The performance of a digital lightwave system is characterized through the bit-error rate (BER). Although the BER can be defined as the number of errors made per million bits, such a definition makes the BER bit-rate dependent. It is customary to define a BER as the average probability of incorrect bit identification. Therefore, a BER of $10^{-9}$ corresponds to an average one error per million bits. Most lightwave systems specify a BER of $10^{-9}$ as the operating requirement; some even require a BER as small as $10^{-12}$. The error-correction codes are sometimes used to improve the raw BER of a lightwave system.

An important parameter for any receiver is the receiver sensitivity. It is usually defined as the minimum average optical power required to realize a BER of $10^{-9}$. Receiver sensitivity depends on the SNR, which in turn depends on various noise sources that corrupt the signal received. Even for a perfect receiver, some noise is introduced in the process of photodetection itself. This is referred to as the quantum noise or the shot noise, as it has its origin in the particle nature of electrons. Optical receivers operating at the shot-noise limit are called quantum-noise-limited receivers. No practical receiver operates at the quantum-noise limit because of the presence of several other noise sources. Some of the noise sources such as thermal noise are internal to the receiver. Others originate at the transmitter or during propagation along the fiber link. For instance, any amplification of the optical signal along the transmission line with the help of optical amplifiers introduces the so-called amplifier noise that has its origin in the fundamental process of spontaneous emission. Chromatic dispersion in optical fibers can add additional noise through phenomena such as intersymbol interference and mode-partition noise. The receiver sensitivity is determined by a cumulative effect of all possible noise mechanisms that degrade the SNR at the decision circuit. In general, it also depends on the bit rate as the contribution of some noise sources (e.g., thermal noise) increases in proportion to the signal bandwidth. Chapter 4 is devoted to signal and sensitivity issues of optical receivers by considering the SNR and the BER of digital lightwave systems.

Problems

1.1 Calculate the carrier frequency for optical communication systems operating at 0.88, 1.3, and $1.55 \, \mu m$. What is the photon energy (in eV) in each case?

1.2 Calculate the transmission distance over which the optical power will attenuate by a factor of 10 for three fibers with losses of 0.2, 20, and 2000 dB/km. Assuming that the optical power decreases as $\exp(-\alpha L)$, calculate $\alpha$ (in cm$^{-1}$) for the three fibers.

1.3 Assume that a digital communication system can be operated at a bit rate of up to 1% of the carrier frequency. How many audio channels at 64 kb/s can be transmitted over a microwave carrier at 5 GHz and an optical carrier at $1.55 \, \mu m$?

1.4 A 1-hour lecture script is stored on the computer hard disk in the ASCII format. Estimate the total number of bits assuming a delivery rate of 200 words per minute and on average 5 letters per word. How long will it take to transmit the script at a bit rate of 1 Gb/s?
1.5 A 1.55-μm digital communication system operating at 1 Gb/s receives an average power of −40 dBm at the detector. Assuming that 1 and 0 bits are equally likely to occur, calculate the number of photons received within each 1 bit.

1.6 An analog voice signal that can vary over the range 0–50 mA is digitized by sampling it at 8 kHz. The first four sample values are 10, 21, 36, and 16 mA. Write the corresponding digital signal (a string of 1 and 0 bits) by using a 4-bit representation for each sample.

1.7 Sketch the variation of optical power with time for a digital NRZ bit stream 01011101110 by assuming a bit rate of 2.5 Gb/s. What is the duration of the shortest and widest optical pulse?

1.8 A 1.55-μm fiber-optic communication system is transmitting digital signals over 100 km at 2 Gb/s. The transmitter launches 2 mW of average power into the fiber cable, having a net loss of 0.3 dB/km. How many photons are incident on the receiver during a single 1 bit? Assume that 0 bits carry no power, while 1 bits are in the form of a rectangular pulse occupying the entire bit slot (NRZ format).

1.9 A 0.8-μm optical receiver needs at least 1000 photons to detect the 1 bits accurately. What is the maximum possible length of the fiber link for a 100-Mb/s optical communication system designed to transmit −10 dBm of average power? The fiber loss is 2 dB/km at 0.8 μm. Assume the NRZ format and a rectangular pulse shape.

1.10 A 1.3-μm optical transmitter is used to obtain a digital bit stream at a bit rate of 2 Gb/s. Calculate the number of photons contained in a single 1 bit when the average power emitted by the transmitter is 4 mW. Assume that the 0 bits carry no energy.

References