COMP 3721
Introduction to Data Communications

03. Week 3

Learning Outcomes

- By the end of this lecture, you will be able to:
  - Explain the transmission of digital signals.
  - Explain what are the categories of transmission impairment and how they affect signals.
  - Explain and compute the limits of data rate using Shannon Capacity and Nyquist formulas.
  - Describe what is bandwidth.
  - Describe transmission modes.

Review

- Data must be changed to **signals** for **transmission**.
- **Analog** vs **digital** signals.
- Characteristics of **periodic analog signals**.
- **Composite** analog signals.
- Characteristics of **digital signals**.

Transmission of Digital Signals

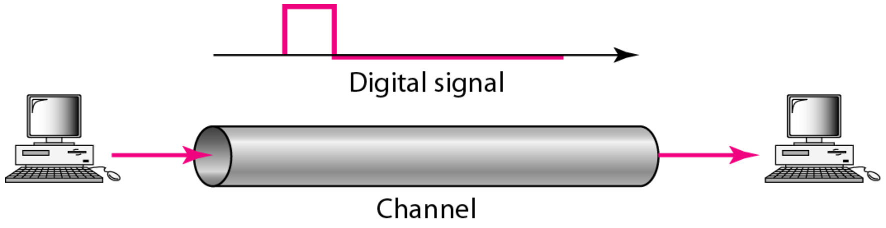
- From now on, we consider **nonperiodic digital signals**.
- **Two approaches** for transmission of digital signals:

Baseband Transmission

Broadband Transmission (Modulation)

Baseband Transmission

- **Baseband Transmission**
  - A digital signal is sent over a channel **without changing** the digital signal to an analog signal.
  - **Requirement**: a **low-pass channel** (i.e., the lowest frequency contained in the channel is zero).
  - If the channel primarily passes signals below a certain frequency, it is called a **low-pass channel** (**has an upper bound**).
  - We have a **dedicated medium** with a bandwidth constituting **only one channel**.
  - Real-life example:
    - A LAN: almost every **wired LAN** today uses a dedicated channel for two stations communicating with each other (bus and star topologies, etc.)



Baseband Transmission –
a Low-pass Channel with a Wide Bandwidth

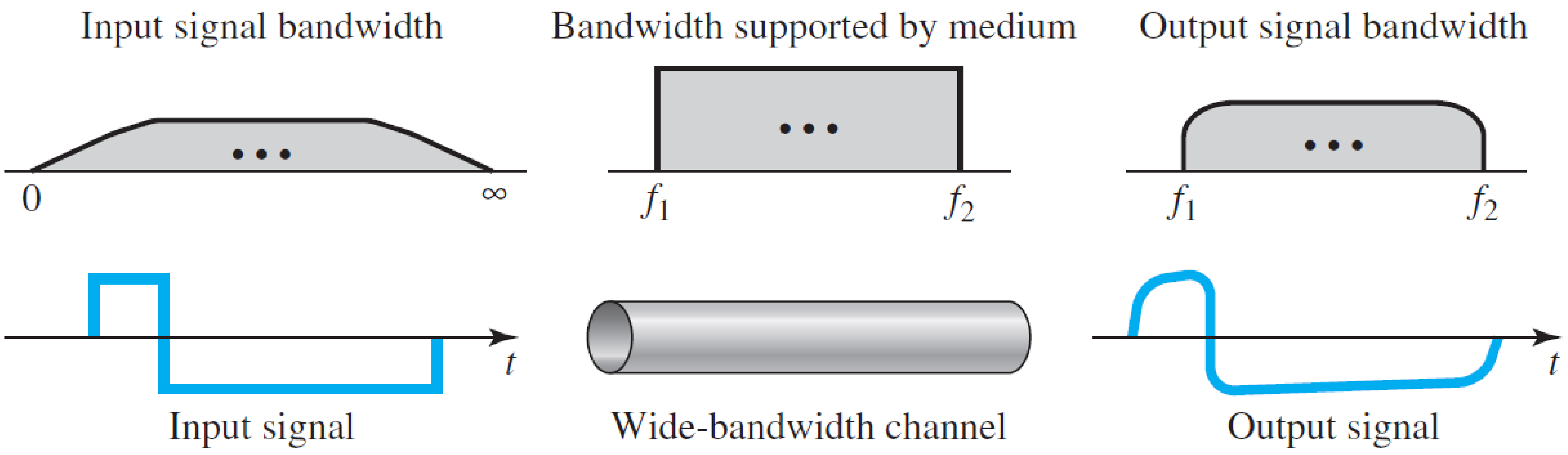
- Baseband transmission of a digital signal that **preserves the shape** of the digital signal is possible only if we have a **low-pass channel** with an **infinite** or **very wide bandwidth**.
- Why a low-pass channel with infinite bandwidth is ideal?
  - We know that according to Fourier analysis, each **digital** signal corresponds to a **composite analog** signal with **infinite bandwidth**. So, to transmit it, we need a channel with infinite bandwidth or a very wide bandwidth.

a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

Baseband Transmission – a Low-pass Channel with a Wide Bandwidth

- If we have a medium, such as a coaxial cable or fiber optic cable, with a **very wide bandwidth**, two stations can communicate by using digital signals with **very good accuracy**.



Baseband Transmission (Cont.)

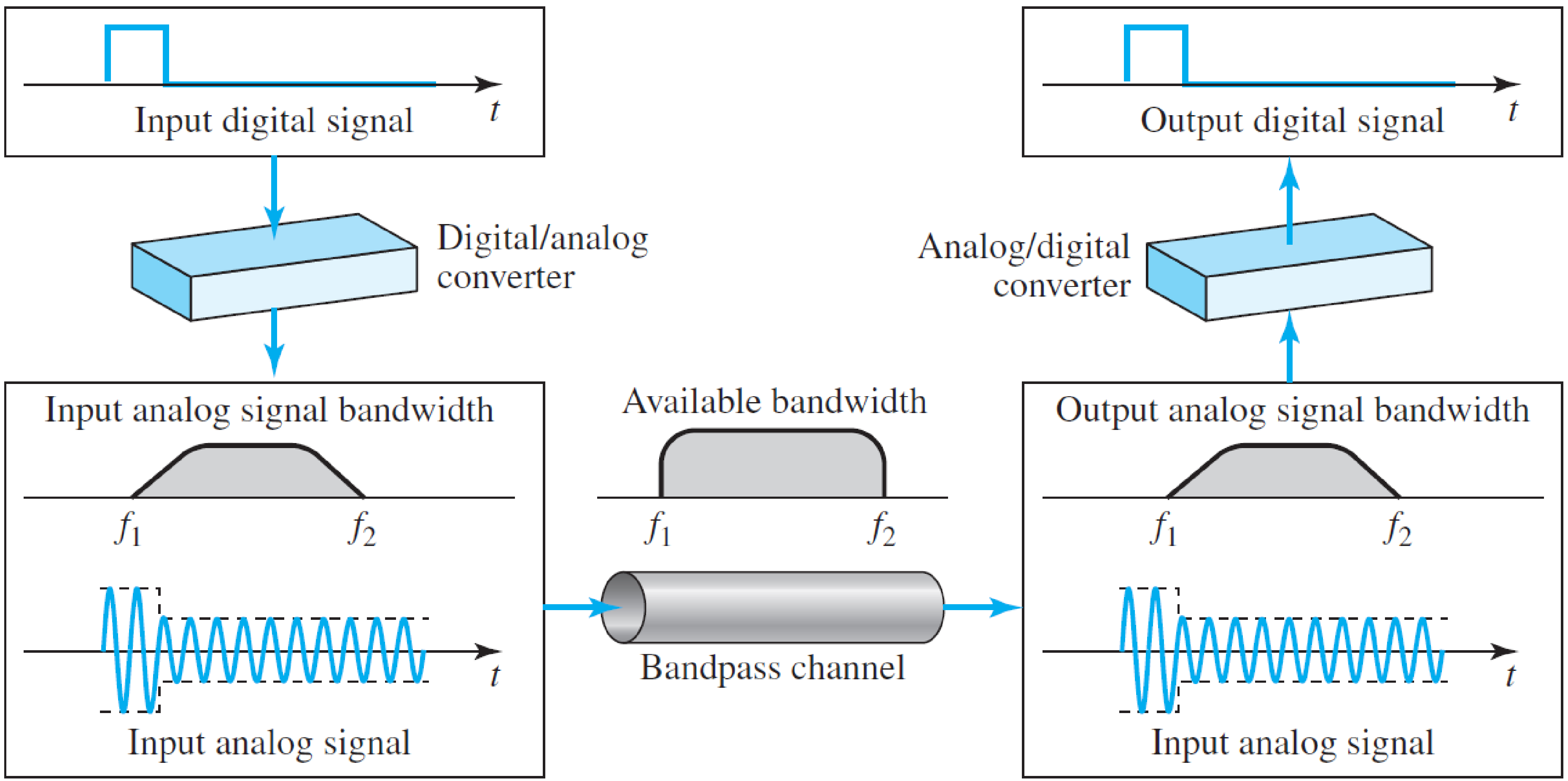
In baseband transmission, the **required bandwidth** is **proportional** to the **bit rate**; if we need to send bits faster, we need more bandwidth.

Unfortunately, low-pass channels are less common in real life.

Broadband Transmission

- **Broadband Transmission** (**modulation**)
  - Changing the digital signal to an analog signal for transmission.
  - **Requirement**: a **bandpass channel** (one that allows signals to pass between two frequency limits OR a channel with a bandwidth that does not start from zero).
    - More available than a low-pass channel.
    - The digital signal cannot be directly sent to the channel; it **must be converted** to an analog signal before transmission.
  - We can install two converters to change the digital signal to analog and vice versa at the receiving end.
    - The converter, in this case, is called a **modem** (modulator/demodulator).

Modulation of a Digital Signal for Transmission on a Bandpass Channel



Real-Life Examples of Broadband Transmission

1. Sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office.
   - The lines designed to carry voice and have a bandwidth with frequencies between 0 and 4 kHz → can be used as a low-pass channel but it is considered as a bandpass channel, why?

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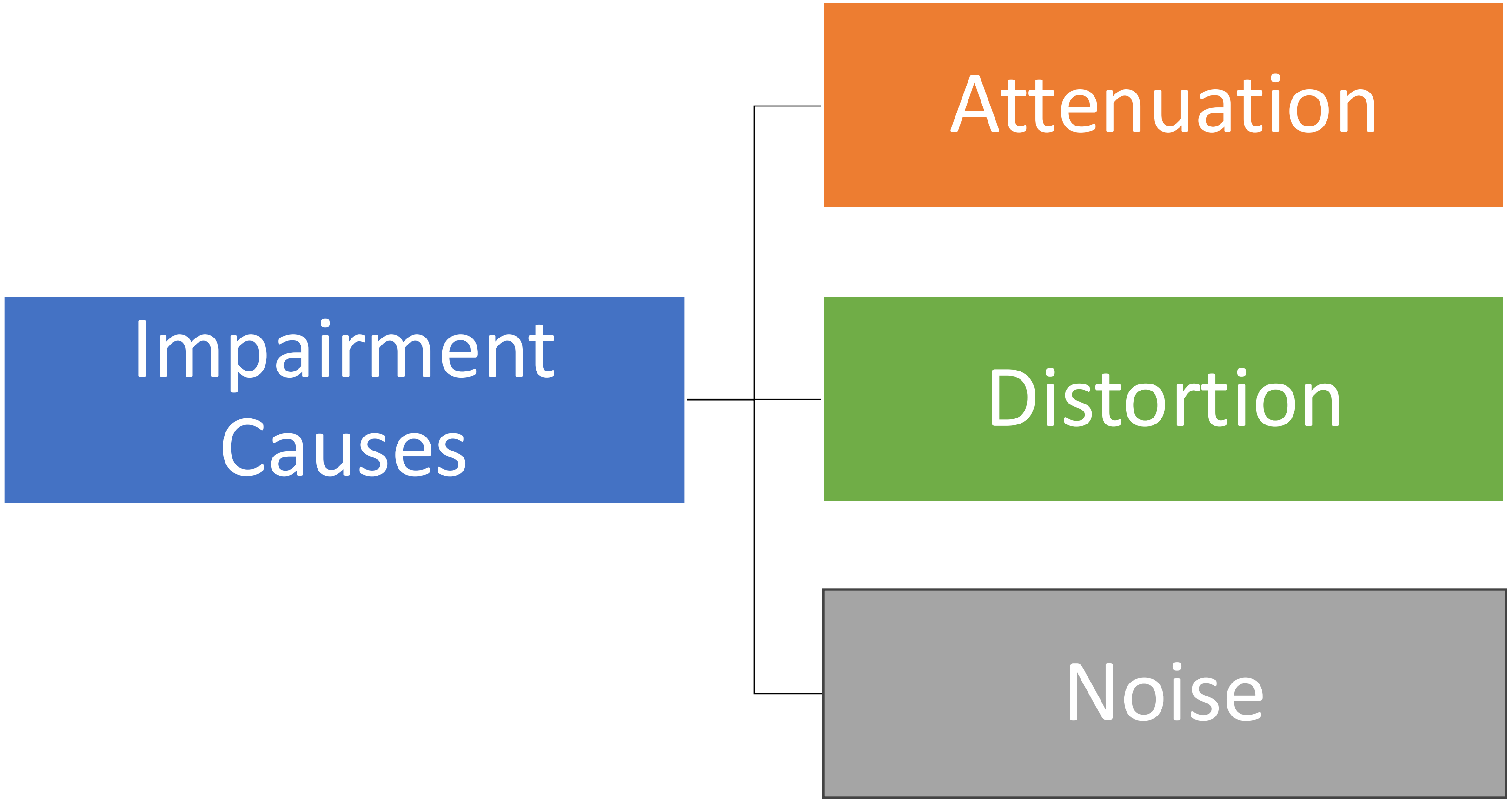
2. Digital cellular phones convert the digitized voice signal to a composite analog signal before sending.
   - Their allocated bandwidth is very wide, so, why not sending the digital signal without conversion?

Transmission Impairment

- The **imperfection** of transmission media causes **signal impairment**.

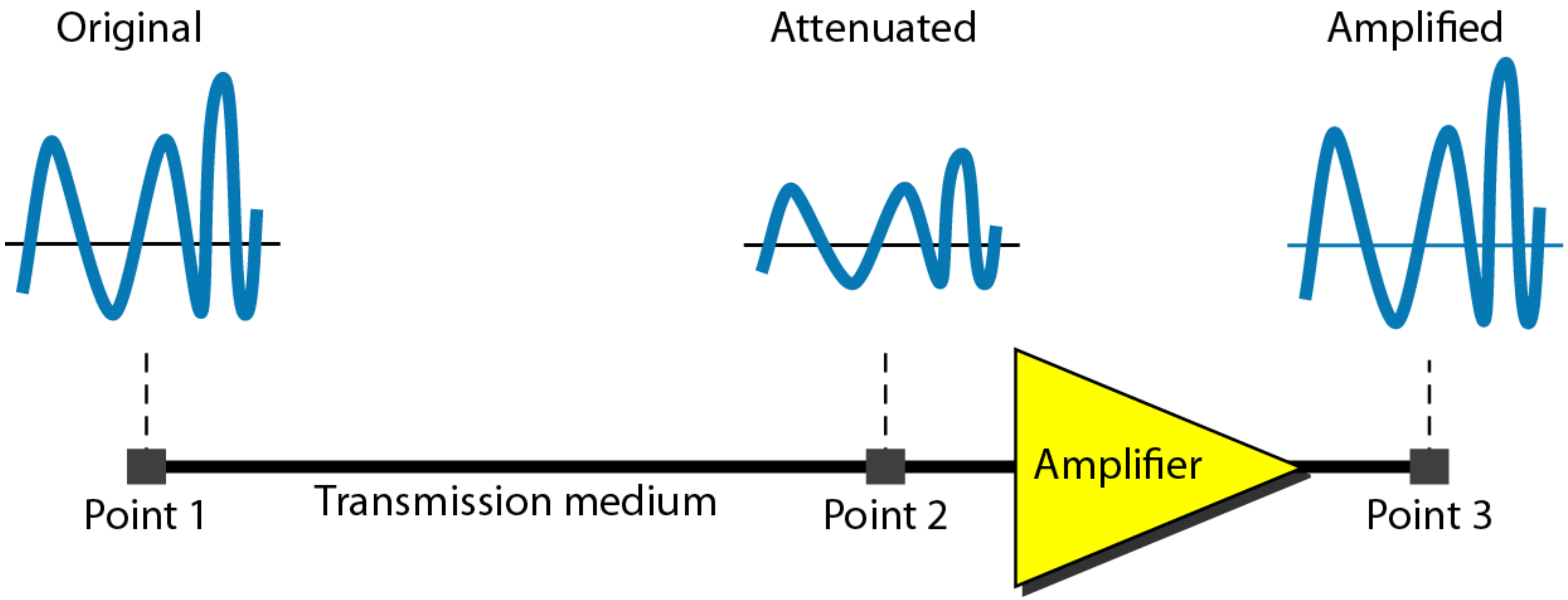


Attenuation

- A wire carrying electric signals gets warm, if not hot, after a while, why?

Attenuation

- **Attenuation**: Loss of energy to overcome the resistance of the medium.
- **Amplifier**: To compensate for the loss.



Attenuation – Decibel

- decibel (dB)
  - Measures the **relative strengths** of **two signals** or **one signal** at **two different points** (to show that a signal has lost or gained strength).
  - **Negative**: if a signal is **attenuated**.
  - **Positive**: if a signal is **amplified**.

$$\boxed{\mathrm{dB} = 10\log_{10}\frac{P_2}{P_1} = 20\log_{10}\frac{V_2}{V_1}}$$

- P_1 and P_2: Powers of a signal at points 1 and 2, respectively.
- V_1 and V_2: Voltages of a signal at points 1 and 2, respectively.

Decibel – Example

- Suppose a signal travels through a transmission medium and its power is reduced to one-half. Find the attenuation (loss of power).

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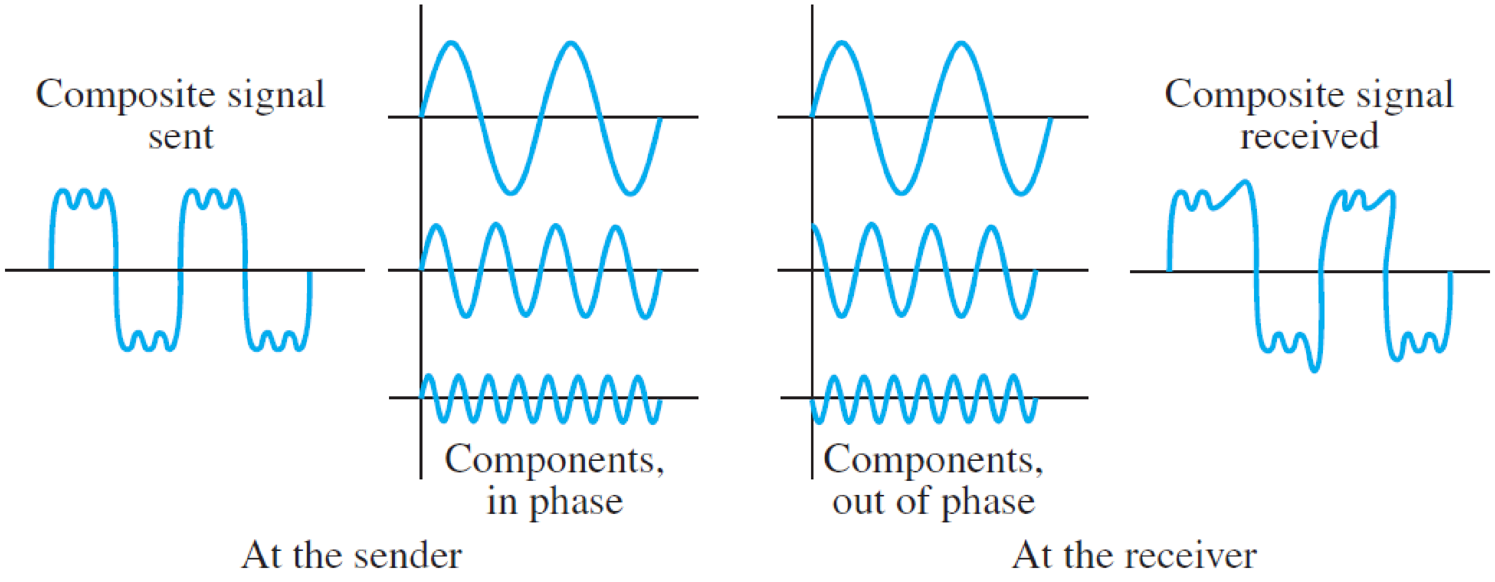
- **Answer**:

$$
\begin{aligned}
\mathrm{dB} &= 10\log_{10}\frac{P_2}{P_1} \\
&= 10\log_{10}\frac{0.5P_1}{P_1} \\
&= 10\log_{10}0.5 \\
&= 10(-0.3) \\
&= \mathbf{-3\ dB}
\end{aligned}
$$

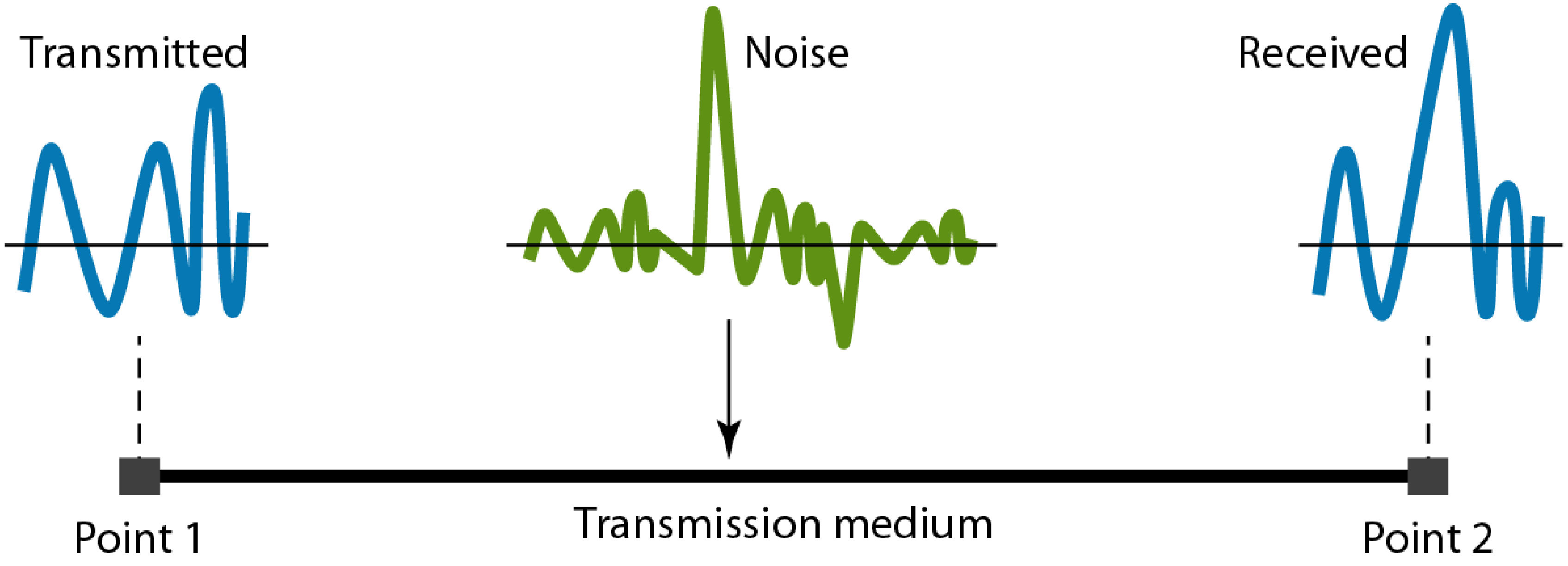
Distortion

- **Distortion**: The signal changes its form or shape.
  - Can occur in a composite signal made of different frequencies.
  - Signal components at the receiver have **phases different** from what they had at the sender.



Noise

- Different types of **noise** may **corrupt the signal**.



Noise

Type	Definition
Thermal noise	The random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter.
Induced noise	From sources such as motors and appliances (these devices act as a sending antenna, and the transmission medium acts as the receiving antenna).
Crosstalk noise	The effect of one wire on the other (one wire acts as a sending antenna and the other as the receiving antenna).
Impulse noise	A spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on.

Noise – SNR

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

- **Signal-to-Noise-Ratio** (**SNR**):
  - **High SNR**: The signal is less corrupted by noise.
  - **Low SNR**: The signal is more corrupted by noise.
  - Since SNR is the ratio of two powers, it is often described in decibel units.

$$\text{SNR}_{\text{dB}} = 10 \log_{10} \text{SNR}$$

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

$$\textbf{SNR} = \textbf{(signal power) / 0} = \infty \quad \longrightarrow \quad \textbf{SNR}_{\textbf{dB}} = \textbf{10} \log_{10} \infty = \infty$$

Noise – SNR

- Why do we need to calculate the SNR?
  - To find the **theoretical bit rate limit**, we need to know the ratio of the signal power to the noise power. → We will see later.
- Why the average signal power and the average noise power?
  - We need to consider the average signal power and the average noise power because **these may change with time**.

SNR is the ratio of what is **wanted** (signal)
to what is **not wanted** (noise).

SNR – Example

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- **Answer**:

$$10\ \text{mW} = 10000\ \mu\text{W}$$

$$\mathbf{SNR} = \frac{10000\ \mu\text{W}}{1\ \mu\text{W}} = \mathbf{10000}$$

$$\mathbf{SNR_{dB}} = 10 \log_{10} 10000 = 10 \log_{10} 10^4 = \mathbf{40\ dB}$$

Data Rate Limits

- **Data rate** (also called **bit rate** or **capacity**)
  - Indicates how fast we can send the data, in bps, over a channel.
- Relies on **three** factors:
  1. The available bandwidth
  2. The number of signal levels
  3. The quality of the channel (the level of noise)
- **Two theoretical formulas** for calculating the data rate:
  1. **Nyquist** (for a noiseless channel)
  2. **Shannon** (for a noisy channel)

Noiseless Channel: Nyquist Bit Rate

- The **Nyquist bit rate** formula defines the **theoretical maximum bit rate** for a **noiseless channel**:

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

bps

Bandwidth of the channel

Number of signal levels

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> Increasing the **levels** of a signal may **reduce** the **reliability** of the system. Why?

Example 1

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

Noisy Channel: Shannon Capacity

- In reality, we **cannot** have a noiseless channel; the channel is always **noisy**.
- The **Shannon capacity** indicates the theoretical highest data rate for a **noisy channel**:

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

Capacity of the channel in bps

Bandwidth of the channel

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Capacity of the channel in bps

Bandwidth of the channel

> No matter how many **levels** we have, we **cannot** achieve a data rate **higher** than the **capacity** of the channel.

Noisy Channel: Shannon Capacity (Cont.)

- If we have an **extremely noisy channel** in which the value of the signal-to-noise ratio is almost **zero** (the noise is so strong that the signal is faint), the **capacity** of this channel is **zero** regardless of the bandwidth (we cannot receive any data through this channel).

$$
\begin{aligned}
C &= B\log_2(1+\mathrm{SNR}) \\
&= B\log_2(1+0) \\
&= B\log_2 1 \\
&= B \times 0 \\
&= 0
\end{aligned}
$$

Using Both Nyquist Bit Rate and Shannon Capacity

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

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- Then, we use the Nyquist formula as follows:

$$\begin{aligned} \mathrm{BitRate} &= 2 \times \mathrm{Bandwidth} \times \log_2 L \\ 6\ \mathrm{Mbps} &= 2 \times 1\ \mathrm{MHz} \times \log_2 L \\ \log_2 L &= 3 \\ \boldsymbol{L} &= 2^3 = \mathbf{8} \end{aligned}$$

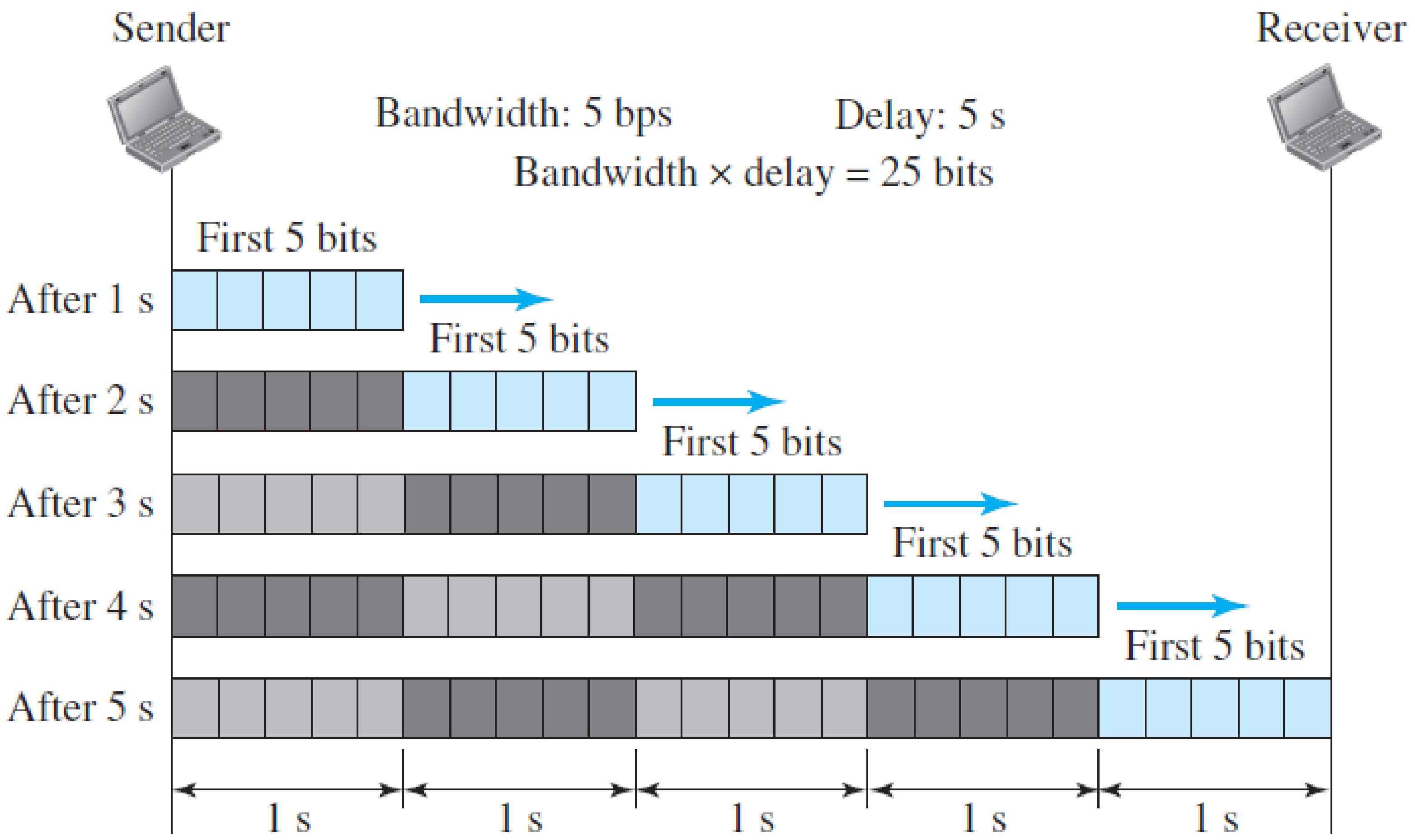
Bandwidth

- In networking, the term "**bandwidth**" can be used in two different contexts:
    1. Bandwidth in **hertz**
        - The range of frequencies included in a composite signal or the range of frequencies a channel can pass.
    2. Bandwidth in **bits per second** → We call this **bit rate**
        - The number of bits per second that a channel, a link, or even a network can transmit (the speed of bit transmission in a channel or link).
- Relationship between the bandwidth in hertz and bandwidth in bits per second
    - An **increase** in bandwidth in hertz → an **increase** in bandwidth in bits per second.

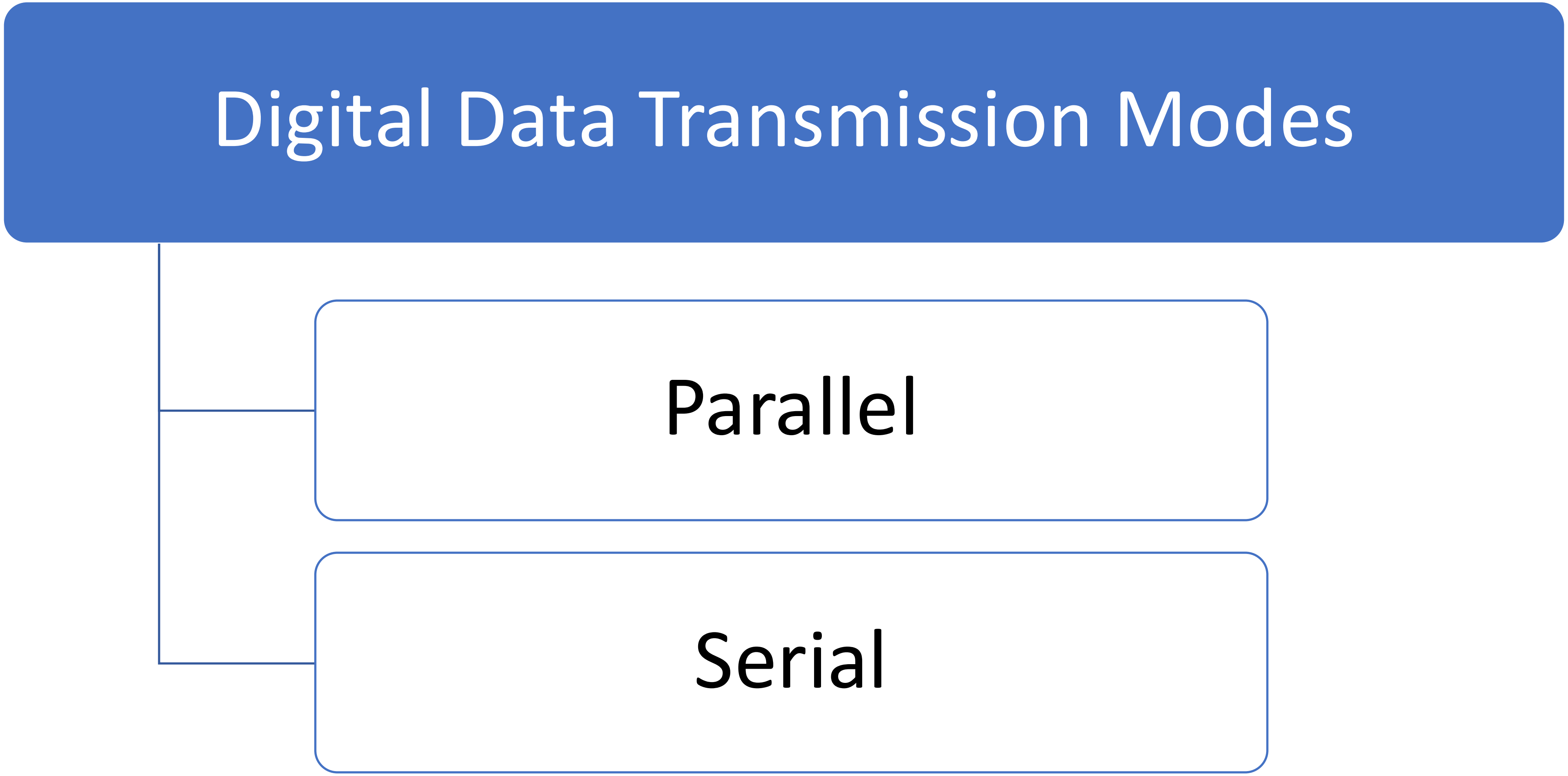
Bandwidth-Delay Product

- The **number of bits** that can **fill the link**.
- Important if we need to **send data in bursts** and **wait for the acknowledgment of each burst** before sending the next one.
- To use the maximum capability of the link, we need to make the size of our burst **2 times the product of bandwidth and delay** (we need to fill up the full-duplex channel, i.e., two directions).
  - The number of bits that can be in transition at any time $= 2 \times \text{bandwidth} \times \text{delay}$

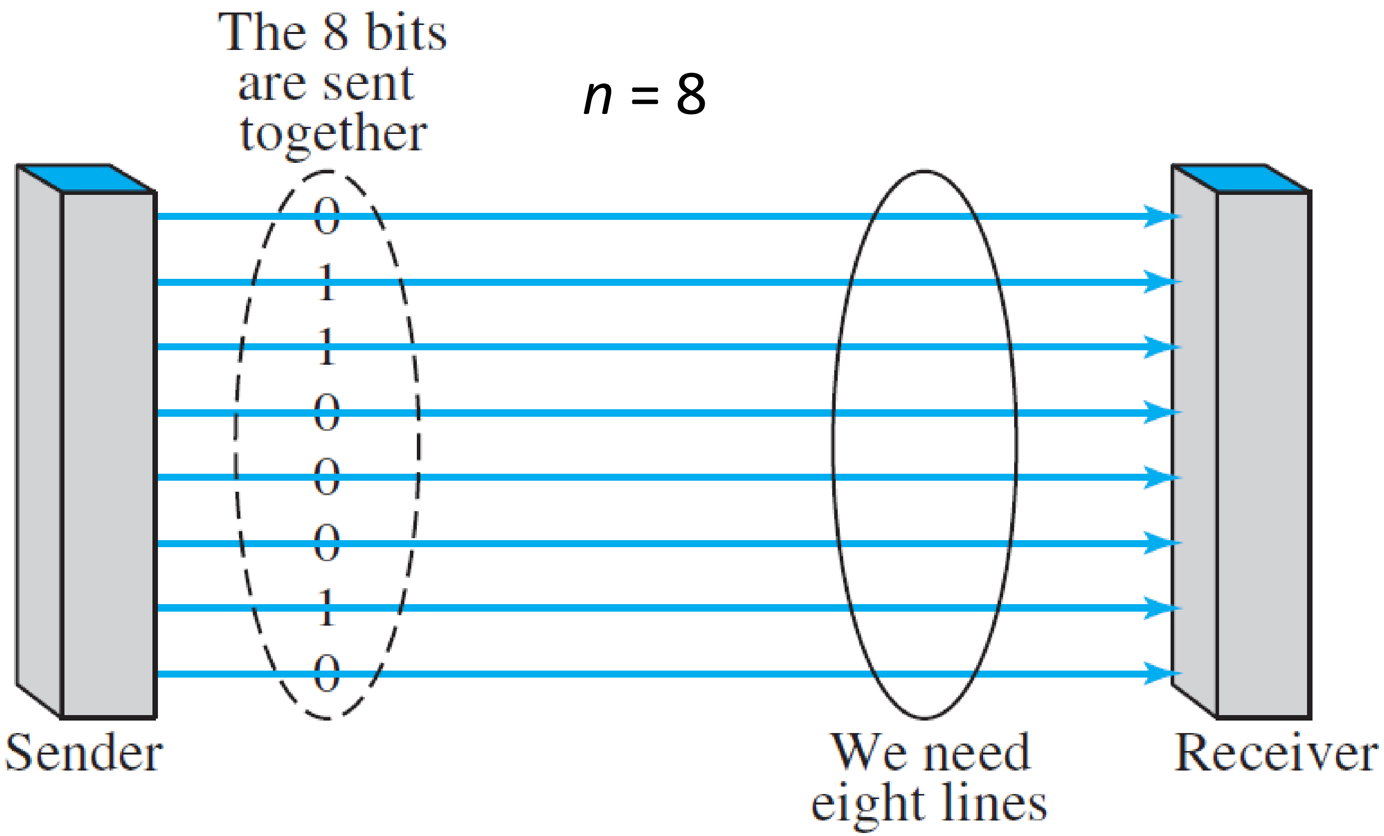
Bandwidth-Delay Product (Example)



Transmission Modes



Transmission Modes – Parallel Transmission



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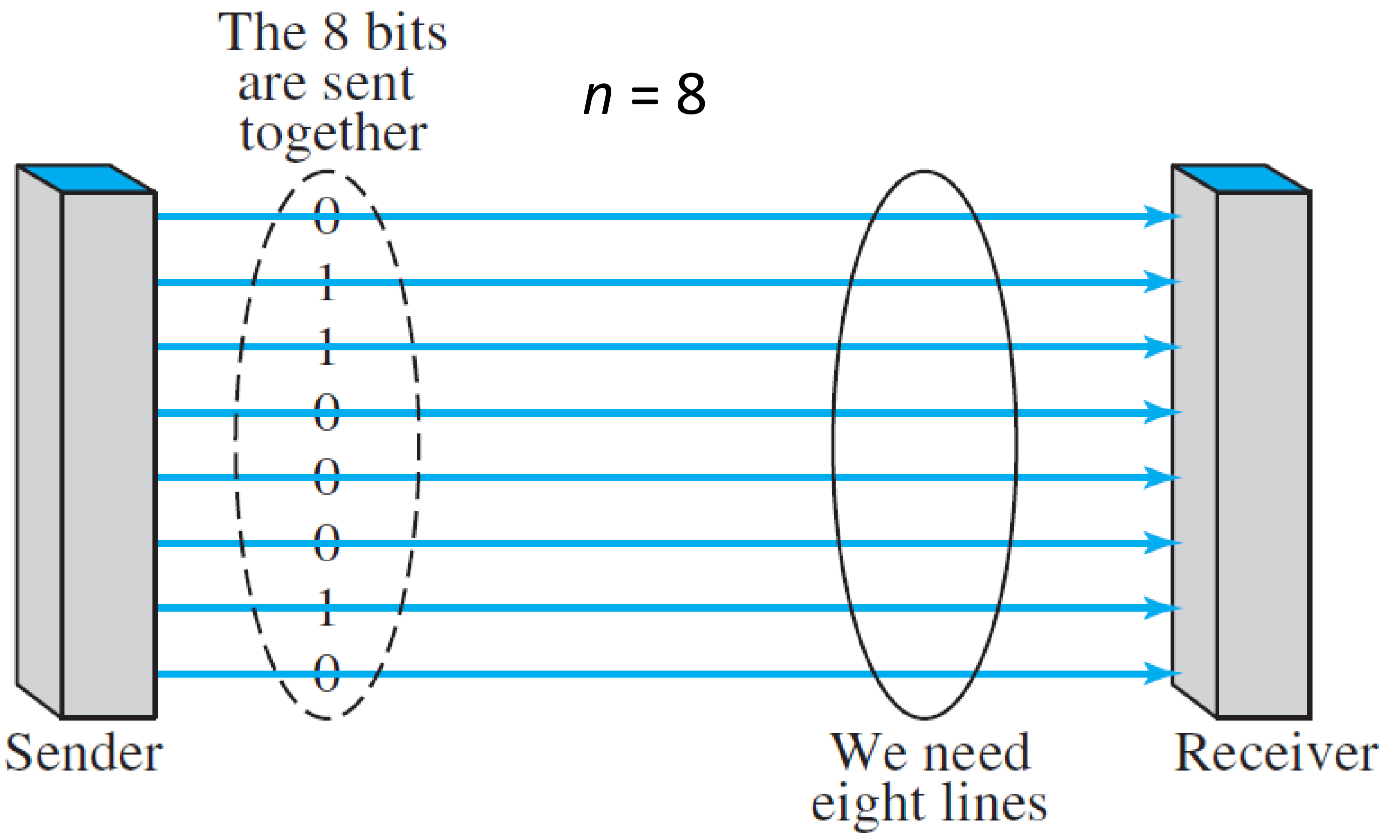
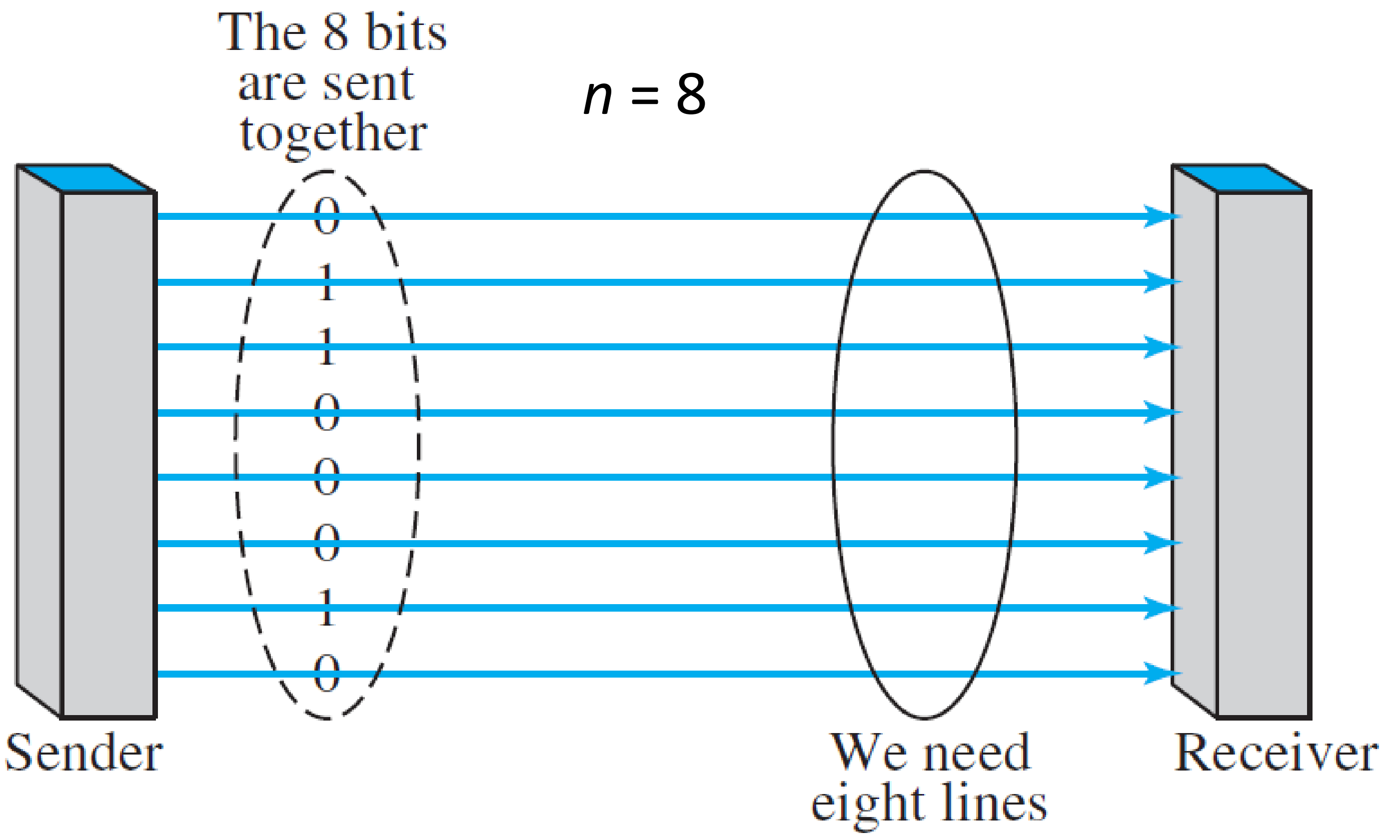


Parallel transmission can **increase the transfer speed** by a factor of *n* over serial transmission.

Transmission Modes – Parallel Transmission

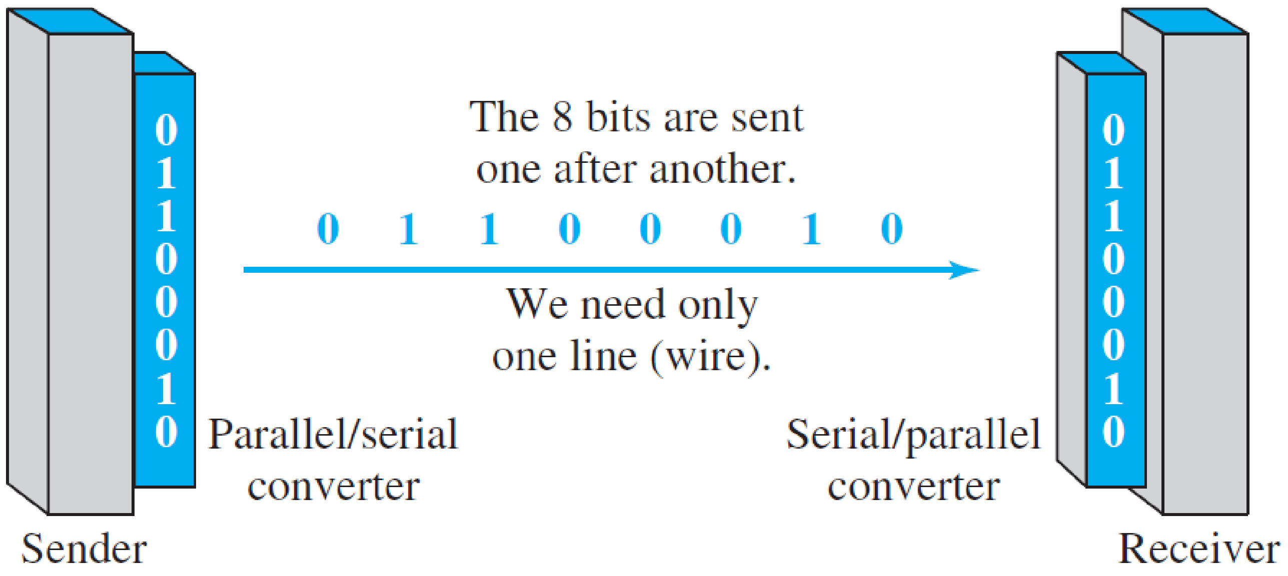


$n = 8$

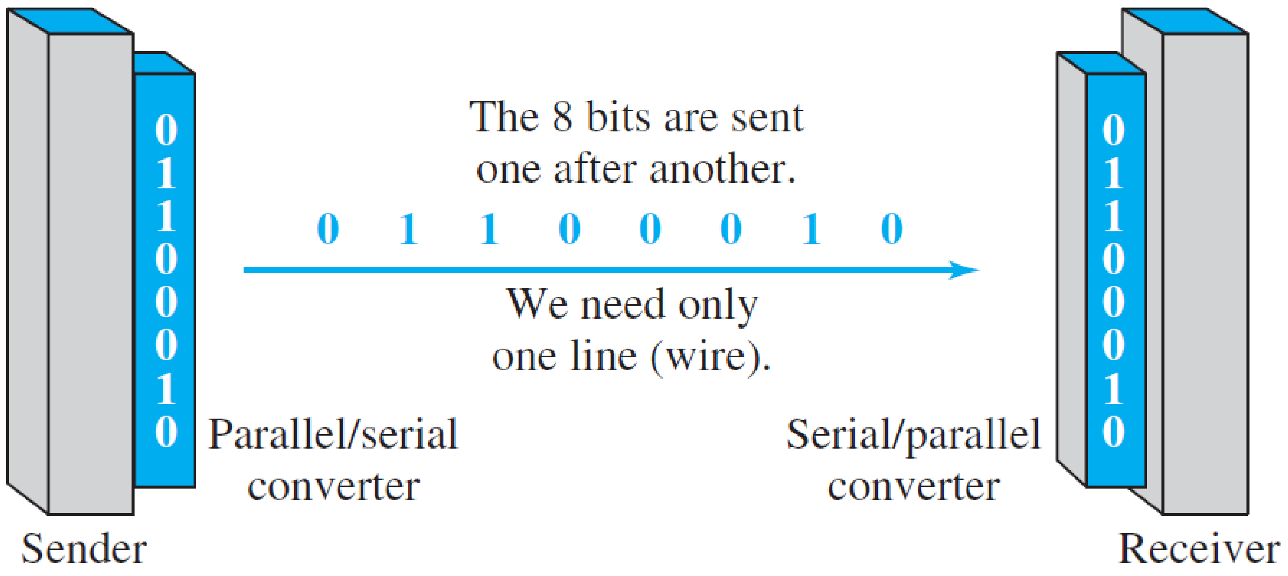
Advantage: Speed
Disadvantage: Cost

Parallel transmission can **increase the transfer speed** by a factor of n over serial transmission.

Transmission Modes – Serial Transmission

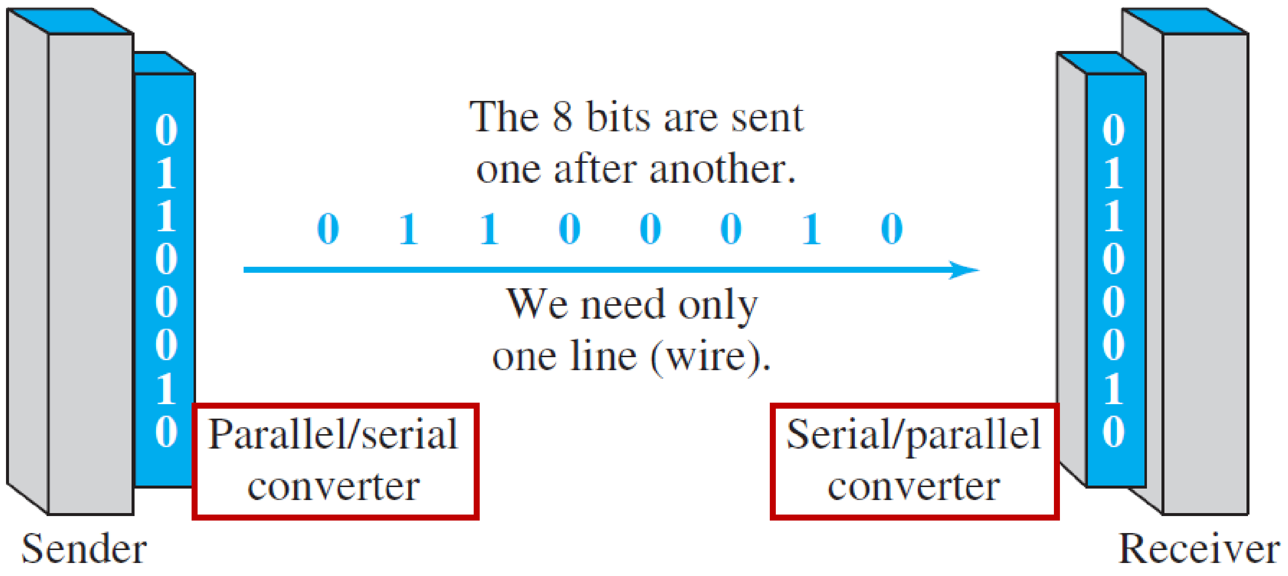


Transmission Modes – Serial Transmission



With only **one communication channel**, serial transmission **reduces the cost of transmission** over parallel by roughly a factor of *n*.

Transmission Modes – Serial Transmission



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Summary

- **Baseband** and **broadband** transmission of digital signals.
- **Transmission impairment**, including attenuation, distortion, and noise can impair a signal.
- Data rate limits using **Shannon Capacity** and **Nyquist formula**.
- **Bandwidth** is one of the main performance metrics used in data communications.

References

[1] Behrouz A.Forouzan, Data Communications & Networking with TCP/IP Protocol Suite, 6th Ed, 2022, McGraw-Hill companies.

Reading

- Chapter 2 of the textbook, section 2.1 (Transmission of Digital Signals) and section 2.2.
- Chapter 2 of the textbook, section 2.8 (Practice Test)