CHAPTER

21

Single-Channel System Design

About This Chapter

Now that you have learned the ideas behind fiber-optic communication systems, it's time to look at how they are designed. Design is a big topic, so it is split into two chapters. This chapter covers design of single-channel systems to meet loss and bandwidth requirements. Chapter 22 covers design considerations for wavelength-division multiplexing and optical networking.

Loss budgets and transmission capacity, or bandwidth, are crucial in both single- and multichannel systems, but the basic principles are the same for both. You calculate loss budget to be sure that enough signal reaches the receiver to give adequate performance. Likewise, you must calculate pulse dispersion, or bandwidth, to be sure the system can transmit signals at the proper speed. Some simple guidelines will give you rough assessments. In the real world, you also must consider cost-effectiveness and make trade-offs among various approaches to find the best performance at the most reasonable cost. Single-channel design techniques can be applied to each channel in a multiwavelength system.

These two chapters will not prepare you for heavy-duty system design. However, they will give you the basic understanding of design concepts and technical trade-offs you need to assess fiber-optic systems.

Variables

Design of a fiber-optic system is a balancing act. You start with a set of performance requirements, such as sending 2.5 Gbit/s through a 5-km cable. You add some subsidiary goals, sometimes explicitly, sometimes implicitly. For example, you may demand cost as low as possible, less than another alternative, or no more than a given amount. Your system might need an error rate of no more than 10^{-15} and should operate without interruption for at least 5 years.

Design of fiber-optic systems requires balancing many cost and performance goals.

You must look at each goal carefully to decide how much it is worth. Suppose, for instance, you decide that your system absolutely must operate 100% of the time. You're willing to pay premium prices for transmitters, receivers, and super-duper heavily armored absolutely gopher-proof cable. But how far should you go? If that is an absolute must because of national security and you have unlimited quantities of money, you might buy up the entire right of way, install the cable in ducts embedded in a meter of concrete, and post guards armed with tanks and bazookas to make sure no one comes near the cable with a backhoe. If its purpose is just to keep two corporate computers linked together, you might be satisfied with laying a redundant gopher-proof cable along a second route different enough from the first that no single accident would knock out both.

Many variables enter into system design.

That facetious example indicates how many variables can enter into system design. In this chapter, I will concentrate on the major goals of achieving specified transmission distance and data rate at reasonable cost in the simple case of a fiber carrying only one optical channel. Many design variables can enter into the equation, directly or indirectly. Among them are the following:

- Light source output power (into fiber)
- Coupling losses
- Spectral linewidth of the light source
- Response time of the light source and transmitter
- Signal coding
- Splice and connector loss
- Type of fiber (single- or multimode)
- Fiber attenuation and dispersion
- Fiber core diameter
- Fiber NA
- Operating wavelength
- Optical amplifiers
- Direct versus indirect modulation of transmitter
- Switching requirements
- Receiver sensitivity
- Bit error rate or signal-to-noise ratio
- Receiver bandwidth
- System configuration
- Number of splices, couplers, and connectors
- Type of couplers
- Costs
- Upgradability of design

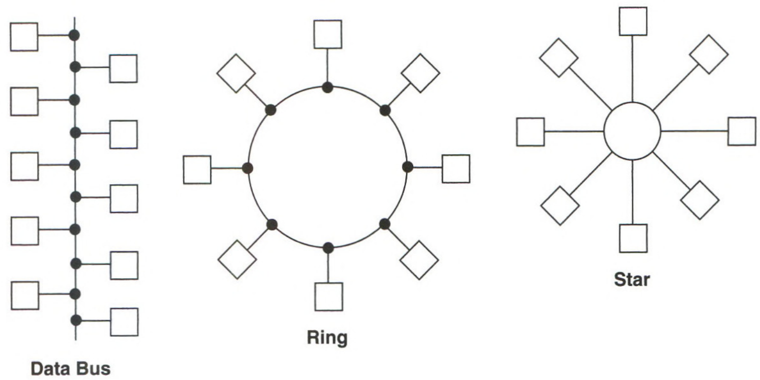

FIGURE 21.1
Three ways to interconnect computer terminals.

Many of these variables are interrelated. For example, fiber attenuation and dispersion depend on operating wavelength as well as the fiber type. Coupling losses depend on factors such as fiber NA and core diameter. Some interrelationships limit the choices available. For example, the need to achieve low fiber loss may require operation at 1300 or 1550 nm, and the need for optical amplification may dictate 1550 nm.

Some variables may not give you as many degrees of freedom as you might wish. For example, you may need to interconnect several computer terminals. You have enough flexibility to pick any of the possible layouts in Figure 21.1, but you still have to connect all the terminals, and that requires enough optical power to drive them all.

The type of system dictates the features you consider. If your goal is to connect computer terminals on a single floor of an office building, coupling loss will be more important than fiber attenuation. If your goal is to span the Pacific Ocean, fiber attenuation, dispersion, and optical amplifiers will be your main concerns. Designers of a transpacific cable must carefully consider how to achieve maximum transmission capacity, but the office-network designer must try to minimize coupling losses.

Often you can reach similar performance goals in more than one way. As you will learn in Chapter 22, a typical example is whether to transmit one signal at 10 Gbit/s or four WDM signals at 2.5 Gbit/s. Both choices can deliver a total of 10 Gbit/s, so the choice must depend on other factors, such as the cost, expected reliability, and potential for future upgrades.

Real fiber-optic system design is inherently a complex task, like trying to solve many simultaneous equations in algebra. The best way to understand the concepts is to look at them one at a time before you worry about how they interact. For that reason, the examples that follow are kept simple, without worrying about the complex trade-offs that affect real design decisions.

Power Budgeting

Power budgeting verifies that enough light reaches the receiver for proper system operation.

Power budgeting is much like making sure you have enough money to pay your bills. In this case, you need enough light to cover all optical transmission losses and to deliver enough light to the receiver to achieve the desired signal-to-noise ratio or bit error rate.

That design should leave some extra margin above the receiver's minimum requirements to allow for system aging, fluctuations, and repairs, such as splicing a broken cable. However, it should not deliver so much power that it overloads the receiver.

One note of warning: be sure you know what power is specified where. You can lose 3 dB if the transmitter manufacturer specifies output as peak power but the receiver manufacturer specifies average power.

In simplest form, the power budget is

The difference between transmitter output and receiver input equals the sum of system losses and margin.

$$\text{Power}_{\text{transmitter}} - \text{total loss} + \text{amplification} = \text{margin} + \text{receiver sensitivity}$$

when the arithmetic is done in decibels or related units such as dBm. The simplicity of these calculations is a main reason for using decibel units.

Remember that optical amplification can offset loss in the system budget. Optical amplifiers are expensive, but that high cost is justified in some cases. You wouldn't buy a $3000 optical amplifier so you could replace a $100 laser source with a $10 LED, but you would if you could avoid spending $10,000 on an electro-optic regenerator.

All factors that affect power in the system must be considered. These include:

- Light source output power
- Loss in transferring light from source into fiber
- Connector loss
- Splice loss
- Coupler loss
- Fiber loss
- Loss coupling to receiver
- Receiver sensitivity at data rate
- Forward error correction

Some of these factors have been covered in detail before, but others deserve more explanation.

Light Coupling Losses

Light is lost coupling into fibers.

Most light coupling losses come in transferring light from a source into a fiber; little is lost delivering light to a receiver. The main problem is matching the source emitting area to the fiber core.

TYPES OF SOURCES

Many LEDs emit from areas on their surfaces that are larger than the cores of 62.5/125 or 50/125 graded-index multimode fibers. As shown in Figure 21.2, when the emitting area is larger than the fiber core, some light enters the fiber core and escapes. The smaller the fiber core and the numerical aperture, the larger the loss. Large-area LEDs couple

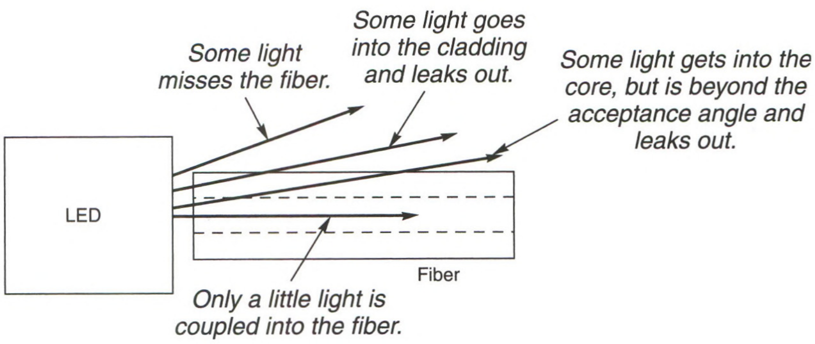

FIGURE 21.2
Light losses in transferring LED output into a fiber.

efficiently into large-core step-index multimode fibers, but their coupling losses can be up to 13 dB. Losses are lower for edge-emitting LEDs, which have smaller emitting areas than surface emitting LEDs. Power coupled into a graded-index fiber typically is tens of microwatts.

Semiconductor lasers have smaller emitting areas than surface-emitting LEDs, and deliver more light into fibers. VCSELs have light-emitting areas tens of micrometers across, which couple well to graded-index multimode fibers. Edge-emitting diode lasers have emitting areas only a few micrometers across, which match well with single-mode fiber cores. One drawback of edge emitters is that their small emitting area gives them a relatively large beam divergence, so some of the light that enters the core may leak into the cladding. Both VCSELs and edge emitters can transfer a milliwatt or more into a fiber.

FIBER CHOICE

Fibers with larger cores or NAs collect more light.

Another factor affecting light collection is the fiber. A fiber core diameter larger than the emitting area will decrease losses, although increasing core diameter further gives no benefit.

If the emitting area is larger than both fiber cores, you can estimate the difference in efficiency of light collection by a pair of fibers—fiber 1 and fiber 2—using the equation

$$\Delta\text{Loss (dB)} = 20 \log_{10}\left(\frac{D_1}{D_2}\right) + 20 \log_{10}\left(\frac{\text{NA}_1}{\text{NA}_2}\right)$$

where the *D*s are core diameters and the NAs are numerical apertures of the two fibers. You can use the formula as long as no optics are used to change the effective size of the emitting area or the effective NA of the source.

The difference can be significant with a large source. Consider, for example, the difference between a step-index fiber with 100-μm core and 0.3 NA and a graded-index fiber with 50-μm core and 0.2 NA. Substituting the numbers gives:

$$\Delta\text{Loss} = 20 \log\left(\frac{100}{50}\right) + 20 \log\left(\frac{0.3}{0.2}\right) = 9.6 \text{ dB}$$

That difference is nearly a factor of 10, well worth considering if you have run out of loss budget.

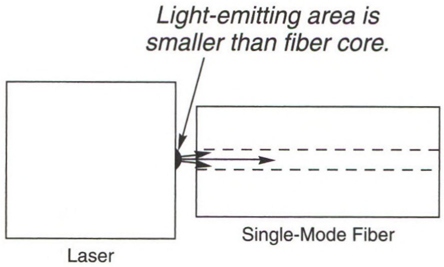

FIGURE 21.3
Laser output couples easily into a single-mode fiber core.

On the other hand, remember that a larger core reduces transmission bandwidth as well as increasing light-collection efficiency. The sacrifices are largest in moving from single-mode to multimode graded-index fiber and from graded-index multimode to step-index multimode.

SINGLE-MODE FIBERS

Single-mode fibers are used with laser sources.

Single-mode fibers normally are used only with laser sources. Edge-emitting lasers work best because their emitting area is smaller than that of a single-mode fiber core, as shown in Figure 21.3. VCSELs generally have larger light-emitting areas, so they typically are used with 50/125 or 62.5/125 μm graded-index multimode fibers. Fabricating a microlens on the fiber tip, or adding a microlens to the laser package, can enhance light coupling.

LEDs are a poor match to single-mode fibers. Carry the preceding example for multimode fibers a step further to a single-mode fiber with a nominal 10-μm core and NA of 0.11, and you will find it collects 19.2 dB less light from an LED than does a 50/125-μm fiber. Microlenses can reduce this excess loss, but in general single-mode fibers are not used with large-area LEDs.

Fiber Loss

Fiber loss equals attenuation times distance, sometimes plus transient losses.

Fiber loss nominally equals the attenuation (in decibels per kilometer) times the transmission distance:

$$\text{Total loss} = (\text{dB/km}) \times \text{length}$$

However, this is only an approximation for multimode fibers. One problem is that measurements of fiber attenuation in dB/km do not consider transient losses that occur near the start of a multimode fiber. An LED with a large emitting area and high NA excites high-order modes that leak out as they travel along the fiber. Typically this transient loss is 1 to 1.5 dB, concentrated in the first few hundred meters of fiber following the transmitter. This loss becomes less significant after you go a kilometer or two, but graded-index multimode fibers are rarely used over much longer distances. Thus, it's important to remember transient loss and allow for it in your system margin.

An additional problem that can occur with graded-index fiber is uneven and unpredictable coupling of modes between adjacent lengths of fiber. These concatenation effects make loss of long lengths of spliced graded-index fiber difficult to calculate; fortunately, such systems are extremely rare.

Single-mode fibers are much better behaved because they carry only one mode, avoiding differential mode attenuation.

Fiber-to-Receiver Coupling

One of the rare places where the fiber-optic engineer wins is in coupling light from a fiber to a detector or receiver. The light-sensitive areas of most detectors are larger than most fiber cores, and their acceptance angles are larger than those of multimode fibers. Of course, if you're determined to screw things up, you can find a detector with a light-collecting area smaller than the core of large-core multimode fibers. But that isn't likely.

Losses are normally small in transferring light from fibers to receivers.

Receiver Sensitivity and Error Correction

The rest of this chapter assumes that receivers have a fixed sensitivity. That is, I assume that a system has to deliver a minimum power to the receiver to ensure proper function. Things aren't really that simple, however, because a number of factors determine receiver sensitivity.

Forward error correction enhances receiver sensitivity.

As you learned in Chapter 11, receiver sensitivity as measured by power level drops as data rate increases because the bits are shorter at higher speeds, so fewer photons arrive during one bit interval. Thus, as the bit rate increases, the error rate increases if the power is held constant.

Forward error correction, described in Chapter 19, enhances receiver sensitivity by transmitting extra bits to detect and correct transmission errors. Forward error correction can also greatly improve system performance; but for simplicity we will ignore its effects and just assume the receiver requires a minimum input power to operate.

Other Losses

Splices, connectors, and couplers contribute significant losses in a fiber-optic system. Fortunately, these losses generally are easy to measure and calculate. Each device has a specified loss that you can multiply by the number of devices to estimate total loss.

Total connector loss is the number of connectors times "typical" loss.

The amount of loss varies, particularly among connectors. A data sheet may specify a connector as having maximum loss of 1.0 dB and "typical" loss of 0.5 dB. The maximum loss is the specified upper limit for the device; none of these devices should have higher loss if installed properly. The typical value is nominally an average value over a large number of connectors. Usually the typical value is a conservative figure, so if you had 100 connectors with typical loss of 0.5 dB, the total might be 35 dB rather than the 50 dB you would expect. That makes it unlikely that anyone will wind up with a batch of 10 connectors with total loss of 7 dB, or 0.7 dB per connector, well above the "typical" loss.

The typical value generally is most important in a system containing multiple connectors, but sometimes the maximum may be important. Overestimating loss and overloading the receiver, as well as underestimating loss, can cause problems.

The accumulation of transient losses is a potential problem in multimode systems. Coupling light into a fiber from a light source or another length of fiber shifts some of the light into higher-order modes, which leak out along the length of the fiber. This can increase loss depending on the system configuration.

Margin

System margin is a safety factor to allow for repairs and uncertainties.

One quantity that always figures in the loss budget is system *margin*, a safety factor for system designers. This allows for uncertainties in calculating losses, for minor repairs, and for minor degradation of system components. Uncertainties are inevitable because component losses are specified within ranges and because components change as they age and are used. Margin also allows for repairs in case of cable damage, which typically add to cable loss.

Depending on the application, the performance requirements, the cost, and the ease of repair, the loss margin added by designers may be 3 to 10 dB.

Optical Amplifiers

Optical amplifiers boost signal strength.

Optical amplifiers can overcome losses by boosting signal strength, but practical concerns may offset this advantage. Optical amplifiers are expensive, and as analog devices inevitably amplify background noise as well as signal. On the other hand, they can amplify gigabit signals and multiple wavelengths in their operating ranges. Thus they are mainly used in high-performance and WDM systems, where their high cost can be spread among many signals being amplified.

You can use optical amplifiers in several places:

- As postamplifiers after transmitters, to generate high-power signals in fibers
- In the middle of long transmission systems, to boost signal strength for further transmission
- As preamplifiers before receivers, to raise signal strength to the proper level for the receiver
- Before or after couplers, which divide input signals among many outputs.

Examples of Loss Budgeting

To see how *loss budgeting* works, I'll step through three simple examples. Example A, shown in Figure 21.4, is a short system transmitting 100 Mbit/s between two points in a building. Example B, shown in Figure 21.5, is a telephone system carrying 2.5 Gbit/s between two switching offices 300 km apart. Example C, shown in Figure 21.6, is an intrabuilding network linking 10 terminals with each other at a signal speed of 100 Mbit/s. The examples are arbitrary and are intended to show how design works rather than to illustrate actual systems. Note that in considering only the loss budget, you don't directly address whether or not the system can carry the data rate listed. We'll look at that issue later in this chapter.

Connectors can contribute the dominant losses if several are in a short system.

Example A

In Figure 21.4, designers need to transmit signals through 200 m of fiber already installed in a building. That means that they must route the signal through patch panels with

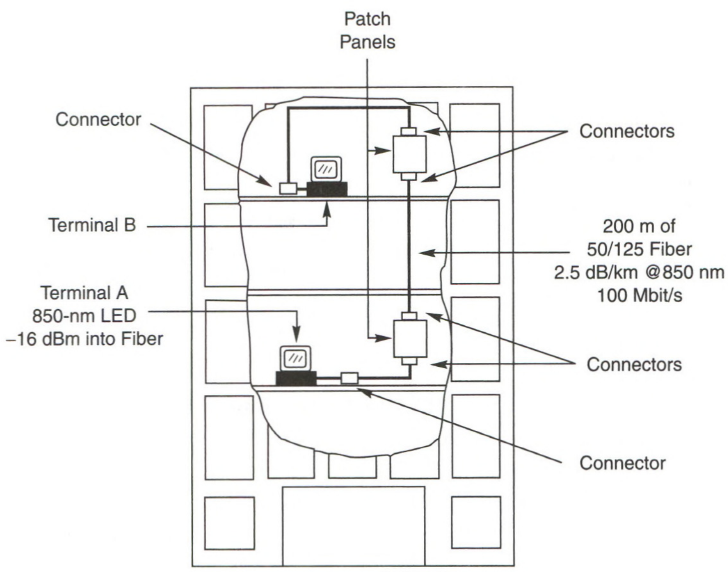

FIGURE 21.4
Example A: Point-to-point link in a building.

connectors. In this example, they have six connector pairs, three on each floor: one linking the terminal device to the cable network for that floor, and one pair on each end of a short cable in the patch panel. (Connectors also attach the fiber to transmitter and receiver, but their losses are included under LED power transfer and receiver sensitivity.) The 50/125 graded-index multimode fiber has attenuation of 2.5 dB/km at the 850-nm wavelength of the LED transmitter. The loss budget is as follows:

LED power into fiber	−16.0 dBm
Connector pairs (6 @ 0.7 dB)	− 4.2 dB
Fiber loss (200 m @ 2.5 dB/km)	−0.5 dB
System margin	−10.0 dB
Required receiver sensitivity	−30.7 dBm

The calculation shows that the dominant loss is from the connectors. The fiber loss may underestimate transient loss, but the large system margin leaves plenty of room.

The calculated receiver sensitivity is a reasonable level, and system margin could be improved by picking a more sensitive receiver. This calculation started with a given loss, system margin, and input power, but you could start by specifying receiver sensitivity, system margin, and loss to calculate the needed input power. Note that the LED transmitter provides a low input power, but that is adequate for this short system.

Example B

Fiber attenuation dominates loss in a 300-km fiber system.

Loss sources in the telephone system shown in Figure 21.5 are quite different. The system spans 300 km, with one splice every 10 km in a single-mode fiber with loss of 0.25 dB/km

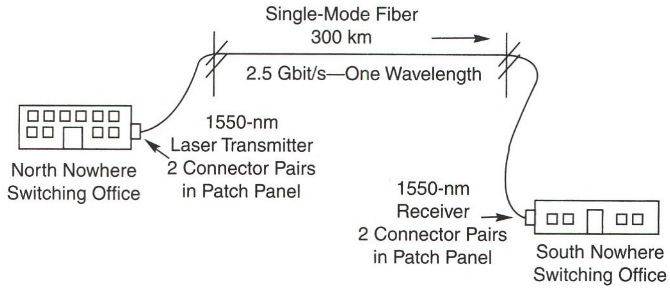

FIGURE 21.5
Example B: 300-km single-mode fiber system.

at 1550 nm. It links two rural areas, carrying a single wavelength at 2.5 Gbit/s. The high speed and long distance demand a laser source and a more sensitive receiver. Signals go through two connector pairs in patch panels at each end. Although the fiber loss is very low at 1550 nm, the long distance makes fiber attenuation the dominant loss. The sample calculation shows the laser transmitter alone does not deliver enough power to span that distance:

Laser power into single-mode fiber	0.0 dBm
Fiber loss (300 km × 0.25 dB/km)	−75.0 dB
Splice loss (29 × 0.1 dB)	−2.9 dB
Connector pairs (4 × 0.8 dB)	−3.2 dB
Power at receiver	−81.1 dBm
Receiver sensitivity	−32.0 dBm
System power deficit	−49.1dB

The output power falls far short of system requirements. You need optical amplifiers. Suppose you add a pair of optical amplifiers with 30-dB gain, one at the 100-km point and the second at 200 km. This requires four extra connector pairs (one on each end of each optical amplifier), which replace two splices. The loss budget then becomes:

Laser power into single-mode fiber	0.0 dBm
Fiber loss (300 km × 0.25 dB/km)	−75.0 dB
Optical amplifier gain	60.0 dB
Splice loss (27 × 0.1 dB)	−2.7 dB
Connector pairs (8 × 0.8 dB)	−6.4 dB
Power at receiver	−24.1 dBm
Receiver sensitivity	−32.0 dBm
System power margin	7.9 dB

That looks much better. To verify that the loss budget works for the whole system, you should check the budget for each segment.

Segment 1:

Laser power into single-mode fiber	0.0 dBm
Fiber loss (100 km × 0.25 dB/km)	−25.0 dB
Splice loss (9 × 0.1 dB)	−0.9 dB
Connector pairs (3 × 0.8 dB)	−2.4 dB
Power at optical amplifier	−28.3 dBm
Gain of optical amplifier	30.0 dB
Output of segment 1	1.7 dBm

Segment 2:

Optical amplifier into single-mode fiber	1.7 dBm
Fiber loss (100 km × 0.25 dB/km)	−25.0 dB
Splice loss (9 × 0.1 dB)	−0.9 dB
Connector pairs (2 × 0.8 dB)	−1.6 dB
Power at optical amplifier 2	−25.8 dBm
Gain of optical amplifier	30.0 dB
Output of segment 2	4.2 dBm

Segment 3:

Laser power into single-mode fiber	4.2 dBm
Fiber loss (100 km × 0.25 dB/m)	−25.0 dB
Splice loss (9 × 0.1 dB)	−0.9 dB
Connector pairs (3 × 0.8 dB)	−2.4 dB
Power at receiver	−24.1 dBm
Receiver sensitivity	−32.0 dBm
System power margin	7.9 dB

For our purposes, 7.9 dB seems an adequate power margin. In practice, the system margin probably will be better, because I have assumed a relatively high connector loss of 0.8 dB and a low laser output of 0 dBm.

Segment-by-segment calculations both check your result and make sure that placement of optical amplifiers doesn't get you into trouble. In practice, optical amplifiers saturate at high powers, so you may get only 25 dB of gain with 20 dBm input. In this example, suppose you put the second optical amplifier at the 170-km point because you happen to have a storage building at that point. Then the calculations for segments 2 and 3 are as follows:

Segment 2:

Optical amplifier into single-mode fiber	1.7 dBm
Fiber loss (70 km × 0.25 dB/km)	−17.5 dB
Splice loss (6 × 0.1 dB)	−0.6 dB
Connector pairs (2 × 0.8 dB)	−1.6 dB
Power at optical amplifier 2	−18.0 dBm
Reduced gain of optical amplifier	25.0 dB
Output of segment 2	7.0 dBm

Segment 3:

Laser power into single-mode fiber	7.0 dBm
Fiber loss (130 km × 0.25 dB/m)	−32.5 dB
Splice loss (12 × 0.1 dB)	−1.2 dB
Connector pairs (3 × 0.8 dB)	−2.4 dB
Power at receiver	−29.1 dBm
Receiver sensitivity	−32.0 dBm
System power margin	2.9 dB

Although the receiver power is above the required level, a system margin of 2.9 dB is inadequate for contingencies. This is a reminder that you can't simply add up the losses and gains of all components without considering the input conditions to components such as optical amplifiers.

Example C

Coupling losses are largest in a network distributing signals to many terminals.

Complications also arise when you have to divide input signals among many outputs, as shown in Figure 21.6. In this case, you need to connect 10 terminals so the output of each one is divided among the receivers of all 10 terminals. You can do this with a 10 × 10 directional star coupler, which divides an input signal from any of the 10 incoming fibers (one from the transmitter end of each terminal) among the 10 output fibers going to the receiver end of each terminal. Assume the coupler divides the signals equally and has excess loss of 3 dB. Because the data rate is a modest 100 Mbit/s, let's calculate the loss budget with an LED source.

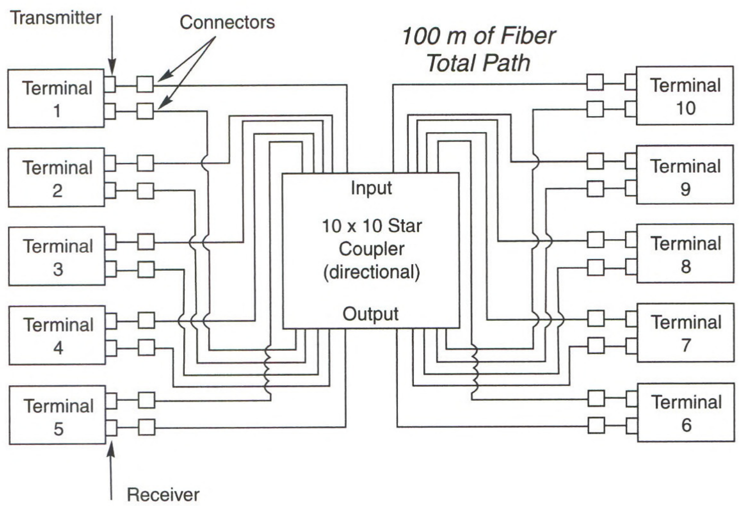

FIGURE 21.6 *Example C: 10-terminal network.*

LED transmitter (850 nm)	−16.0 dBm
Fiber loss (100 m @ 2.5 dB/km)	−0.25 dB
Connector pair loss (2 @ 0.5 dB)	−1.0 dB
Coupler loss (includes its own connections)	−13.0 dB
Power at receiver	−30.25 dBm
Receiver sensitivity	−30.0 dBm
System power deficit	−0.25 dB

The calculations show we are in trouble, with a negative system margin of –0.25 dB. The system might work, but we're right at the threshold of receiver sensitivity. As the system ages, performance will only get worse. We need to do something else.

A single component, the coupler, dominates the loss budget, but it is not easy to eliminate because it is needed to distribute the signal to all terminals. One way to overcome the power deficit is by replacing the LED with a more powerful VCSEL source. In this case, the power budget becomes

VCSEL transmitter (850 nm)	0.0 dBm
Fiber loss (100 m @ 2.5 dB/km)	−0.25 dB
Connector pair loss (2 @ 0.5 dB)	−1.0 dB
Coupler loss (includes its own connections)	−13.0 dB
Power at receiver	−14.25 dBm
Receiver sensitivity	−30.0 dBm
System power margin	15.75 dB

This may be too much of a good thing, depending on the power level that overloads the receiver. If the receiver overloads at −15 dBm, you can add a 3-dB attenuator to bring the receiver power down to −17.25 dBm, well within the operating range of −15 to −30 dBm. An alternative is to use a lower-power VCSEL, with output of −5 dBm. In this, the power budget becomes:

VCSEL transmitter	−5 dBm
Fiber loss (10 m @ 2.5 dB/km)	−0.25 dB
Connector pair loss (2 @ 0.5 dB)	−1.0 dB
Coupler loss (includes its own connectors)	−13.0 dB
Power at receiver	−19.25 dBm
Receiver sensitivity	−30.0 dBm
System power margin	10.75 dB

This should avoid overloading the receiver without the need for an attenuator.

Transmission Capacity Budget

Bandwidth or bit rate depends on fiber, source, and receiver characteristics.

The transmission capacity of a fiber-optic system is the total analog bandwidth or digital data rate it can carry. With wavelength-division multiplexing, total capacity of a fiber is the sum of the capacities of all optical channels the fiber carries. In this section, we will cover only the transmission capacity of a single optical channel; Chapter 22 will cover multi-channel systems.

Single-channel capacity depends on how fast all the parts of the system respond to changes in signal intensity. In practice, transmission speed is mainly affected by properties of the transmitter, fiber, and receiver. For simplicity, I will ignore secondary effects such as noisy amplifiers and nonlinear effects that also can restrict data rates.

The simplest way to calculate transmission capacity is from the time response or rise time of the signal in the important components. This corresponds to the rise time of a transmitter or receiver, and dispersion in a fiber. As you will see below, this response is cumulative, and as you saw in Chapter 5, it is the sum of the squares of the responses of the various components.

Bandwidth and data rate can be calculated from rise time.

Both analog bandwidth and digital bit rate are related to the time response or rise time, although the relationships are approximate and depend on details.

For an analog system, the 3-dB bandwidth B in megahertz is inversely proportional to the rise time Δt in nanoseconds

$$B(\text{MHz}) = \frac{350}{\Delta t\,(\text{ns})}$$

Thus an analog system with 1-ns rise time has a roughly 350-MHz bandwidth.

For NRZ-coded digital signals, the rise time can be as large as 0.7 times the bit interval. If rise time is in nanoseconds, the maximum data rate in Gbit/s is

$$\text{NRZ data rate (Gbit/s)} = \frac{0.7}{\Delta t\,(\text{ns})}$$

Thus a digital system with 1-ns rise time can support an NRZ data rate of roughly 700 Mbit/s. RZ codes require double the bandwidth or rise times twice as fast:

$$\text{RZ data rate (Gbit/s)} = \frac{0.35}{\Delta t\,(\text{ns})}$$

These relationships are not exact, but they are useful for rough calculations.

The speed limits on digital signals are often easier to understand. You can get an intuitive feel for the impact of response time on a digital signal by thinking about pulse detection. If pulses follow each other at a certain speed, you need to be able to detect a pulse in less time than the interval between pulses.

Overall Time Response

The choice of time response or rise time simplifies calculations. The overall time response of a system is the square root of the sum of the squares of the response times of individual components:

Overall time response is the square root of the sum of the squares of component rise times.

$$\Delta t_{\text{overall}} = \sqrt{\sum (\Delta t_i^2)}$$

where $\Delta t_{\text{overall}}$ is the overall time response and Δt_i is the time response of each component.

Connectors, splices, couplers, and optical amplifiers do not affect time response significantly in current systems. The important response times are those of the transmitter, receiver, and fiber:

$$\Delta t_{\text{overall}} = \sqrt{\Delta t^2_{\text{transmitter}} + \Delta t^2_{\text{receiver}} + \Delta t^2_{\text{fiber}}}$$

That is, the overall response time is the square root of the sum of the squares of transmitter rise time, receiver rise time, and the pulse spreading caused by fiber dispersion.

Transmitter and receiver rise and fall times are listed on data sheets, ready to plug into the formula. Fiber response times must be calculated from the fiber's dispersion properties. You can see how transmitter and receiver properties affect data rate if we assume dispersion is small. Suppose we have a short data link spanning only 20 m of fiber, so we can neglect dispersion. If transmitter and receiver rise times are both 1 ns, the overall response time is:

$$\Delta t_{\text{overall}} = \sqrt{\Delta t^2_{\text{transmitter}} + \Delta t^2_{\text{receiver}}} = \sqrt{2} = 1.414\ \text{ns}$$

Going back to the earlier formula for maximum data rate, we see it is:

$$\text{Data rate (Gbit/s)} = \frac{0.7}{1.4\ (\text{ns})} = 0.5\ \text{Gbit/s}$$

If one component is much slower than the other, it dominates the response time. For example, if the transmitter had 1-ns rise time but the receiver had a 10-ns response, the overall response time would be 10.05 ns, limiting data rate to 70 Mbit/s.

Fiber dispersion becomes important in longer systems and deserves a closer look.

Fiber Dispersion Effects

Fiber response times must be calculated from the fiber length, the characteristic dispersion per unit length, and the source spectral width. As you learned earlier, fibers show modal, material, and polarization-mode dispersion. Which types are most important depends on

Fiber response must be calculated from dispersion.

the type of fiber. In multimode fibers, modal dispersion and chromatic dispersion are important. In single-mode fibers, modal dispersion is zero, but chromatic dispersion and polarization-mode dispersion are significant. (Remember that chromatic dispersion is the sum of material and waveguide dispersion.)

You estimate total pulse spreading caused by dispersion with a sum-of-squares formula similar to that for overall time response:

$$\Delta t = \sqrt{\Delta t_{\text{modal}}^2 + \Delta t_{\text{chromatic}}^2 + \Delta t_{\text{PMD}}^2}$$

In practice, this can be simplified. For multimode fibers, polarization-mode dispersion is insignificant, so only modal and chromatic dispersions are considered. Single-mode fibers do not suffer modal dispersion, so only chromatic and polarization-mode dispersions are considered. In practice, polarization-mode dispersion is negligible for data rates below 2.5 Gbit/s.

The equation can be converted to units of dispersion by substituting values of the pulse spreading for each type of dispersion. Modal dispersion is a characteristic value D_{modal} (specified in ns/km) times fiber length (in km). Chromatic dispersion is a characteristic value $D_{\text{chromatic}}$ (specified in ps/km-nm) times the fiber length (in km) and the spectral width of the transmitter (in nm). Polarization-mode dispersion is more complex because it varies randomly in time, but an average value is obtained by multiplying the nominal characteristic value D_{PMD} (specified in ps/root-km) by the square root of fiber length (in km).

Plugging these quantities into the pulse-spreading equation gives different formulas for multimode and single-mode fibers, based on fiber-dispersion properties, fiber length L, and spectral width of the light source $\Delta\lambda$. For multimode fiber, the pulse spreading is:

$$\Delta t_{\text{multimode}} = \sqrt{(D_{\text{modal}} \times L)^2 + (D_{\text{chromatic}} \times L \times \Delta\lambda)^2}$$

For single-mode fiber, this formula is:

$$\Delta t_{\text{single mode}} = \sqrt{(D_{\text{chromatic}} \times L \times \Delta\lambda)^2 + (\mathrm{D}_{\text{PMD}} \times \sqrt{L})^2}$$

A couple of examples will show how dispersion calculations work.

MULTIMODE DISPERSION EXAMPLE

In Example A, considered earlier in this chapter, an 850-nm LED sends 100 Mbit/s through 200 m of 50/125-μm fiber. Modal bandwidth of a typical commercial 50/125-μm fiber is 400 MHz, which is equivalent to a modal dispersion of 2.5 ns/km. For a 200-m length, that corresponds to modal dispersion of 0.5 ns.

To that, you add the chromatic dispersion, calculated from the formula:

$$\Delta t_{\text{chromatic}} = D_{\text{chromatic}} \times L \times \Delta\lambda$$

A typical value of chromatic dispersion is 100 ps/nm · km at 850 nm, which combined with a linewidth of 50 nm for a typical 850-nm LED gives a chromatic dispersion of 1.0 ns for a 200-m length of fiber. This means that the chromatic dispersion is higher than modal dispersion because of the large LED spectral linewidth.

Adding modal and chromatic dispersions together according to the sum-of-squares formula indicates total dispersion is 1.1 ns. That leaves plenty of room for transmitting 100 Mbit/s, assuming the transmitter and receiver are fast enough.

If you wanted to transmit 1 Gbit/s, you could try using a VCSEL source with a 1-nm linewidth. In that case, total dispersion is

$$\Delta t = \sqrt{(0.5\ \text{ns})^2_{\text{modal}} + (100\ \text{ps/nm} \cdot \text{km} \times 0.2\ \text{km} \times 1\ \text{nm})^2} = 0.50\ \text{ns}$$

This is essentially equal to the modal dispersion of 0.5 ns and is adequate for gigabit transmission over 200 m.

SINGLE-MODE TRANSMISSION EXAMPLE

In Example B, we considered transmitting a 2.5-Gbit/s signal a total of 300 km through a single-mode fiber at 1550 nm. Assume that chromatic dispersion is specified at 3 ps/nm·km, a relatively low value at 1550 nm. Let's consider two cases: a Fabry-Perot laser with linewidth of 1 nm and an externally modulated distributed-feedback laser with linewidth of 0.1 nm. For a first approximation, ignore polarization-mode dispersion.

For the 1-nm laser, chromatic dispersion is

$$\Delta t_{\text{chromatic}} = 3\ \text{ps/nm} \cdot \text{km} \times 300\ \text{km} \times 1\ \text{nm} = 900\ \text{ps}$$

This value is much too high for a 2.5-Gbit/s system.

With the distributed-feedback laser, chromatic dispersion is

$$\Delta t_{\text{chromatic}} = 3\ \text{ps/nm} \cdot \text{km} \times 300\ \text{km} \times 0.1\ \text{nm} = 90\ \text{ps}$$

Thus using fiber with low chromatic dispersion near 1550 nm leaves plenty of margin. However, you could not get away with using step-index single-mode fiber with dispersion around 20 ps/nm-km at 1550 nm.

$$\Delta t_{\text{chromatic}} = 20\ \text{ps/nm-km} \times 300\ \text{km} \times 0.1\ \text{m} = 600\ \text{ps}$$

We also need to consider polarization-mode dispersion. A typical value for new nonzero dispersion-shifted fiber is about 0.5 ps/root-km, so for 300 km of single-mode fiber, the average polarization-mode dispersion is

$$\Delta t_{\text{PMD}} = 0.5\ \text{ps}/\sqrt{\text{km}} \times \sqrt{300\ \text{km}} = 8.7\ \text{ps}$$

This is only a tenth as large as chromatic dispersion, so it makes a negligible contribution to total dispersion, and does not affect transmission at 2.5 Gbit/s.

To fully assess performance of the system, you need to consider transmitter and receiver rise time as well. Suppose both have rise times of 100 ps, reasonable for products designed to work at 2.5 Gbit/s. Then the total pulse spreading is

$$\Delta t = \sqrt{100^2 + 100^2 + 90^2} = 168\ \text{ps}$$

Our earlier formula shows that this is adequate for transmitting 4 Gbit/s.

LONG-DISTANCE SINGLE-MODE EXAMPLE

Dispersion poses more problems at long distances.

Long-distance systems must span longer distances of several hundred to several thousand kilometers. Dispersion poses more problems in these systems because the total pulse spreading increases with the length of the system. The seriousness of dispersion effects also increases with data rate.

Suppose you are using nonzero dispersion-shifted fiber with a chromatic dispersion of 3 ps/km-nm and PMD of 0.5 ps/root-km to span a distance of 1000 km. As in the last example, you are using an externally modulated laser with spectral width of 0.1 nm. Plug in the numbers and you find:

$$\Delta t_{\text{chromatic}} = 3 \text{ ps/nm} \cdot \text{km} \times 1000 \text{ km} \times 0.1 \text{ nm} = 300 \text{ ps}$$
$$\Delta t_{\text{PMD}} = 0.5 \text{ ps}/\sqrt{\text{km}} \times \sqrt{1000 \text{ km}} = 15.8 \text{ ps}$$
$$\Delta t_{\text{total}} = \sqrt{300^2 + 15.8^2} = 300.4 \text{ ps}$$

This response time is too long to allow good transmission at 2.5 Gbit/s, according to the criteria described earlier. This means that some form of dispersion compensation is needed to reduce average chromatic dispersion along the length of the fiber so it can carry 2.5 Gbit/s.

Things get even more difficult at 10 Gbit/s. If you flip the formula for maximum NRZ data rate to show the maximum allowable pulse spreading for a given data rate, you get

$$\Delta t_{\text{maximum}} = \frac{0.7}{\text{Data rate}}$$

For a 10 Gbit/s signal, this gives a maximum pulse spreading of 70 ps, which requires considerably more dispersion compensation. Let's assume that the transmitter bandwidth remains 0.1 nm, although high-speed modulation can increase this number. Suppose we can reduce the average chromatic dispersion by a factor of 5, to 0.6 ps/nm·km. Using the same assumptions above gives us:

$$\Delta t_{\text{chromatic}} = 0.6 \text{ ps/nm} \cdot \text{km} \times 1000 \text{ km} \times 0.1 \text{ nm} = 60 \text{ ps}$$
$$\Delta t_{\text{PMD}} = 0.5 \text{ ps}/\sqrt{\text{km}} \times \sqrt{1000 \text{ km}} = 15.8 \text{ ps}$$
$$\Delta t_{\text{total}} = \sqrt{60^2 + 15.8^2} = 62 \text{ ps}$$

That figure is adequate if you only consider fiber response, but you also have to consider transmitter and receiver rise times. If they both equal 25 ps—very fast devices—that would bring the total pulse spreading to the 70 ps limit. You might want average chromatic dispersion reduced even further, to about 0.3 ps/nm · km.

So far we have assumed polarization-mode dispersion is fairly benign by using specifications for new fibers fresh from the factory. However, older fibers or fibers installed under less than ideal conditions may have higher polarization-mode dispersion. Suppose we want to use older fibers with a realistic value of 2 ps/root-km for polarization-mode dispersion. Those calculations give us:

$$\Delta t_{\text{chromatic}} = 0.6 \text{ ps/nm} \cdot \text{km} \times 1000 \text{ km} \times 0.1 \text{ nm} = 60 \text{ ps}$$
$$\Delta t_{\text{PMD}} = 2 \text{ ps}/\sqrt{\text{km}} \times \sqrt{1000 \text{ km}} = 63.2 \text{ ps}$$
$$\Delta t_{\text{total}} = \sqrt{60^2 + 63.2^2} = 87 \text{ ps}$$

This produces polarization-mode dispersion slightly larger than the chromatic dispersion, and yields a total pulse spreading too high for 10 Gbit/s transmission, even ignoring transmitter and receiver rise times.

Dispersion Compensation

As these examples show, dispersion compensation becomes essential as transmission speeds and distances increase.

Dispersion compensation becomes important at high speeds or over long distances.

Compensation is easiest for chromatic dispersion. As you learned in Chapter 5, chromatic dispersion has a characteristic sign that indicates whether the shorter or longer wavelengths have gone farther in the fiber. To compensate for chromatic dispersion, you add a length of fiber (or some other optical component) with dispersion of the opposite sign. If the shorter wavelengths are falling behind, adding a length of fiber that makes the longer wavelengths fall behind serves to compress the length of the output pulse.

One approach to chromatic dispersion compensation is by alternating segments of fiber with a different dispersion sign, as shown in Figure 21.7. In this example, one fiber has a positive dispersion and the other a negative dispersion that is smaller in magnitude. This mixture is possible by using two types of nonzero dispersion-shifted fibers, one with zero dispersion at wavelengths shorter than the 1550-nm band, the other with zero dispersion at longer wavelengths. Optical signals pass through alternating segments of the two fibers, so the cumulative chromatic dispersion is first negative, then shifts positive, and so on. This is called *distributed compensation,* because the fibers that compensate for the pulse spreading are distributed along the fiber segment. In this example, the dispersions of the two fibers do not differ greatly in magnitude, but do differ in sign.

An alternative is to insert dispersion-compensation modules at selected points along the length of the system. Each module has chromatic dispersion opposite in sign to that of a certain length of the transmission fiber, so one module might compensate for 20 km of

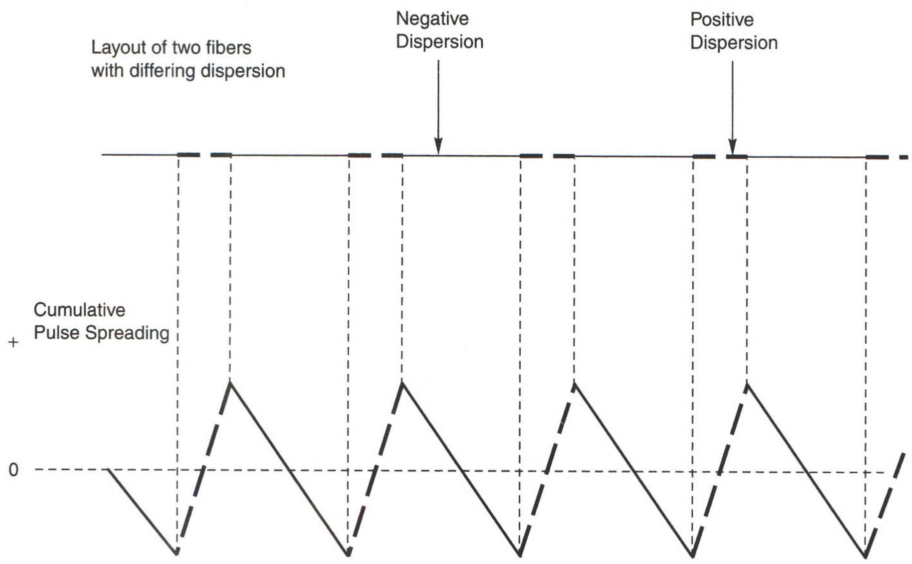

FIGURE 21.7 *Dispersion compensation distributed along length of system.*

dispersion. Modules can be built with fiber Bragg gratings that provide dispersion compensation. However, they more typically consist of easy-to-install coiled fibers designed specifically for dispersion compensation, which have chromatic dispersion higher in magnitude but opposite in sign to that of the transmission fiber. Chromatic dispersion in compensating fibers typically is several times larger than it is in transmission fibers, so shorter lengths are required. That's an advantage because compensating fibers generally have poorer transmission.

It is relatively simple to compensate chromatic dispersion at one wavelength to give a net chromatic dispersion of zero along a fiber segment, as shown in Figure 21.7. It is virtually impossible to compensate for chromatic dispersion across a wide range of wavelengths, as you will learn in Chapter 22.

Compensation for polarization-mode dispersion is very difficult. Unlike chromatic dispersion, PMD is a dynamic effect, which means its degree varies randomly over time. Thus PMD compensation also must be dynamic, with automatic adjustment over time. Both optical and electronic techniques have been demonstrated in the lab, but they are not yet widely accepted or in practical use.

Transmitter and Receiver Response Times

Transmitters and receivers must be matched to fiber characteristics.

So far I have concentrated on fiber dispersion, but transmitter and receiver response times also play critical roles in system bandwidth budgets. Just because a transmitter and receiver are rated to operate at 10 Gbit/s in some situations does not mean they can transmit at that speed in *all* systems. For example, a transmitter and receiver, both having 40 ps rise times, can transmit 10 Gbit/s signals through fiber with up to 40 ps of cumulative pulse spreading. However, they couldn't be used in the example I showed earlier, where total pulse spreading in the fiber was 62 ps. That would require a faster transmitter and receiver, with response times around 25 ps.

For this reason manufacturers sell different models of transmitters and receivers for transmission at the same data rates through different types of fibers. Transmitter–receiver pairs intended for short-distance use do not have to meet the same stringent speed requirements as those used for long-distance systems. In short, you have to match transmitters and receivers to the fiber system used to assure you get the desired transmission speed.

To show you how time-response calculations work, I have chosen simple examples. In reality there are a few other complications that come from the nature of transmitters and receivers. In particular, the range of wavelengths from transmitters is broadened by a couple of distinct effects.

Transmitter Spectral Broadening

As you learned earlier, directly modulating a semiconductor laser changes its refractive index as the density of current carriers changes. This effect, called *chirp*, causes the resonant wavelength to shift during a pulse, effectively spreading the range of output wavelengths. A laser that emits a bandwidth of 0.001 nm in a continuous beam spans a much larger range when directly modulated. External modulation can avoid chirp.

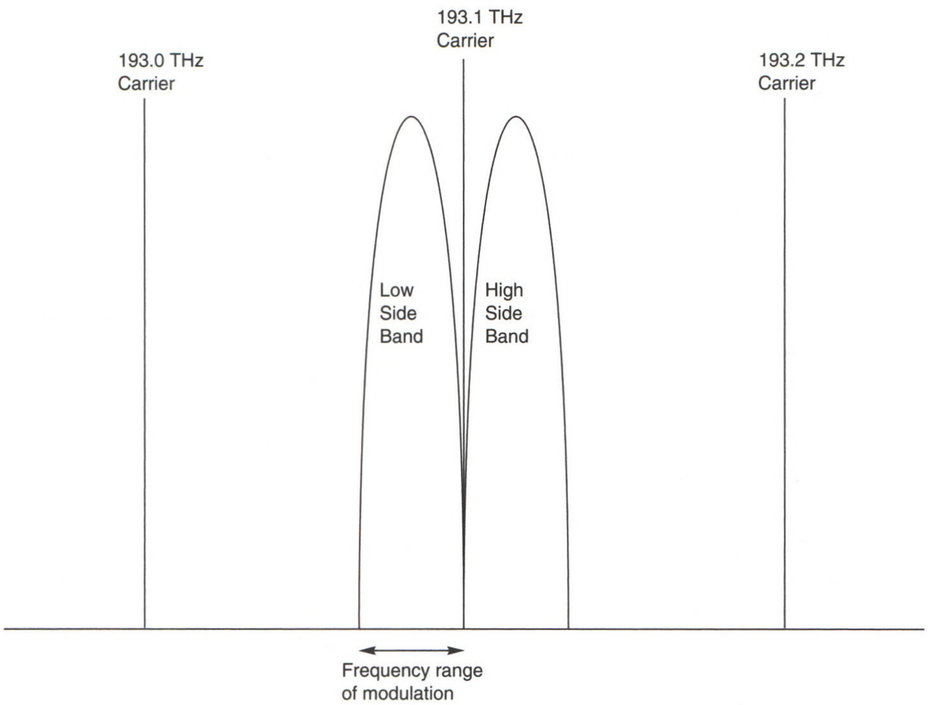

FIGURE 21.8
Modulation broadening is caused by side bands generated by the modulating signal.

External modulation cannot prevent a second type of spectral broadening that arises from any amplitude modulation of a pure carrier signal. The same effect occurs with radio. Modulation generates new frequency components by adding (and subtracting) the frequency of the modulating signal to the carrier frequency, as shown in Figure 21.8. This process generates *side bands* at frequencies both above and below the carrier.

Modulation broadens the wavelengths in an optical carrier.

The two side bands contain identical information, so radio transmitters generally suppress one side band to conserve scarce frequency space. Side-band suppression is difficult at optical wavelengths, so normally both side bands are present. The result is an effective broadening of the transmitter spectrum that increases directly with the bandwidth. If modulation produces a 10-GHz range of frequencies, it generates 10-GHz side bands on each side for a total spectral range of 20 GHz. This affects both chromatic dispersion in the fiber and the channel spacing possible in DWDM systems.

Cost/Performance Trade-offs

So far I have only mentioned in passing a critical concern in real-world system design—cost. Minimizing cost is an implicit goal in all system design. I list some simple guidelines below, but it is impossible to give hard-and-fast rules for the tough job of making trade-offs between cost and performance. Ultimately it is your judgement as a system buyer or designer whether pushing error rate from 10^{-9} to 10^{-12} is worth an extra $1000. The best I can give you are some ideas to apply in working situations.

Users must make cost/performance trade-offs.

Choice of Fiber Type

The choice of fiber type is crucial.

The choice of fiber type has a tremendous impact on the cost and performance of any system. A fundamental choice is between single- and multimode fiber, but several variations on both types are available. Installation is expensive, so you want to allow room for your system to expand. Bandwidth requirements inevitably increase, just as each new generation of software demands more computer memory and hard-disk space.

You need single-mode fiber if your system spans more than a couple of kilometers. Premium types, preferred for amplified WDM systems, are nonzero dispersion-shifted fibers, with low dispersion through the 1550-nm erbium amplifier window. Some single-mode fibers are optimized for "metro" applications over distances to a few hundred kilometers; others are optimized for terrestrial long-haul or submarine systems. Step-index single-mode fiber, with zero dispersion near 1310 nm, is still common, but normally is used at shorter distances because of its high dispersion at 1550 nm. Low-water fibers have a broader transmission window where amplification is not critical.

Single-mode fiber sometimes is used at distances shorter than a couple of kilometers, especially for high-speed transmission, such as 10-Gigabit Ethernet.

Graded-index multimode fibers are normally preferred for networks where transmission distances are up to a couple of kilometers, speeds are moderate, and many connections are required. Their big advantage is easier coupling to each other and to low-cost light sources. Bandwidth is significantly higher for 50/125-μm fiber than for 62.5/125-μm fiber. Remember that transmission speeds are sure to increase, so plan for future capacity expansion.

Plastic fibers and large-core step-index multimode fibers have very limited distance ranges. Plastic fibers have high attenuation, and large-core multimode fibers have low bandwidth. Their applications remain limited, but they can be valuable in certain situations, such as short data links inside equipment.

Other Guidelines

It's impossible to give a comprehensive set of guidelines for fiber system design, but I can give a set of rough-and-ready suggestions, starting with a few common-sense rules:

Don't forget to apply common sense in system design. Labor is never free.

- Your time is valuable. If you spend an entire day trying to save $5 on hardware, the result will be a net loss unless you are mass-producing the design.
- Installation, assembly, operation, and support are not free. For a surprising number of fiber-optic systems, installation and maintenance cost more than the hardware. You may save money in the long term by paying extra for hardware that is easier to install and service.
- It can cost less to pay an expert to do it than to learn how yourself. Unless you need to practice installing connectors, it's much easier to buy connectorized cables or hire a fiber-optic contractor for your first fiber-optic system.
- You can save money by using standard mass-produced components rather than developing special-purpose components optimized for a particular application.

Some basic cost trade-offs are common in designing fiber-optic systems.

- The performance of low-loss fiber, high-sensitivity detectors, and powerful transmitters must be balanced against price advantages of lower-performance devices.
- Low-loss, high-bandwidth fibers generally accept less light than higher-loss, lower-bandwidth fibers. Over short distances, you can save money and overall attenuation by using a higher-loss, more costly cable that collects light more efficiently from lower-cost LEDs. (Because of the economics of production and material requirements, large-core multimode fibers are considerably more expensive than step-index single-mode fibers.)
- The marginal costs of adding extra fibers to a cable are modest and much cheaper than installing a second parallel cable. However, if reliability is important, the extra cost of a second cable on a different route is a worthwhile insurance premium.
- LEDs are much cheaper and require less environmental protection than lasers, but they produce much less power and are harder to couple to small-core fibers. Their broad range of wavelengths and their limited modulation speed limit system bandwidth.
- Fiber attenuation contributes less to losses of short systems than do losses in transferring light into and between fibers.
- Topology of multiterminal networks can have a large impact on system requirements and cost because of their differences in component requirements. Coupler losses may severely restrict options in some designs.
- Light sources and detectors for 1300 and 1550 nm cost more than those for the 650- or 800- to 900-nm windows, although fiber and cable for the longer wavelength may be less expensive.
- 1550-nm light sources cost more than 1300-nm sources.
- Fiber and cable become a larger fraction of total cost—and have more impact on performance—the longer the system.
- Balance the advantages of eliminating extra components with the higher costs of the components needed to eliminate them. For example, it's hard to justify the expense of two-way transmission through a single fiber over short distances.
- Optical amplifiers or high-power laser transmitters make sense in systems distributing signals to many terminals.
- Compare costs of high-speed TDM on single channels or lower-speed TDM at multiple wavelengths.
- *Dark fibers*—extra fibers installed in the original cable that were never hooked up to light sources—are often available in existing cables.
- Remember that human actions—not defective equipment—cause most fiber-optic failures. Consider ring or mesh topologies that can survive a single break. Take the extra time and spend the extra money to make important systems less vulnerable to damage. This means labeling and documenting the system carefully, as well as not leaving cables where people can trip over them.

Always leave room for future upgrades. Bandwidth requirements are sure to increase, and it costs less overall to install higher-capacity fiber now than to install a cheap one that you have to replace with a more expensive one later.

- Install extra fibers in your cables; they're a lot cheaper than going back later to install more cables.
- Leave margin for repair, such as slack in cables. It costs much less than complete replacement later.
- Leave room for expansion by adding WDM to your system.
- Watch for potential bottlenecks that might prevent future expansion.

As you grow more familiar with fiber optics, you will develop your own guidelines based on your own experience.

What Have You Learned?

1. Design of fiber-optic systems requires balancing sometimes-conflicting performance goals as well as costs.
2. The system loss budget is calculated by subtracting all system losses from the transmitter output power plus the gain of any optical amplifiers. The resulting output power should equal the input power required by the receiver plus system margin.
3. Significant losses can occur in coupling light from sources into fibers. You need multimode fibers to collect light from LED sources and single-mode fibers to collect light from edge-emitting laser sources. Large-core fibers are more efficient for large-area LEDs.
4. Total fiber loss equals attenuation (dB/km) multiplied by transmission distance. Multimode fibers may suffer transient losses in the first 100 to 200 m.
5. Total loss from connectors, couplers, and splices is their characteristic loss multiplied by the number of each in the system. You calculate the most likely loss using average loss and the worst case using maximum specified loss.
6. System margin is a safety factor that allows for repairs and aging of components. Typical values are 5 to 10 dB.
7. Optical amplifiers boost signal strength, but because of their high cost they are best used in long, high-speed systems or systems that distribute signals from one source to many receivers.
8. Transmission capacity budgets calculate bandwidth or bit rate; they depend only on source, fiber, and receiver characteristics. You can estimate capacity by calculating response time.
9. Response time of a system is the square root of the sum of the squares of component response times. Calculations must include transmitter and receiver response times as well as fiber dispersion.

10. Modal dispersion and chromatic dispersion combine to limit capacity of multimode fibers. Because of these capacity limits, multimode fibers are rarely used over more than a couple of kilometers.
11. Chromatic dispersion and polarization-mode dispersion limit capacity of single-mode fibers, which usually transmit over a kilometer or more. Chromatic dispersion depends on source spectral width as well as fiber dispersion.
12. Dispersion compensation becomes important at high speeds or over long distances. The compensating elements can be fibers distributed through the length of the system, or lumped at certain points.
13. Transmitters and receivers must be matched to fiber characteristics.
14. Modulation broadens the range of wavelengths in the optical carrier. The largest effect is chirp for directly modulated lasers, but external modulation also broadens transmitter spectral range.
15. Installation can cost much more than hardware. With demand for transmission capacity rising steadily, you should keep your upgrade paths open.

What's Next?

Chapter 22 covers the fundamentals of optical networking design, including wavelength-division multiplexing.

Further Reading

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

Gerd Keiser, *Optical Fiber Communications*, 3rd ed. (McGraw-Hill, 2000)

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

Questions to Think About

1. Why is the relative light-collection efficiency of fibers in decibels proportional to 20 times, rather than 10 times, the log of the ratio of their diameters?
2. Suppose the amplifiers in a transatlantic cable are limited to 12 dB of gain to limit noise. How far apart can they be spaced if the fiber attenuation averages 0.24 dB? You can neglect splices, and the system contains no connectors.
3. You are installing a fiber-optic data link between a laboratory and a remote data-collection center 5 km away. You want to use a VCSEL transmitter with −5 dBm output and a fiber with loss of 2.5 dB/km at 850 nm. The system includes patch panels on each end, with two connector pairs at each patch panel, and additional connectors on the terminal equipment. If connector loss is 0.5 dB, and you want a 10 dB margin, how sensitive must your receiver be?

4. You have to design a system with 1 Gbit/s data rate using return-to-zero (RZ) digital coding. What is the 3-dB analog bandwidth of this system? What NRZ data rate could this system transmit?
5. You want to transmit 1 Gbit/s through 100 km of single-mode fiber, using a transmitter and receiver that each have response times of 0.4 ns. The transmitter has line width of 0.1 nm. Neglecting polarization mode dispersion, what is the maximum chromatic dispersion allowable in the fiber?
6. Can you get away with using a 1550 nm VCSEL in the system of Problem 5 if the VCSEL has linewidth of 0.5 nm, output of −5 dBm, and the fiber loss is 0.25 dBm? (This assumes you can find such a VCSEL.) Check both the pulse spreading and the power level, assuming receiver sensitivity of −30 dBm.

Chapter Quiz

1. A large-area LED transfers 10 μW (10 dBμ) into an optical fiber with core diameter of 100 μm and numerical aperture of 0.30. What power should it couple into a fiber with 50 μm core and NA of 0.2?
   a. 10 dBμ
   b. 9.5 dBμ
   c. 3 dBμ
   d. 1.0 dBμ
   e. 0.4 dBμ
2. A connector is specified as having loss of 0.6 dB ± 0.2 dB. What is the maximum connector loss in a system containing five such connector pairs?
   a. 0.6 dB
   b. 3.0 dB
   c. 4.0 dB
   d. 5.0 dB
   e. none of the above
3. A 100-Mbit/s signal must be sent through a 100-m length of fiber with eight connector pairs to a receiver with sensitivity of −30 dBm. The fiber loss is 4 dB/km, and the average connector loss is 1.0 dB. If the system margin is 5 dB, what is the minimum power that the light source must couple into the fiber?
   a. −13.0 dBm
   b. −13.4 dBm
   c. −16.0 dBm
   d. −16.6 dBm
   e. −20.0 dBm
4. A system is designed to transmit 622 Mbit/s through 50 km of cable with attenuation of 0.4 dB/km. The system contains two connector pairs with 1.5 dB

loss, a laser source that couples 0 dBm into the fiber, and a receiver with sensitivity of −34 dBm. How many splices with average loss of 0.15 dB can the system contain if the system margin must be at least 8 dB?

a. none
b. 10
c. 20
d. 30
e. 40
f. none of the above

5. A 2.5-Gbit/system must span a distance of 2000 km, with optical amplifiers every 80 km. If the fiber loss is 0.3 dB/km at 1550 nm and there is one 0.1 dB splice every 16 km, what must the amplifier gain be if the system is not to gain or lose signal strength across its entire length?

a. 20 dB
b. 24.4 dB
c. 26.4 dB
d. 30 dB
e. 34.4 dB

6. You need to transmit identical 1-Gbit/s signals to 200 homes using a 1310-nm laser source. The homes are 1 to 4 km from your transmitter and use receivers sensitive to 30 dBm. What transmitter power do you need to achieve a 5-dB system margin if your fiber has a 0.4-dB/km loss at 1310 nm, each signal path from transmitter to home includes 6 connectors with a 0.5-dB average loss, and you split the signal in a 1 × 200 tree coupler with no excess loss?

a. 4.6 dBm
b. 9.6 dBm
c. 2.6 dBm
d. 0.0 dBm
e. −0.4 dBm

7. What is the duration of a single-bit interval in a 1.7-Gbit/s signal?

a. 1.7 ns
b. 1 ns
c. 0.588 ns
d. 0.294 ns
f. 0.170 ns

8. What is the response time of a system with transmitter response of 2 ns, receiver response of 1 ns, and 100 m of multimode fiber with dispersion of 20 ns/km (including both modal and chromatic dispersions)?

a. 2 ns
b. 2.236 ns

c. 2.646 ns

d. 2.828 ns

e. 3 ns

9. What is the total dispersion of 10 km of graded-index fiber with modal dispersion of 2.5 ns/km and chromatic dispersion of 100 ps/nm · km when it is used with an 850-nm LED having a 50-nm spectral width?

a. 5 ns

b. 25 ns

c. 50 ns

d. 55.9 ns

e. 75 ns

10. What is the total dispersion of 10 km of single-mode fiber with chromatic dispersion of 17 ps/nm · km and average polarization-mode dispersion of 0.5 ps/$\sqrt{\text{km}}$ at 1550 nm when used with a laser source with spectral width of 1 nm?

a. 1.58 ps

b. 10 ps

c. 17 ps

d. 170 ps

e. 172 ps

11. You are designing a 1-Gbit/s system using NRZ-coded signals with a transmitter with 0.3 ns rise time and a receiver that also has 0.3 ns rise time. What is the maximum total dispersion allowable through the entire length of the fiber?

a. 0.1 ns

b. 0.3 ns

c. 0.44 ns

d. 0.56 ns

e. 0.7 ns

12. You generate a 2.5-Gbit/s NRZ signal with rise time of 0.15 ns and spectral width of 0.1 nm. You have to send it through 80 km of nonzero dispersion-shifted fiber with chromatic dispersion of 6 ps/km·nm at the transmitter wavelength. Average polarization-mode dispersion is 0.5 ps/root-km. What is the total pulse dispersion in the fiber?

a. 4.5 ps

b. 45 ps

c. 48 ps

d. 52.5 ps

e. 80 ps