System Design

Power Budget

Band width Budget

Rise time Budget.

8.1 POINT-TO-POINT LINKS

The simplest transmission link is a point-to-point line that has a transmitter on one end and a receiver on the other, as is shown in Fig. 8-1. This type of link places the least demand on optical fiber technology and thus sets the basis for examining more complex system architectures.[1-8]

The design of an optical link involves many interrelated variables among the fiber, source, and photodetector operating characteristics, so that the actual link design and analysis may require several iterations before they are completed satisfactorily. Since performance and cost constraints are very important factors in fiber optic communication links, the designer must carefully choose the components to ensure that the desired performance level can be maintained over the expected system lifetime without overspecifying the component characteristics.

The following key system requirements are needed in analyzing a link:

1. The desired (or possible) transmission distance
2. The data rate or channel bandwidth
3. The bit-error rate (BER)

To fulfill these requirements the designer has a choice of the following components and their associated characteristics:

1. Multimode or single-mode optical fiber
    - (*a*) Core size
    - (*b*) Core refractive-index profile
    - (*c*) Bandwidth or dispersion
    - (*d*) Attenuation
    - (*e*) Numerical aperture or mode-field diameter

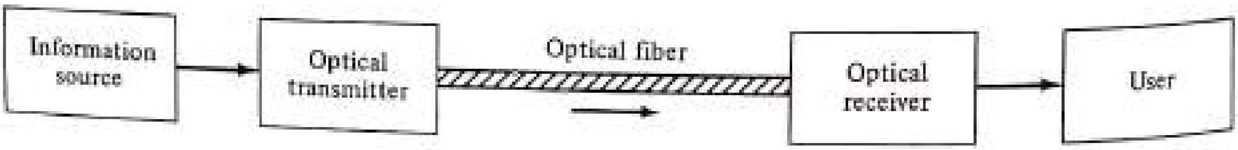

FIGURE 8-1
Simplex point-to-point link.

2. LED or laser diode optical source
    - (*a*) Emission wavelength
    - (*b*) Spectral line width
    - (*c*) Output power
    - (*d*) Effective radiating area
    - (*e*) Emission pattern
    - (*f*) Number of emitting modes
3. *pin* or avalanche photodiode
    - (*a*) Responsivity
    - (*b*) Operating wavelength
    - (*c*) Speed
    - (*d*) Sensitivity

Two analyses are usually carried out to ensure that the desired system performance can be met: these are the *link power budget* and the system *rise-time budget* analyses. In the link power budget analysis one first determines the power margin between the optical transmitter output and the minimum receiver sensitivity needed to establish a specified BER. This margin can then be allocated to connector, splice, and fiber losses, plus any additional margins required for possible component degradations, transmission-line impairments, or temperature effects. If the choice of components did not allow the desired transmission distance to be achieved, the components might have to be changed or amplifiers might have to be incorporated into the link.

Once the link power budget has been established, the designer can perform a system rise-time analysis to ensure that the desired overall system performance has been met. We shall now examine these two analyses in more detail.

8.1.1 System Considerations

In carrying out a link power budget, we first decide at which wavelength to transmit and then choose components that operate in this region. If the distance over which the data are to be transmitted is not too far, we may decide to operate in the 800-to-900-nm region. On the other hand, if the transmission distance is relatively long, we may want to take advantage of the lower attenuation and dispersion that occurs at wavelengths around 1300 or 1550 nm.

Having decided on a wavelength, we next interrelate the system performances of the three major optical link building blocks; that is, the receiver, transmitter, and optical fiber. Normally, the designer chooses the characteristics of two of these elements and then computes those of the third to see if the system performance requirements are met. If the components have been over- or underspecified, a design iteration may be needed. The procedure we shall follow here is first to select the photodetector. We then choose an optical source and see how far data can be transmitted over a particular fiber before an amplifier is needed in the line to boost up the power level of the optical signal.

In choosing a particular photodetector, we mainly need to determine the minimum optical power that must fall on the photodetector to satisfy the bit-error rate (BER) requirement at the specified data rate. In making this choice, the designer also needs to take into account any design cost and complexity constraints. As noted in Chaps. 6 and 7, a *pin* photodiode receiver is simpler, more stable with changes in temperature, and less expensive than an avalanche photodiode receiver. In addition, *pin* photodiode bias voltages are normally less than 5 V, whereas those of avalanche photodiodes range from 40 V to several hundred volts. However, the advantages of *pin* photodiodes may be overruled by the increased sensitivity of the avalanche photodiode if very low optical power levels are to be detected.

The system parameters involved in deciding between the use of an LED and a laser diode are signal dispersion, data rate, transmission distance, and cost. As shown in Chap. 4, the spectral width of the laser output is much narrower than that of an LED. This is of importance in the 800-to-900-nm region, where the spectral width of an LED and the dispersion characteristics of silica fibers limit the data-rate–distance product to around 150 (Mb/s) · km. For higher values [up to 2500 (Mb/s) · km], a laser must be used at these wavelengths. At wavelengths around 1.3 μm, where signal dispersion is very low, bit-rate–distance products of at least 1500 (Mb/s) · km are achievable with LEDs. For InGaAsP lasers, this figure is in excess of 25 (Gb/s) · km at 1.3 μm. A single-mode fiber can provide the ultimate bit-rate–distance product, with values of over 500 (Gb/s) · km having been demonstrated at 1550 nm.

Since laser diodes typically couple from 10 to 15 dB more optical power into a fiber than an LED, greater repeaterless transmission distances are possible with a laser. This advantage and the lower dispersion capability of laser diodes may be offset by cost constraints. Not only is a laser diode itself more expensive than an LED, but also the laser transmitter circuitry is much more complex, since the lasing threshold has to be dynamically controlled as a function of temperature and device aging.

For the optical fiber, we have a choice between single-mode and multimode fiber, either of which could have a step- or a graded-index core. This choice depends on the type of light source used and on the amount of dispersion that can be tolerated. Light-emitting diodes (LEDs) tend to be used with multimode fibers, although, as we saw in Chap. 5, edge-emitting LEDs can launch sufficient optical power into a single-mode fiber for transmission at data rates greater than 500 Mb/s over several kilometers. The optical power that can be coupled into a fiber from an LED depends on the core–cladding index difference Δ, which, in turn, is related to the numerical aperture of the fiber (for $\Delta = 0.01$, the numerical aperture NA $\simeq 0.21$). As Δ increases, the fiber-coupled power increases correspondingly. However, since dispersion also becomes greater with increasing Δ, a tradeoff must be made between the optical power that can be launched into the fiber and the maximum tolerable dispersion.

When choosing the attenuation characteristics of a cabled fiber, the excess loss that results from the cabling process must be considered in addition to the attenuation of the fiber itself. This must also include connector and splice losses as well as environmental-induced losses that could arise from temperature variations, radiation effects, and dust and moisture on the connectors.

8.1.2 Link Power Budget

An optical power loss model for a point-to-point link is shown in Fig. 8-2. The optical power received at the photodetector depends on the amount of light coupled into the fiber and the losses occurring in the fiber and at the connectors and splices. The link loss budget is derived from the sequential loss contributions of each element in the link. Each of these loss elements is expressed in decibels (dB) as

$$\text{loss} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}} \tag{8-1}$$

where P_{in} and P_{out} are the optical powers emanating into and out of the loss element, respectively.

In addition to the link loss contributors shown in Fig. 8-2, a link power margin is normally provided in the analysis to allow for component aging, temperature fluctuations, and losses arising from components that might be added at future dates. A link margin of 6–8 dB is generally used for systems that are not expected to have additional components incorporated into the link in the future.

The link loss budget simply considers the total optical power loss P_T that is allowed between the light source and the photodetector, and allocates this loss to cable attenuation, connector loss, splice loss, and system margin. Thus, if P_S is the optical power emerging from the end of a fiber flylead attached to the light source, and if P_R is the receiver sensitivity, then

$$\begin{aligned} P_T &= P_S - P_R \\ &= 2l_c + \alpha_f L + \text{system margin} \end{aligned} \tag{8-2}$$

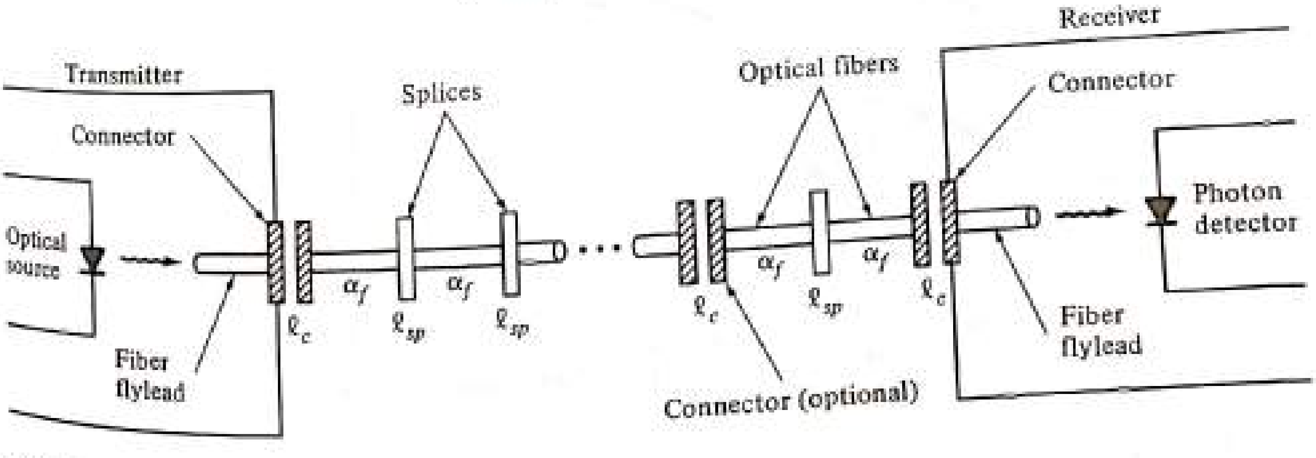

FIGURE 8-2
Optical power loss model for a point-to-point link. The losses occur at connectors (l_c), at splices (l_{sp}), and in the fiber (α_f).

Here, l_c is the connector loss, α_f is the fiber attenuation (dB/km), L is the transmission distance, and the system margin is nominally taken as 6 dB. Here, we assume that the cable of length L has connectors only on the ends and none in between. The splice loss is incorporated into the cable loss for simplicity.

Example 8-1. To illustrate how a link loss budget is set up, let us carry out a specific design example. We shall begin by specifying a data rate of 20 Mb/s and a bit-error rate of 10^{-9} (i.e., at most one error can occur for every 10^9 bits sent). For the receiver, we shall choose a silicon *pin* photodiode operating at 850 nm. Figure 8-3 shows that the required receiver input signal is −42 dBm (42 dB below 1 mW). We next select a GaAlAs LED that can couple a 50-μW (−13-dBm) average optical power level into a fiber flylead with a 50-μm core diameter. We thus have a 29-dB allowable power loss. Assume further that a 1-dB loss occurs when the fiber flylead is connected to the cable and another 1-dB connector loss occurs at the cable–photodetector interface. Including a 6-dB system margin, the possible transmission distance for a cable with an attenuation of α_f dB/km can be found from Eq. (8-2):

$$
\begin{aligned}
P_T = P_S - P_R &= 29\,\text{dB} \\
&= 2(1\ \text{dB}) + \alpha_f L + 6\,\text{dB}
\end{aligned}
$$

If $\alpha_f = 3.5$ dB/km, then a 6.0-km transmission path is possible.

The link power budget can be represented graphically as is shown in Fig. 8-4. The vertical axis represents the optical power loss allowed between the transmitter and the receiver. The horizontal axis give the transmission distance. Here, we show a

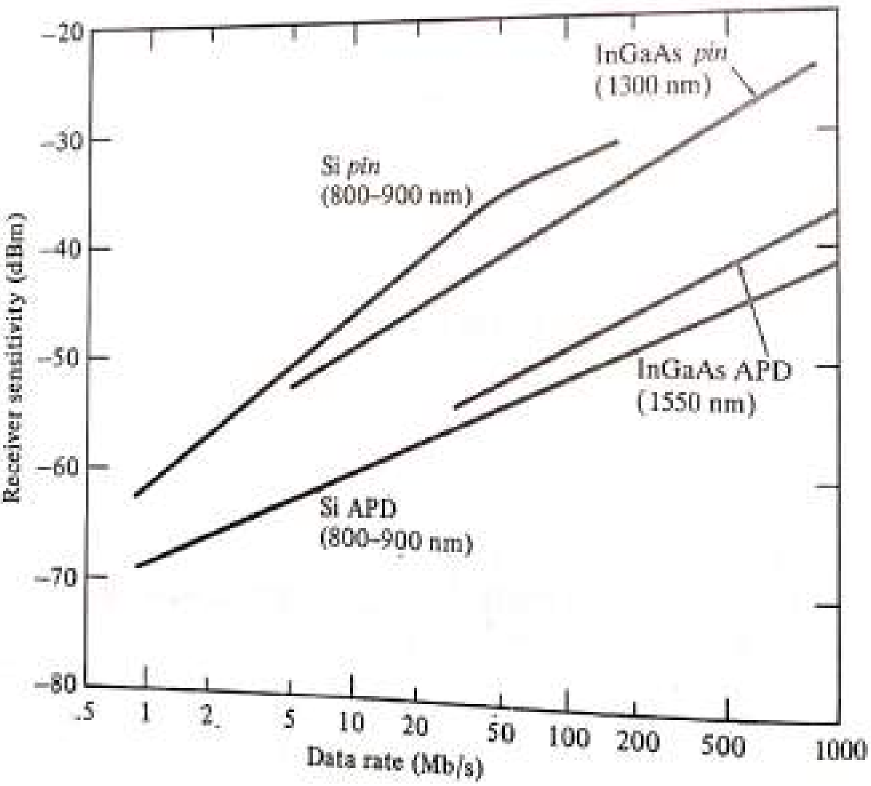

FIGURE 8-3

Receiver sensitivities as a function of bit rate. The Si *pin*, Si APD, and InGaAs *pin* curves are for a 10^{-9} BER. The InGaAs APD curve is for a 10^{-11} BER.

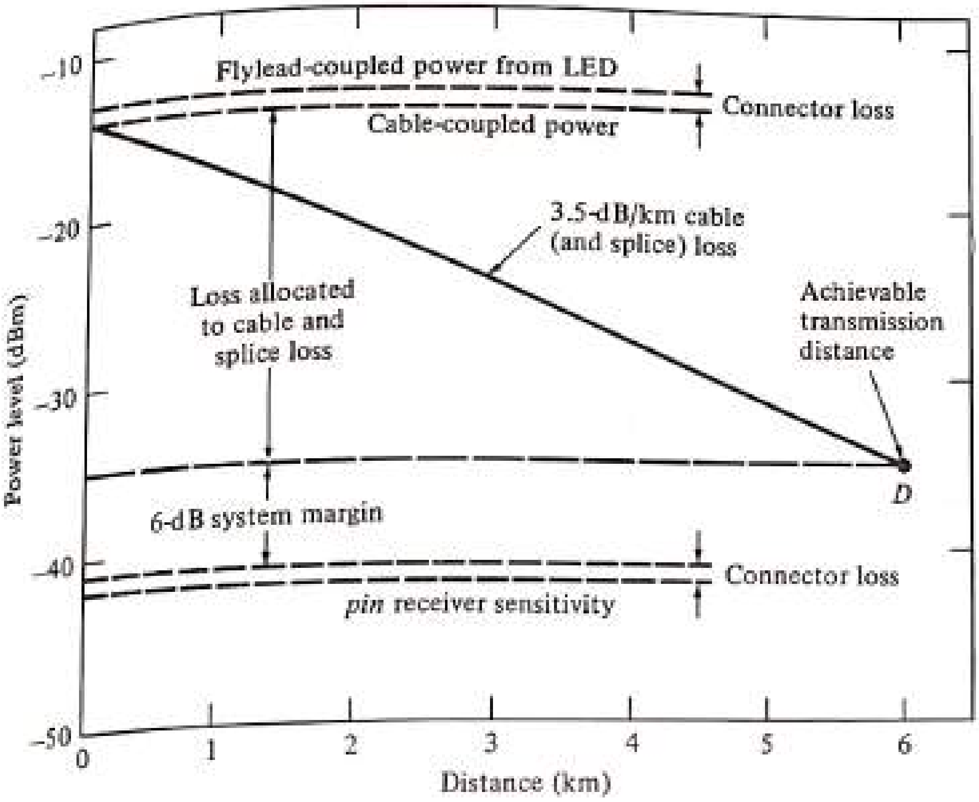

FIGURE 8-4
Graphical representation of a link-loss budget for an 800-nm LED/*pin* system operating at 20 Mb/s.

silicon *pin* receiver with a sensitivity of −42 dBm (at 20 Mb/s) and an LED with an output power of −13 dBm coupled into a fiber flylead. We subtract a 1-dB connector loss at each end, which leaves a total margin of 27 dB. Subtracting a 6-dB system safety margin leaves us with a tolerable loss of 21 dB that can be allocated to cable and splice loss. The slope of the line shown in Fig. 8-4 is the 3.5-dB/km cable (and splice, in this case) loss. This line starts at the −14-dBm point (which is the optical power coupled into the cabled fiber) and ends at the −35-dBm level (the receiver sensitivity minus a 1-dB connector loss and a 6-dB system margin). The intersection point *D* then defines the maximum possible transmission path length.

A convenient procedure for calculating the power budget is to use a tabular or spreadsheet form. We will illustrate this by way of an example for a SONET OC-48 (2.5 Gb/s) link.

Example 8-2. Consider a 1550-nm laser diode that launched a +3-dBm (2-mW) optical power level into a fiber flylead, an InGaAs APD with a −32-dBm sensitivity at 2.5 Gb/s, and a 60-km long optical cable with a 0.3-dB/km attenuation. Assume that here, because of the way the equipment is arranged, a short optical jumper cable is needed at each end between the end of the transmission cable and the SONET equipment rack. Assume that each jumper cable introduces a loss of 3 dB. In addition, assume a 1-dB connector loss occurs at each fiber joint (two at each end because of the jumper cables).

Table 8-1 lists the components in column 1 and the associated optical output, sensitivity, or loss in column 2. Column 3 gives the power margin available after subtracting the component loss from the total optical power loss that is allowed

TABLE 8-1
Example of a spreadsheet for calculating an optical-link power budget

Component/loss parameter	Output/sensitivity/loss	Power margin (dB)
Laser output	3 dBm	
APD sensitivity at 2.5 Gb/s	−32 dBm	
Allowed loss [3 − (−32)]		35
Source connector loss	1 dB	34
Jumper + connector loss	3 + 1 dB	30
Cable attenuation (60 km)	18 dB	12
Jumper + connector loss	3 + 1 dB	8
Receiver connector loss	1 dB	7 (final margin)

between the light source and the photodetector, which, in this case, is 35 dB. Adding all the losses results in a final power margin of 7 dB.

8.1.3 Rise-Time Budget

A rise-time budget analysis is a convenient method for determining the dispersion limitation of an optical fiber link. This is particularly useful for digital systems. In this approach, the total rise time t_{sys} of the link is the root sum square of the rise times from each contributor t_i to the pulse rise-time degradation:

$$t_{\text{sys}} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2} \tag{8-3}$$

The four basic elements that may significantly limit system speed are the transmitter rise time t_{tx}, the group-velocity dispersion (GVD) rise time t_{GVD} of the fiber, the modal dispersion rise time t_{mod} of the fiber, and the receiver rise time t_{rx}. Single-mode fibers do not experience modal dispersion, so in these fibers the rise time is related only to GVD. Generally, the total transition-time degradation of a digital link should not exceed 70 percent of an NRZ (non-return-to-zero) bit period or 35 percent of a bit period for RZ (return-to-zero) data, where one bit period is defined as the reciprocal of the data rate (NRZ and RZ data formats are discussed in more detail in Sec. 8.2).

The rise times of transmitters and receivers are generally known to the designer. The transmitter rise time is attributable primarily to the light source and its drive circuitry. The receiver rise time results from the photodetector response and the 3-dB electrical bandwidth of the receiver front end. The response of the receiver front end can be modeled by a first-order lowpass filter having a step response[9]

$$g(t) = [1 - \exp(-2\pi B_{rx} t)]u(t)$$

where B_{rx} is the 3-dB electrical bandwidth of the receiver and $u(t)$ is the unit step function which is 1 for $t \geq 0$ and 0 for $t < 0$. The rise time t_{rx} of the receiver is usually defined as the time interval between $g(t) = 0.1$ and $g(t) = 0.9$. This is known as the *10- to 90-percent rise time*. Thus, if B_{rx} is given in megahertz, then the receiver front-end rise time in nanoseconds is (see Prob. 8-3)

$$t_{rx} = \frac{350}{B_{rx}} \tag{8-4}$$

In practice, an optical fiber link seldom consists of a uniform, continuous, jointless fiber. Instead, a transmission link nominally is formed from several concatenated (tandemly joined) fibers that may have different dispersion characteristics. This is especially true for dispersion-compensated links operating at 10 Gb/s and higher (see Chap. 12). In addition, multimode fibers experience modal distributions at fiber-to-fiber joints owing to misaligned joints, different core index profiles in each fiber, and/or different degrees of mode mixing in individual fibers. Determining the fiber rise times resulting from GVD and modal dispersion then becomes more complex than for the case of a single uniform fiber.

The fiber rise time t_{GVD} resulting from GVD over a length L can be approximated by Eq. (3-54) as

$$t_{\mathrm{GVD}} \approx |D| L \sigma_\lambda \tag{8-5}$$

where σ_λ is the half-power spectral width of the source, and the dispersion D is given by Eq. (3-57) for a non-dispersion-shifted fiber and by Eq. (3-59) for a dispersion-shifted fiber. Since the dispersion value generally changes from fiber section to section in a long link, an average value should be used for D in Eq. (8-5).

The difficulty in predicting the bandwidth (and hence the modal rise time) of a series of concatenated multimode fibers arises from the observation that the total route bandwidth can be a function of the order in which fibers are joined. For example, instead of randomly joining together arbitrary (but very similar) fibers, an improved total link bandwidth can be obtained by selecting adjoining fibers with alternating over- and undercompensated refractive-index profiles to provide some modal delay equalization. Although the ultimate concatenated fiber bandwidth can be obtained by judiciously selecting adjoining fibers for optimum modal delay equalization, in practice this is unwieldy and time-consuming, particularly since the initial fiber in the link appears to control the final link characteristics.

A variety of empirical expressions for modal dispersion have thus been developed.[10-15] From practical field experience, it has been found that the bandwidth B_M in a link of length L can be expressed to a reasonable approximation by the empirical relation

$$B_M(L) = \frac{B_0}{L^q} \tag{8-6}$$

where the parameter q ranges between 0.5 and 1, and B_0 is the bandwidth of a 1-km length of cable. A value of $q = 0.5$ indicates that a steady-state modal equilibrium has been reached, whereas $q = 1$ indicates little mode mixing. Based on field experience, a reasonable estimate is $q = 0.7$.

Another expression that has been proposed for B_M, based on curve fitting of experimental data, is

$$\frac{1}{B_M} = \left[\sum_{n=1}^{N}\left(\frac{1}{B_n}\right)^{1/q}\right]^q \tag{8-7}$$

where the parameter q ranges between 0.5 (quadrature addition) and 1.0 (linear addition), and B_n is the bandwidth of the nth fiber section. Alternatively, Eq. (8-7) can be written as

$$t_M(N) = \left[\sum_{n=1}^{N}(t_n)^{1/q}\right]^1 \tag{8-8}$$

where $t_M(N)$ is the pulse broadening occurring over N cable sections in which the individual pulse broadenings are given by t_n.

We now need to find the relation between the fiber rise time and the 3-dB bandwidth. For this, we use a variation of the expression derived by Midwinter.[16] We assume that the optical power emerging from the fiber has a gaussian temporal response described by

$$g(t) = \frac{1}{\sqrt{2\pi}\sigma}e^{-t^2/2\sigma^2} \tag{8-9}$$

where σ is the rms pulse width.

The Fourier transform of this function is

$$G(\omega) = \frac{1}{\sqrt{2\pi}}e^{-\omega^2\sigma^2/2} \tag{8-10}$$

From Eq. (8-9) the time $t_{1/2}$ required for the pulse to reach its half-maximum value; that is, the time required to have

$$g(t_{1/2}) = 0.5g(0) \tag{8-11}$$

is given by

$$t_{1/2} = (2\ln 2)^{1/2}\sigma \tag{8-12}$$

If we define the time t_{FWHM} as the full width of the pulse at its half-maximum value, then

$$t_{\text{FWHM}} = 2t_{1/2} = 2\sigma(2\ln 2)^{1/2} \tag{8-13}$$

The 3-dB optical bandwidth $B_{3\text{dB}}$ is defined as the modulation frequency $f_{3\text{dB}}$ at which the received optical power has fallen to 0.5 of the zero frequency value. Thus, from Eqs. (8-10) and (8-13), we find that the relation between the full-width half-maximum rise time t_{FWHM} and the 3-dB optical bandwidth is

$$f_{3\text{dB}} = B_{3\text{dB}} = \frac{0.44}{t_{\text{FWHM}}} \tag{8-14}$$

Using Eq. (8-6) for the 3-dB optical bandwidth of the fiber link and letting t_{FWHM} be the rise time resulting from modal dispersion, then, from Eq. (8-14),

$$t_{\text{mod}} = \frac{0.44}{B_M} = \frac{0.44L^q}{B_0} \tag{8-15}$$

If t_{mod} is expressed in nanoseconds and B_M is given in megahertz, then

$$t_{\text{mod}} = \frac{440}{B_M} = \frac{440L^q}{B_0} \tag{8-16}$$

Substituting Eqs. (3-20), (8-4), and (8-16) into Eq. (8-3) gives a total system rise time of

$$\begin{aligned} t_{\text{sys}} &= \left[t_{tx}^2 + t_{\text{mod}}^2 + t_{\text{GVD}}^2 + t_{rx}^2\right]^{1/2} \\ &= \left[t_{tx}^2 + \left(\frac{440L^q}{B_0}\right)^2 + D^2\sigma_\lambda^2 L^2 + \left(\frac{350}{B_{rx}}\right)^2\right]^{1/2} \end{aligned} \tag{8-17}$$

where all the times are given in nanoseconds, σ_λ is the half-power spectral width of the source, and the dispersion D [expressed in ns/(nm · km)] is given by Eq. (3-57) for a non-dispersion-shifted fiber and by Eq. (3-59) for a dispersion-shifted fiber. In the 800-to-900-nm region, D is about 0.07 ns/(nm · km), which is principally due to material dispersion, so that $t_{\text{GVD}}^2 \approx t_{\text{mat}}^2 = D_{\text{mat}}^2 \sigma_\lambda^2 L^2$. Much smaller values of D are seen in the 1300- and 1550-nm window (see Fig. 3-26).

Example 8-3. As an example of a rise-time budget for a multimode link, let us continue the analysis of the link we started to examine in Sec. 8.1.2. We shall assume that the LED together with its drive circuit has a rise time of 15 ns. Taking a typical LED spectral width of 40 nm, we have a material-dispersion-related rise-time degradation of 21 ns over the 6-km link. Assuming the receiver has a 25-MHz bandwidth, then from Eq. (8-4) the contribution to the rise-time degradation from the receiver is 14 ns. If the fiber we select has a 400-MHz · km bandwidth–distance product and with $q = 0.7$ in Eq. (8-6), then from Eq. (8-15) the modal-dispersion-induced fiber rise time is 3.9 ns. Substituting all these values back into Eq. (8-17) results in a link rise time of

$$\begin{aligned} t_{\text{sys}} &= (t_{tx}^2 + t_{\text{mat}}^2 + t_{\text{mod}}^2 + t_{rx}^2)^{1/2} \\ &= \left[(15\ \text{ns})^2 + (21\ \text{ns})^2 + (3.9\ \text{ns})^2 + (14\ \text{ns})^2\right]^{1/2} \\ &= 30\ \text{ns} \end{aligned}$$

This value falls below the maximum allowable 35-ns rise-time degradation for our 20-Mb/s NRZ data stream. The choice of components was thus adequate to meet our system design criteria.