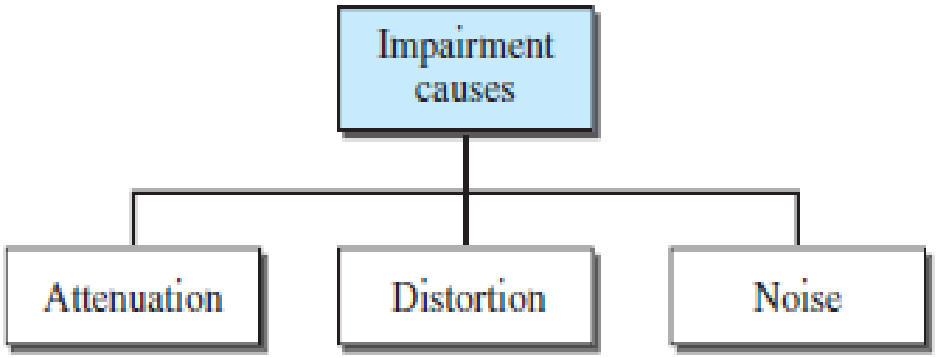
Physical Layer

Transmission Impairments

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.
- What is sent is not what is received. Three causes of impairment are attenuation, distortion, and noise.
- For analog signal, these impairments cause various modifications that degrade the signal quality.
- For digital signal, due to bit error a binary 1 maybe changed into binary 0 and vice versa



1.Attenuation

- Means **loss of energy** -> weaker signal
- When a signal travels through a medium it loses energy **overcoming the resistance of the medium**
- At Attenuation, signal strength falls off with distance. It happens exponentially with the travelled distance.
- **Amplifiers** are used to compensate for this loss of energy by amplifying the signal.
- Attenuation affects the propagation of waves and signals in electrical circuits, in optical fibers, as well as in air

Measurement of Attenuation

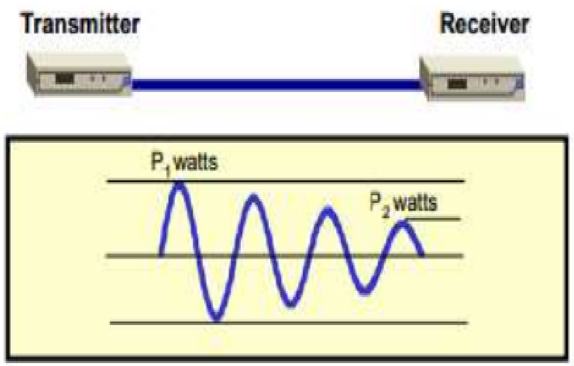
- To show the ***loss or gain of energy of a signal***, the unit "**decibel**" is used.

$$dB = 10\log_{10} P_2/P_1$$

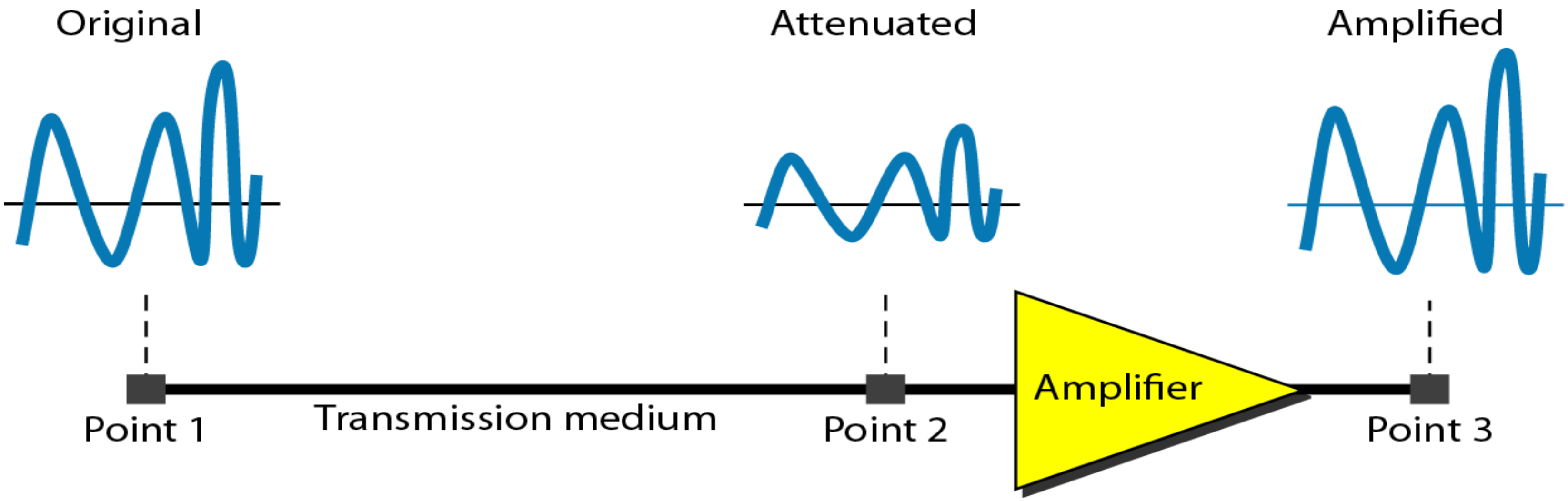
P_1 – power of input signal

P_2 – power of output signal

- The decibel (db) measures the relative strengths of two signals or one signal at two different points (P1, P2)
- Decibel is negative, if signal is attenuated
- Decibel is positive, if signal is amplified



Attenuation



Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 is (1/2)P1. In this case, the attenuation (loss of power) can be calculated as

Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P2 is (1/2)P1. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

A loss of 3 dB (–3 dB) is equivalent to losing one-half the power.

Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

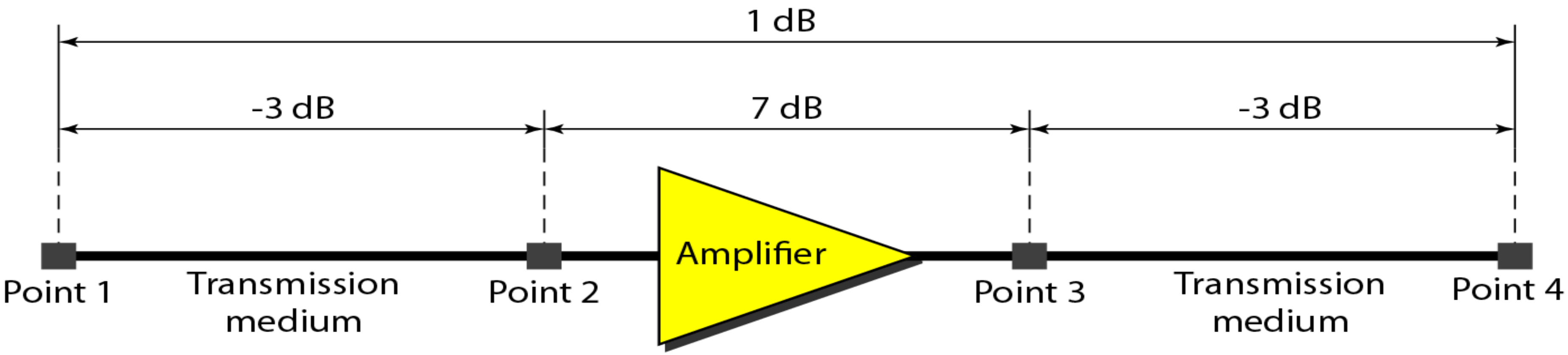
Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

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

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

Decibels for Example One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two.



$$dB = -3 + 7 - 3 = +1$$

Example

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as $dB_m = 10 \log10 P_m$, where P_m is the power in milliwatts. Calculate the power of a signal with $dB_m = -30$.

Solution

We can calculate the power in the signal as

$$\mathrm{dB_m} = 10 \log_{10} P_m = -30$$

$$\log_{10} P_m = -3 \qquad P_m = 10^{-3} \ \mathrm{mW}$$

Example

The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with −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 decibels is 5 × (−0.3) = −1.5 dB. We can calculate the power as

$$\mathrm{dB} = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

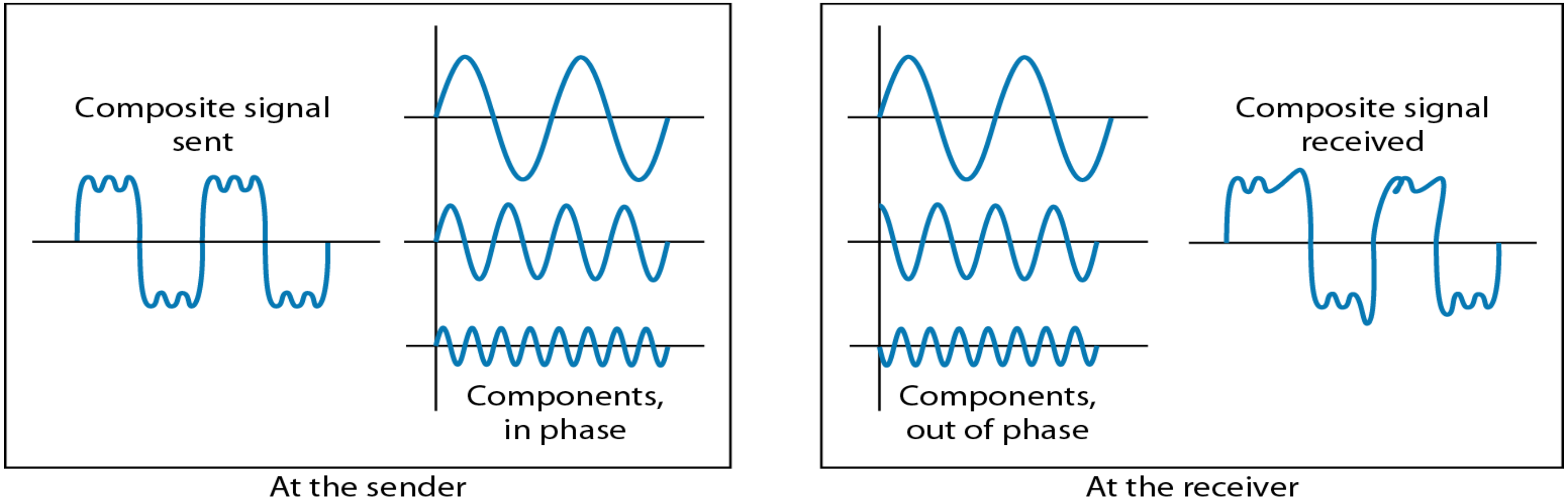
$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

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

2.Distortion

- Means that the signal changes its form or shape
- Distortion occurs in composite signals made of different frequencies
- Each frequency component has its own propagation speed traveling through a medium
- The different components therefore arrive with different delays at the receiver
- Differences in delay may create difference in phase
- That means that the signals have **different phases** at the receiver than they did at the source
- Measuring distortion is possible but complicated
- Can be solved by equalizing circuits.

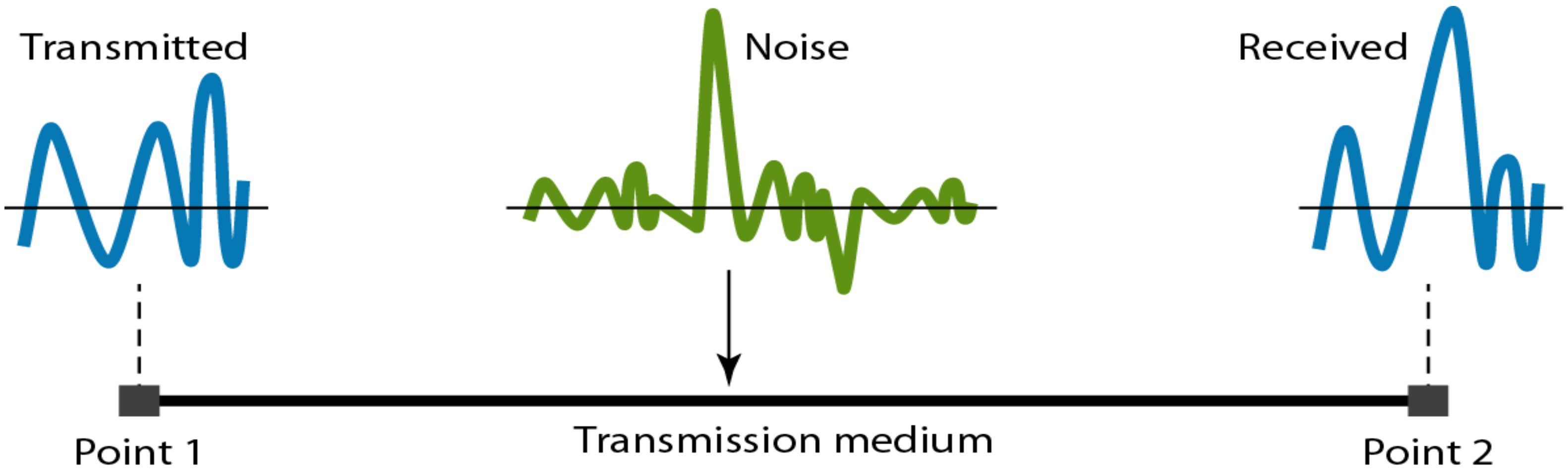
Effect of Distortion on a composite signal



3.Noise

- There are different types of noise(based on source that creates noise)
  - Thermal - random noise of electrons in the wire creates an extra signal (not originally sent by transmitter)
  - Induced - from motors and appliances. Devices act as transmitter antenna and medium as receiving antenna(mitigate-insulation)

Noise



Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

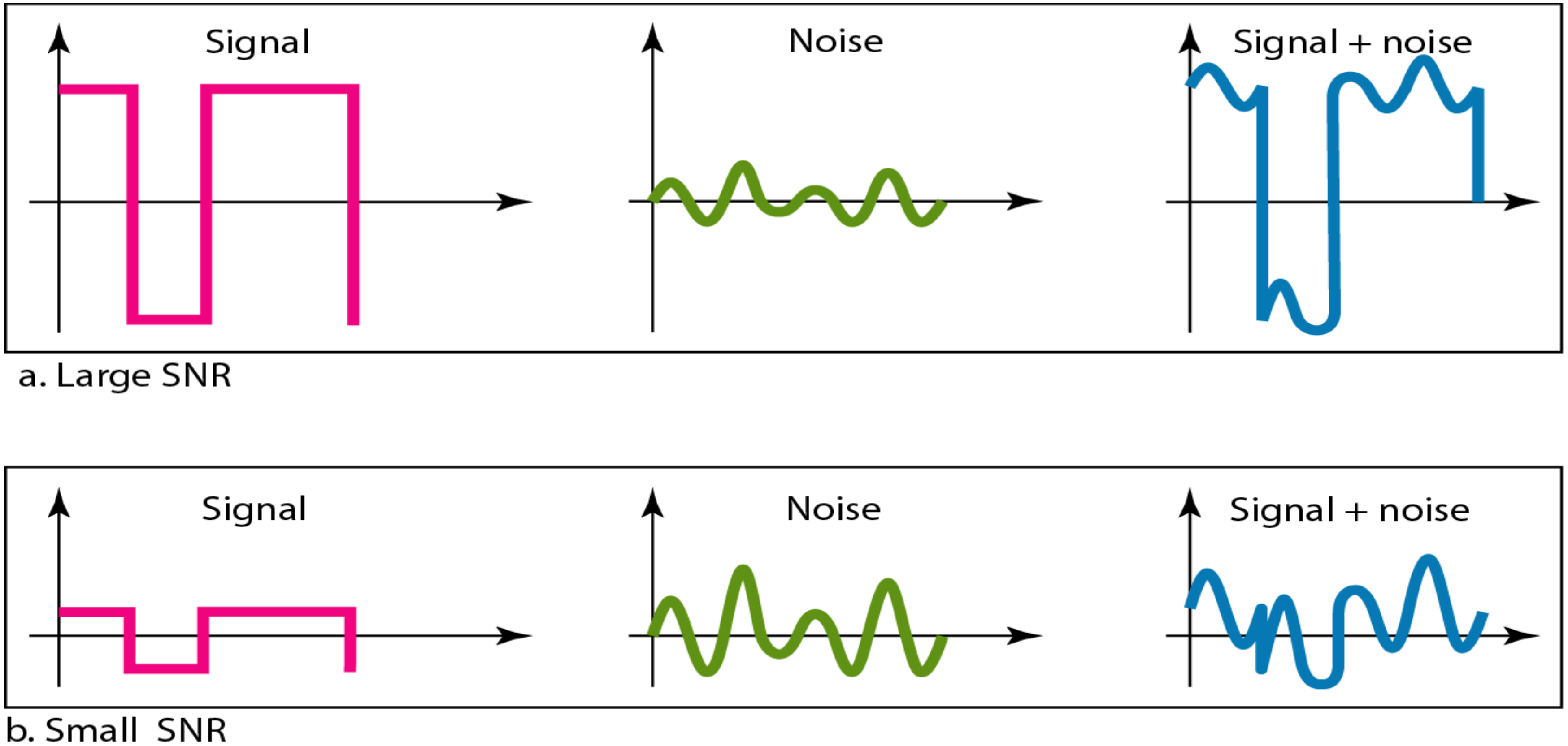
3.Noise

- Crosstalk – Effect of one wire on the other. One wire acting as sending antenna and the other acting as receiving antenna(mitigate-twisting)
- Impulse - Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

Signal to Noise Ratio (SNR)

- To measure the quality of a system, the SNR is often used. It indicates the strength of the signal wrt the noise power in the system.
- It is the ratio between two powers.
  - **SNR = average signal power / average noise power**
- It is usually given in dB and referred to as $SNR_{dB.}$
- $\mathbf{SNR_{db} = 10Log_{10}SNR}$

Two cases of SNR: a high SNR and a low SNR



Example

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

Solution

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

Example

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

Solution

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

$$SNR = \frac{10\,mW}{1\,\mu W} = \frac{10{,}000\,\mu W}{1\,\mu W} = 10^4$$

$$SNR_{dB} = 10\log_{10} SNR = 10\log_{10} 10^4 = 40\,dB$$

Example

The values of SNR and SNRdB for a noiseless channel are

$$\mathrm{SNR} = \frac{\text{signal power}}{0} = \infty$$

$$\mathrm{SNR}_{\mathrm{dB}} = 10 \log_{10} \infty = \infty$$

We can never achieve this ratio in real life; it is an ideal.

Data Rate Limit

DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel. Data rate depends on three factors:

1. The bandwidth available
2. The level of the signals we use
3. The quality of the channel (the level of noise)

Channel capacity : The maximum possible data rate under the given conditions

Capacity of a System

- The bit rate of a system increases with an increase in the number of signal levels we use to denote a symbol.
- A symbol can consist of a single bit or “n” bits.
- The number of signal levels = 2^n.
- As the number of levels goes up, the spacing between level decreases -> increasing the probability of an error occurring in the presence of transmission impairments.

Nyquist Theorem

- Nyquist gives the upper bound for the bit rate of a transmission system by calculating the bit rate directly from the number of bits in a symbol (or signal levels) and the bandwidth of the system (assuming 2 symbols/per cycle and first harmonic).
- Nyquist theorem states that for a noiseless channel:

$$C = 2\, B \log_2 2^n$$

C= capacity in bps

B = bandwidth in Hz

Example

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

Example

Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

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

Example

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

Example

Consider the same noiseless channel transmitting a signal with four signal levels (for each level, we send 2 bits). The maximum bit rate can be calculated as

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

Example

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:

Example

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:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result 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, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps.

Shannon’s Theorem

- Shannon’s theorem gives the capacity of a system in the presence of noise.

$$C = B \log_2(1 + SNR)$$

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. For this channel the capacity C is calculated as

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. For this channel the capacity C is calculated as

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

This means that the capacity of this channel is zero 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. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 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.

Example

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

Example

The signal-to-noise ratio is often given in decibels. Assume that SNR_{dB} = 36 and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

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

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

Example

For practical purposes, when the SNR is very high, we can assume that SNR + 1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified to

$$\boxed{C = B \times \frac{\text{SNR}_{\text{dB}}}{3}}$$

For example, we can calculate the theoretical capacity of the previous example as

$$\boxed{C = 2 \text{ MHz} \times \frac{36}{3} = 24 \text{ Mbps}}$$

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?

Solution

First, we use the Shannon formula to find the upper limit.

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

Example

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

$$\boxed{4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \quad \Rightarrow \quad L = 4}$$

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

Performance

Performance

- One important issue in networking is the performance of the network—how good is it?
  - Bandwidth
- • Throughput
- • Latency (Delay)

Bandwidth

- In networking, we use the term bandwidth in two contexts.
- ❑ The first, bandwidth in hertz, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.
- ❑ The second, bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.

Example

- The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog. What is the max bit rate if the signal level is 2 (binary signal) under noiseless condition?

Nyquist: $C = 2B\log_2 L$

$C = 2 \times 4000 \times \log_2 2 = 8000\text{bps} = 8\text{kbps}$

Throughput

- Throughput: how fast bps of data we can actually send.
- Throughput is always smaller than link bandwidth
- Why?
  - Data impairment causes data error
  - Data congestion causes delay

Example

A network with bandwidth of 10 Mbps can pass only 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

$$\text{Throughput} = 10000 \text{ bit} \times 12{,}000/\text{min}$$

$$= \frac{10000 \times 12000}{60} = 2 \times 10^6 \text{ bps} = 2 \text{ Mbps}$$

The throughput is almost one-fifth of the bandwidth in this case.

Latency (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 = propagation time+ transmission time+ queuing time+ processing delay

Propagation Time

- Measures the time required for a bit to travel from the source to the destination.

$$\boxed{\mathrm{Pr}\,opagationTime = \frac{dis\,\mathrm{tan}\,ce}{propagationspeed}}$$

Transmission Time

- First bit received → last bit received

$$\boxed{TransmisisonTime = \frac{MessageSize}{Bandwidth}}$$

Queuing Time

- It is the time needed for each intermediate or end device to hold the message before it can processed.
- Top performance metric for networking routers

Example

- What are the propagation time and the transmission time for a 5-Mbyte message (an image) if the bandwidth of the network is 1 Mbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4 × 108 m/s.

$$\text{Propagation time} = \frac{12000 \times 10^3\ m}{2.4 \times 10^8\ m/s} = 50\ ms$$

$$\text{transmission time} = \frac{5 \times 10^6 \times 8\ bit}{1 \times 10^6\ bit/s} = 40\ s$$

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored in most cases.

$$\log_2\left(1+\frac{S}{N}\right) \approx \log_2 \frac{S}{N} = \frac{\ln 10}{\ln 2} \cdot \log_{10} \frac{S}{N} \approx 3.32 \cdot \log_{10} \frac{S}{N},$$

in which case the capacity is logarithmic in power and approximately linear in bandwidth (not quite linear, since N increases with bandwidth, imparting a logarithmic effect). This is called the **bandwidth-limited regime**.

$$C \approx 0.332 \cdot B \cdot \mathrm{SNR}\ (\mathrm{in\ dB})$$