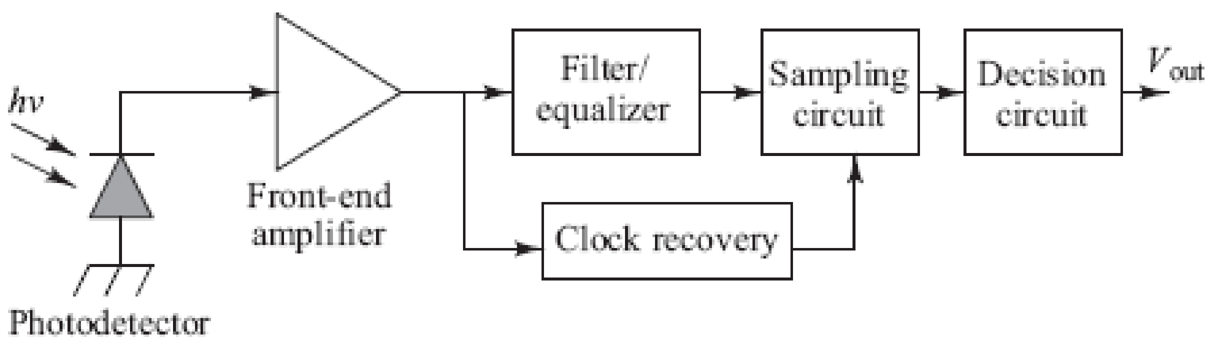
Optical Fiber Communications

Chapter 7

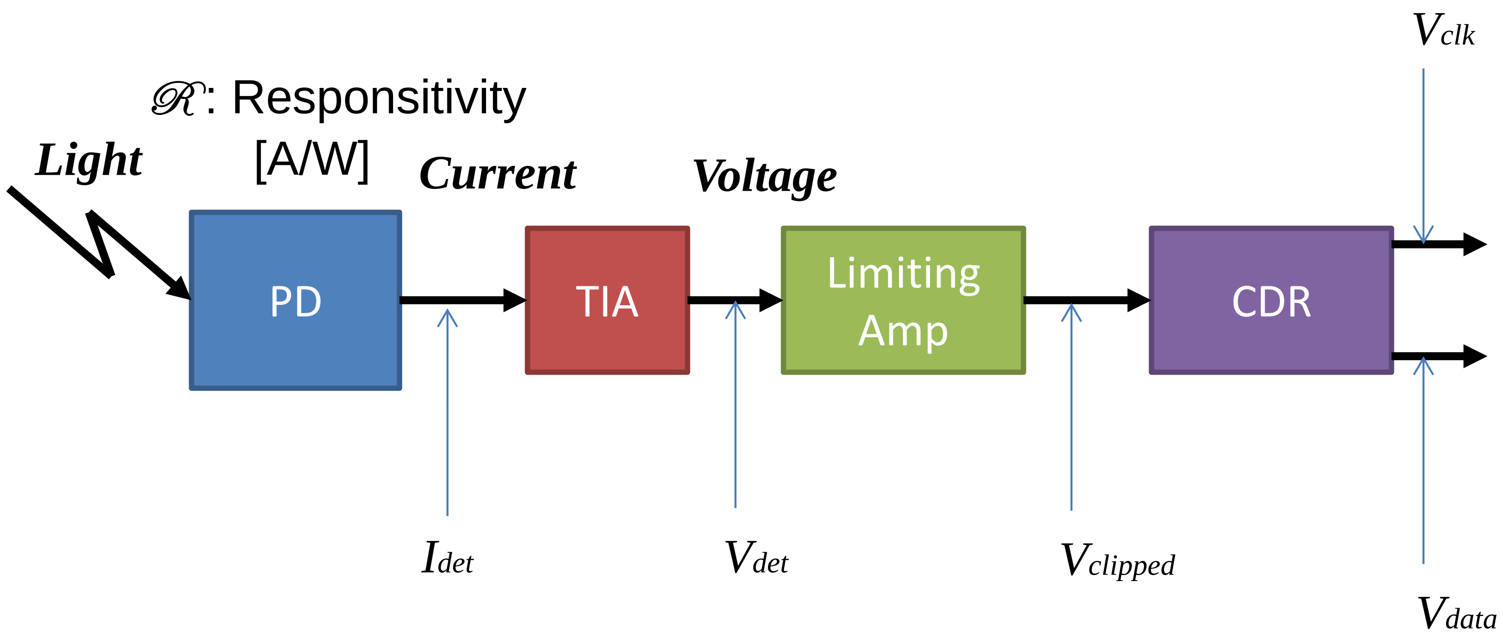
Optical Receiver Operation

7.1 Fundamental Receiver Operation

- **The first receiver element is a *pin* or an avalanche photodiode, which produces an electric current proportional to the received power level.**
- **Since this electric current typically is very weak, a *front-end amplifier* boosts it to a level that can be used by the following electronics.**
- **After being amplified, the signal passes through a *low-pass filter* to reduce the noise that is outside of the signal bandwidth.**
- **The filter also can reshape (equalize) the pulses that have become distorted as they traveled through the fiber.**
- **Together with a *clock (timing) recovery circuit,* a *decision circuit* decides whether a 1 or 0 pulse was received,**



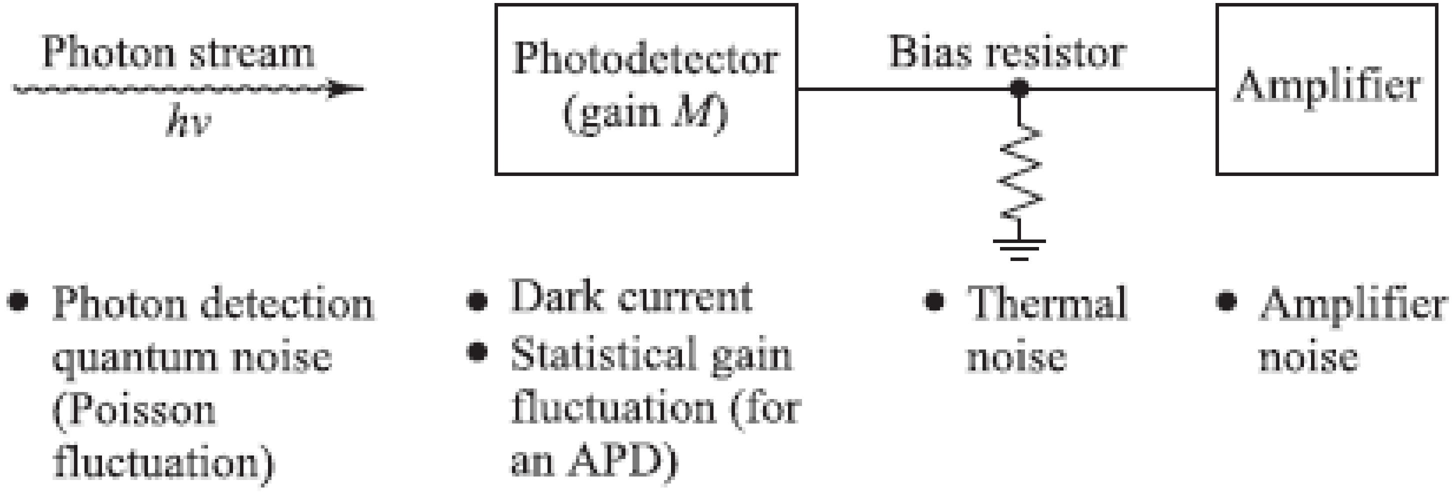
7.1 Fundamental Receiver Operation



Noise Sources in a Receiver

The term *noise* describes unwanted components of an electric signal that tend to disturb the transmission and processing of the signal

- The random arrival rate of signal photons produces quantum (shot) noise
- Dark current comes from thermally generated eh pairs in the pn junction
- Additional shot noise arises from the statistical nature of the APD process
- Thermal noises arise from the random motion of electrons in the detector load resistor and in the amplifier electronics



APD Gain Effect on Noise Figure

The APD noise level increases with larger avalanche gain *M*.

Example 7.1 Consider the following two avalanche photodiodes: (*a*) a Si APD with an ionization rate ratio $k = 0.02$ and (*b*) an InGaAs APD with an ionization rate ratio $k = 0.50$. (*a*) What is the excess noise factor $F(M)$ for electron injection for each device if they both operate with a multiplication factor $M = 30$? (*b*) What is the estimate of $F(M)$ for the InGaAs APD if $M = 10$? (*c*) Compare the results in (*a*) and (*b*) with the empirical expression given in Eq. (7.4) if $x = 0.3$ for Si and 0.7 for InGaAs.

Solution: (*a*) From Eq. (7.3) we find that for the Si APD

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1 - k)$$

$$= 0.02(30) + (2 - 0.033)(1 - 0.02)$$

$$= 2.53 = 4.03 \text{ dB}$$

Similarly, for the InGaAs APD with $M = 30$

$$F(M) = kM + \left(2 - \frac{1}{M}\right)(1 - k)$$

$$= 0.50(30) + (2 - 0.033)(1 - 0.50)$$

$$= 16.0 = 12.0 \text{ dB}$$

(*b*) For the InGaAs APD with $M = 10$

$$F(M) = 0.50(10) + (2 - 0.10)(1 - 0.50) = 6.00 = 7.78 \text{ dB}$$

(*c*) For the Si APD with $M = 30$, Eq. (7.4) yields $F(M) \approx 30^{0.3} = 2.77 = 4.42$ dB

For the InGaAs APD with $M = 30$, Eq. (7.4) yields $F(M) \approx 30^{0.7} = 10.8 = 10.3$ dB

For the InGaAs APD with $M = 10$, Eq. (7.4) yields $F(M) \approx 10^{0.7} = 5.01 = 7.00$ dB

Probability of Error (BER)

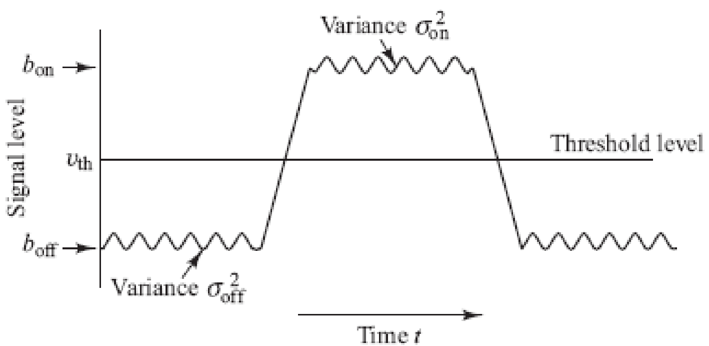
- **A simple way to measure the error rate in a digital data stream is to divide the number N_e of errors occurring over a certain time interval t by the number N_t of pulses (ones and zeros) transmitted during this interval.**
- **This is the *bit-error rate (BER)***

$$\mathrm{BER} = \frac{N_e}{N_t} = \frac{N_e}{Bt}$$

- **Here B is the bit rate.**
- **Typical error rates for optical fiber telecom systems range from 10^{-9} to 10^{-12}.**
- **The error rate depends on the signal-to-noise ratio at the receiver (the ratio of signal power to noise power).**

Derived BER Expression

- A simple estimation of the BER can be calculated by assuming the equalizer output is a *gaussian random variable*.
- Let the mean and variance of the gaussian output for a 1 pulse be b_{on} and σ^2_{on}, respectively, and b_{off} and σ^2_{off} for a 0 pulse.
- If the probabilities of 0 and 1 pulses are equally likely, the *bit error rate* or the *error probability* P_e becomes



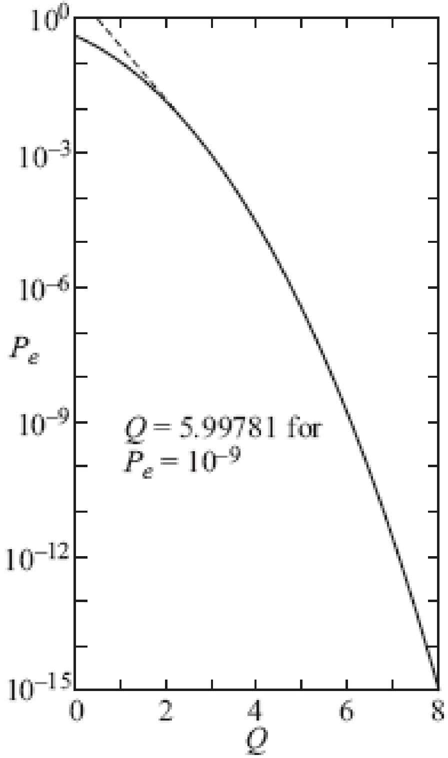
$$\text{BER} = P_e(Q) = \frac{1}{\sqrt{\pi}} \int_{Q/\sqrt{2}}^{\infty} e^{-x^2}\,dx$$

$$= \frac{1}{2}\left[1 - \text{erf}\left(\frac{Q}{\sqrt{2}}\right)\right] \approx \frac{1}{\sqrt{2\pi}} \frac{e^{-Q^2/2}}{Q}$$

$$Q = \frac{v_{th} - b_{off}}{\sigma_{off}} = \frac{b_{on} - v_{th}}{\sigma_{on}} = \frac{b_{on} - b_{off}}{\sigma_{on} + \sigma_{off}}$$

Probability of Error Calculation

- **The factor Q is widely used to specify receiver performance, since it is related to the SNR required to achieve a specific BER.**
- **There exists a narrow range of SNR above which the error rate is tolerable and below which a highly unacceptable number of errors occur. The SNR at which this transition occurs is called the *threshold level*.**



Example 7.3 For an error rate of 10^{-9} we have from Eq. (7.13) that

$$P_e(Q) = 10^{-9} = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{Q}{\sqrt{2}}\right)\right]$$

From Fig. 7.9 we have that $Q \simeq 6$ (an exact evaluation yields $Q = 5.99781$), which gives a signal-to-noise ratio of 12, or 10.8 dB [i.e., $10 \log(S/N) = 10 \log 12 = 10.8$ dB].

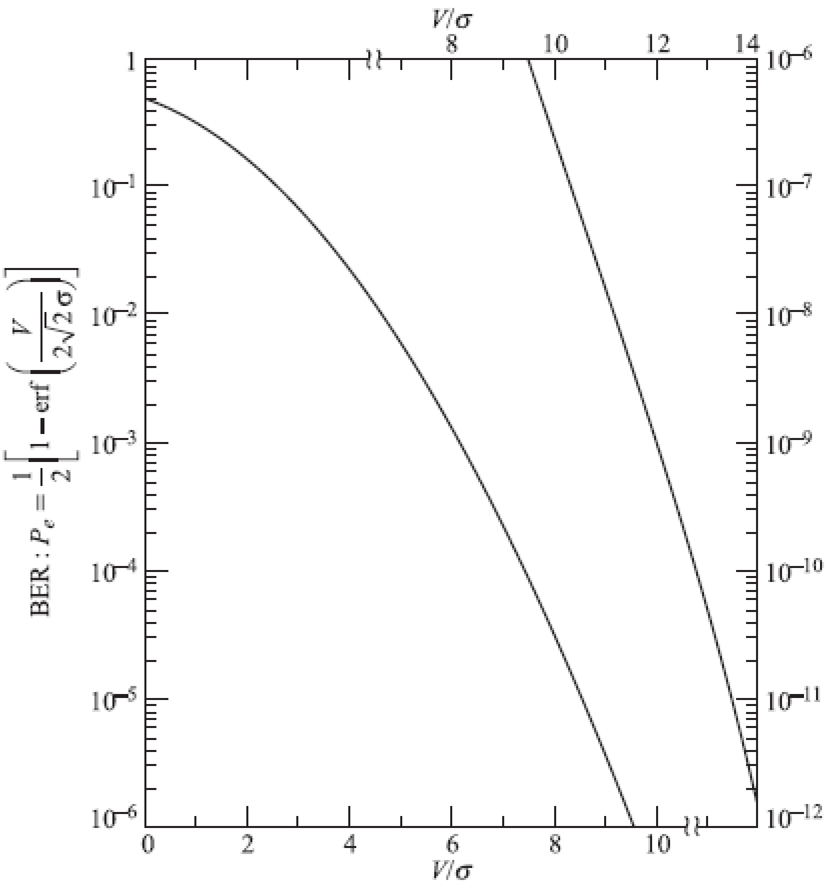
BER as a Function of SNR

BER as a function of SNR when the standard deviations are equal ($\sigma_{on} = \sigma_{off}$) and when $b_{off} = 0$

Example 7.4 Figure 7.10 shows a plot of the BER expression from Eq. (7.16) as a function of the signal-to-noise ratio. Let us look at two cases of transmission rates.

(*a*) For a signal-to-noise ratio of 8.5 (18.6 dB) we have $P_e = 10^{-5}$. If this is the received signal level for a standard DS1 telephone rate of 1.544 Mb/s, this BER results in a misinterpreted bit every 0.065 s, which is highly unsatisfactory. However, by increasing the signal strength so that $V/\sigma = 12.0$ (21.6 dB), the BER decreases to $P_e = 10^{-9}$. For the DS1 case, this means that a bit is misinterpreted every 650 s (or 11 min), which, in general, is tolerable.

(*b*) For high-speed SONET links, say the OC-12 rate that operates at 622 Mb/s, BERs of 10^{-11} or 10^{-12} are required. This means that we need to have at least $V/\sigma = 13.0$ (22.3 dB).



Receiver Sensitivity

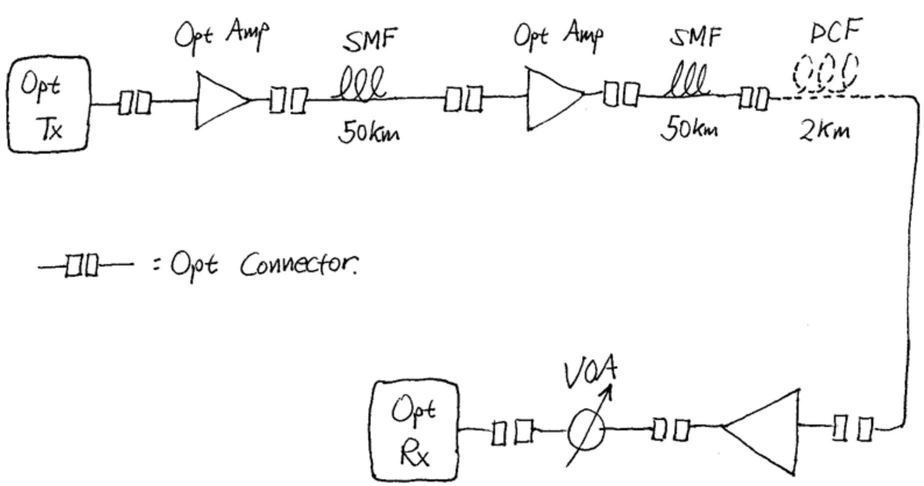
- **To achieve a desired BER at a given data rate, a specific minimum average optical power level must arrive at the photodetector. The value of this minimum power level is called the *receiver sensitivity*.**
- **Assuming there is *no optical power in a received zero pulse*, then the receiver sensitivity is**

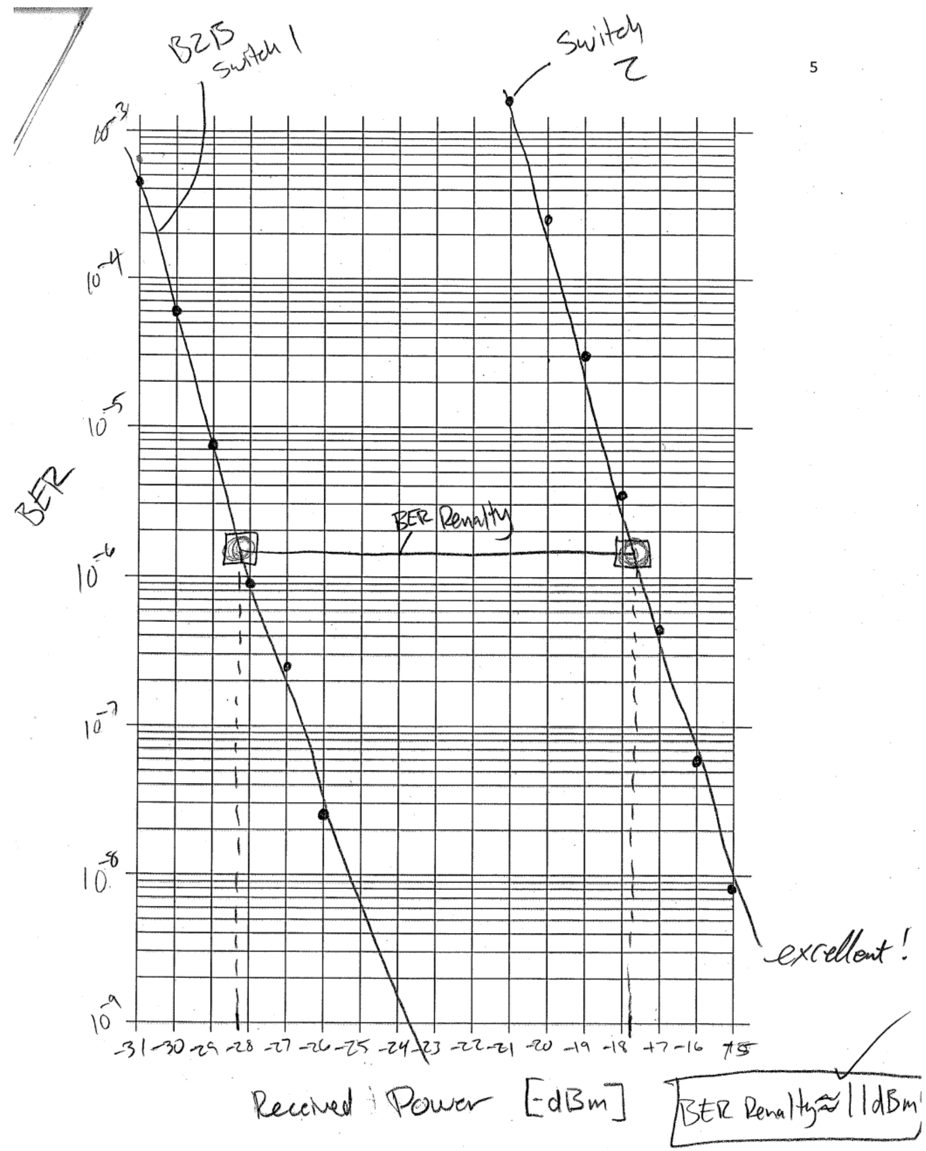
$$P_{\text{sensitivity}} = (1/\mathscr{R})\frac{Q}{M}\left[\frac{qMF(M)BQ}{2} + \sigma_T\right]$$

Where, including an *amplifier noise figure* F_n, the *thermal noise current variance* is

$$\sigma_T^2 = \frac{4k_BT}{R_L}F_n\frac{B}{2}$$

Receiver Sensitivity





Receiver Sensitivity Calculation

The receiver sensitivity as a function of bit rate will change for a given photodiode depending on values of parameters such as wavelength, APD gain, and noise figure.

Example 7.5 To see the behavior of the receiver sensitivity as a function of the BER, first consider the receiver to have a load resistor R_L = 200 Ω and let the temperature be T = 300°K. Letting the amplifier noise figure be F_n = 3 dB (a factor of 2), then from Eq. (7.20) the thermal noise current variance is $\sigma_T = 9.10 \times 10^{-12} B^{1/2}$. Next, select an InGaAs photodiode with a unity-gain responsivity $\mathscr{R}$ = 0.95 A/W at 1550 nm and assume an operating BER = 10^{-12} so that a value of $Q = 7$ is needed. If the photodiode gain is M, then the receiver sensitivity is

$$P_{\text{sensitivity}} = \frac{7.37}{M}\left[5.6 \times 10^{-19} MF(M)B + 9.10 \times 10^{-12} B^{1/2}\right] \tag{7.22}$$

Example 7.7 Consider an InGaAs avalanche photodiode for which M = 10 and $F(M)$ = 5. For the conditions in Eq. (7.22), what is the receiver sensitivity at a 1-Gb/s data rate for a 10^{-12} BER requirement?

Solution: From Eq. (7.22) we have

$$\begin{aligned} P_{\text{sensitivity}} &= 0.737\left[5.6 \times 10^{-19}(50)(1 \times 10^9) + 9.10 \times 10^{-12}(1 \times 10^9)^{\frac{1}{2}}\right] \\ &= 2.32 \times 10^{-4} \text{ mW} = -36.3 \text{ dBm} \end{aligned}$$

The Quantum Limit

- The *minimum received optical power* required for a specific bit-error rate performance in a digital system.
- This power level is called the *quantum limit*, since all system parameters are assumed ideal and the performance is limited only by the detection statistics.

Example 7.8 A digital fiber optic link operating at 850 nm requires a maximum BER of 10^{-9}.

(*a*) Let us first find the quantum limit in terms of the quantum efficiency of the detector and the energy of the incident photon. From Eq. (7.23) the probability of error is

$$P_r(0) = e^{-\bar{N}} = 10^{-9}$$

Solving for $\bar{N}$, we have $\bar{N} = 9 \ln 10 = 20.7 \sim 21$. Hence, an average of 21 photons per pulse is required for this BER. Using Eq. (7.1) and solving for E, we get

$$E = 20.7 \frac{h\nu}{\eta}$$

(*b*) Now let us find the minimum incident optical power P_i that must fall on the photodetector to achieve a 10^{-9} BER at a data rate of 10 Mb/s for a simple binary-level signaling scheme. If the detector quantum efficiency $\eta = 1$, then

$$E = P_i \tau = 20.7 h\nu = 20.7 \frac{hc}{\lambda}$$

where $1/\tau$ is one-half the data rate B; that is, $1/\tau = B/2$. (*Note:* This assumes an equal number of 0 and 1 pulses.) Solving for P_i,

$$P_i = 20.7 \frac{hcB}{2\lambda}$$

$$= \frac{20.7(6.626 \times 10^{-34}\ \text{J·s})(3.0 \times 10^{8}\ \text{m/s})(10 \times 10^{6}\ \text{bits/s})}{2(0.85 \times 10^{-6}\ \text{m})}$$

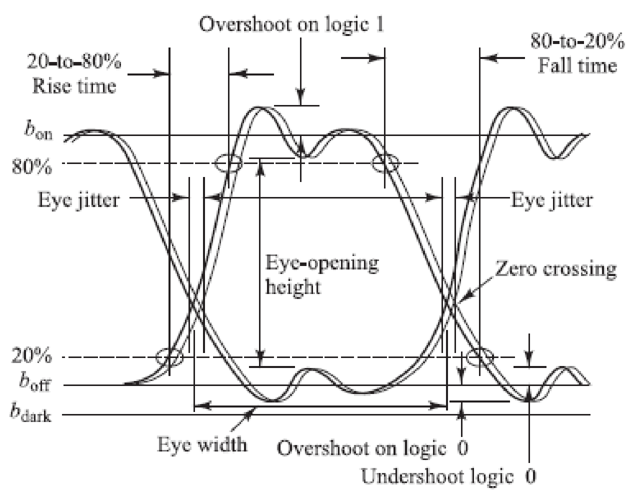
$$= 24.2\ \text{pW}$$

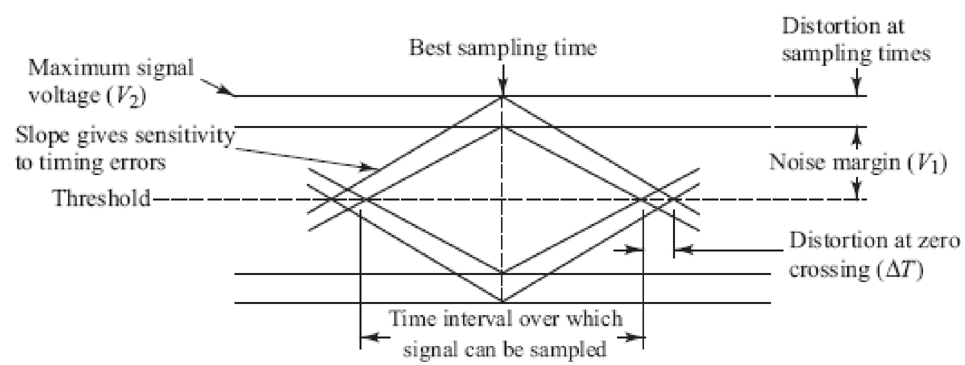
or, when the reference power level is 1 mW,

$$P_i = -76.2\ \text{dBm}$$

7.3 Eye Diagrams

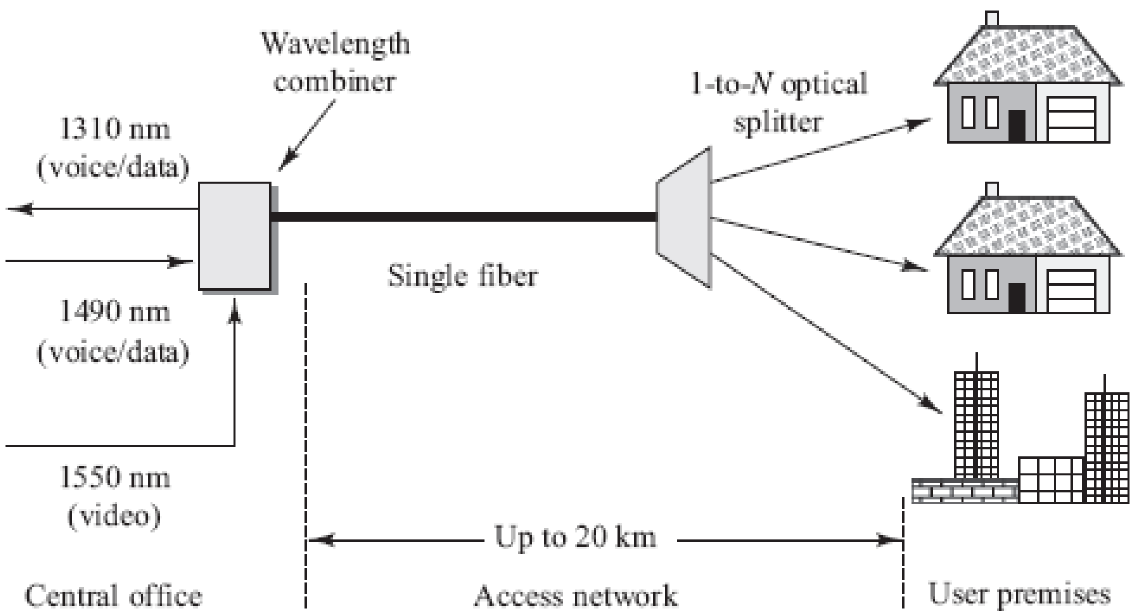
- ***Eye pattern measurements*** **are made in the time domain and immediately show the effects of waveform distortion on the display screen of standard BER test equipment.**
  - **The *eye opening width* defines the time interval over which signals can be sampled without interference from adjacent pulses (ISI).**
  - **The best sampling time is at the height of the *largest eye opening*.**
  - **The *eye opening height* shows the noise margin or immunity to noise.**
  - **The *rate at which the eye closes* gives the sensitivity to *timing errors*.**
  - **The *rise time* is the interval between the 10 and 90% rising-edge points**





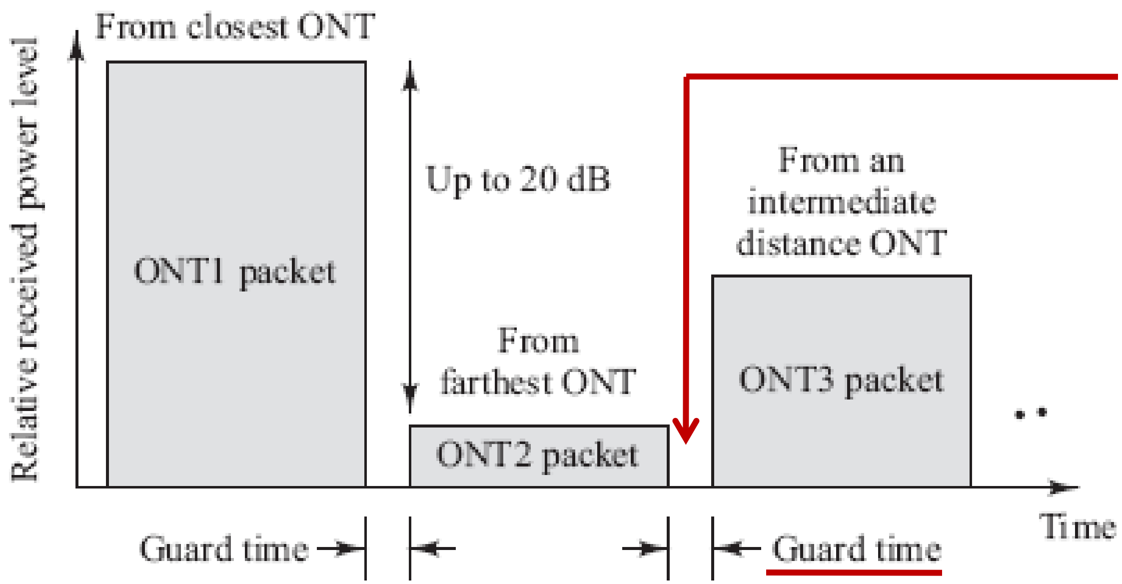
Architecture of a Typical PON

- A *passive optical network* (PON) connects switching equipment in a central office (CO) with N service subscribers
- Digitized voice and data are sent ***downstream*** from the CO to customers over an optical link by using a 1490-nm wavelength.
- The ***upstream*** (customer to central office) return path for the data and voice uses a 1310-nm wavelength.



Burst-Mode Receivers

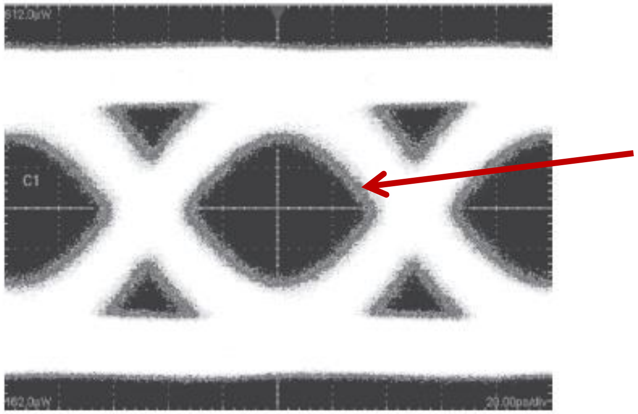
- The amplitude and phase of packets received in successive time slots from different user locations can vary widely from packet to packet.
- If the fiber attenuation is 0.5 dB/km, there is a 10-dB difference in the signal amplitudes from the closest and farthest users.
- If there are additional optical components in one of the transmission paths, then the signal levels arriving at the OLT could vary up to 20 dB.
- A fast-responding ***burst-mode receiver*** with high sensitivity is needed



The *guard time* provides a sufficient delay time to prevent collisions between successive packets that may come from different ONTs.

Stressed Eye Tests

- The IEEE 802.3ae spec for testing 10-Gigabit Ethernet (10-GbE) devices describes performance measures using a degraded signal.
- This *stressed eye test* examines the worst-case condition of a poor extinction ratio plus multiple stresses, ISI or vertical eye closure, sinusoidal interference, and sinusoidal jitter.
- The test assumes that all different possible signal impairments will close the eye down to a diamond shaped area (0.10 and 0.25 of the full pattern height).
- If the eye opening is greater than this area, the receiver being tested is expected to operate properly in an actual fielded system.



The inclusion of all possible signal distortion effects results in a stressed eye with only a small diamond-shaped opening