network can understand each other. Standards codify a standard language or *protocol* for signal transmission. Industry groups establish most standards, and many companies produce products that adhere to such standards.

Standards define common languages for signal transmission.

Many different standards exist, but some are basic to system operation because they specify how bits are arranged for transmission. The *Internet Protocol (IP)* covers the arrangement of data packets for packet switching. *SONET, Asynchronous Transfer Mode (ATM),* and the *Plesiochronous Digital Hierarchy* determine how data streams are interleaved to provide virtual circuits for circuit switching. You'll earn more about these standards in Chapter 20.

Transmission Topologies

In Chapter 3 you learned about the basic building blocks of telecommunications networks. Figure 19.3 shows four basic types of transmission that are important in fiber-optic systems. Let's look at each of these transmission topologies in more detail.

Point to Point

Point-to-point transmission provides two-way communication between a pair of terminals that are permanently linked together, with a transmitter and receiver on both ends.

Point-to-point transmission links pairs of terminals.

Conceptually, the distance between terminals doesn't matter. The two could be on opposite sides of the room or on opposite sides of the ocean. If the transmitter can't send signals through the entire length of fiber, optical amplifiers or repeaters can be added to boost signal strength. Examples of point-to-point links range from a cable linking a personal computer and a dedicated printer to a transatlantic submarine cable.

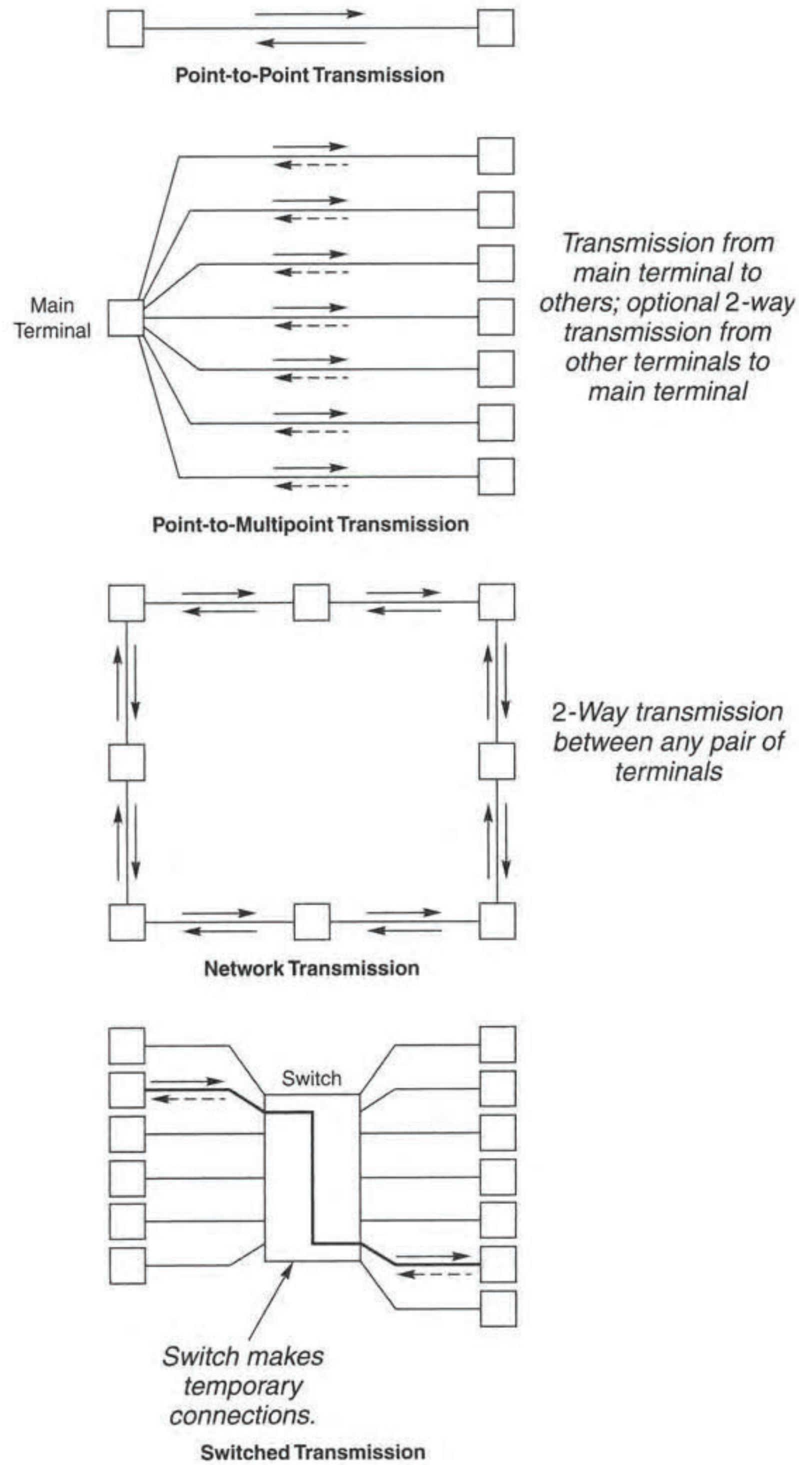


FIGURE 19.3
Types of transmission.

If you look closely enough, you can break other fiber-optic systems into point-to-point links. That reflects the reality that any fiber system has a transmitter on one end and a receiver on the other, although couplers in between may split the signals among multiple fibers.

Point to Multipoint (Broadcast)

Another family of systems sends the signal from one transmitter to many terminals. This is sometimes called *broadcasting* because it is analogous to the way a radio or television transmitter broadcasts signals through the air to many receivers. In a fiber-optic system, the terminals may or may not return signals to the central transmitter. If there is a return signal it is often at a lower speed than the broadcast transmission.

Point-to-multipoint transmission uses one transmitter to serve many terminals.

Because they serve many terminals, point-to-multipoint transmitters generally send higher-power signals than those in point-to-point systems. The basic design can vary considerably, as shown in Figure 19.4. A tree or star coupler can split the signal from one transmitter to drive

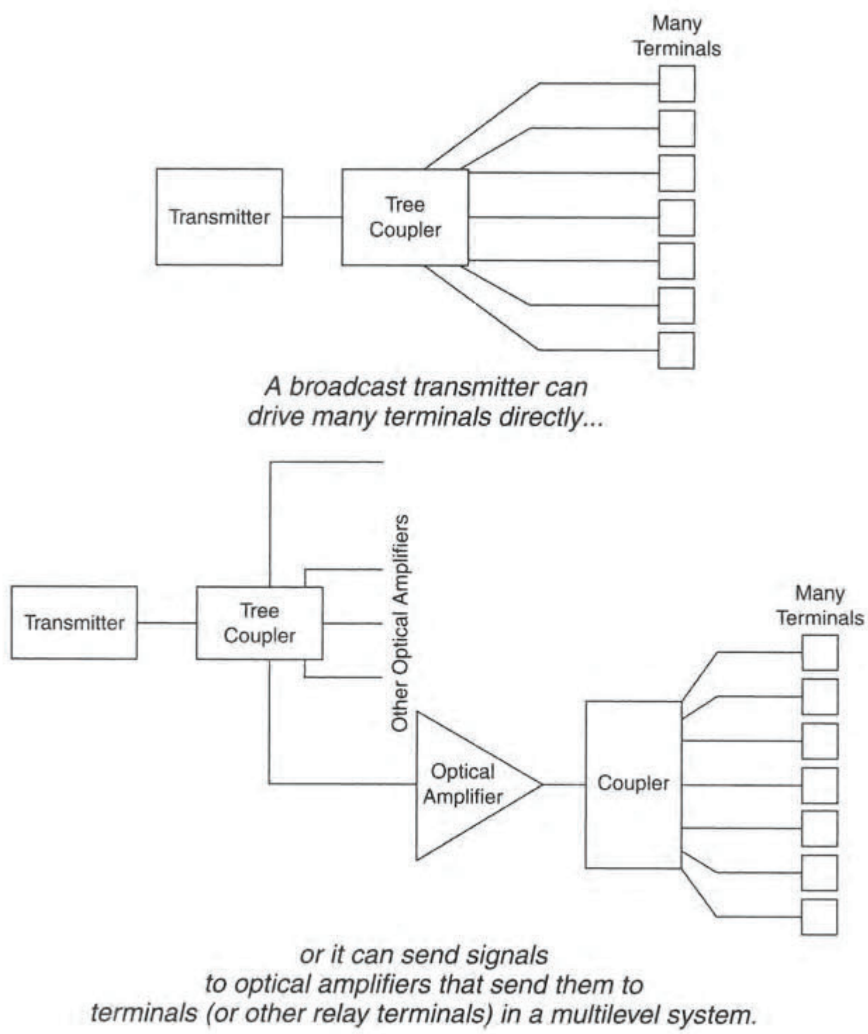


FIGURE 19.4
Point-to-multipoint transmission.

many terminals. Or the split signals can drive optical amplifiers that amplify the signal from the main transmitter and send it to terminals (or another stage of optical amplifiers).

Like a point-to-point fiber system, a point-to-multipoint fiber system makes quasi-permanent connections between transmitters and receivers. Typically, point-to-point systems include multiple levels of signal distribution. For example, the head end of a cable-television system sends signals to local distribution nodes, which in turn send signals to neighborhood nodes, which distribute signals to individual homes. Typically these systems send relatively few signals "upstream" from home terminals to the head end where signals originate. A *pure* point-to-multipoint system distributes identical signals to all terminals, but modern cable-television systems can distribute some unique signals to individual homes.

The main transmitter in a point-to-multipoint system is more "important" than the terminals it serves. Even in a two-way system, it sends most information handled by the system and is essentially an information provider (whatever you think of the offerings of your local cable system). Individual terminals provide little or no information, and they can link only to the main transmitter; they generally cannot communicate directly with each other. If the main transmitter fails, a point-to-multipoint system is off the air.

The most important point-to-multipoint fiber systems are cable television distribution networks. Most wireless networks, including cellular telephones as well as broadcast radio and television also use point-to-multipoint architecture. Functionally, however a broadcast television receiver is designed to decode all signals from transmitters in its area, while a cellular phone decodes only signals from the nearest available cell tower addressed to that phone.

Network Topology

Network topology directly interconnects many terminals.

The term *network* denotes interconnection, but it has a specific meaning when it refers to topology. *Network topology* is an arrangement of links that directly connects all terminals. Several variations of network topology are shown in Figure 19.5. All terminals can send and receive signals to or from any other terminal on the network. Small networks are often called *local-area networks.* Larger ones may be called *metropolitan-area networks* or *wide-area networks.*

Networks may link terminals in various configurations. Terminals may be arranged in a *ring,* with signals split from the ring and directed to their destination terminal, or passed directly through each terminal. Some ring networks are collections of point-to-point links that are regenerated at each terminal to overcome coupling losses. In *star* networks, signals travelling to and from each terminal pass through a central node, which may be either a passive coupler, which divides the input light, or an active coupler, which receives and re-transmits the signal.

A mesh network lacks a highly organized geometry.

An alternative is the *mesh* network, also shown in Figure 19.5, where interconnections do *not* organize terminals in a ring or star configuration, but instead form a mesh-like grid. In the example, each node has links to at least three other nodes. This creates multiple routes between nodes, a robust architecture.

As you can see, a mesh lacks a highly organized geometry. You can't just direct signals from one node to the next because typically there is no single *next* node. Switches or routers must be programmed where they should direct signals.

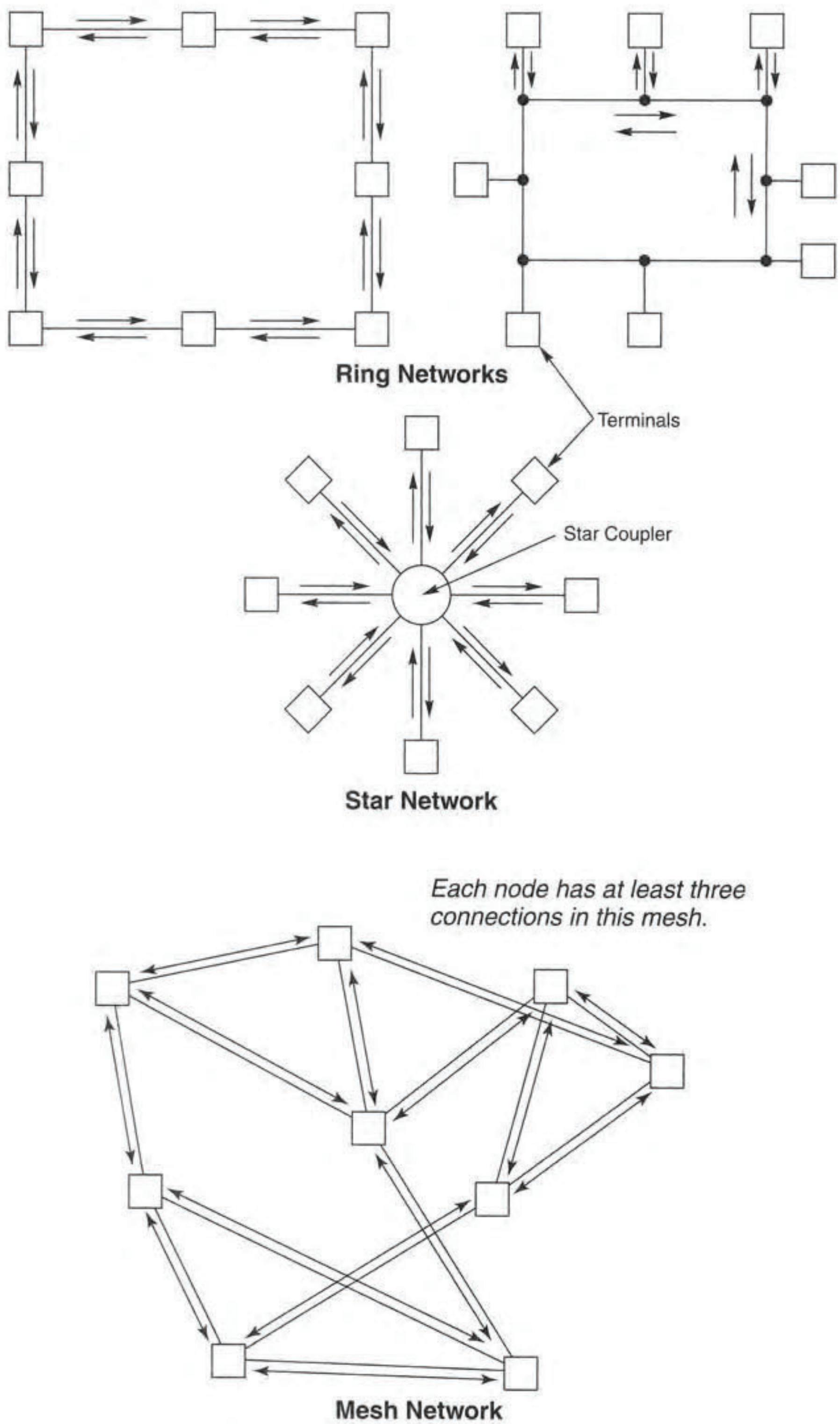


FIGURE 19.5 *Network transmission.*

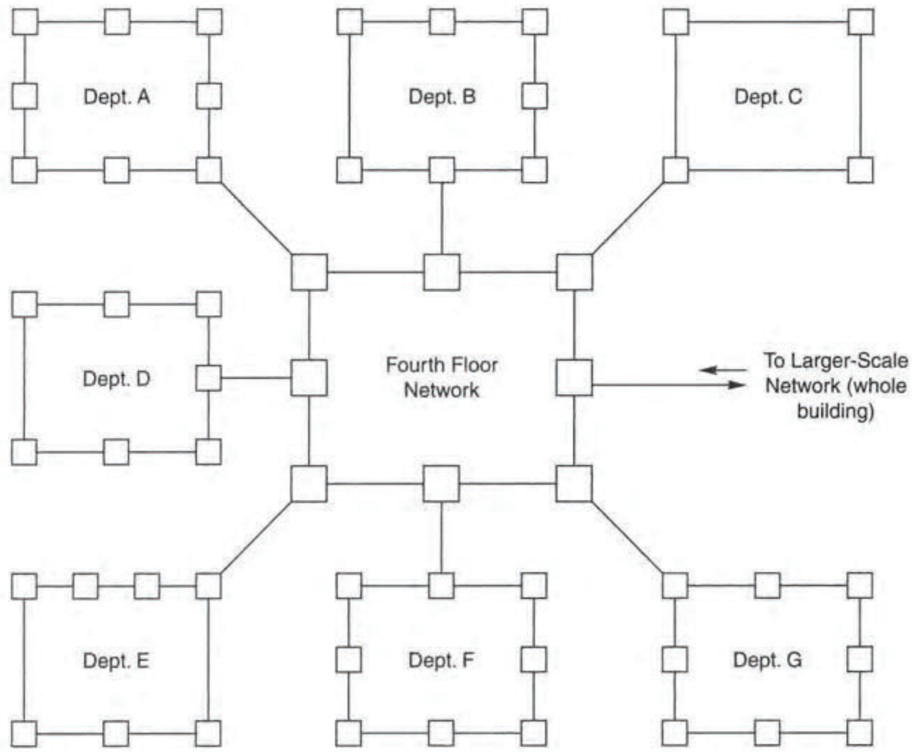


FIGURE 19.6
A network hierarchy, with small networks interconnected to make a large network.

Networks can be linked to make a network of networks.

Networks can be linked together with other networks to make a network of networks, as shown in Figure 19.6. In this example, each small-scale (department) network interfaces with a larger-scale (floor-wide) network, which in turn interfaces with an even larger (building-wide) network. Scaling this network-of-networks approach even further leads to the Internet.

As with point-to-point and point-to-multipoint systems, networks have permanent connections to each node and, except in mesh networks, the routing of signals can be changed only by rearranging cables. This means that the same terminals always talk to each other unless the configuration is changed. In practice, network connections usually go through patch panels with connectors that allow attaching and removing terminals. A typical example is a local-area network (LAN) for personal computers in an office. The terminals do not have to be identical, but do require a common protocol to talk with one another.

Switched Transmission

Switching allows temporary connections between pairs of terminals.

Adding switches to a communication network makes it more flexible. Switches allow any pair of terminals to send and receive signals directly to and from each other. The connections are inherently temporary, so each terminal can talk—at different times—to any other terminal, as shown in Figure 19.3. Depending on the system design, more than two terminals may be linked together at once. The telephone network is the standard example.

Switching increases system complexity, but adds tremendous power by making temporary connections to send signals between any pair of terminals linked to the switch. You can assemble switches in series, so each one directs signals at a different level. This allows the global telephone network to send calls around the world. To give a simplified example, one switch might direct a long-distance call to your state, another to the city where you live, a third to your part of town, a fourth to your block, and a fifth to your home. In practice, several of these switches may be in the same place—typically those serving your part of town, your block, and your home all are installed in the local telephone-company switching office.

Directing Signals

Point-to-point links direct signals to the desired destination because they connect only two points. Other transmission topologies require specific methods to direct signals to intended recipients. These methods vary considerably.

Broadcasting

Broadcasting is the simplest type of point-to-multipoint transmission. It simply sends the same signals to everybody. For example, everybody receives the same radio and television broadcasts if they have the proper antennas and receivers. Likewise, cable and satellite systems deliver the same television signals to all their customers, although premium channels require a special receiver that can decode the encrypted signals.

Broadcasting sends the same signals to everybody.

Wireless transmission broadcasts radio signals to all receivers in the area, so wireless services like cellular telephones require additional features that make them switched services.

Selective Reception

Point-to-multipoint transmission can function like point-to-point transmission if the receivers are selective. Selective receivers can't decode or are programmed to ignore any signals not directed to them.

Decades ago, party-line telephone service worked using a form of selective reception. Two homes would share the same phone line, which rang differently for each number. Residents were supposed to pick up the phone only when the call was to their number. Some services today use the same idea, as a distinctive ring that adds an extra number to an existing phone line.

Networks and cellular telephones require better security, called authentication, to assure that no one receives a call intended for someone else. Cellular signals can be encrypted so that only the phone to which the call is directed can decode them, although the radio waves reach other phones. The same can be done with local-area networks, so each terminal sees only the messages directed to it, although other messages may physically pass through the terminal. Authentication is handled by receiver electronics.

Authentication and encryption protect against eavesdropping.

Switching and Routing

Switching and routing are different operations.

Switching can take one of two different forms—*circuit switching* and *packet switching*. Circuit switching is used in the telephone network and performed by electronic or

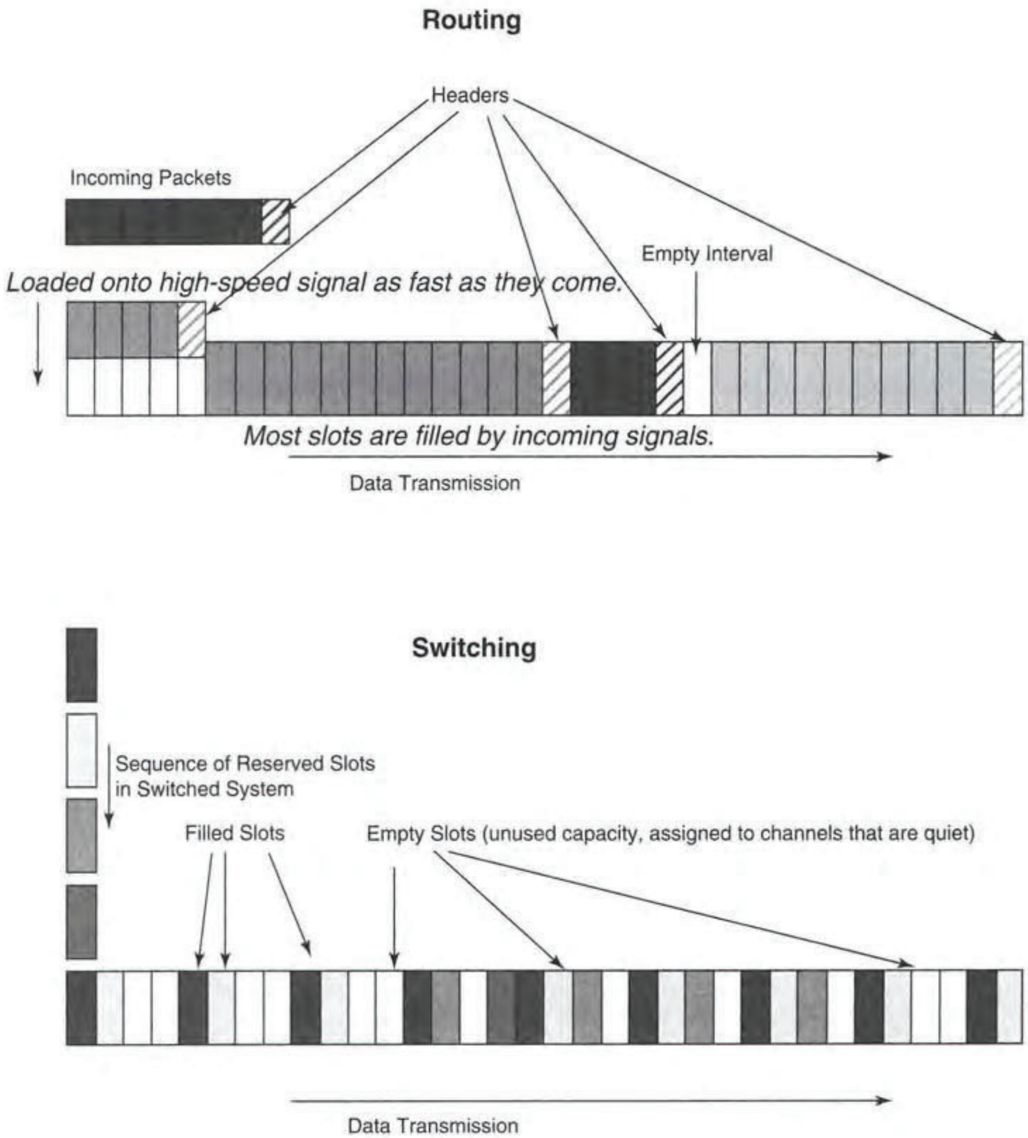


FIGURE 19.7
Routers use transmission capacity more effectively by packing signals closely together. Switches leave slots open because they reserve capacity.

mechanical devices that are confusingly called *switches*. Packet switching is used on the Internet and performed by hardware called *routers*. It's vital to remember that switches and routers are different types of devices, although they sometimes are mislabelled. To understand how they differ, let's look at each in more detail.

Switches are relatively simple electronic systems that create a temporary circuit linking two points. The connection process is controlled by information transmitted by the source when the circuit is set up—typically, when you dial a telephone number. Circuit-switched connections may be physical links through wires or optical fibers, or reserved bit slots in a high-speed digital signal that provide the equivalent capacity. As Figure 19.7 shows, the slots for each circuit switched signal are always available but may not be filled by data bits. Telephone switches create a temporary path for signals that guarantees the capacity of one voice circuit while both phones are off the hook, whether or not anyone is talking. Circuit switches work like the switches on a model train layout; once you set them, they automatically guide all signals to their destination.

Routers are more complex systems used for packet switching over a mesh network. At its source, the signal is broken down into one or more data packets, and each data packet is assigned a header that specifies the destination for the data. This can pack data bits together more efficiently, as shown in Figure 19.7. The router reads the header on each packet and determines the best route for each packet to follow, based on information including traffic conditions on the network. It then sends the packet to another router at a node closer to its destination. The next router repeats the process, sending the packet to another node, until the packet reaches the node that can direct it to the target terminal.

Routers direct packets by reading the attached headers.

Signal Formats

Signals can be transmitted through any medium in a variety of formats. The basic idea, as you learned in Chapter 3, is to modulate some property of a carrier with the signal to be transmitted. The transmission process is based on three key concepts: the carrier, modulation, and coding. Radio signals give a good example of these concepts.

A signal modulates a carrier wave.

Radio stations transmit at specific *carrier frequencies*, which are much higher than the frequency at which the transmitted signal varies. An oscillator at the station generates a continuous signal at the station's assigned carrier frequency; then the station modulates the carrier with the radio program being transmitted. For example, an FM station transmitting at 89.7 MHz has an oscillator that generates that frequency, and modulates that carrier with an audio signal, which is the program being broadcast. The broadcast signal is centered on the 89.7-MHz frequency, and your radio receivers tune into that frequency. The receiver electronically extracts the program and amplifies it, discarding the carrier. The coding of the signal determines how the receiver interprets it. Let's look at each of these steps.

Types of Modulation

The signal can modulate three properties of the carrier wave: its amplitude, frequency, and phase.

Amplitude modulation is the most common type of modulation in fiber optics, and is the simplest to understand. The amplitude of the carrier wave varies with the instantaneous strength of the signal being transmitted, as you saw earlier in Figure 10.5. For an AM radio station, when the program is loud, the amplitude is high, and when the program is quiet, the amplitude is low. The same type of variation occurs in fiber-optic transmission. An optical carrier wave, however, oscillates much faster than the signal varies, so the scale of Figure 10.5 is deceptive. If you were transmitting a 10-Gbit/s signal at a wavelength of 1537.4 nm (195 THz), the carrier wave would oscillate 19,500 times during the length of a single bit. Amplitude modulation can be viewed as multiplying the constant amplitude of the carrier by the time-varying amplitude of the transmitted signal.

Amplitude modulation is most common in fiber optics.

Frequency modulation is common in radio and television transmission, but unusual in fiber-optic transmission. Frequency modulation changes the carrier frequency instead of the carrier amplitude. In radio transmission, frequency modulation is easy to implement electronically and effectively filters out random static. However, frequency modulation is rarely used in fiber-optic transmission because it's much harder to implement and background noise is much lower. Frequency modulation has been used in experimental fiber-optic systems, where it's sometimes called *coherent transmission*. Digital frequency modulation is known as *frequency-shift keying*.

Phase-shift modulation varies the phase of transmitted waves in proportion to the instantaneous strength of the signal. In principle, a receiver can decode the phase-shift signal by combining the shifted input with an identical carrier wave generated at the receiver. Phase-shift modulation is more practical than frequency modulation in fiber-optic systems, but so far it's been used only in high-speed transmission demonstrations. Digital phase-shift modulation is known as *phase-shift keying*.

Analog Signal Coding

Signal coding is the form in which the transmitted information is represented. Analog signals are replicas of the original rather than coding; digital signals, however, require special coding, which also can enhance system performance by detecting and correcting transmission errors.

Analog signals replicate the original.

An analog signal is an exact electronic replica (or analog) of the input. For example, if the input signal is a 1000-Hz sound wave, the analog is a 1000-Hz electronic signal. An analog signal varies continuously with the instantaneous strength of the input. Amplitude modulation illustrates this most clearly, and Figure 10.5 shows how carrier-wave amplitude varies with the amplitude of the input signal. Analog transmission has long been standard for FM radio and television, although digital transmission is beginning to replace analog broadcasts. Cable television systems are the only place where analog transmission is widely used in fiber optics.

Digital Signal Coding

So far we've considered digital transmission to be simply a series of 1 and 0 bits, but it's not always that simple in practice. The signal level may be coded in various ways to optimize transmission.

NRZ coding is used in most fiber-optic systems.

The simplest approach is to send a high signal level for a 1 bit and a low signal level for a 0 bit, as shown at the top of Figure 19.8. This is called *NRZ* or *no return to zero coding* because the signal level does not change between bits if the value of the second bit is the same as the first. Thus the signal level stays high throughout a series of 1 bits and only drops to the low level to transmit a 0 bit. NRZ coding is used in most fiber-optic systems, but has performance problems at high transmission speeds. Long strings of identical bits keep the transmitter operating at the same level, making it easy for the receiver to lose the clock signal, causing transmission errors.

Several alternative approaches change the signal level more often to better preserve clock transmission. These schemes are more elaborate, but may be required at high transmission speeds. The most important of these is *return to zero (RZ) coding*. The signal level during the first half of a bit interval is low for a 0 bit and high for a 1 bit. In both cases, the signal level returns to 0 for the last half of the bit interval, as shown in Figure 19.8. This assures more transitions, making it easier to retain clock signals at high speeds, although there still are no transitions during series of 0 bits.

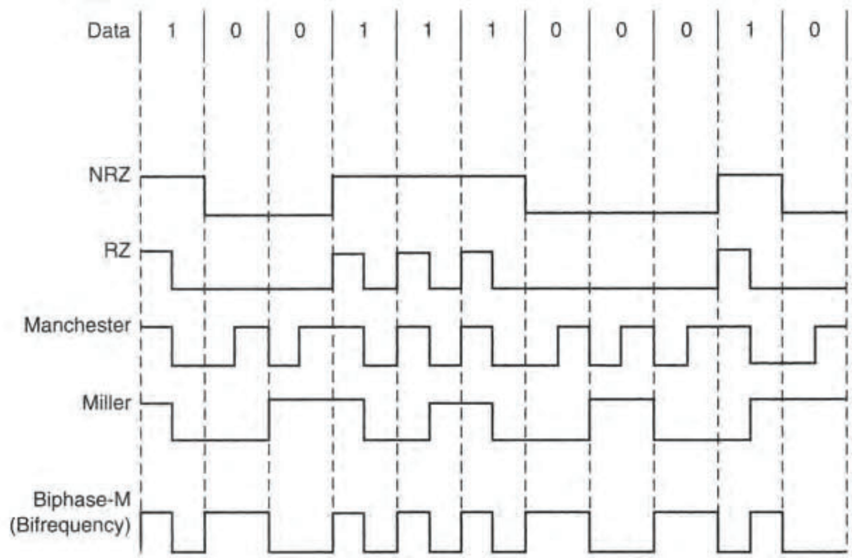


FIGURE 19.8
Digital data codes.

Other digital coding schemes further increase the number of level transitions. These include:

- *Manchester coding*—Signal level always changes in the middle of a bit interval. For a 0 bit, the signal starts out low and changes to high. For a 1 bit, the signal starts out high and changes to low. This means that the signal level changes at the end of a bit interval only when two successive bits are identical (e.g., between two 0s).
- *Miller coding*—For a 1 bit, the signal changes in the middle of a bit interval but not at the beginning or end. For a 0 bit, the signal level remains constant through a bit interval, changing at the end of it if followed by another 0 but not if it is followed by a 1.
- *Biphase-M or bifrequency coding*—For a 0 bit, the signal level changes at the start of an interval. For a 1 bit, the signal level changes at the start and at the middle of a bit interval.

Each type of coding has its own advantages and disadvantages. NRZ coding is simple to implement, and requires no more than one transition per bit, easing bandwidth requirements. However, long intervals of 0s or 1s can produce a steady signal level, making it easy to lose clock timing. RZ coding has more transitions during "on" bits, but can produce long intervals of 0 signal during a sequence of 0s. Codes that always have transitions during bits, such as Manchester and biphase coding, require higher bandwidth but generate their own clock signal to aid in timing. Other types of digital coding also are possible, but the details fall outside the scope of this book.

Error Correction

A different kind of digital coding, often called *forward error correction*, adds extra bits to the original signal in order to detect and correct errors. These techniques evolved from simple error-detecting schemes for computer data that added parity bits to the sequence of stored bits. Forward error correction greatly reduces transmission errors, allowing designers to stretch system margin. Instead of adding an optical amplifier, a more powerful transmitter, or a more sensitive receiver, the designer can add forward error correction circuits in the transmitter and decoding circuits in the receiver.

Error-correction codes operate on blocks of data.

Error-correction codes operate on a block of data. Their power depends on both the mathematical code used and the number of bits added. All codes have limited capacity, and can be overwhelmed by large numbers of errors. Their overall effect is to reduce the bit error rate, so an otherwise limited system can give acceptable performance.

Error detection is simpler than correction, and can be done simply by adding one extra bit to each eight-bit byte of data in computer storage. This extra bit, called a *parity bit*, is calculated by the system so the sum of the digits is always either an odd or an even number. If the sum gives the wrong parity, the computer flags an error. Addition of a second bit to each byte, with proper coding, allows correction as well as detection of one bit error. This simple coding is relatively inefficient, but information theorists have devised much more efficient ones.

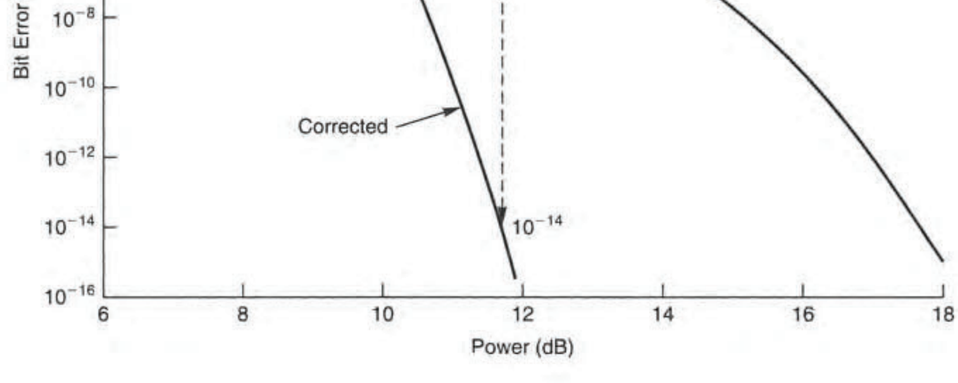
Error correction requires extra bits, but improves bit error rate.

Codes are usually identified by a pair of numbers (n, k), where n is the total number of bits in the block and k is the number of data bits. (The numbers may also refer to bytes in a block.) Adding $n - k$ bits imposes an overhead, additional bits that have to be transmitted in order to carry the nominal data rate. The smaller the number of added bits $(n - k)$, the more efficient the code. Efficiency is measured by the overhead ratio, $(n - k)/k$, and generally increases with the size of the coded blocks. Blocks of hundreds or thousands of bits can overhead from 7% to 25%.

Many codes are possible, although only a few are in practical use. One important type is *Reed-Solomon codes,* which group m-bit symbols into blocks containing $2^m - 1$ symbols or $m(2^m - 1)$ bits. Thus 8-bit bytes are grouped into 255-byte blocks. The code can correct errors in up to half the number of added bytes, so a (255, 239) Reed-Solomon code with 16 check bytes can correct up to 8 errors in 239 data bytes and has 6.3% overhead. It can reduce bit error rate from a raw 10^{-4} to a corrected rate of 10^{-15}, as shown in Figure 19.9. A (255, 223) code has about 13% overhead but can correct up to 16 byte errors, and enhances performance even more. Both codes have been adopted as standards for fiber-optic transmission.

FIGURE 19.9

Raw and corrected bit error rate with a Reed-Solomon (255, 239) code.



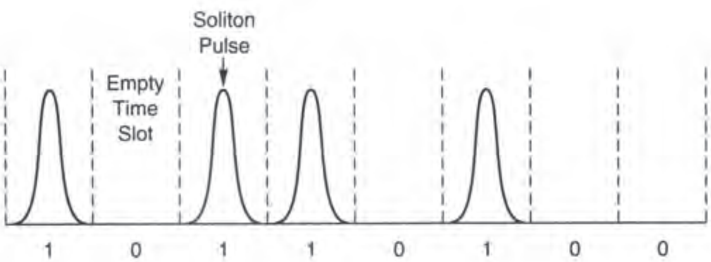


FIGURE 19.10
Soliton pulses modulated with a digital signal.

Soliton Transmission

Solitons retain their shape as they travel through a fiber.

Soliton transmission has unusual properties that deserve additional explanation. *Solitons* are a special type of return-to-zero pulse coding based on pulses that rise and fall in a specific pattern, which allows them to regenerate their shape as they travel along a fiber. The transmitter generates a series of solitons, some of which are switched off by an external modulator, producing a train of pulses as shown in Figure 19.10.

Solitons strike a delicate balance between two effects that tend to degrade normal pulse transmission. Chromatic dispersion stretches out pulses carrying a range of wavelengths, while self-phase modulation spreads out the range of wavelengths. For pulses of the proper shape, the two types of stretching offset each other, keeping the pulse shape unchanged as it travels through the fiber. The mathematics of soliton transmission are complex, but the physics were first observed in waves of water seen on canals in the nineteenth century.

Soliton pulses suffer attenuation, but optical amplifiers can compensate for the loss. Their nature enables them to retain their original shape, canceling out distortion. In fact, the input pulses don't have to be perfect solitons because they adapt their shape as they pass through the fiber. In practice, interactions between soliton pulses traveling in the same fiber at different wavelengths complicate transmission. Nonetheless, solitons continue to be developed for high-speed, long-distance transmission.

Transmission Capacity

Transmission capacity is the amount of information a fiber can carry.

Transmission capacity is a key figure of merit, which measures the amount of information a communication system can carry. In fiber-optic systems it usually is specified for a single fiber. Two-way communication usually requires a pair of fibers, one to carry signals in each direction. (In some cases a single fiber carries signals simultaneously in both directions.) Capacity may also be given for an entire cable, particularly for submarine cables. Total cable capacity is the sum of the capacities of all the fiber pairs.

The usual measurement of capacity for analog systems is the bandwidth in megahertz or gigahertz. For digital transmission, capacity is measured in *megabits, gigabits,* or *terabits per second*—that is, how fast the system can transmit bits.

Capacity is increased by multiplexing, the combination of many signals into one. As you learned in Chapter 3, you can multiplex electronic signals in time or frequency, and multiplex optical signals by wavelength. Let's take a closer look at each of these approaches, and see how they combine to determine capacity.

Electronic and Time-Division Multiplexing

Electronic multiplexers combine two or more signals to produce a signal that drives a fiber-optic transmitter.

Time-division multiplexers generate a single bit stream.

Electronic multiplexing began long before optical fibers were first used in telecommunications. Electronic equipment combines two or more separate input signals into a single output signal. That combined signal is transmitted through a communication system and then "demultiplexed" to break it into its original components. Multiplexing takes different forms in digital and analog systems.

Digital systems use time-division multiplexing (TDM), which combines several input signals into a single bit stream, as shown in Figure 19.11. In the example shown, four separate 1.5-Mbit/s inputs feed into a multiplexer. The multiplexer combines the signals, selecting first one pulse from input 1, then a pulse from input 2, and so on, in sequence. Essentially, the multiplexer shuffles the pulses together and retimes them because the lower-speed pulses are too long to stuff into a faster stream of bits. At the other end of the system, a demultiplexer sorts the bits out, putting bit 1 into channel 1, bit 2 into channel 2, and so forth. Interleaving also can be done byte by byte or in larger chunks.

Time-division multiplexing can shuffle incoming data bits together so perfectly because all the input data signals must arrive at the same rate. That is, you can only make a 6 Mbit/s output signal by interleaving four 1.5 Mbit/s data streams. A time-division multiplexer could not combine signals at 3, 2, and 1 Mbit/s to yield one 6 Mbit/s data stream, although the total input and output rates match. You would need to combine those signals in some other way.

As you will learn in Chapter 20, time-division multiplexing works with a fixed *hierarchy* of data rates. Several signals at one rate are merged to make one signal at a higher rate, and several signals at that rate are merged to make one at an even faster rate. This is an inherent limitation of time-division multiplexing, but not all fast digital signals are assembled in this way.

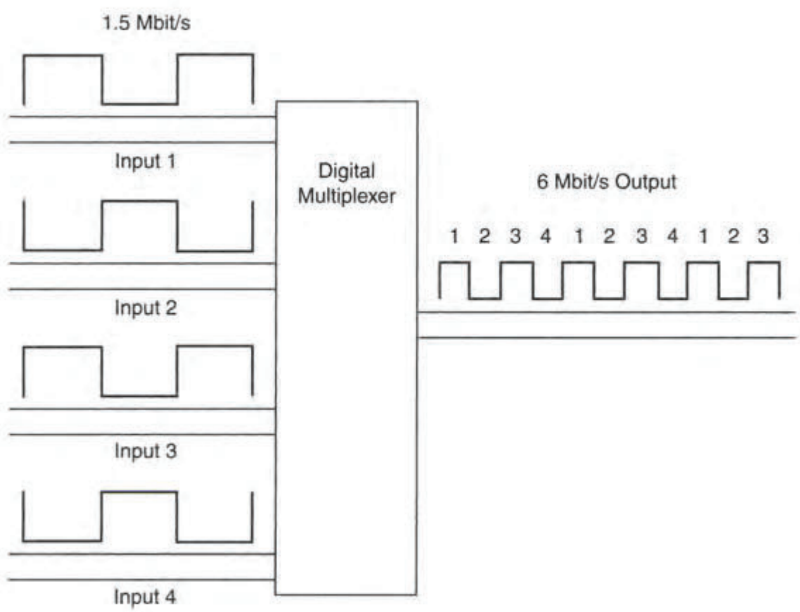


FIGURE 19.11 *Time-division multiplexing combines digital signals.*

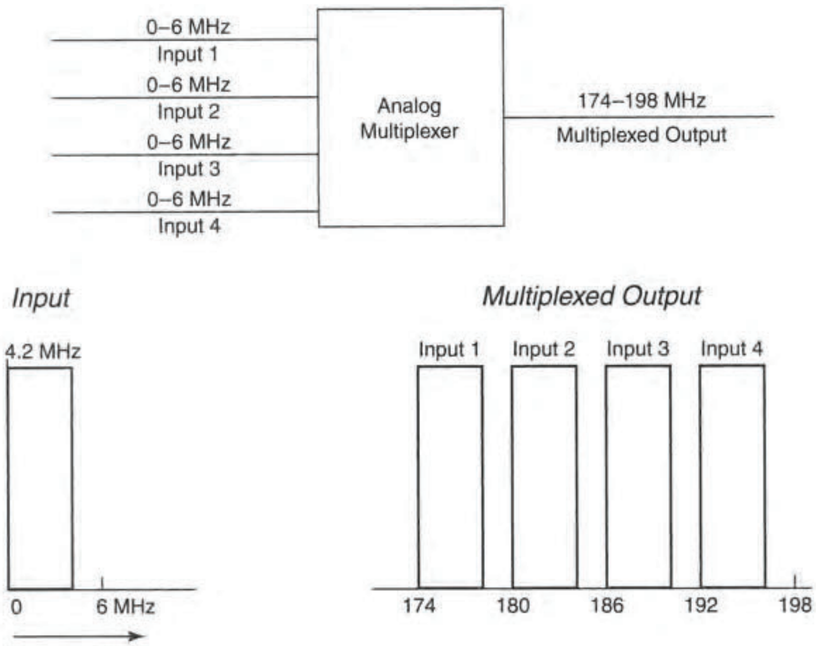


FIGURE 19.12
Analog frequency-division multiplexing for cable television.

Analog multiplexing works differently, by modulating carrier signals at separate frequencies with separate analog input signals. This is often called *frequency-division multiplexing* because it multiplexes by assigning each input signal to its own carrier frequency. Radio stations share the broadcast spectrum in this way, each transmitting at a different frequency to avoid interfering with each other. In an analog cable-television system, each video channel is assigned to a separate carrier frequency.

Analog multiplexing modulates multiple carrier frequencies.

Figure 19.12 shows a simplified example of frequency-division multiplexing in a small part of a cable transmission band. Each analog input signal has a video bandwidth of 4.2 MHz, with the audio carried at a slightly higher frequency. Each channel is assigned a bandwidth of 6 MHz, the standard for analog video, but the figure uses only a narrower 4.2 MHz band to show the separation of the channels. In this example, the first signal modulates a carrier to produce signals at 174–180 MHz, the second modulates a carrier at 180–186 MHz, the third a carrier at 186–192 MHz, and the fourth a carrier at 192–198 MHz. This generates a composite signal of 174–198 MHz at the transmitter. At the receiver, bandpass filters pick out the original channels. (Broadcast radio and television leave empty slots between adjacent channels in the same area to prevent interference, but this is not necessary in cable systems.)

Both analog and digital electronic multiplexers generate composite signals at the combined bandwidth or data rate. Digital signals can be further multiplexed to higher data rates, but this is rarely done for analog signals. The maximum data rate for a single channel depends on the transmitter, receiver, and fiber capacity.

Multiplexing in Packet Switching

High-speed signals can be generated directly, without TDM.

You don't need to interleave input data streams by time-division multiplexing to generate a high-speed digital signal. You can build up high-speed digital signals by assembling them