

# Fiber Optic Communication Link Design

By

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*Abstract* – The fundamental building blocks of an optical fiber transmission link are the optical source, the optical fiber transmission medium with associated connectors, and the photodetector with its associated receiver [1]. The system designer must select from a set of device components to meet a given set of system requirements. Analysis and/or simulation are required to validate that the designed system meets those requirements.

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## I. INTRODUCTION

A fiber-optic communication system comprises three basic elements: a compact light source, a low-loss and low-dispersion optical fiber, and a photodetector [2]. We have already covered these devices individually earlier in the course. In this handout, we examine their role in the context of the overall design, operation and performance of an optical communication link. Optical accessories such as connectors, couplers, switches, splices and multiplexing devices are essential to the successful operation of fiber links and networks [2]. From a selection set of device components and a given set of system requirements, analysis and/or simulation is required to determine if the system being designed will meet the requirements [3].

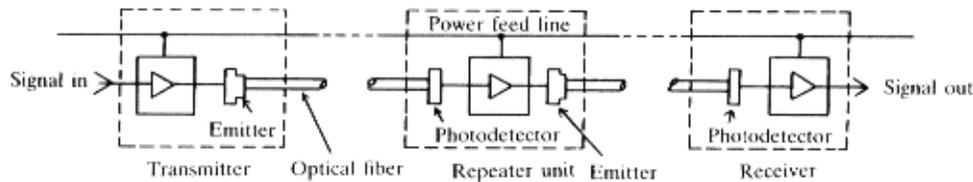


FIG. 9.10 Schematic diagram of the main components of a fiber optical communication system involving a repeater.

Figure 1 - Link Diagram [4].

As a first approximation one can employ an analytical method for link power budget to determine power attenuation limits and system rise time budget to verify data integrity. The maximum fiber length that can be used to transmit data at a given data rate and with a prescribed level of performance is determined. The analytical method relies on static, worst-case performance values of the components, and will usually result in an over-designed and higher-cost system.

Computer-aided modeling and simulation (such as *LinkSim* by Rsoft, or MATLAB® SIMULINK®) will allow device operation around an average value, and rely on statistical methods in the design approach. In addition, as link systems become large and complex, device parameter modeling, noise source modeling, and measurement methods of waveform distortion such as the eye-diagram are essential for characterizing the performance. Often, an iteration of experimental verification of particular elements into the device modeling is essential to build valid and reliable state-of-the-art system simulation models. Whenever possible a correlation of the model with experimental results should be performed. This will provide validation of modeling techniques and confidence regarding its use for alternate parameter selections.

For digital systems, the accepted performance criteria is a bit error rate of  $BER \leq 10^{-9}$ . This is a bit error rate where no more than one error should occur in the transmitting of  $10^9$  data bits. In analog terms this is a signal to noise ratio  $SNR = 21.6$  dB or in linear terms a  $SNR = 144$ .

$$BER = \frac{1}{2} \operatorname{erfc} \left( \frac{\sqrt{\frac{Signal}{Noise}}}{2\sqrt{2}} \right) \quad (1)$$

where  $\operatorname{erfc}$  is the error function.

In the lab, a test called the eye pattern measures the system performance. The test is named for the appearance of the signal on an oscilloscope. As the figure below shows, the pattern resembles an eye.

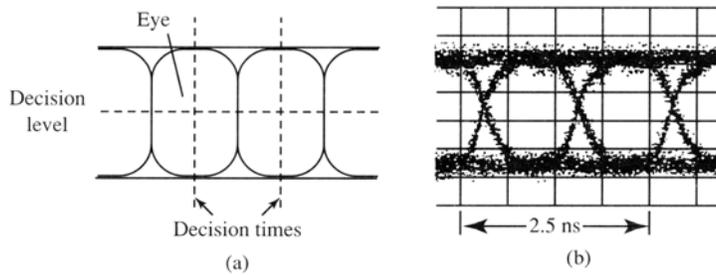


FIG. 9.28 (a) An idealized eye diagram where the pulses exhibit little dispersion and jitter. The decision times and decision levels are shown. (b) A typical eye diagram as obtained in practice.

Figure 2 - Eye Diagram [4].

The measurements are made in the time domain and allow the effects of waveform distortion to be shown immediately on an oscilloscope. A random data signal generates ones and zeros at a uniform rate but in a random manner. When this random data stream is the input signal, then the eye pattern is presented. Figure 2 a) shows an ideal response to this random pattern. However, in a real system, distortion of the pulse, and nonlinearities result in a pattern similar to figure 2 b).

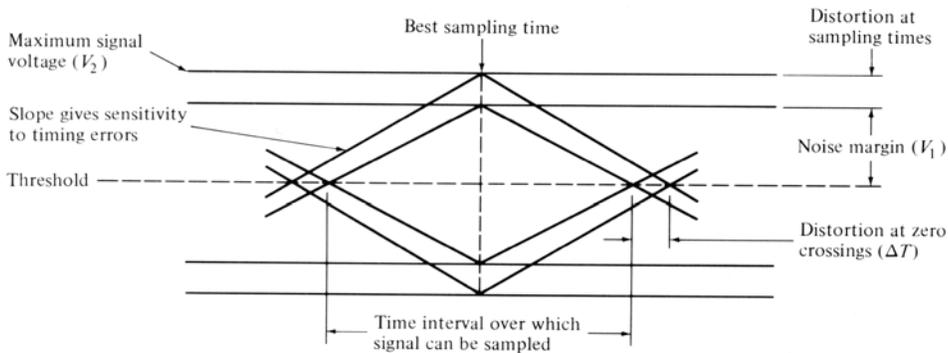


FIGURE 8-13 Simplified eye-pattern diagram and its interpretation.

Figure 3 - Eye diagram interpretation [1].

The eye pattern reveals the following (in brief):

Width of the eye – maximum time interval without intersymbol interference.

Height of the eye – shows the noise margin. The ratio of peak signal voltage ( $V_1$  in Figure 3) to the maximum signal voltage ( $V_2$  in Figure 3) is the noise margin which is a measure of the immunity to noise of the system.

System rise time (10% to 90% of max value) is easily measured.

Nonlinearities in the system will result in an asymmetry in the eye pattern.

## II. COMPONENTS

### A. Photodetector

The photodetector is typically a *pin* or avalanche photodetector (APD) device. Thermal detectors do not achieve a bandwidth useful for communications. Whatever the specific photodetector, you must examine the responsivity  $R$  at the operating (source) wavelength. Can the device create a sufficient photogenerated current at the source wavelength? This depends on the sensitivity of the device. That is, its noise characteristics must meet the required signal to noise ratio (or carrier to noise ratio) at the desired bandwidth.

$$1) \text{ Responsivity } R = \frac{I_{\text{photocurrent}}}{\text{Power}_{\text{incident}}} = \frac{I_{ph}}{P_o} \quad (2)$$

- 2) Speed – usually given as bandwidth in Hz
- 3) Operating wavelength - set by light source
- 4) Sensitivity – What is the minimum incident light power that can be detected by the photodetector and receiver combination reliably.

### B. Optical Source

The basic requirements for the light sources used in optical communication systems depend on the nature of the intended application (long-haul communication, local-area network, etc.). [2] Both light-emitting diodes (LEDs) and laser diodes are used as sources. Laser diodes have the advantage of high power (tens of mW), high speeds, and narrow spectral width. LEDs have the advantages of ruggedness, reliability, lower cost, long lifetime, and simplicity of design. However, they suffer from relatively broader linewidth and lower bandwidth.

Only that light which can couple to an optical fiber is useful. The output light angle is given by

$$\alpha_{\max} = \sin^{-1}\left(\frac{\text{NumericalAperture}}{\eta_0}\right) \quad (3)$$

where  $\eta_0$  is the interfaces refractive index.

Thus the size of the emitting area and the emitting pattern can be important to the amount of light coupled to the fiber. The source will also have a finite spectral wavelength  $\Delta\lambda$  around the center emission wavelength. This  $\Delta\lambda$  can give rise to dispersion if coupled to the fiber. If we use external wavelength filters, this may decrease the power coupled. Even at a single “color” (wavelength) several modes may be present. Coupling to a single-mode fiber will lose the power in these other modes.

Thus the main features for a light source are:

- 1) Power. The source power must be sufficiently high so that after transmission through the fiber the received signal is detectable with the required accuracy. This includes stability of that power both in amplitude and frequency.
- 2) Speed. It must be possible to modulate the source power at the desired rate.
- 3) Spectral linewidth. The source must have a narrow spectral linewidth so that the effect of chromatic dispersion in the fiber is minimized. What is the effect of a finite  $\Delta\lambda$  (dispersion) on your system?
- 4) Noise. The source must be free of random fluctuations.
- 5) Emission wavelength. Contrast to fiber attenuation.
- 6) Emission pattern – The source power must be coupled to the fiber. Both light output area and mode distribution in the beam can be important.

### C. Optical Fiber

Light waves travel in the optical fiber in the form of modes, each with a distinct spatial distribution, polarization, propagation constant, group velocity, and attenuation coefficient. Thus the fiber chosen for your system must meet the design goals after consideration of:

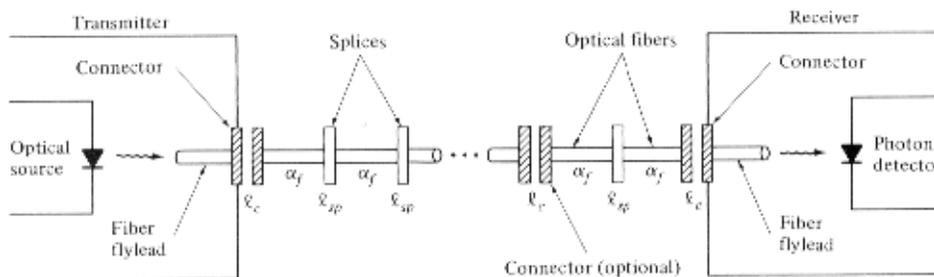
- 1) Multi-mode fiber whether step-index, or graded-index. Single-mode fiber.
- 2) Core size
- 3) Core refractive index profile
- 4) Bandwidth and dispersion characteristics
- 5) Attenuation dB/km (including any connectors and splices) which is a function of central wavelength.
- 6) Numerical aperture  $NA = \sqrt{n_1^2 - n_2^2}$  (4)

## III. SYSTEM REQUIREMENTS

### A. System Overview

The design of an optical link involves many interrelated variables among the fiber, source and photodetector operating characteristics. In carrying out an optical fiber link analysis, several iterations with different device characteristics may be required before it is satisfactorily completed. The key requirements needed in analyzing a link are: [1]

- 1) Desired (or possible) transmission distance
- 2) Data rate or channel bandwidth
- 3) Bit error rate (BER) allowed. Signal to noise ratio (SNR) allowed for an analog system



**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 ( $\alpha_f$ ).

Figure 4 - Component loss diagram [1].

## B. Power Budget

Power budget considers the total allowed optical power loss  $P_T$  between the source and the detector. The designer must account for losses due to fiber optic fiber attenuation, connectors, splices and allow for a “system margin” as a safety factor. The measure of the total power loss is given as:

$$P_{\text{loss}} = 10 \text{Log}_{10} \left( \frac{P_{\text{out}}}{P_{\text{in}}} \right) \quad (5)$$

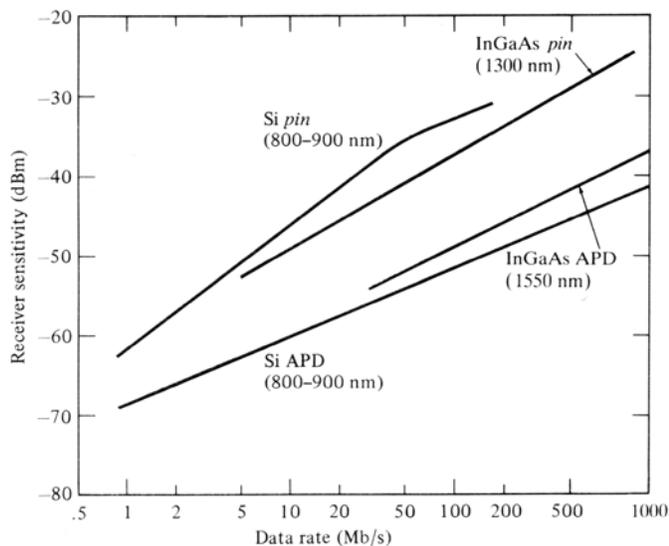
Suppose the designer has the following requirements.

Data rate = 20 Mb/s

Bit error rate =  $1 \times 10^{-9}$  errors/bit

A “short haul” system with an operating wavelength  $\lambda = 850$  nm.

A Si *p-i-n* photodiode is selected as the photodetector. What is the receiver sensitivity at this wavelength?



**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 5 - Receiver sensitivities [1].

The above graph shows that the Si *pin* photodiode has a receiver sensitivity of about  $-42$  dBm (63.1 nW) at the required bandwidth of 20 Mb/s and in the wavelength range 800 – 900 nm.

Now suppose you chose to use a GaAlAs LED for this short haul system. The data sheet for the LED states that it can achieve  $P_{\text{coupled}} = 50 \mu\text{W}$  into a multi-mode fiber with a core diameter of 50  $\mu\text{m}$ . The power includes all coupling loss involved in launching the power into the fiber. A point-to-point system (no repeaters) will be used, so there is one connector to the detector. The loss is  $L_c = 1$  db per connector. Splices will be required for each kilometer of fiber. The attenuation loss for the fiber which was previously installed is  $\alpha_F = 3.5$  dB/km. You decide to allow for a sufficient safety margin for temperature ranges, ageing effects and future splices. The following table shows the Power Budget.

Table I. - System Power Budget.

Optical Transmitter Output Power	-13 dBm
Receiver sensitivity	-42 dBm
Required margin	29 dBm

System Loss:

Fiber Loss 3.5 dB/km X 5 km	17.5 dB
Connector Loss 1dB x 2 connectors	2 dB
Total Splicing Loss (0.5 dB X 5)	2.5 dB
System margin (Headroom)	6 dB
Total Attenuation	28 dB

So in this example, we have an excess power margin of 29 dB – 28 dB = 1 dB. Thus we have a total headroom of 7 dB when we include the system margin of 6 dB. The following figure graphically presents this information.

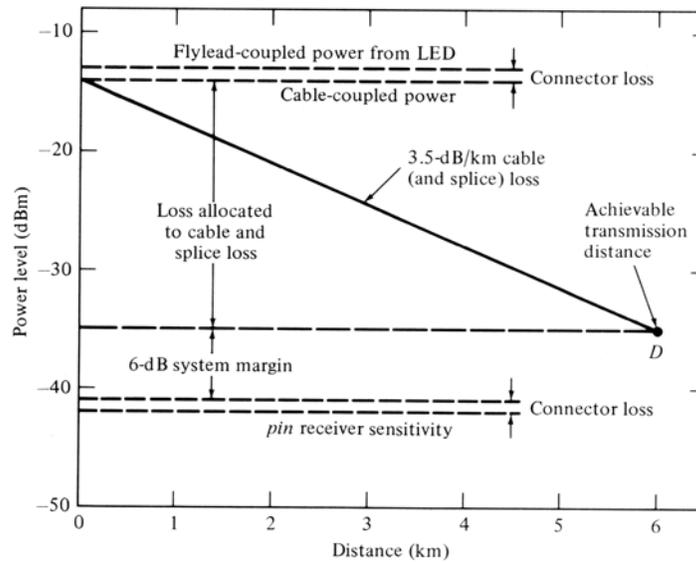


Figure 6 - Graph of power budget [1].

### C. Rise Time Budget

The rise time budget determines the dispersion limitation of a link. Dispersion is the broadening of a pulse as it travels through an optical fiber as discussed earlier in the course. We will define a rise time due to the material (chromatic) ( $t_{mat}$ ) and modal dispersion ( $t_{mod}$ ). Thus the total rise time of the system is the rms sum of all the rise times.

$$\text{Total rise time: } t_{sys} = \sqrt{\sum_{i=1}^N t_i^2} = \sqrt{t_{tx}^2 + t_{mat}^2 + t_{mod}^2 + t_{rx}^2} \quad (6)$$

For digital data, two main coding schemes are used. They are the return-to-zero (RZ) and non-return-to-zero (NRZ). The NRZ method occupies the entire bit width (bit period), whereas the RZ method occupies only a portion of the bit period.

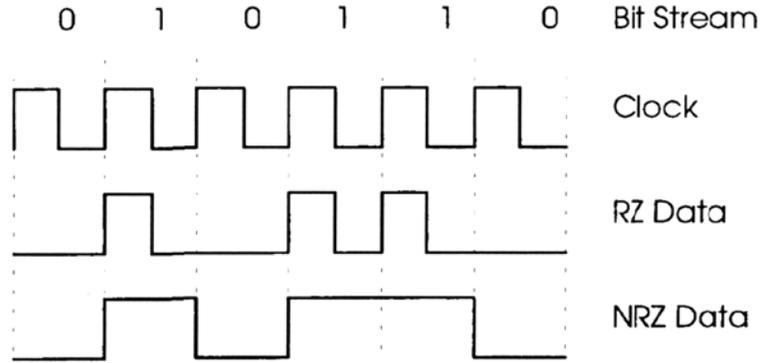


Figure 7 - RZ and NRZ coding schemes [4].

A general rule of thumb is the system rise time should be less than a percentage of one of these methods. The bit period in seconds is the reciprocal of the bit rate in Hertz.

$$t_{\text{sys}}(\text{RZ}) \leq 35\% \left( \frac{1}{\text{BitRate}} \right) = 35\% (\text{Bit Period}) \quad (7)$$

$$t_{\text{sys}}(\text{NRZ}) \leq 70\% \left( \frac{1}{\text{BitRate}} \right) = 70\% (\text{Bit Period}) \quad (8)$$

The rise times of the optical transmitter and receiver are usually known to a designer. Define  $t_{\text{tx}}$  as the light source and drive circuit rise time. The optical detector and receiver circuitry rise time can be approximated by  $t_{\text{rx}}(\text{in nsec}) = 350/B_{\text{rx}}$  where  $B_{\text{rx}}$  in MHz is the rms of the photodetector response bandwidth and the 3 dB electrical bandwidth of the receiver circuitry. [1]

The rise time due to material (chromatic) dispersion is given by

$$t_{\text{mat}} = D_{\text{mat}} \sigma_{\lambda} L \quad (9)$$

Where  $\sigma_{\lambda}$  is the spectral width of the optical source. This is a little bit of nomenclature variation here. In the Kasap text, the value is given as  $\Delta\lambda_{1,2}$  which is full width at half maximum value. The  $D_{\text{mat}}$  term is the material dispersion factor of the fiber to be used and is usually given in ns / (nm x km).

The rise time due to intermodal dispersion in the optical fiber can also be approximated if necessary. The bandwidth of a fiber of length  $L$  is defined as  $B_{\text{M}}(L)$ .  $B_0$  is the bandwidth distance product for a 1 km length of fiber as given by the product's specifications. The power  $q$  of  $L$  in the equation below has been found thru experiment to be between 0.5 and 1. Here we will let  $q = 0.7$  as a reasonable estimate for design. Thus the bandwidth distance product over length  $L$  can be estimated as [1]:

$$B_{\text{M}}(L) = \frac{B_0}{L^q} \quad (10)$$

#### IV. TOP DOWN DESIGN ANALYSIS [5]

Step 1 – What wavelength do we wish to operate at?

- “Short haul” (e.g. LAN): 800 – 900 nm
- “Long haul” (e.g. transatlantic cable): 1300 or 1550  $\mu\text{m}$

Step 2 – Select a photodetector

- What is minimum light power incident on the detector as driven by the BER or SNR?
- Should I pick a *pin* or an APD type of detector?

Step 3 – Select an optical light source

- Criteria includes Cost, signal dispersion, and distance
- 800 – 900 nm    LED: 150 (Mb/s) (km) data-rate distance product  
                          Laser: 2.5 (Gb/s) (km)
- 1300 to 1550 nm    LED: 1.5 (Gb/s) (km)  
                          Laser: 25 (Gb/s) (km)

Step 4 – Select an optical fiber

- LEDs usually connect to multi-mode optical fibers in order to launch an acceptable amount of light power
- Lasers can connect to either multi-mode or single-mode fibers. What are the advantages/disadvantages of selecting a single-mode fiber?

#### V. CONCLUSION

An optical link design must meet both the link power budget and the system rise time analysis. 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 (or SNR for an analog system). Once the link power budget has been established, the designer makes a system rise time analysis to ensure that the dispersion limit of the link has not been exceeded [1].

In designing an optical-fiber system, one should take into account that the individual component parameters can vary considerably. Statistical analysis can refine the design to a less conservative approach at the assumed cost of a small number of failures. In the future such an analysis will become increasingly important as size, complexity and speed of links continue to evolve.

## REFERENCES

- [1] G. Keiser, *Optical Fiber Communications*, 2<sup>nd</sup> ed., New York, McGraw Hill , 1991.
- [2] B. Saleh and M. Teich, *Fundamental of Photonics*, New York, Wiley & Sons, 1991.
- [3] H. Tanzer, Course materials for EEE 167, California State University Sacramento, 2002.
- [4] J. Wilson and J. Hawkes, *Optoelectronics, An introduction*, 3<sup>rd</sup> ed., London, Prentice Hall Europe, 1998.
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Problem 9.8 [4] An emitter can couple some  $10^{-3}$  W of optical radiation at 900 nm into a fiber which has an attenuation of  $\alpha = -5$  db/km. A receiver is used which requires an average of 500 photons per bit for an acceptable bit error rate. Plot a graph of the maximum fiber length possible for bit rates of between  $10^5$  and  $10^9$  bits per second (bps). Modify this diagram to include the effects of fiber dispersion of 5 ns/km if the maximum allowable pulse spreading must not exceed  $1/(2 \times \text{bit rate})$ .

Solution:

If  $P_{out}$  is the power launched into the optical fiber and  $P_{in}$  is the minimum detectable power at the detector, then the total loss thru a length of fiber is given as:

$$\text{Loss} = 10 \log_{10} \frac{P_{out}}{P_{in}} \text{ where the loss} = \text{attenuation} \times \text{distance} = \alpha L$$

Thus the distance L is then:

$$L = \frac{10 \log_{10} \left( \frac{P_{out}}{P_{in}} \right)}{\alpha}$$

The minimum power ( $P_D$ ) that can be detected is given as

$P_D$	= (number of photons/bit)(Bits/sec)(Energy/photon)
	= $\frac{500 \text{ photons}}{\text{bit}} \times \frac{\text{Bits}}{\text{sec}} \times \frac{hc}{\lambda}$
	= $\frac{500 \text{ photons}}{\text{bit}} \times \frac{\text{Bits}}{\text{sec}} \times \left( 2.21 \times 10^{-19} \frac{\text{Joules}}{\text{Photon}} \right)$
$P_D(10^5 \text{ bps})$	= $1.104 \times 10^{-11} \text{ W}$
$P_D(10^6 \text{ bps})$	= $1.104 \times 10^{-10} \text{ W}$
$P_D(10^7 \text{ bps})$	= $1.104 \times 10^{-9} \text{ W}$
$P_D(10^8 \text{ bps})$	= $1.104 \times 10^{-8} \text{ W}$
$P_D(10^9 \text{ bps})$	= $1.104 \times 10^{-7} \text{ W}$

Now we can find the distance L for each of these detectable powers  $P_D$ .

- $L(10^5 \text{ bps}) = 15.9 \text{ km}$
- $L(10^6 \text{ bps}) = 13.9 \text{ km}$
- $L(10^7 \text{ bps}) = 11.9 \text{ km}$
- $L(10^8 \text{ bps}) = 9.9 \text{ km}$
- $L(10^9 \text{ bps}) = 7.9 \text{ km}$

You'll see this attenuation limited fiber length plotted on a graph shortly. First, let us look at the effects of dispersion which results in pulse broadening.

The problem gave the maximum allowable pulse spreading  $\tau$  must be less than  $1/(2 \times \text{bit rate})$ . The dispersion per kilometer  $\sigma = 5 \text{ ns/km}$ . Thus  $\tau = \sigma L \leq 1/(2B)$ . In terms of length, we can write

$$L = \frac{1}{\sigma 2B}$$

$$L(10^5 \text{ bps}) = 1000 \text{ km}$$

$$L(10^6 \text{ bps}) = 100 \text{ km}$$

$$L(10^7 \text{ bps}) = 10 \text{ km}$$

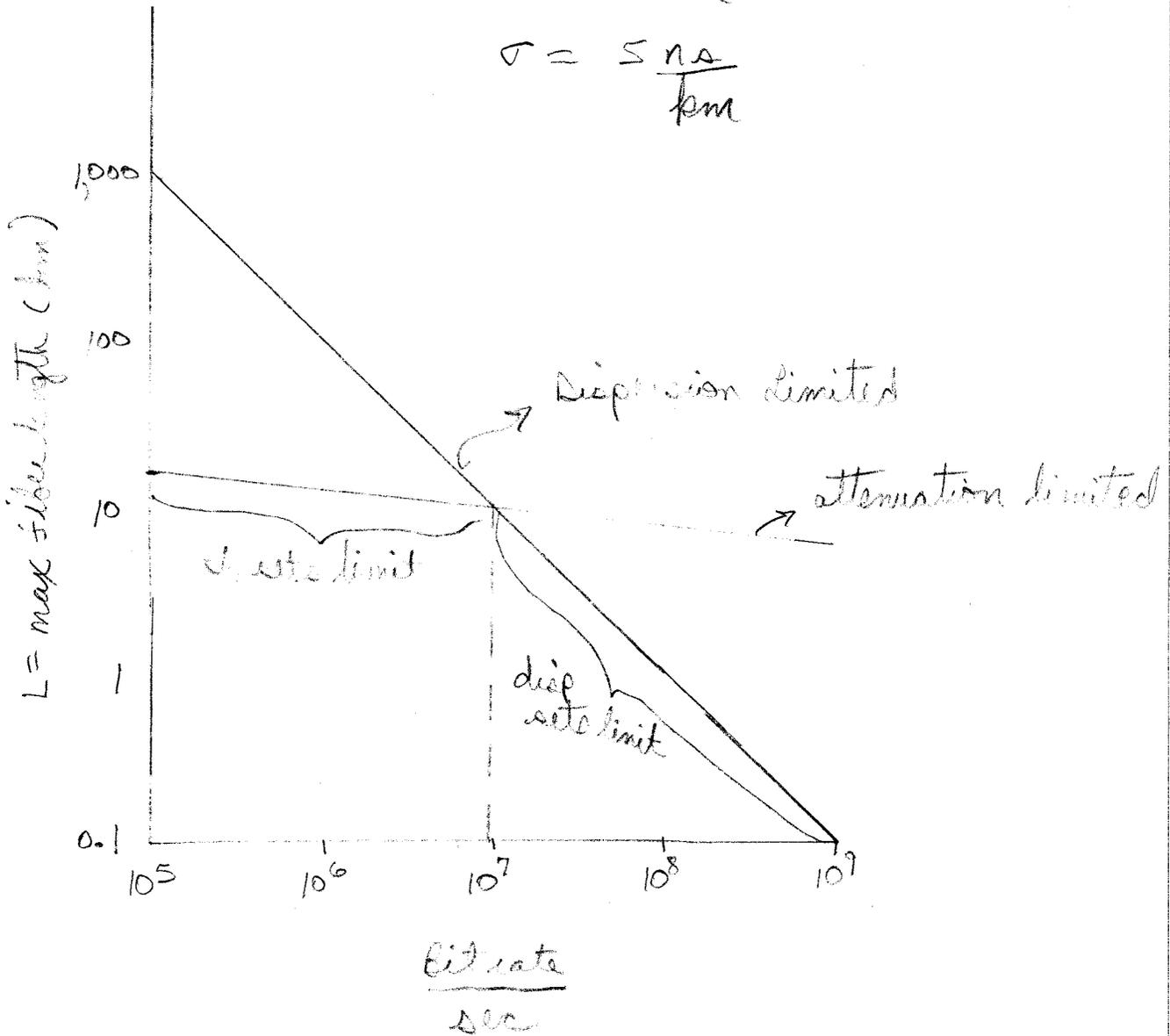
$$L(10^8 \text{ bps}) = 1 \text{ km}$$

$$L(10^9 \text{ bps}) = 0.1 \text{ km}$$

Now look at the graph on the next page. Two lines are plotted. For a given bit rate, when one looks up from the horizontal axis, the first line you run into is the limiting factor. Thus, above  $10^7$  bit per second, dispersion limits the fiber length. Below  $10^7$  bit per second, attenuation limits the fiber length.

$$\alpha = 5 \frac{\text{dB}}{\text{km}}$$

$$\sigma = 5 \frac{\text{ns}}{\text{km}}$$



Below  $\approx 10^7$   $\frac{\text{attenuation limited fiber length}}{\text{bit rate}}$

Above  $\approx 10^7$  bit rate dispersion limited length

Problem 9.14 [4] It is required to construct an optical fiber communications link 5 km long with an analog modulation bandwidth of 10 MHz. The proposed system uses multimode step index fiber with core and cladding refractive indices of 1.48 and 1.46 respectively. At the operating wavelength the fiber exhibits an attenuation of 3 dB/km. The emitter is an LED which can launch 200  $\mu\text{W}$  of optical power into the fiber and the detector is a p-I-n photodiode which requires  $-40$  dBm to achieve the required signal-to-noise ratio (SNR). No splices are required. The detector and emitter have rise times of 100 ns and 10 ns respectively. Determine whether the link should operate satisfactorily and if not discuss the component changes you would recommend.

$$L = 5 \text{ km}$$

$$\text{Bandwidth (BW)} = 10 \text{ MHz}$$

$$\text{Fiber attenuation } \alpha = 3 \text{ dB/km at central wavelength } \lambda_0$$

$$t_{rx} = 100 \text{ ns}$$

$$t_{tx} = 10 \text{ ns}$$

$$P_{\min} \text{ at the detector} = -40 \text{ dBm} = 100 \text{ nW}$$

Solution:

### Power Budget

$$\text{The power launched into the fiber } P_{\text{LED}} = 200 \mu\text{W} = 10 \log_{10} (200 \mu\text{W}/1\text{mW}) = -7 \text{ dBm}$$

$$\text{Total power budget } P_T = P_{\text{LED}} - P_{\min}(\text{at the detector}) = -7 \text{ dBm} - (-40 \text{ dBm}) = 33 \text{ dBm}$$

### System Losses

Fiber Loss 5 km x 3 dB/km	15 dB
Detector – assume one connector at 1 dB	1 dB
Splices or other connectors – none	0 dB
System Margin (Headroom)	6 dB
Total Losses	22 dB

So the excess power margin is  $33\text{dB} - 22 \text{ dB} = 11 \text{ dB}$  which seems very ample in this case.

Now for the sake of argument, let us suppose that the LED is capable of emitting 200  $\mu\text{W}$  of power, but it must still be coupled to a fiber. The coupling efficiency  $\eta_c$  is given by:

$$\eta_c = \frac{NA^2}{n_0^2} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0^2} = \frac{\sqrt{1.48^2 - 1.46^2}}{1^2} = 0.242$$

where the interface between the fiber and the LED is assumed to be air with  $n_0 = 1$ .

Thus the power coupled by the LED into the fiber is

$$P_{\text{LED}} \times \eta_c = 200 \mu\text{W} \times 0.242 = 48.4 \mu\text{W} = -13.2 \text{ dBm}.$$

The system margin now becomes  $-13.2 \text{ dBm} - (-40 \text{ dBm}) = 26.8 \text{ dBm}$ . The excess power margin is still 4.8 dBm, and the system power budget is acceptable.

### Rise Time Budget

The bandwidth  $BW = 10$  MHz. So the pulse period is  $1/BW = 100$  nsec. Also note that the problem did not give a central wavelength nor a spectral linewidth  $\Delta\lambda$ . Thus we have insufficient data to determine the dispersion. So the total system rise time with dispersion excluded is:

$$t_{\text{sys}} = \sqrt{t_{\text{tx}}^2 + t_{\text{rx}}^2} = \sqrt{100\text{ns}^2 + 10\text{ns}^2} = 100.5 \text{ ns}$$

Since  $t_{\text{sys}} >$  allowed pulse width (100 ns), the systems design fails even without including the effects of dispersion. The component that must be changed is the detector. A faster photodetector is needed. But be sure to account for the total power budget with the new photodetector's minimum power sensitivity.