DATA COMMUNICATIONS AND NETWORKING

Data and Signals
Part 2

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Outline

- Transmission Impairment
  - Attenuation
  - Distortion
  - Noise
- Data Rate Limits
- Performance
- Summary

TRANSMISSION OF DIGITAL SIGNALS

- A digital signal is a composite analog signal with an infinite bandwidth.
- The transmitted digital signal depends on using one of two different approaches: baseband transmission and broadband transmission
- (using modulation).
- Baseband transmission: Sending a digital signal without changing into an analog signal.

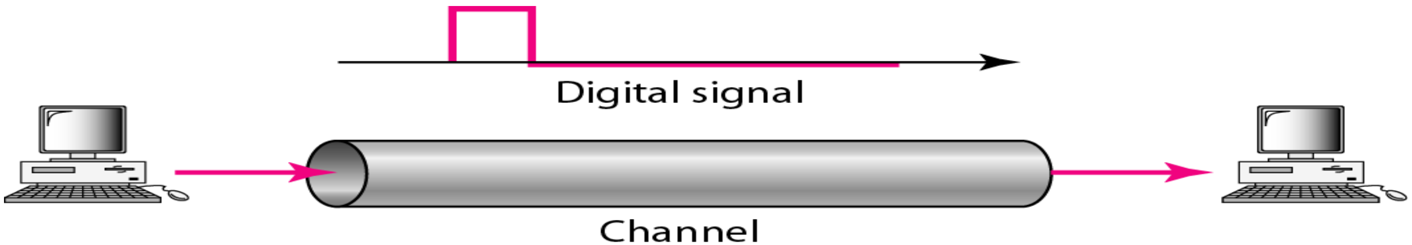


Figure 19. Baseband transmission

- Baseband Transmission
- Baseband transmission requires that we have a low-pass channel, a channel with a bandwidth that starts from zero. This is the case if we have a dedicated medium with a bandwidth constituting only one channel. For example, the entire bandwidth of a cable connecting two computers is one single channel. As another example, we may connect several computers to a bus, but not allow more than two stations to communicate at a time. Again we have a low-pass channel, and we can use it for baseband communication, as shown in figure 20.

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)

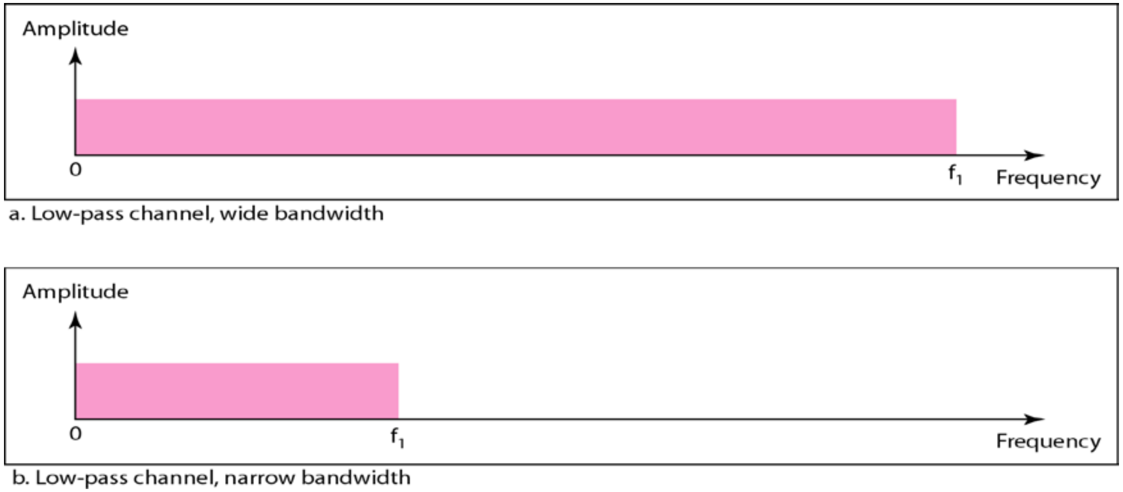


Figure 20. Bandwidths of two low-pass channels

Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with infinite or very wide bandwidth.

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)

Case 1: Low-Pass Channel with Wide Bandwidth

- If we want to preserve the exact form of a nonperiodic digital signal with vertical segments, we need to send the entire spectrum, the continuous range of frequencies between zero and infinity.
- This is possible if we have a dedicated medium with an infinite bandwidth between the sender and receiver that preserves the exact amplitude of each component of the composite signal.

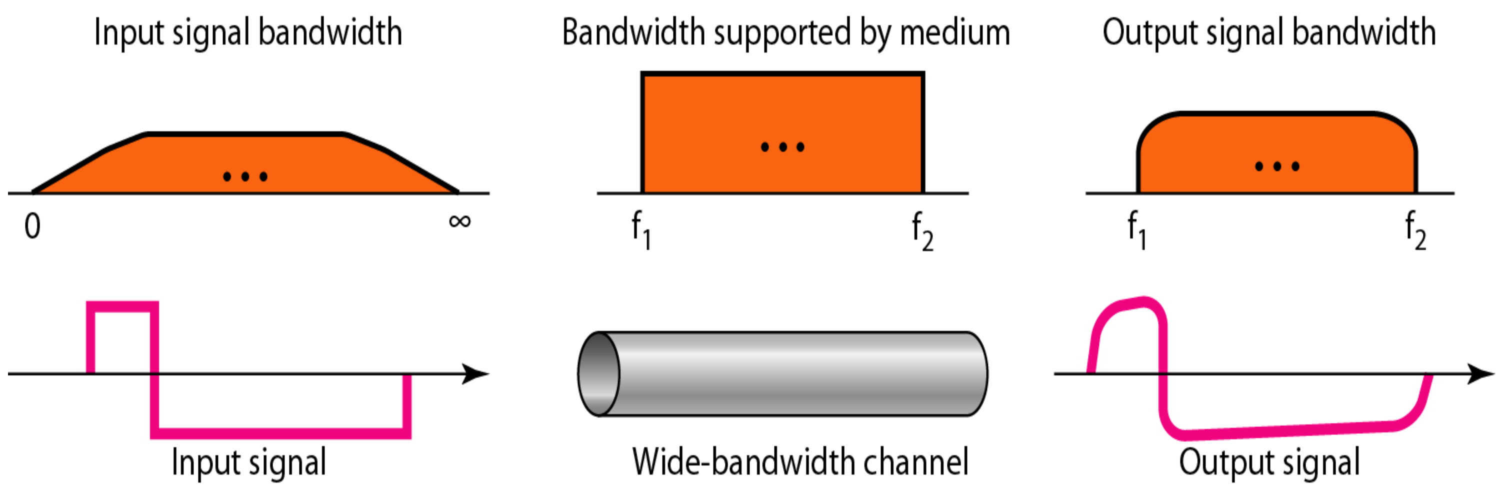


Figure 21. Baseband transmission using a dedicated medium

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)

Case 2: Low-Pass Channel with Limited Bandwidth

In a low-pass channel with limited bandwidth, we approximate the digital signal with an analog signal. The level of approximation depends on the bandwidth available.

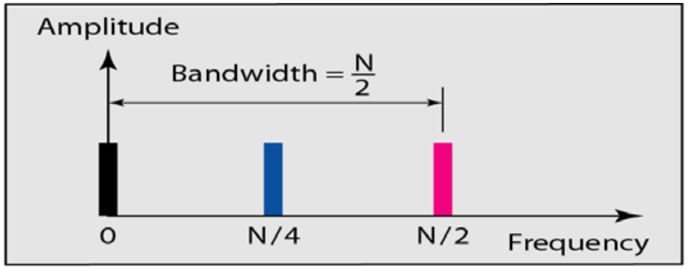
Rough Approximation Let us assume that we have a digital signal of bit rate N. If we want to send analog signals to roughly simulate this signal, we need to consider the worst case, a maximum number of changes in the digital signal. This happens when the signal carries the sequence 01010101 ... or the 10101010· ... To simulate these two cases, we need an analog signal of f = N/ 2. sequence Let 1 be the positive peak value and 0 be the negative peak value.

Figure 22 shows the idea. The two similar cases (000 and 111) are simulated with a signal with frequency f =0 and a phase of 180° for 000 and a phase of 0° for 111. The two worst cases (010 and 101) are simulated with an analog signal with frequency f =N/2 and phases of 180° and 0°. The other four cases can only be simulated with an analog signal with f = N/4 and phases of 180°, 270°, 90°, and 0°. In other words, we need a channel that can handle frequencies 0, N/4, and N/2. This rough approximation is referred to as using the first harmonic (N/2) frequency.

- Baseband Transmission(continue…)

Case 2: Low-Pass Channel with Limited Bandwidth (continue…)

The required bandwidth is Bandwidth = N/2 – 0 = N/2



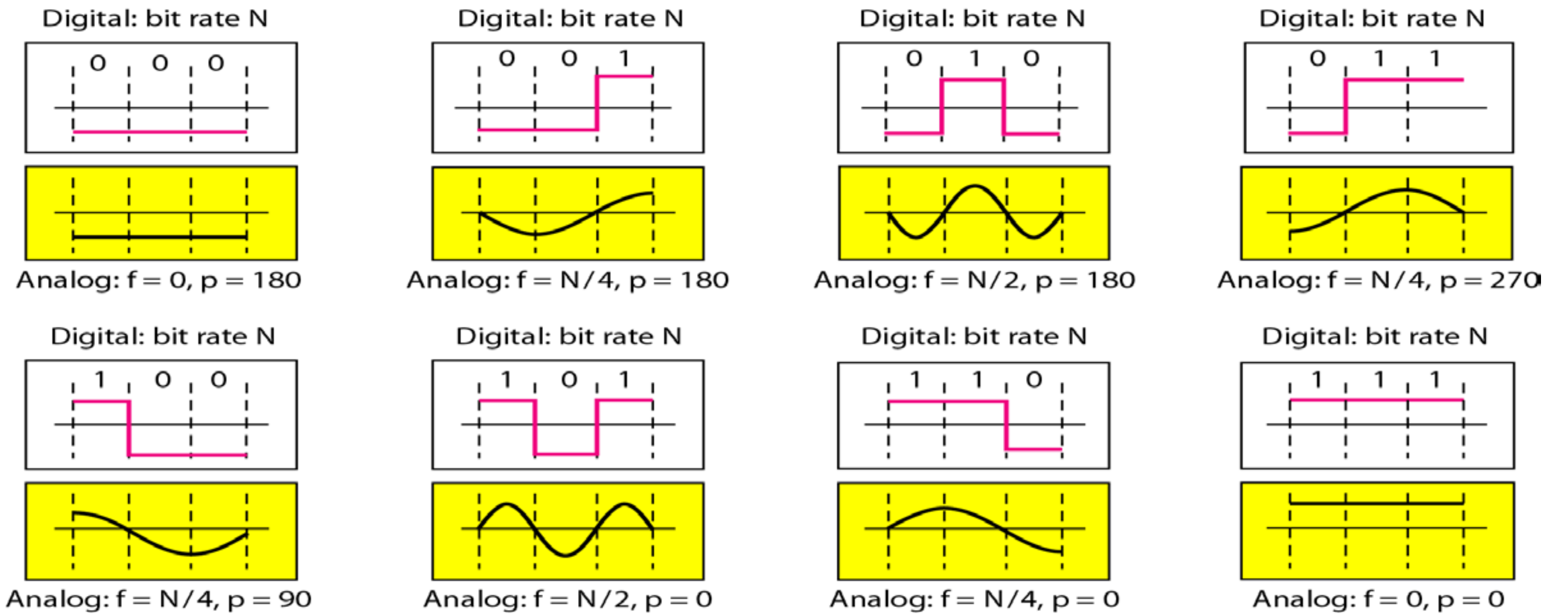


Figure 22. Rough approximation of a digital signal using the first harmonic for worst case

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)
- Better Approximation To make the shape of the analog signal look more like that of a digital signal, we need to add more harmonics of the frequencies. We need to increase the bandwidth. We can increase the bandwidth to 3N/2, 5N/2, 7N/2, and so on.

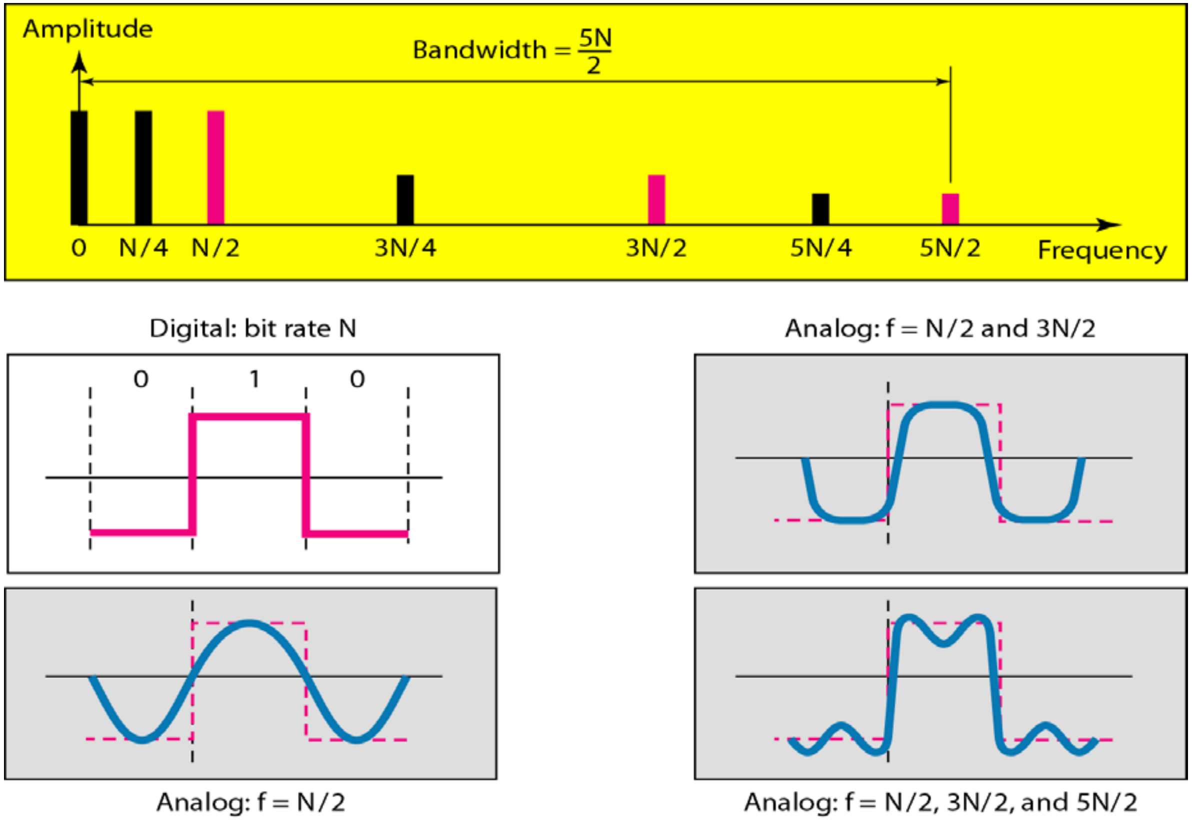


Figure 23. Simulating a digital signal with three first harmonics

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)
- In baseband transmission, the required bandwidth is proportional to the bit rate; if we need to send bits faster, we need more bandwidth.

Table 2. Bandwidth requirements

Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

- Example 9. What is the required bandwidth of a low-pass channel if we need to send 1 Mbps by using baseband transmission?

- Solution
- The answer depends on the accuracy desired.
- a. The minimum bandwidth, is B = bit rate /2, or 500 kHz.

  b. A better solution is to use the first and the third harmonics with B = 3 × 500 kHz = 1.5 MHz.

  c. Still a better solution is to use the first, third, and fifth harmonics with B = 5 × 500 kHz = 2.5 MHz.

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Baseband Transmission(continue…)
- Example10. We have a low-pass channel with bandwidth 100 kHz. What is the maximum bit rate of this channel?
  Solution
- The maximum bit rate can be achieved if we use the first harmonic. The bit rate is 2 times the available bandwidth, or 200 kbps.

- Broadband Transmission (Using Modulation)
- Modulation allows us to use a bandpass channel
- If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

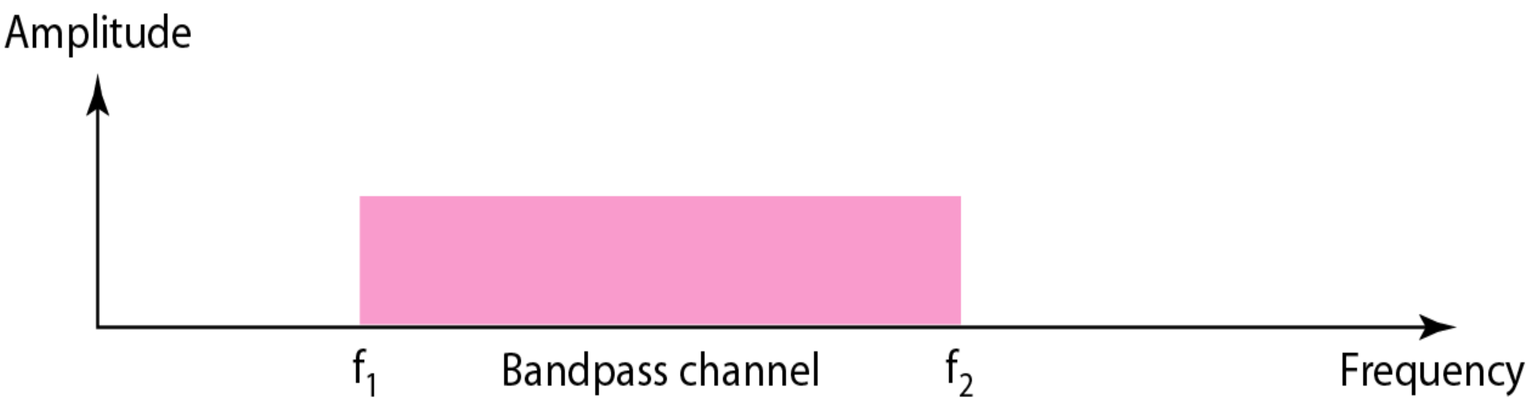


Figure 24. Bandwidth of a bandpass channel

TRANSMISSION OF DIGITAL SIGNALS (continue…)

- Broadband Transmission (Using Modulation) (continue…)
- Note that a low-pass channel can be considered a bandpass channel with the lower frequency starting at zero.
- If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

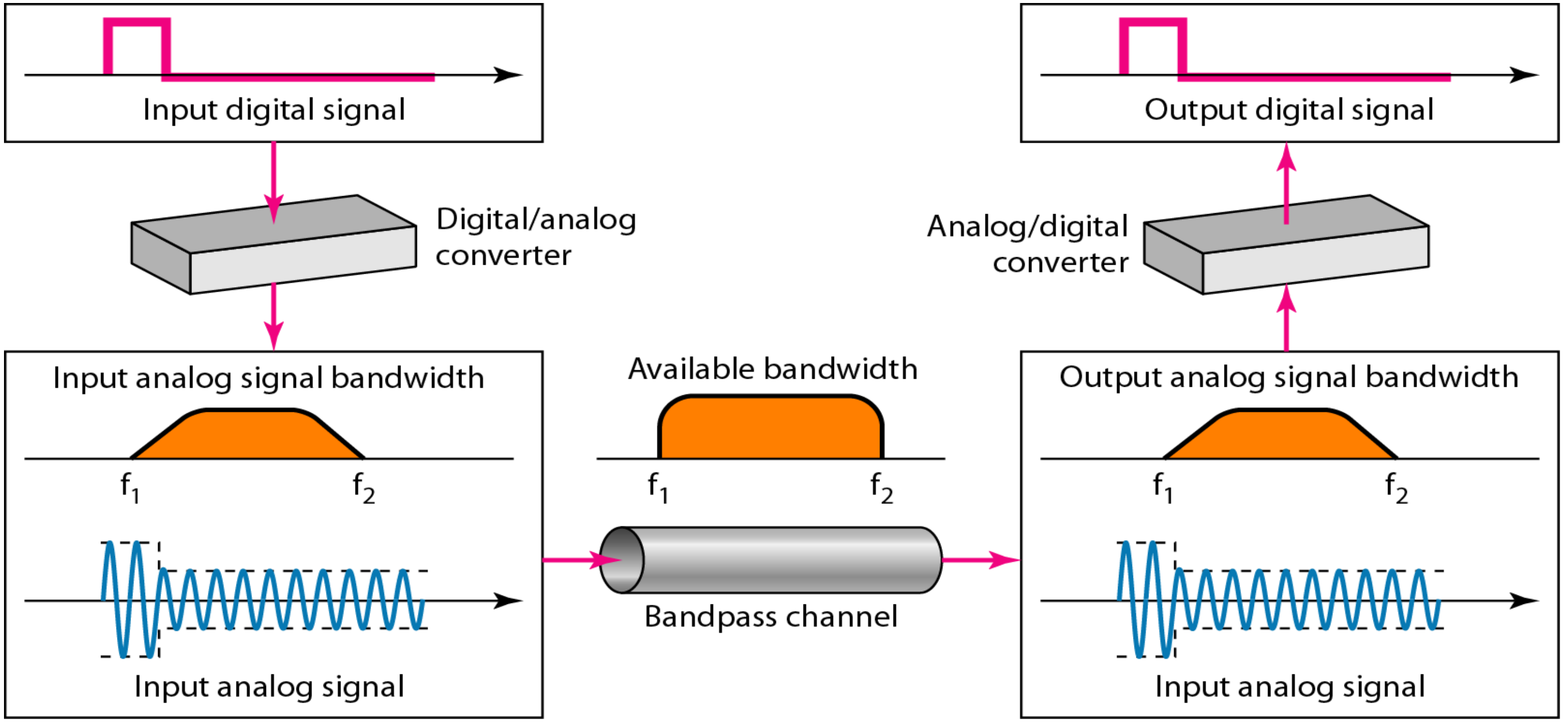


Figure 25. Modulation of a digital signal for transmission on a bandpass channel

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.

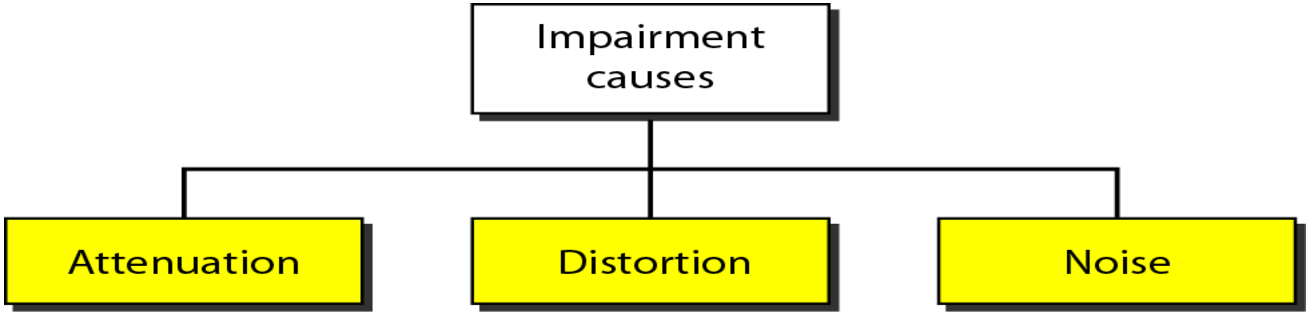


Figure 26. Causes of impairment

- Attenuation
- Attenuation means a loss of energy. When a signal, simple or composite, 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, if not hot, 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.

TRANSMISSION IMPAIRMENT (continue…)

- Attenuation (continue…)

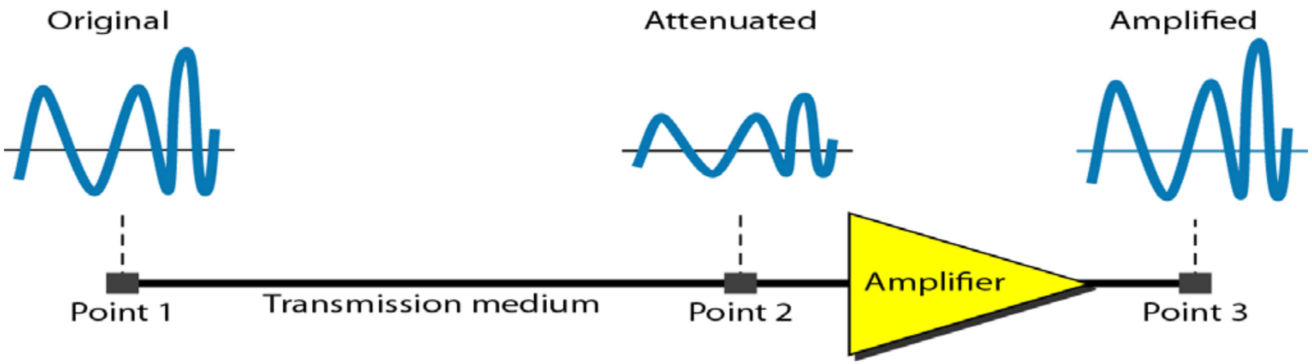


Figure 27. Attenuation

- Decibel:-
- To show that a signal has lost or gained strength, engineers use the unit of the decibel. The decibel (dB) measures the relative strengths of two signals or one signal at two different points. Note that the decibel is negative if a signal is attenuated and positive if a signal is amplified.
- Example 11: 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:

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

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

- Decibel (continue…)
- Example 12. 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 28. a signal travels from point 1 to point 4. 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.

$$\boxed{\mathrm{dB} = -3 + 7 - 3 = +1}$$

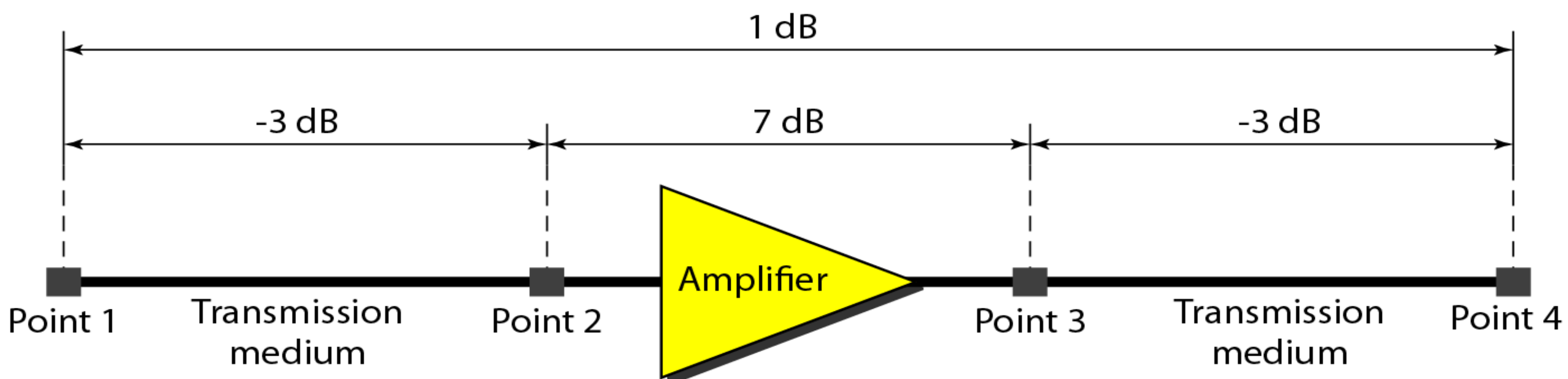


Figure 28. Decibels for Example 12.

TRANSMISSION IMPAIRMENT (continue…)

- Distortion
- The signal changes its form or shape
- Each signal component in a composite signal has its own propagation speed.
- Differences in delay may cause a difference in phase. The signal components at the receiver have phases different from what they had at the sender. The shape of the composite signal is therefore not the same

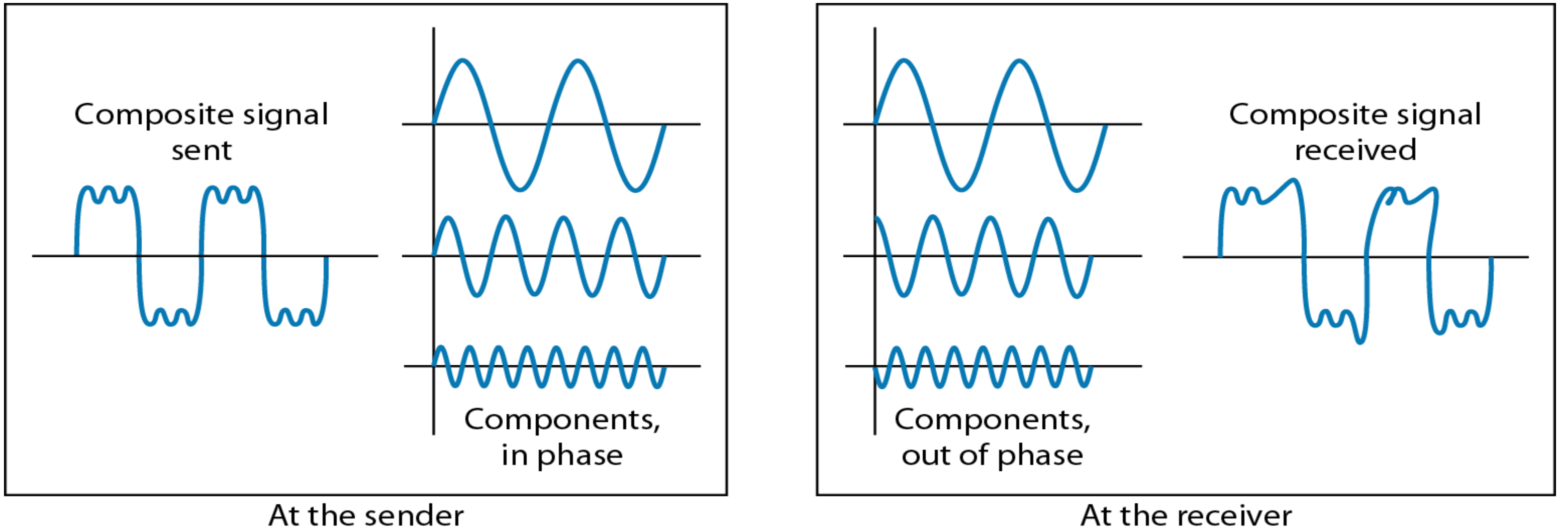


Figure29. Distortion

TRANSMISSION IMPAIRMENT (continue…)

- Noise
- Several types of noises, such as thermal noise, induced noise, crosstalk, and impulse noise, 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. These devices act as a sending antenna, and the transmission medium acts as the receiving antenna.
- Crosstalk is the effect of one wire on the other. One wire acts as a sending antenna and the other as the receiving antenna.
- Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

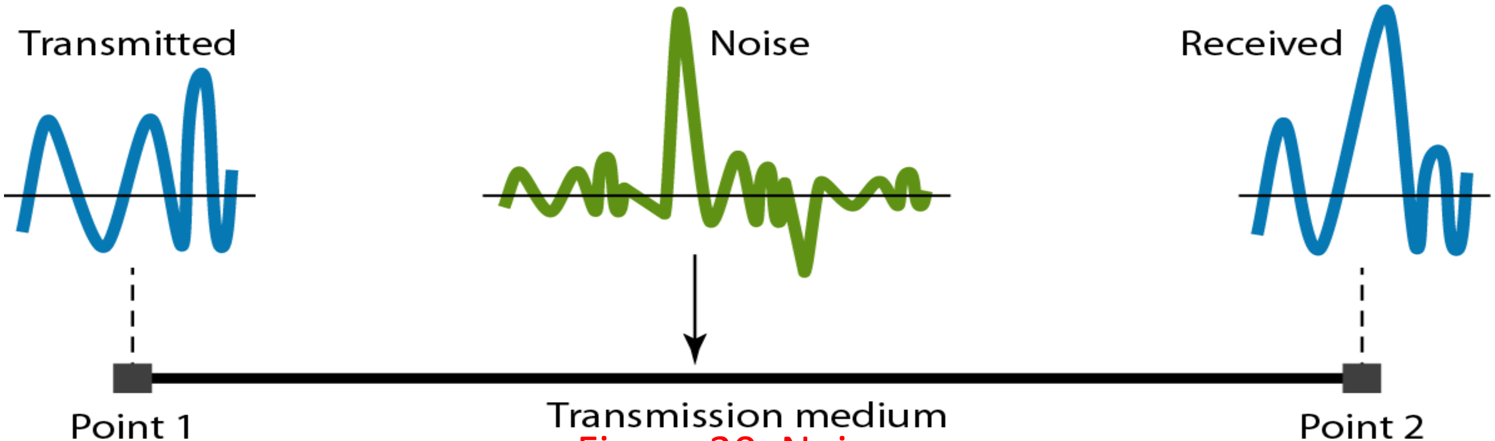


Figure 30. Noise

TRANSMISSION IMPAIRMENT (continue…)

- Noise (continue…)
- Signal-to-Noise Ratio (SNR)
- To find the theoretical bit rate limit
- SNR = average signal power/average noise power
- SNRdB = 10 log10 SNR
- Example 13: The power of a signal is 10 mW and the power of the noise is 1 μW; what are the values of SNR and SNRdB ?
- Solution:

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

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

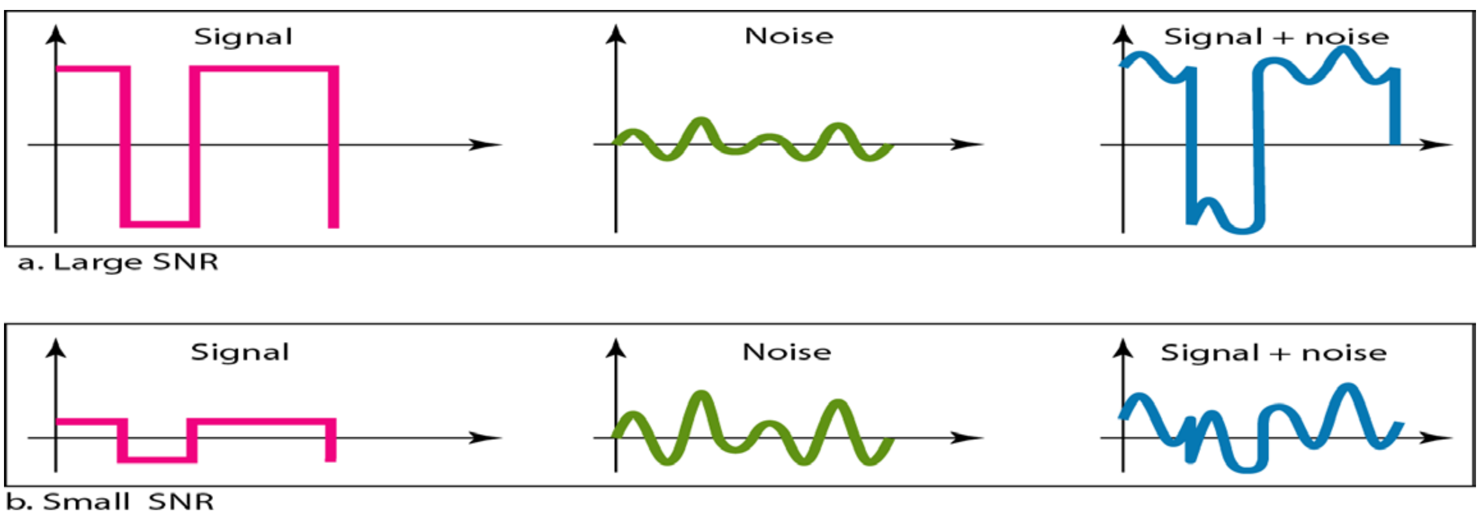


Figure 31. Two cases of SNR: a high SNR and a low SNR

DATA RATE LIMITS

- Noise (continue…)

Data rate depends on three factors:
  - Bandwidth available
  - Level of the signals we use
  - Quality of the channel (the noise level)

- Noiseless channel: Nyquist Bit Rate
- **Bit rate = 2 * Bandwidth * log2L**
- In this formula, bandwidth 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
- Increasing the levels of a signal may reduce the reliability of the system.
- Example 13. 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

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

DATA RATE LIMITS (continue…)

- Noise (continue…)
- Noiseless channel (continue…)
- Example 14. 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

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

- 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 * log2(1 + SNR)**

- In this formula, 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.

DATA RATE LIMITS (continue…)

- Noise (continue…)
- Noiseless channel (continue…)
- Example 15: 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 is calculated as

$$C = B \log2 (1 + SNR) = B \log2 (1 + 0) = B \log2 (1) = B \times 0 = 0$$

- Example 16: We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000 Hz (300 Hz to 3300 Hz). The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

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

DATA RATE LIMITS (continue…)

- Noise (continue…)

Using Both Limits

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

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

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

C = B log2 (1 + SNR) = 10^6 log2 (1 + 63)

= $10^{\wedge 6}$ log2 (64) = 6 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.

4 Mbps = 2 × 1 MHz × log2 L ➔ L = 4

PERFORMANCE

- Bandwidth

- Bandwidth (in two contexts)
- Bandwidth in hertz, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.
- Bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.

- Throughput
- Measurement of how fast we can actually send data through a network.

- Example 17.
- 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?
- Solution
- We can calculate the throughput as

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

PERFORMANCE (continue…)

- Latency (Delay)

- Define 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 = Distance/Propagation speed**
- **Transmission time = Message size/Bandwidth**
- Example 18. 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 x 10^8 m/s.
- Solution
- We can calculate the propagation and transmission time as

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

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

PERFORMANCE (continue…)

- Bandwidth-Delay Product
- Bandwidth and delay are two performance metrics of a link

- Case 1:

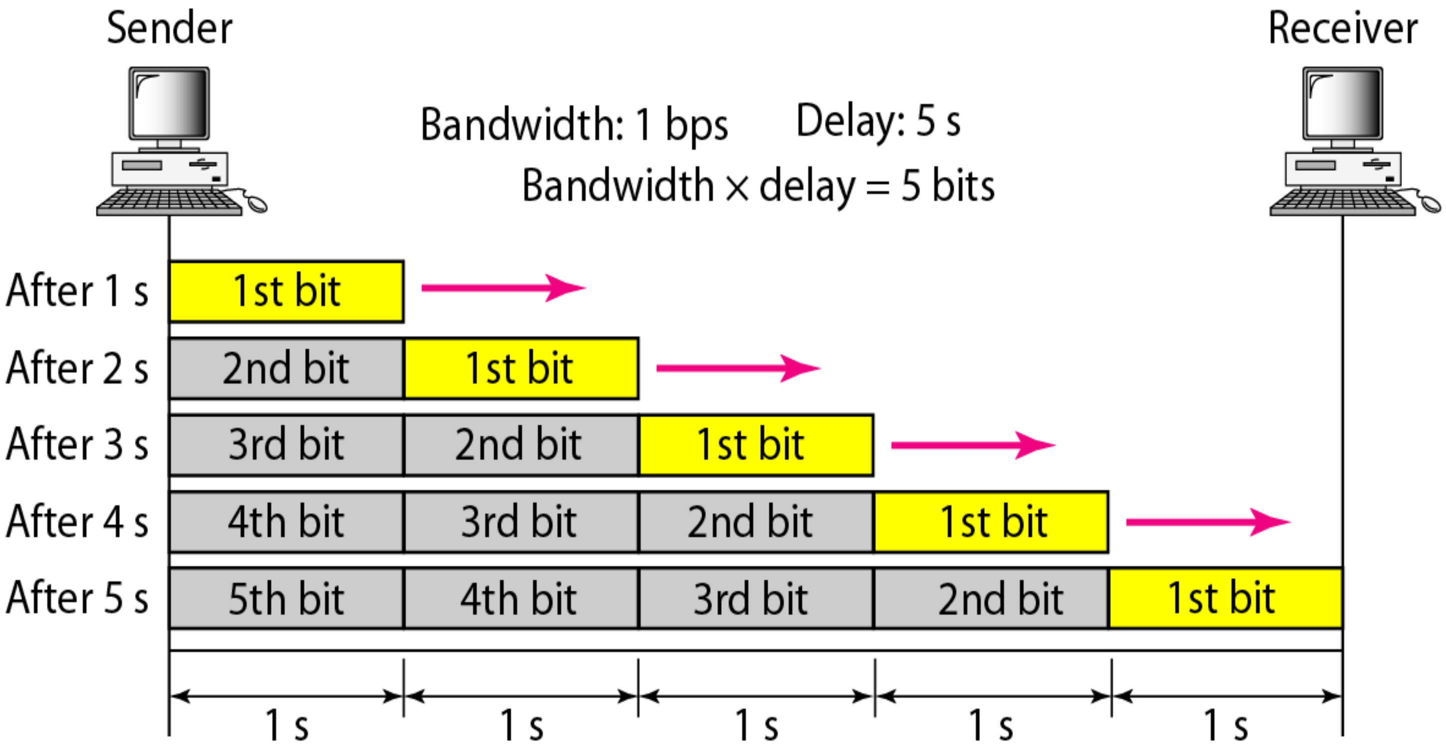


Figure 32 Filling the link with bits for case 1

PERFORMANCE (continue…)

- Bandwidth-Delay Product
- Case 2:

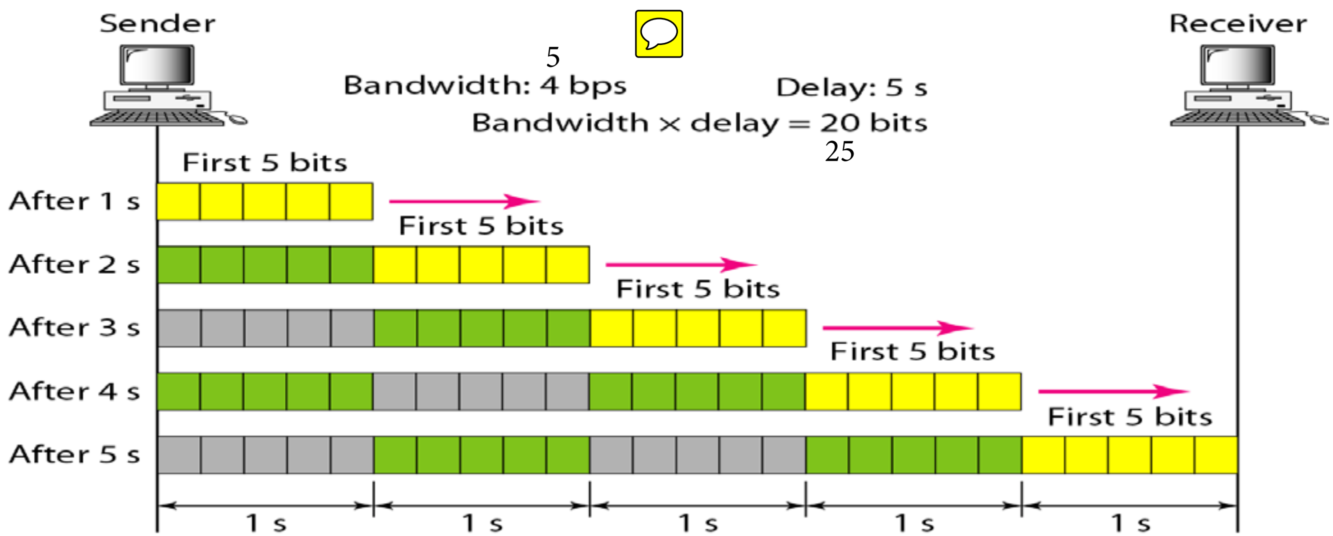


Figure 33. Filling the link with bits in case 2

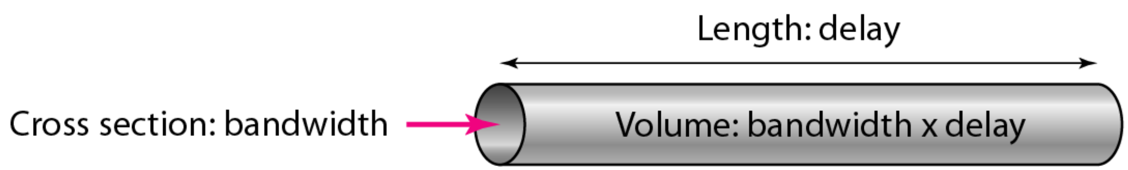


Figure 34. Concept of bandwidth-delay product

➢ Jitter

- We can roughly say that jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive for example (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 endures jitter.

Summary

- Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.
- If the available channel is a bandpass channel, we cannot send a digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.
- For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate. For a noisy channel, we need to use the Shannon capacity to find the maximum bit rate.
- Attenuation, distortion, and noise can impair a signal.
- Attenuation is the loss of a signal's energy due to the resistance of the medium.
- Distortion is the alteration of a signal due to the differing propagation speeds of each of the frequencies that make up a signal.
- Noise is the external energy that corrupts a signal.
- The bandwidth-delay product defines the number of bits that can fill the link.