Chapter 3

Data and Signals
(Transmission Impairments)

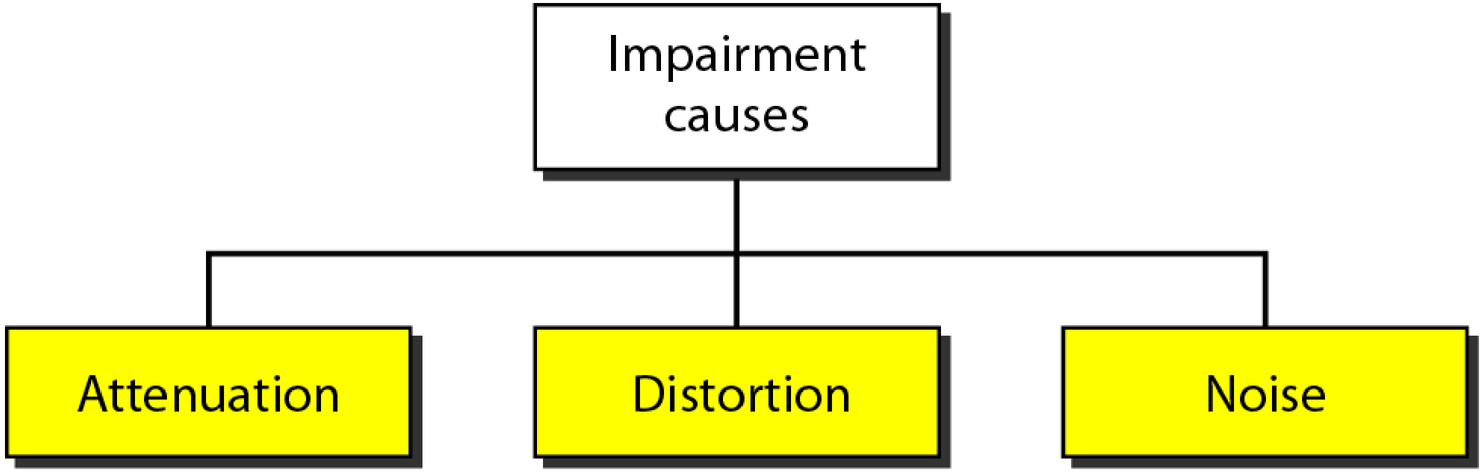
3-4 TRANSMISSION IMPAIRMENT

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. What is sent is not what is received. Three causes of impairment are attenuation, distortion, and noise.

Topics discussed in this section:

- Attenuation
- Distortion
- Noise

Figure 3.25 Causes of impairment



Attenuation

- Means loss of energy -> weaker signal
- When a signal travels through a medium it loses some of its energy in overcoming the resistance of the medium.
- That is why a wire carrying electric signals gets warm after a while. Some of the electrical energy in the signal is converted to heat.
- To compensate for this loss, amplifiers are used to amplify the signal.

Measurement of Attenuation

- To show the loss or gain of energy the unit "decibel" is used.
- To show that a signal has lost or gained strength, engineers use the unit of the decibel.
- Decibel is negative if a signal is attenuated and positive if a signal is amplified.

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

P_1 - input signal

P_2 - output signal

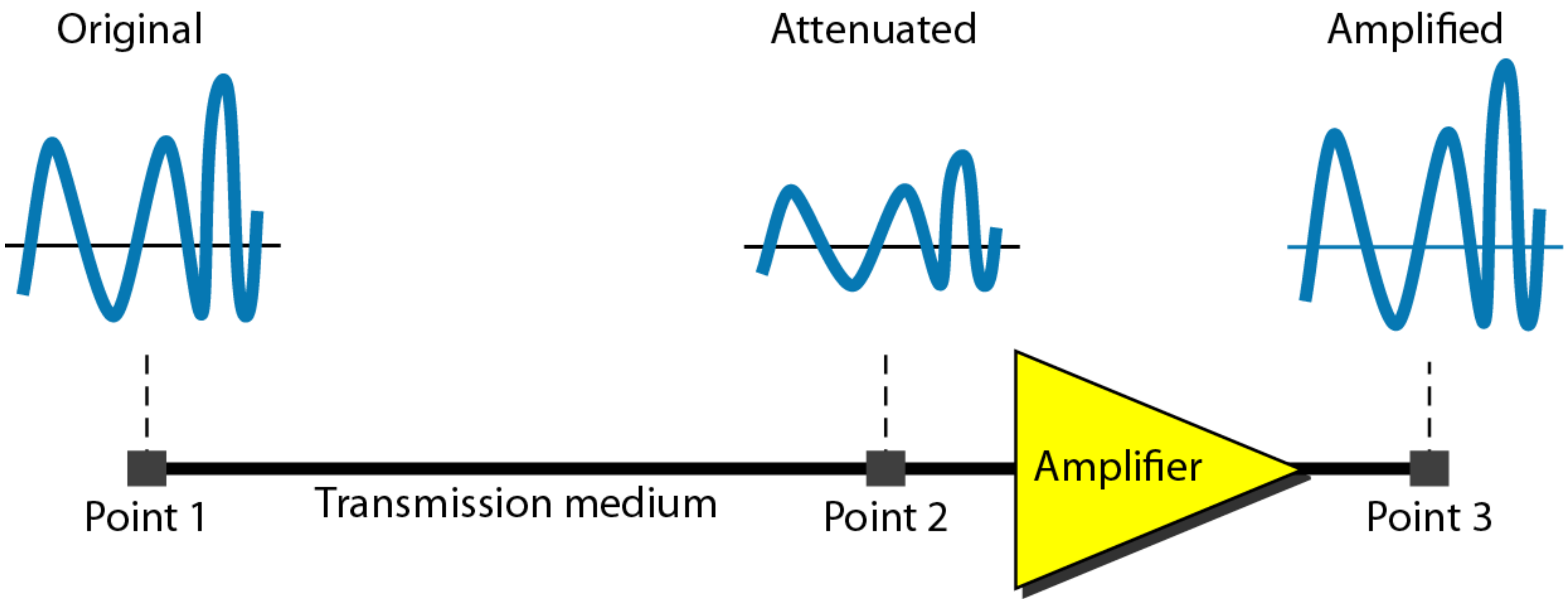
- Variables P_l and P_2 are the powers of a signal at points 1 and 2, respectively.
- Decibel in terms of voltage instead of power, hence,

$$dB = 20\log_{10}V_2/V_1$$

P_1 - input signal

P_2 - output signal

Figure 3.26 Attenuation



Example 3.26

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

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

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

Example 3.27

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

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

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

Example 3.28

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.

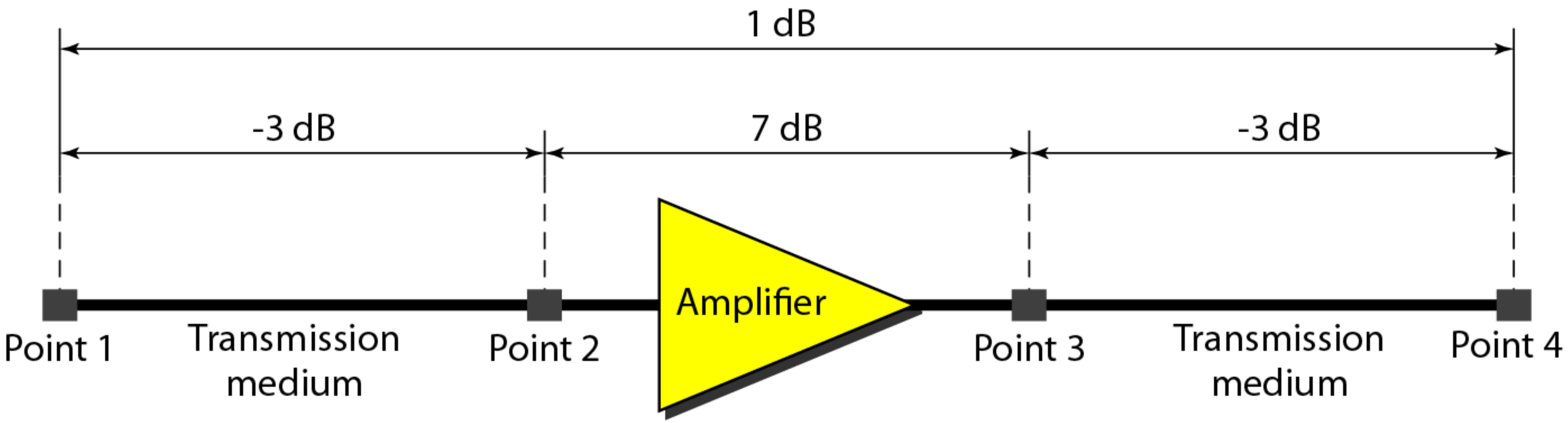
In Figure 3.27 a signal travels from point 1 to point 4.

Figure 3.27 Decibels for Example 3.28

The signal is attenuated by the time it reaches point 2. Between points 2 and 3, the signal is amplified. Again, between points 3 and 4, the signal is attenuated.

We can find the resultant decibel value for the signal just by adding the decibel measurements between each set of points.

In this case, the decibel value can be calculated as $\boxed{dB = -3 + 7 - 3 = +1}$



Example 3.29

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 3.30

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

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

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

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

Noise

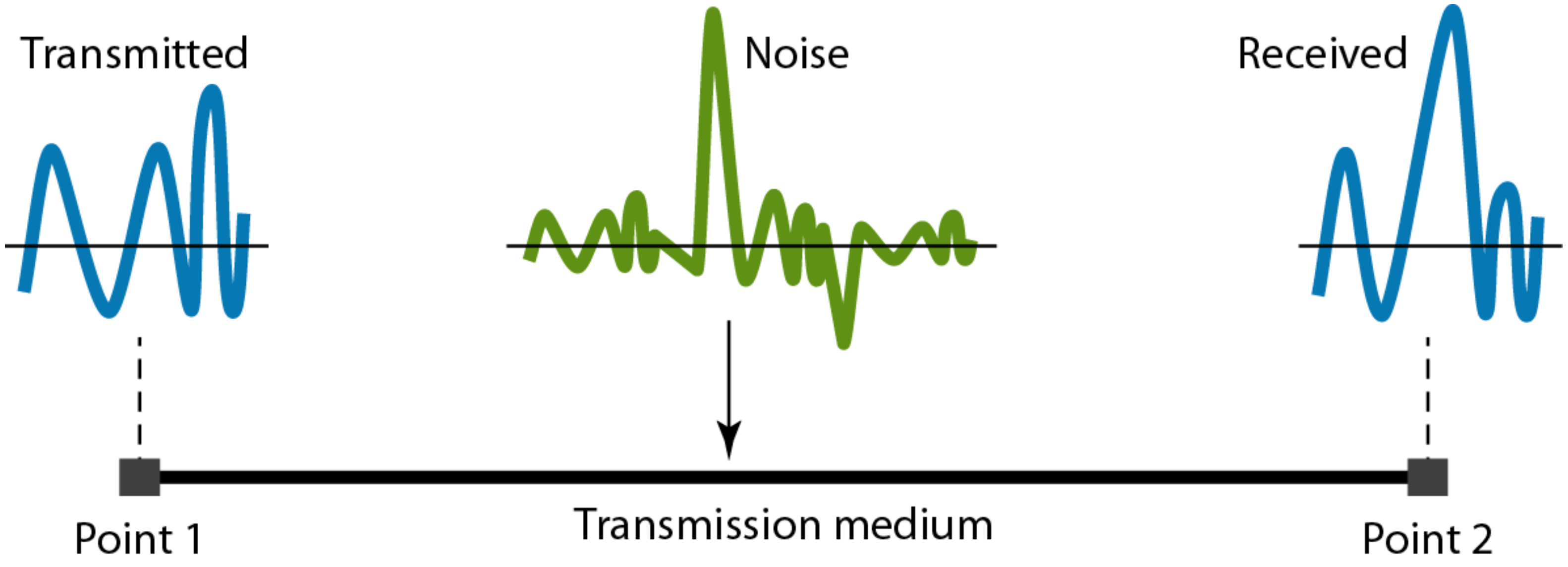
- There are different types of noise

  - Thermal – random motion of electrons in the wire which creates an extra signal not originally sent by transmitter.

  - Crosstalk - Crosstalk is the effect of one wire on the other.

  - Impulse – Spikes (a signal with high energy in a very short time) that comes from power lines, lightning, etc.

Figure 3.29 Noise



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.
- It is usually given in dB and referred to as $SNR_{dB.}$

Example 3.31

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:

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

$$SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

Example 3.32

The values of SNR and SNR_{dB} for a noiseless channel are

$$\boxed{\begin{aligned} SNR &= \frac{\text{signal power}}{0} = \infty \\ SNR_{dB} &= 10 \log_{10} \infty = \infty \end{aligned}}$$

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

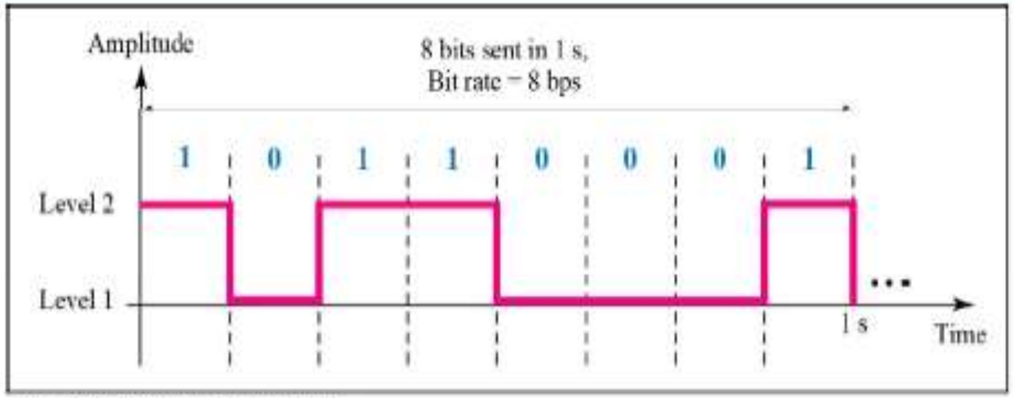
3-3 DIGITAL SIGNALS

In addition to being represented by an analog signal, information can also be represented by a digital signal. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.

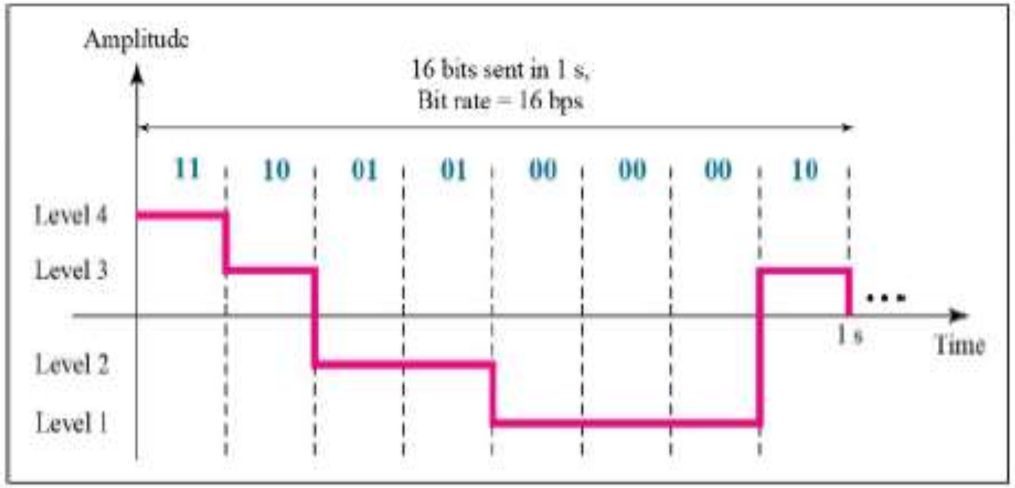
Topics discussed in this section:

Bit Rate
Bit Length
Digital Signal as a Composite Analog Signal
Application Layer

Figure 3.16 *Two digital signals: one with two signal levels and the other with four signal levels*



a. A digital signal with two levels



b. A digital signal with four levels

We send 1 bit per level in part a of the figure and 2 bits per level in part b of the figure.

In general, if a signal has L levels, each level needs $log_2 L$ bits.

Example 3.16

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

$$\boxed{\text{Number of bits per level} = \log_2 8 = 3}$$

Each signal level is represented by 3 bits.

Example 3.17

A digital signal has nine levels. How many bits are needed per level? We calculate the number of bits by using the formula. Each signal level is represented by 3.17 bits. However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2. For this example, 4 bits can represent one level.

Example 3.18

Assume we need to download text documents at the rate of 100 pages per second. What is the required bit rate of the channel?

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

$$\boxed{100 \times 24 \times 80 \times 8 = 1{,}636{,}000 \text{ bps} = 1.636 \text{ Mbps}}$$

Example 3.20

What is the bit rate for high-definition TV (HDTV)?

Solution

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel.

$$1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression.

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)

- Two theoretical formulas were developed to calculate the data rate: one by Nyquist for a noiseless channel. another by Shannon for a noisy channel.

Noiseless Channel: Nyquist Bit Rate

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

$$\text{BitRate} = 2 * \text{BW} * \log_2 L$$

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

- According to the formula, we might think that, given a specific bandwidth, we can have any bit rate we want by increasing the number of signal levels.
- When we increase the number of signal levels, we impose a burden on the receiver.
- If the number of levels in a signal is just 2, the receiver can easily distinguish between a 0 and 1.
- If the level of a signal is 64, the receiver must be very sophisticated to distinguish between 64 different levels.
- In other words, increasing the levels of a signal reduces the reliability of the system.

- 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.

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

- 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

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

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

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.

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:

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

- In the Shannon formula there is no indication of the signal level, which means that no matter how many levels we have, we cannot achieve a data rate higher than the capacity of the channel.
- The formula defines a characteristic of the channel, not the method of transmission.

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

$$\text{Capacity} = \text{bandwidth} \times \log_2 (1 + \text{SNR}) = \text{bandwidth} \times \log_2 (1 + 0) = 0$$

We cannot receive any data through this channel.

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

$$C = B \log2 (1 + SNR) = 3000 \log2 (1 + 3162) = 3000 \log2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

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.

- 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:

$$SNR_{dB} = 10 \log10 \, SNR \quad \Rightarrow \quad SNR = 10^{SNR_{dB}/10} \quad \Rightarrow \quad SNR = 10^{3.6} = 3981$$
$$C = B \log2 (1 + SNR) = 2 \times 10^6 \times \log2 3982 = 24 \text{ Mbps}$$

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

$$C = B \times \frac{SNR_{dB}}{3}$$

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

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

Using Both Limits

- In practice, we need to use both methods to find the limits and signal levels. Let us show this with an 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?

  $C = BW \times \log_2 (1 + SNR) = 6\text{Mbps}$

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.

$BitRate = 2 * BW * \log_2 L \Rightarrow 4\text{Mbps} = 2 * 1\text{MHz} * \log_2 L \Rightarrow L = 4$

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

Performance

Bandwidth

-- ***Bandwidth in Hertz*** *(range of frequencies a channel can pass)*

** For example, we can say the bandwidth of a subscriber telephone line is 4 kHz.*

-- ***Bandwidth in Bits per Seconds*** *(number of bits per second that a channel, a link, or even a network can transmit.)*

* For example, one can say the bandwidth of a Fast Ethernet network (or the links in this network) is a maximum of 100 Mbps. This means that this network can send 100 Mbps.

Throughput

- The throughput is a measure of how fast we can actually send data through a network.
- Bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast we can send data.

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?

We can calculate the throughput as

$$\text{Throughput} = \frac{12{,}000 \times 10{,}000}{60} = 2 \text{ Mbps}$$

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

Latency

- 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 =propagation time +transmission time +queuing time + processing delay

Propagation Time

- Propagation time measures the time required for a bit to travel from the source to the destination.
- The propagation time is calculated by dividing the distance by the propagation speed.
- The propagation speed of electromagnetic signals depends on the medium and on the frequency of the signal.
- For example, in a vacuum, light is propagated with a speed of 3×10^8 m/s. It is lower in air; it is much lower in cable.

- What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

We can calculate the propagation time as

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.

Transmission Time

- The time taken by host to put the packet on outgoing link is called Transmission Time.

Transmission Time = Message Size/ Bw

- What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) 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 *mls.*

We can calculate the propagation and transmission time as

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

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. The transmission time can be ignored.

Queuing and Processing Time

- The time needed for each intermediate or end device to hold the message before it can be processed.
- The queuing time is not a fixed factor; it changes with the load imposed on the network.
- When there is heavy traffic on the network, the queuing time increases.
- An intermediate device, such as a router, queues the arrived messages and processes them one by one.
- If there are many messages, each message will have to wait.

Bandwidth-Delay Product

- Bandwidth and delay are two performance metrics of a link.
- But their product is i.e., the bandwidth-delay product, is highly essential for communication.
- Let us elaborate on this issue, using two hypothetical cases as examples.

Figure 3.31 *Filling the link with bits for case 1*

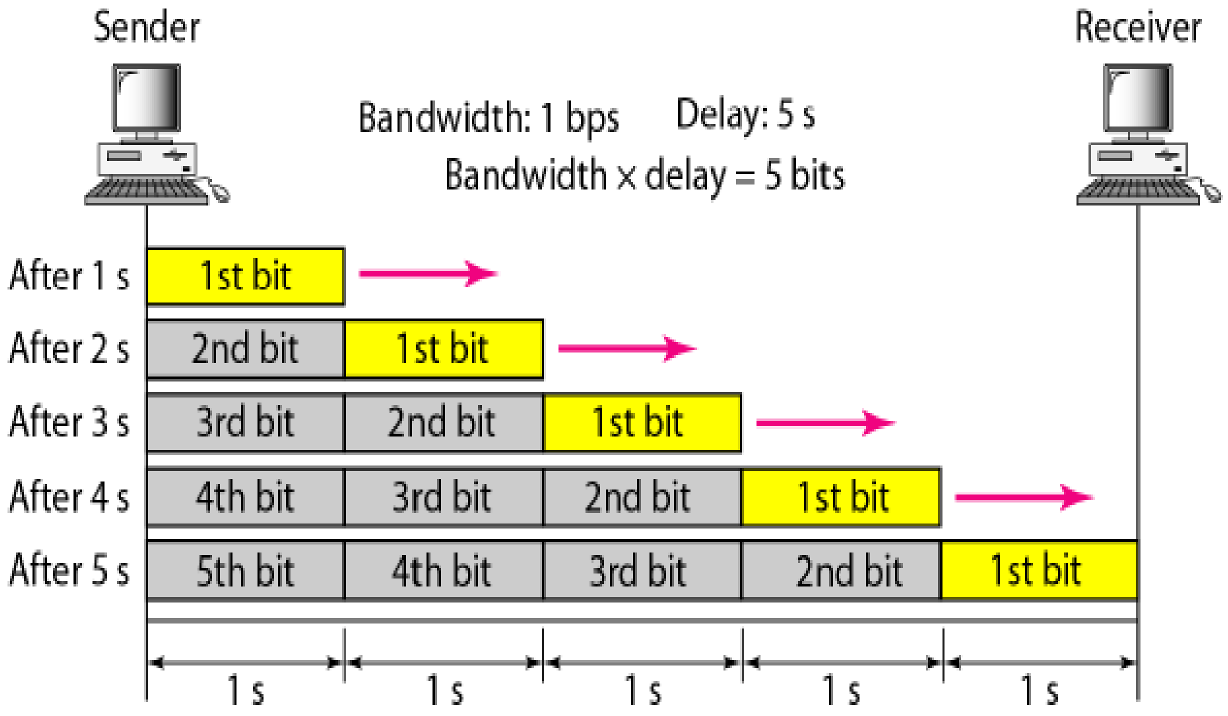


Figure 3.31 shows CASE 1

Assume that we have a link with a bandwidth of 1 bps (unrealistic, but good for demonstration purposes).

We also assume that the delay of the link is 5 s (also unrealistic).

We want to see what the bandwidth-delay product means in this case.

Looking at figure, we can say that this product 1 x 5 is the maximum number of bits that can fill the link.

There can be no more than 5 bits at any time on the link.

Example 3.48

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product, as shown in Figure 3.33.

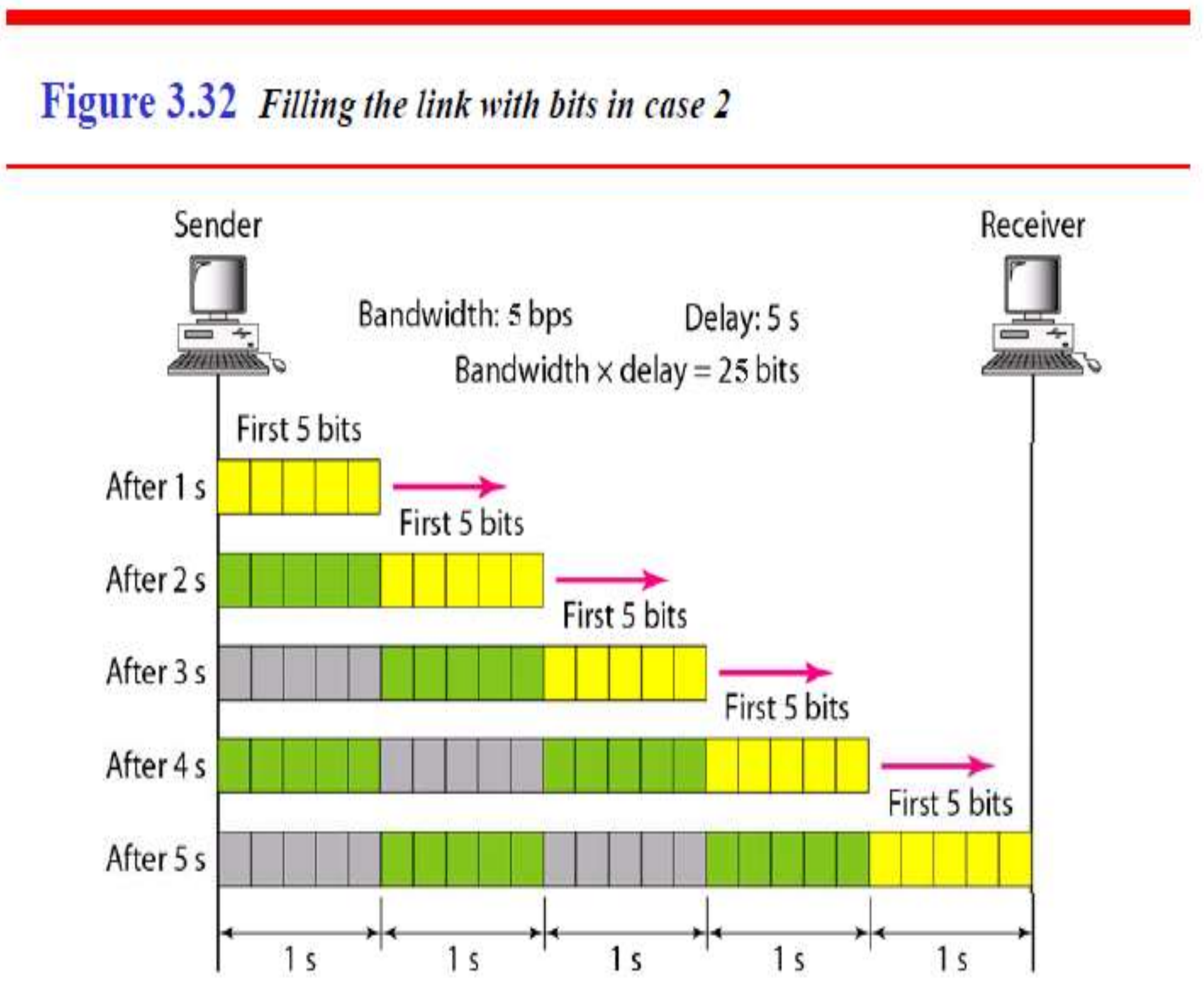


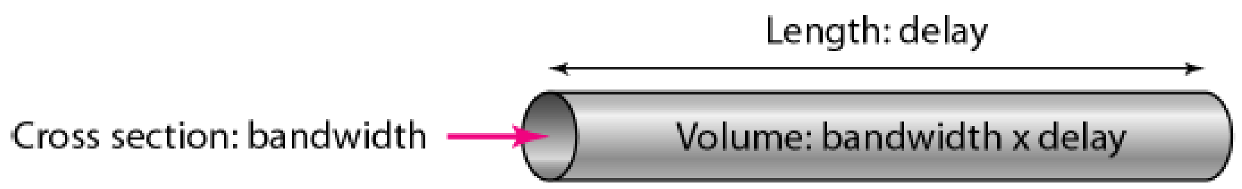
Figure 3.32 shows CASE 2

Now assume we have a bandwidth of 5 bps. Figure 3.32 shows that there can be maximum 5 x 5 = 25 bits on the line.

The reason is that, at each second, there are 5 bits on the line; the duration of each bit is 0.20 s.

These cases show that the product of bandwidth and delay is the number of bits that can fill the link.

Figure 3.33 *Concept of bandwidth-delay product*



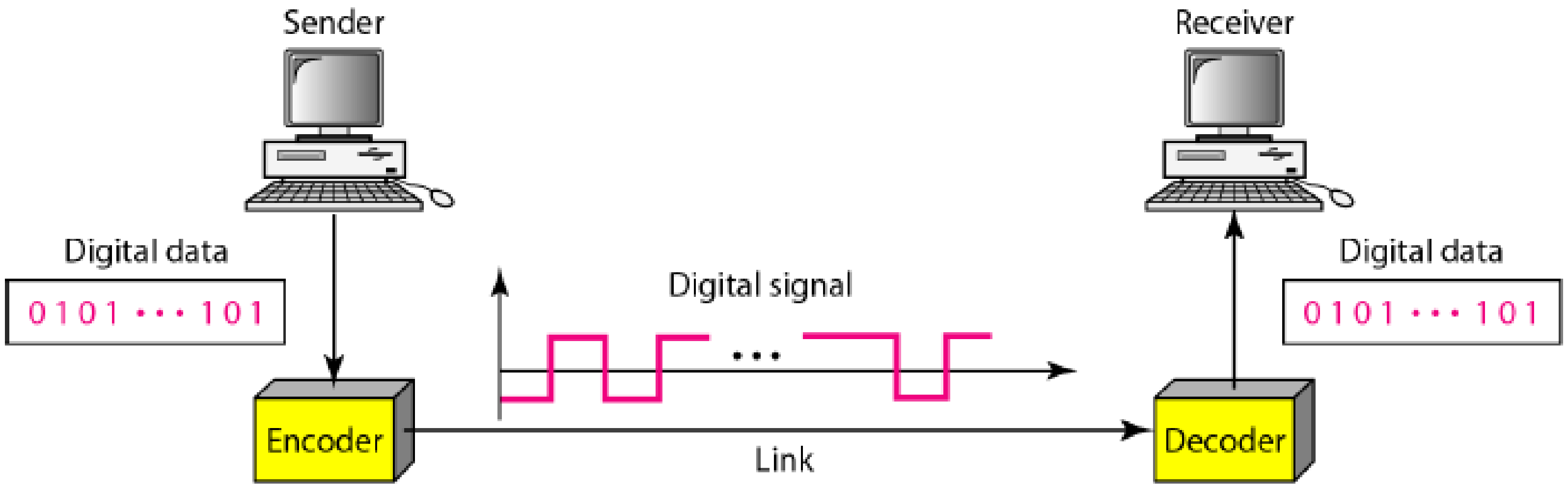
4-1 DIGITAL-TO-DIGITAL CONVERSION

In this section, we see how we can represent digital data by using digital signals. The conversion involves three techniques: line coding, block coding, and scrambling. Line coding is always needed; block coding and scrambling may or may not be needed.

Topics discussed in this section:

Line Coding
Line Coding Schemes
Block Coding
Scrambling

Figure 4.1 *Line coding and decoding*



- *Characteristics*
  - Before discussing different line coding schemes, we address their common characteristics.
  - Signal Elements and Data elements
    - In data communications, our goal is to send **data elements**.
    - A data element is the smallest entity that can represent a piece of information: this is the **bit**.
    - In digital data communications, a **signal element** carries data elements.
    - A signal element is the shortest unit of a digital signal.
    - In other words, data elements are what we need to send; signal elements are what we can send.
    - Data elements are being carried; signal elements are the carriers
    - We define a ratio r which is the number of data elements carried by each signal element.

Figure 4.2 *Signal element versus data element*

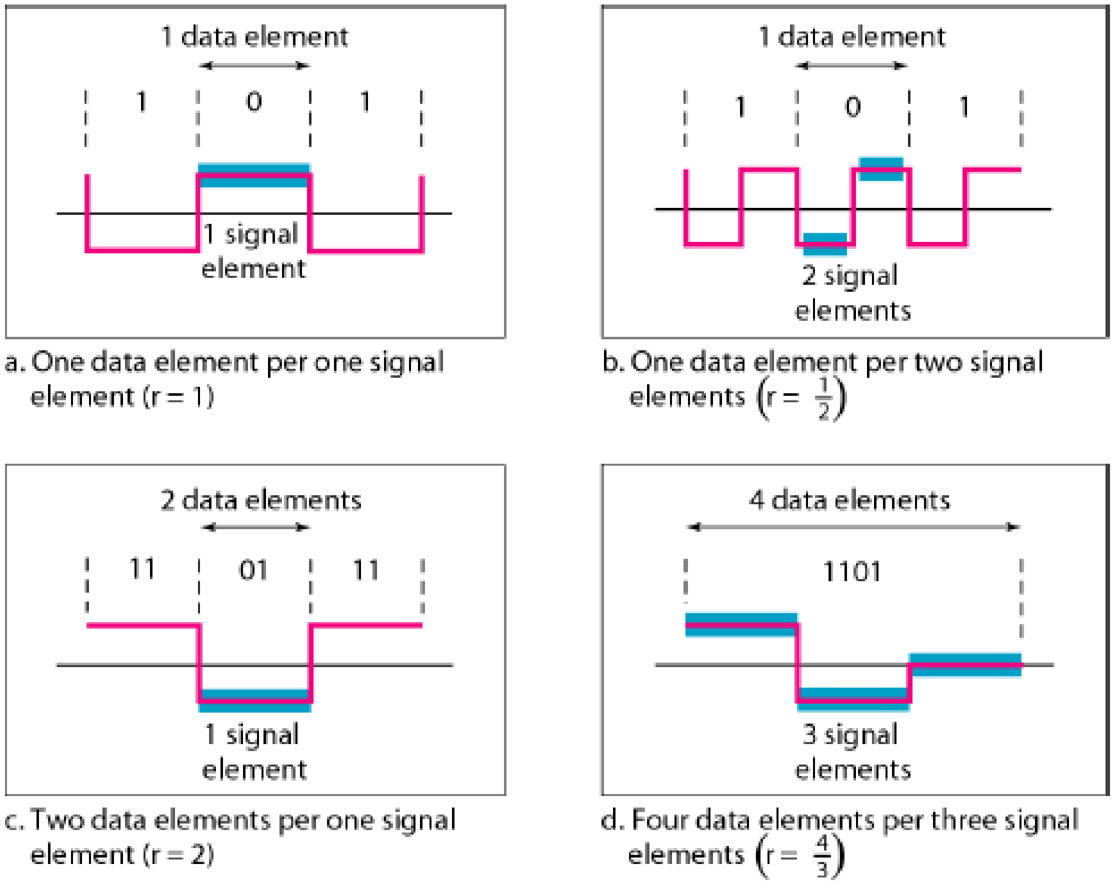


Fig. 4.2 shows several situations with different values of *r*.

- The data rate defines the number of data elements (bits) sent in 1 s. The unit is bits per second (bps).
- The signal rate is the number of signal elements sent in 1 s. The unit is the baud.
- The data rate is sometimes called the bit rate; the signal rate is sometimes called the pulse rate, the modulation rate, or the baud rate.
- One goal in data communications is to increase the data rate while decreasing the signal rate.
- Increasing the data rate increases the speed of transmission; decreasing the signal rate decreases the bandwidth requirement.

Relation between data rate and signal rate

- This relationship depends on the value of *r.* It also depends on the data pattern.
- If we have a data pattern of all 1s or all Os, the signal rate may be different from a data pattern of alternating Os and 1s.
- To derive a formula for the relationship,
  - We need to define three cases: the worst, best, and average.
  - The worst case is when we need the maximum signal rate; the best case is when we need the minimum.
  - In data communications, we are usually interested in the average case. We can formulate the relationship between data rate and signal rate as

$$S = c \times N \times \frac{1}{r} \quad \text{baud}$$

N is the data rate (bps); c is the case factor, which varies for each case; S is the number of signal elements; and r is the previously defined factor.

- A signal is carrying data in which one data element is encoded as one signal element *(r* = 1). If the bit rate is 100 kbps, what is the average value of the baud rate if c is between 0 and l (say c=1/2)?

$$S = c \times N \times \frac{1}{r} \quad \text{baud}$$

S=(1/2)*100*1/1 = 50 kbaud

- We can say that the baud rate, determines the required bandwidth for a digital signal. The minimum bandwidth can be given as:

$$B_{min} = c \times N \times \frac{1}{r}$$

- We can solve for the maximum data rate if the bandwidth of the channel is given.

$$N_{max} = \frac{1}{c} x B x r$$