Chapter 3: Introduction to Physical Layer

Outline

3.4 TRANSMISSION IMPAIRMENT

3.5 DATA RATE LIMITS

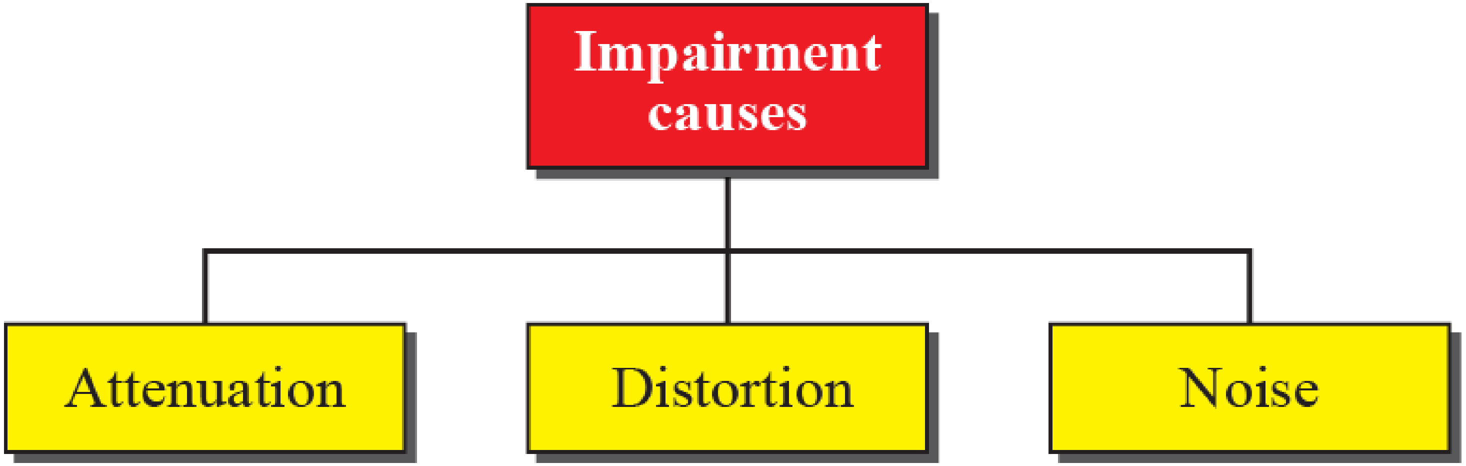
3.6 PERFORMANCE

3-4 TRANSMISSION IMPAIRMENT

Signals travel through transmission media, which are not perfect.

The imperfection causes signal impairment. This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium, i.e., what is sent is not what is received.

Figure 3.26: Causes of impairment



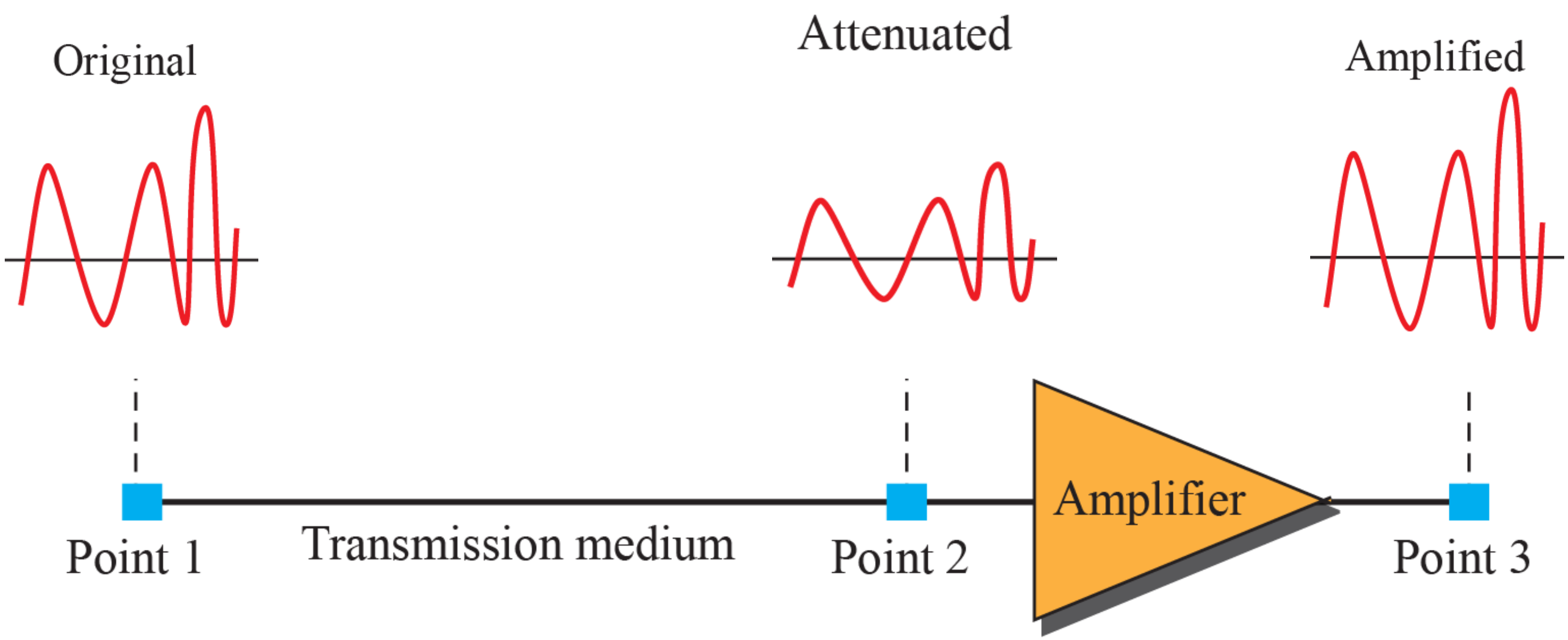
Attenuation: a loss of energy.

Distortion: the signal changes its form or shape.

Noise: an impairment on the signal.

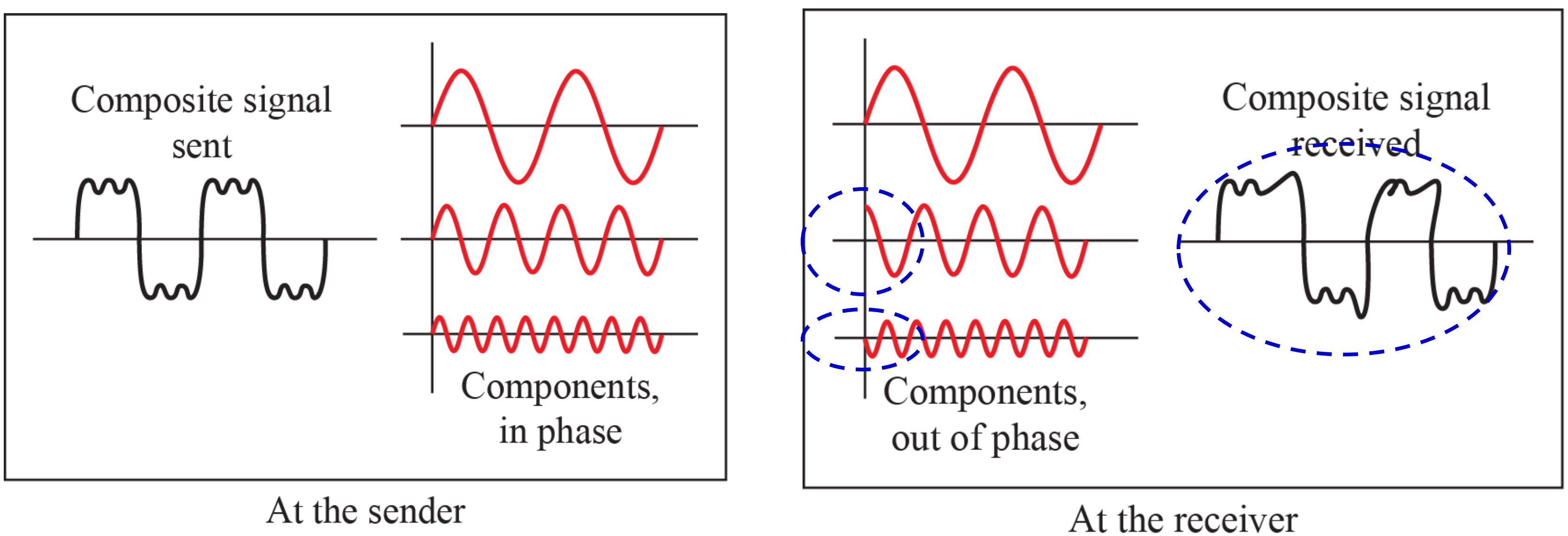
3.4.1 Attenuation

Attenuation means a <u>loss of energy</u>. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. To compensate for this loss, amplifiers may be used to amplify the signal. The figure below shows the effect of attenuation and amplification.



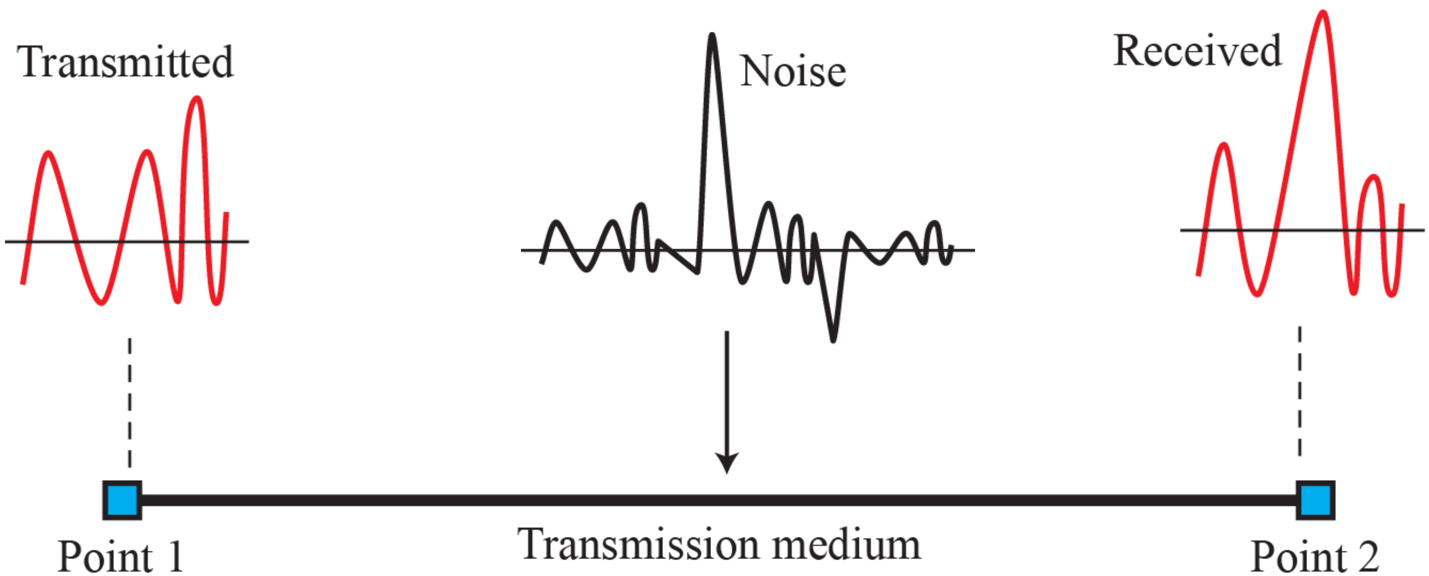
3.4.2 Distortion

Distortion means that the <u>signal changes its form or shape</u>. Distortion can occur in a <u>composite signal</u> made of different frequencies. <u>Each signal component</u> has its <u>own propagation speed</u> through a medium and, therefore, its <u>own delay</u> in arriving at the final destination. Differences in delay may <u>create a difference in phase</u> if the delay is not exactly the same as the period duration.



3.4.3 Noise

Noise is another cause of impairment. Several types of noise, such as <u>thermal noise</u>, <u>induced noise</u>, <u>crosstalk</u> and <u>impulse noise</u> etc., may corrupt the signal. Thermal noise is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter. Induced noise comes from sources such as motors and appliances. Crosstalk is the effect of one wire on the other. Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines and lightning.



Decibel

The decibel (dB) measures the <u>relative strengths</u> of <u>two signals</u> or <u>one signal at two different points</u> to show whether a signal has lost or gained strength.

$$\mathrm{dB} = 10 \log_{10} \frac{P_2}{P_1}$$

where P_1 and P_2 are the powers of a signal at points 1 and 2 respectively.

Note: The decibel is <u>negative</u> if a signal is <u>attenuated</u> and <u>positive</u> if a signal is <u>amplified</u>.

Example

Suppose a signal travels through a transmission medium and its power is reduced to one half, ie., $P_2 = 0.5\ P_1$. What is the attenuation (loss of power) of the signal in dB?

Solution

In this case, the attenuation can be calculated as

$$\boxed{10 \log_{10} P_2/P_1 = 10 \log_{10} (0.5\ P_1)/P_1 = 10 \log_{10} 0.5 = 10 \times (-0.3) = -3 \text{ dB.}}$$

Note: A loss of 3 dB, or -3 dB, is equivalent to losing ½ the power.

Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. What is the amplification (gain of power) of the signal in dB?

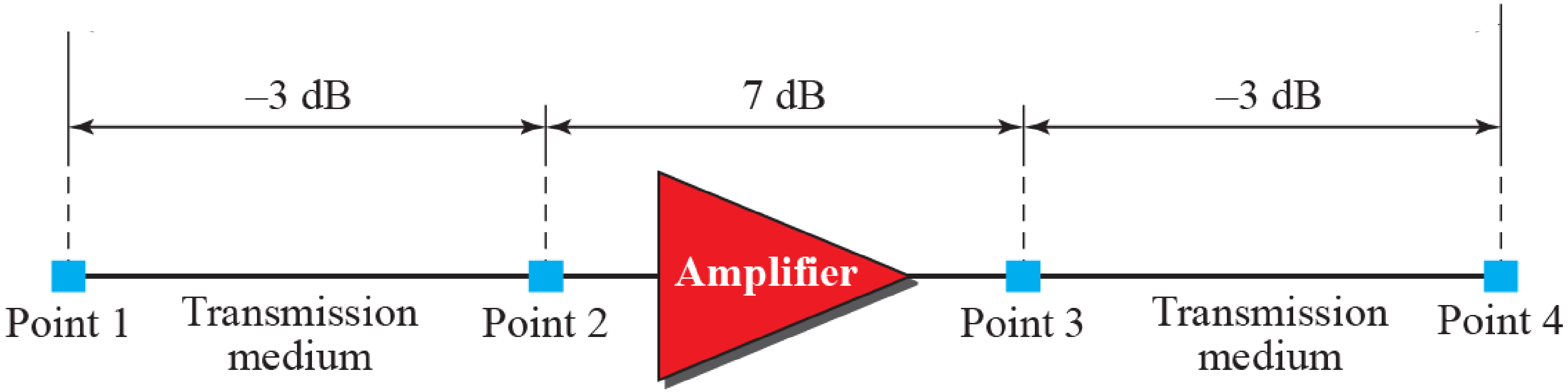
Solution

In this case, the amplification can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1} = 10 \log_{10} 10 = 10(1) = 10 \text{ dB}$$

Problem

What is the resultant gain/loss of the signal (in dB) at Point 4?



Solution

We can find the resultant decibel value for the signal by adding/subtracting the decibel measurements between each set of cascading points. In this case, the resultant decibel value can be calculated as

$$\text{dB} = -3 + 7 - 3 = +1$$

➔ The signal has gained in power.

Problem

The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable (with loss of 0.3 dB/km) has a power of 2 mW, what is the power of the signal at 5 km?

Solution

The loss in the cable in dB is $5 \times (-0.3) = -1.5$ dB. We can calculate the power as

$$\text{dB} = 10 \log_{10}(P_2 / P_1) = -1.5 \quad \longrightarrow \quad (P_2 / P_1) = 10^{-0.15} = 0.71$$

$$P_2 = 0.71 P_1 = 0.7 \times 2 \text{ mW} = 1.4 \text{ mW}$$

Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio (SNR) is defined as

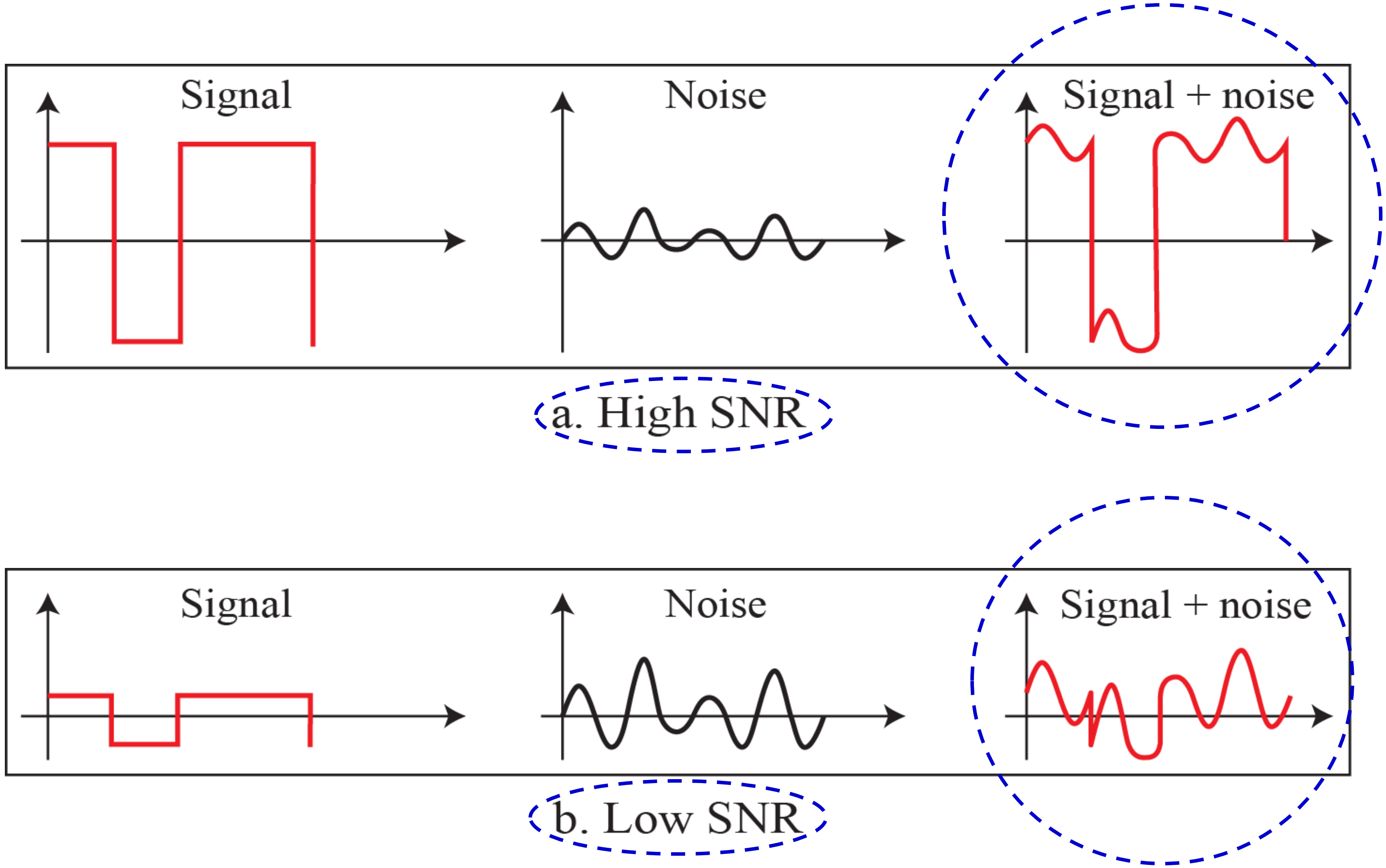
$$SNR = \frac{\text{average signal power}}{\text{average noise power}}$$

Note: A <u>high *SNR*</u> means the signal is <u>less corrupted</u> by noise;
a <u>low *SNR*</u> means the signal is <u>more corrupted</u> by noise.

As SNR is the ratio of two powers, it is often described in <u>decibel</u> (dB) units as

$$SNR_{dB} = 10\log_{10} SNR$$

Figure 3.31: ***Two cases of SNR: a high SNR and a low SNR***



Problem

The power of a signal is 10 mW and the power of the noise is 1 μW. What are the SNR and SNR_{dB}?

Solution

The values of SNR and SNR_{dB} can be calculated as follows:

$$SNR = (10{,}000\ \mu w) / (1\ \mu w) = 10{,}000 \qquad SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

3-5 DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. The <u>data rate</u> depends on three factors: i) <u>bandwidth</u> available, ii) <u>signal levels</u> used and iii) <u>channel</u> quality.

Two <u>theoretical formulas</u> were developed to calculate the data rate: one by <u>Nyquist</u> for a <u>noiseless channel</u>, another by <u>Shannon</u> for a <u>noisy channel</u>.

3.5.1 Noiseless Channel: Nyquist Rate

For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate.

$$\boxed{BitRate = 2 \times bandwidth \times \log_2 L}$$

where *bandwidth* is the bandwidth of the channel, *L* is the number of signal levels used to represent the data, and *BitRate* is the bit rate in bits per second (bps).

Given a specific bandwidth, can we obtain any bit rate by increasing the number of signal levels?

Example

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. What is the maximum bit rate?

Solution

$$\text{BitRate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

Consider the same noiseless channel transmitting a signal with four signal levels (i.e., for each level, we send 2 bits). What is the maximum bit rate?

Solution

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

Problem

We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution

We can use the Nyquist formula as shown:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L \longrightarrow \log_2 L = 6.625 \longrightarrow L = 2^{6.625} = 98.7 \text{ levels}$$

Since the number of signal levels is not a power of 2, we need to either increase the number of levels or reduce the bit rate.

➔ If we have 128 levels, we can achieve a bit rate of 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

3.5.2 Noisy Channel: Shannon Capacity

In reality, we cannot have a noiseless channel; the channel is always noisy. In 1944, Claude Shannon introduced a formula, called the Shannon capacity, to determine the theoretical highest data rate for a noisy channel.

$$Capacity = bandwidth \times \log_2(1 + SNR)$$

where *bandwidth* is the bandwidth of the channel, *SNR* is the signal-to-noise ratio and *capacity* is the capacity of the channel in bits per second (bps).

Notes:

1) SNR not SNR_{dB}

2) Shannon capacity defines characteristics of the channel, not the method of transmission.

Example

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. What is the capacity of such a channel?

Solution

$$C = B \log_2 (1 + \text{SNR}) = B \log_2(1 + 0) = B \log_2 1 = B \times 0 = 0$$

This means that the capacity of this channel is 0 bps regardless of the bandwidth. In other words, we cannot receive any data through this channel.

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 to 3300 Hz) assigned for data communications. The signal-to-noise ratio is usually 3162. What is the capacity for this channel?

Solution

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2(1 + 3162) = 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.86 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

Problem

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. What is the theoretical capacity of this channel?

Solution

***SNR*, not *SNR*$_{dB}$!**

$$\mathrm{SNR_{dB}} = 10 \log_{10}\mathrm{SNR} \longrightarrow \mathrm{SNR} = 10^{\mathrm{SNR_{dB}}/10} \longrightarrow \mathrm{SNR} = 10^{3.6} = 3981$$

$$C = B \log_2(1 + \mathrm{SNR}) = 2 \times 10^6 \times \log_2 3982 = 24 \text{ Mbps}$$

3.5.3 Using Both Limits

In practice, we can use both methods to find the data rate limits and signal levels.

Example: We have a channel with a 1 MHz bandwidth. The SNR for this channel is 63. What are the appropriate bit rate and signal level?

First, we use the Shannon formula to find the upper data rate limit:

$$C = B \log_2(1 + \text{SNR}) = 10^6 \log_2(1 + 63) = 10^6 \log_2 64 = 6 \text{ Mbps}$$

The Shannon formula gives us 6 Mbps (the upper limit). For better performance, we will choose something lower, 4 Mbps. Then we use the Nyquist formula to find the number of signal levels:

$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \longrightarrow L = 4$$

The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.

3-6 PERFORMANCE

Up to now, we have discussed the methods of transmitting data (using signals) over a network and how the data behave.

One important issue in networking is the <u>performance</u> of the network, i.e., how good is it?

3.6.1 Bandwidth

One characteristic that measures network performance is bandwidth. However, the term can be used in two different contexts:

(1) bandwidth in hertz (Hz), refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass (e.g., bandwidth of a telephone line is 4 kHz).

(2) bandwidth in bits per second (bps), refers to the speed of bit transmission in a channel or link (e.g., the bandwidth of an Ethernet network is a maximum of 1 Gbps).

3.6.2 Throughput

The throughput is a measure of how fast we can actually send data through a network.

At first glance, bandwidth, B, and throughput, T, may seem the same, but they are different. A link may have a bandwidth of B bps, but we can only send T bps through this link with $T \leq B$.

The bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast data can be sent.

3.6.3 Latency (Delay)

The latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source.

Latency is made of four components: propagation time, transmission time, queuing time and processing delay.

$$Propagation\ Time = \frac{Distance}{Propagation\ Speed}$$

$$Transmission\ Time = \frac{Message\ Size}{Transmission\ Rate}$$

$$\text{Latency} = \text{propagation time} + \text{transmission time} + \text{queuing time} + \text{processing delay}$$

3.6.5 Jitter

Another performance issue that is related to delay is jitter. It can be loosely defined as <u>different packets of data encountering different delays</u>.

Jitter is a <u>problem</u> if the application using the <u>data</u> at the receiver site is <u>time-sensitive</u> such as audio and video data. If the delay for the first packet is 20 ms, for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets needs to endure jitter.

Problem

A network with bandwidth of 10 Mbps can only pass an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution

We can calculate the throughput as

$$\text{Throughput} = (12{,}000 \times 10{,}000) / 60 = 2 \text{ Mbps}$$

Note: The throughput is 1/5 of the bandwidth in this case.

Problem

What are the propagation time and the transmission time for a 2.5 kB message if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission time as

$$\textbf{Propagation time} = (12{,}000 \times 1000) / (2.4 \times 10^8) = 50 \text{ ms}$$

$$\textbf{Transmission time} = (2500 \times 8) / 10^9 = 0.020 \text{ ms}$$

Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time.