DATA RATE LIMITS

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Dept. of Computer Engineering
Faculty of Engineering

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Lecture Outline

1. Information as Digital Signal
2. Transmission of Digital Signals
3. Bit Rate
4. Data Rate
5. Nyquist Bit Rate
6. Shannon Capacity
7. Network Performance

Information as Digital Signal

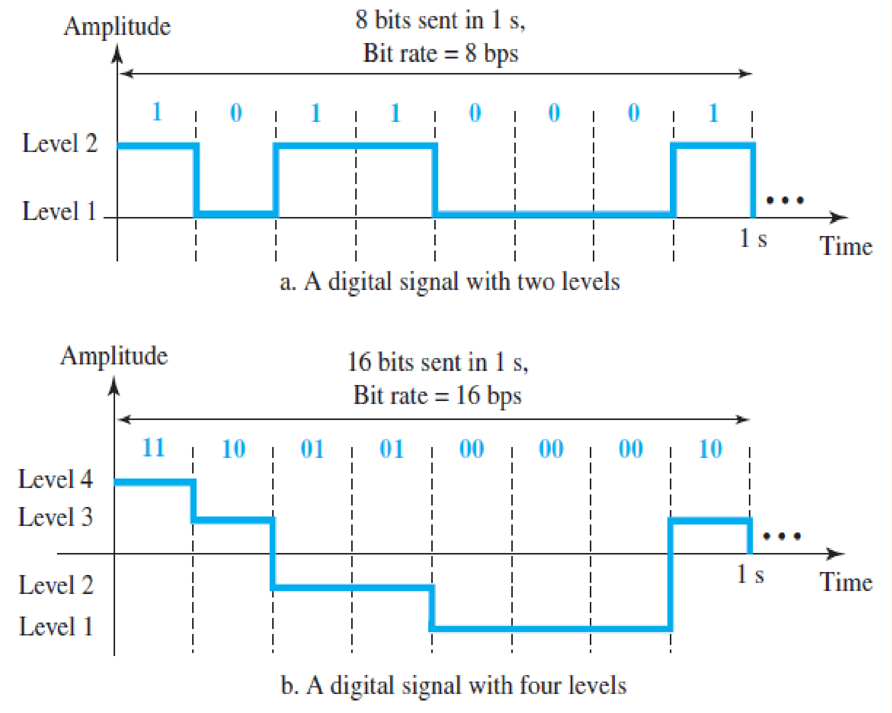
Information can also be represented by a digital signal

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

In general, if a signal has L levels, each level needs $\log_2 L$ bits. For this reason, we can send $\log_2 4 = 2$ bits in (b)



Transmission of Digital Signals

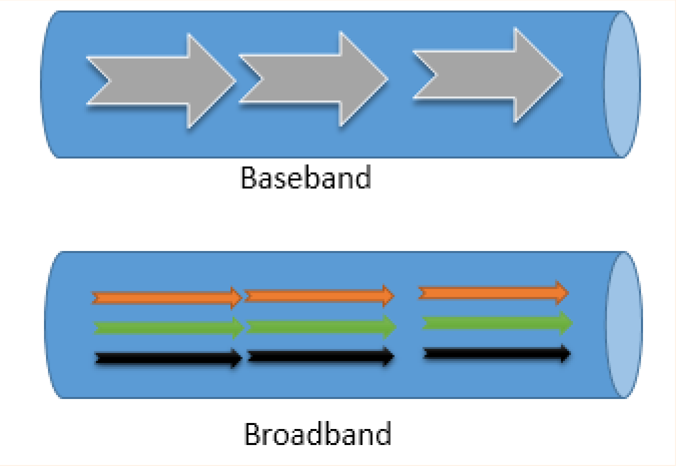
- let us consider a nonperiodic digital signal, similar to the ones we encounter in data communications
- The fundamental question is, How can we send a digital signal from point A to point B?
- We can transmit a digital signal by using

baseband transmission

broadband transmission

- Both baseband and broadband describe how data is transmitted between two nodes.

- Baseband technology transmits a single data signal/stream/channel at a time while broadband technology transmits multiple data signals/streams/channels simultaneously at the same time.



Differences Between Baseband and Broadband Transmissions

Baseband transmission	Broadband transmission
Transmit digital signals	Transmit analog signals
To boost signal strength, use repeaters	To boost signal strength, use amplifiers
Can transmit only a single data stream at a time	Can transmit multiple signal waves at a time
Support bidirectional communication simultaneously	Support unidirectional communication only
Support TDM based multiplexing	Support FDM based multiplexing
Use coaxial, twisted-pair, and fiber-optic cables	Use radio waves, coaxial cables, and fiber optic cables
Mainly used in Ethernet LAN networks	Cable TV, Wi-Fi, and Power Line communication are some examples

Bit Rate

- Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics
- To describe digital signals another term—*bit rate* (instead of *frequency*)
- **Bit rate** is the number of bits sent in 1s
- Expressed in **bits per second (bps)**

- **Example:** 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

$$100 \times 24 \times 80 \times 8 = 1{,}536{,}000 \text{ bps} = 1.536 \text{ Mbps}$$

Data Rate

Factors Impacting Data Rate

An 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)

Formulas to Calculate Data Rate

Two theoretical formulas were developed to calculate the data rate:

1. Nyquist Bit Rate for a noiseless channel.
2. Shannon Capacity for a noisy channel.

Noiseless Channel: Nyquist Bit Rate

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

$$BR = 2\ x\ BW\ x\ log_2\ L$$

Here,

BR = Bit Rate in bps
BW = Bandwidth of the channel in Hz
L = Number of levels representing data

Noiseless Channel: Nyquist Bit Rate

- From the formula it seems like, given a specific bandwidth, we can have any bit rate we want by increasing number of levels. The idea is theoretically correct, but practically there is a limit.

- By increasing number of 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 a 1.

- If the level of a signal is 64, the receiver must be very sophisticated to distinguish between 64 different levels. **So, increasing the levels of a signal reduces the reliability of the system.**

Noiseless Channel: Nyquist Bit Rate

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

Solution:

$$BR = 2\ x\ BW\ x\ log_2\ L$$
$$= 2\ x\ 3000\ xlog_2 2$$
$$= 6000 \text{ bps}$$

Noiseless Channel: Nyquist Bit Rate

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:

$$BR = 2\ x\ BW\ x\ log_2\ L$$

$$265\ x\ 10^3 = 2\ x\ 20\ x\ 10^3\ x\ log_2\ L$$

$$log_2\ L = 6.625$$

$$L = 2^{6.625} = 98.7\ \approx 99\ \text{Levels}$$

Noisy Channel: Shannon Capacity

We cannot have a noiseless channel really. The channel is always noisy. Theoretical highest data rate for a noisy channel can be calculated using Shannon capacity formula:

$$C = BW\ x \log_2(1 + SNR)$$

Here,

C = Capacity in bps

BW = Bandwidth of the channel in Hz

SNR = Signal-to noise ratio

***Shannon formula does not have any 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.

Noisy Channel: Shannon Capacity

Problem: 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 the channel?

Solution:

$$C = BW\ x \log_2(1 + SNR) = BW\ x \log_2(1 + 0) = 0$$

***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 if SNR is zero.

Noisy Channel: Shannon Capacity

Problem: We have a channel with a 1-MHz bandwidth. The SNR for this channel is 63. What is the maximum bit rate That can be achieved in this channel?

Solution:

Maximum bit rate of a channel is its capacity. Using Shannon's formula

$$
\begin{aligned}
C &= BW\ x \log_2(1 + SNR) \\
&= 10^6\ x \log_2(1 + 63) \\
&= 10^6\ x\ 6 \\
&= 6 \text{ Mbps}
\end{aligned}
$$

Using Both Limits

Example

In practice, we need to use both methods to find the limits and signal levels.

Problem: 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:

From previous example we know capacity of the channel is **6 Mbps**. This is the upper limit. For better performance we choose something lower, **4 Mbps**, for example. Then using Nyquist formula we can find the number of signal levels.

Using Both Limits

Continued from previous slide here…

Then using Nyquist formula we can find the number of signal levels.

$$BR = 2\ x\ BW\ x\ log_2\ L$$
$$4\ x10^6 = 2\ x\ 1\ x10^6\ x\ log_2\ L$$
$$log_2\ L = 2$$
$$L = 2^2 = 4 \text{ Levels}$$

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

Network Performance

Quality of Service (QoS) Parameters

The Internet and its underlying local area and wide area networks must include a QoS capability to provide various levels of service to different types of application traffic. A QoS capability can deal with priority, delay constraints, delay variability constraints, and other similar requirements. Some common parameters determining the quality of network performance are:

- Bandwidth
- Throughput
- Latency or Delay
- Bandwidth-Delay Product

Bandwidth

One characteristic that measures network performance is **bandwidth**. However, the term can be used in two different contexts with two different measuring values: bandwidth in hertz and bandwidth in bits per second.

- **Bandwidth in Hertz:** Bandwidth in hertz is the range of frequencies contained in a composite signal or the 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:** The term bandwidth can also refer to the 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.

Bandwidth

Example 1:

The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data trans mission can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.

Example 2:

If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 1.

Throughput

- **Throughput** is a measure of how fast we actually can send data through a network.
- At first glance, bandwidth in bits per second and throughput seem the same, they are different.
- A link may have a bandwidth of *B* bps, but we can only send *T* bps through this link with *T* always less than *B*.
- In other words, the bandwidth is a potential measurement of a link; the throughput is an actual measurement of how fast we can send data.

Throughput

Example 1:

Imagine a highway designed to transmit 1000 cars per minute from one point to another. However, if there is congestion on the road, this figure may be reduced to 100 cars per minute. The bandwidth is 1000 cars per minute; the throughput is 100 cars per minute.

Example 2:

We may have a link with a bandwidth of 1 Mbps, but the devices connected to the end of the link may handle only 200 kbps. This means that we cannot send more than 200 kbps through this link.

Throughput

Problem: 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:

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

Latency or Delay

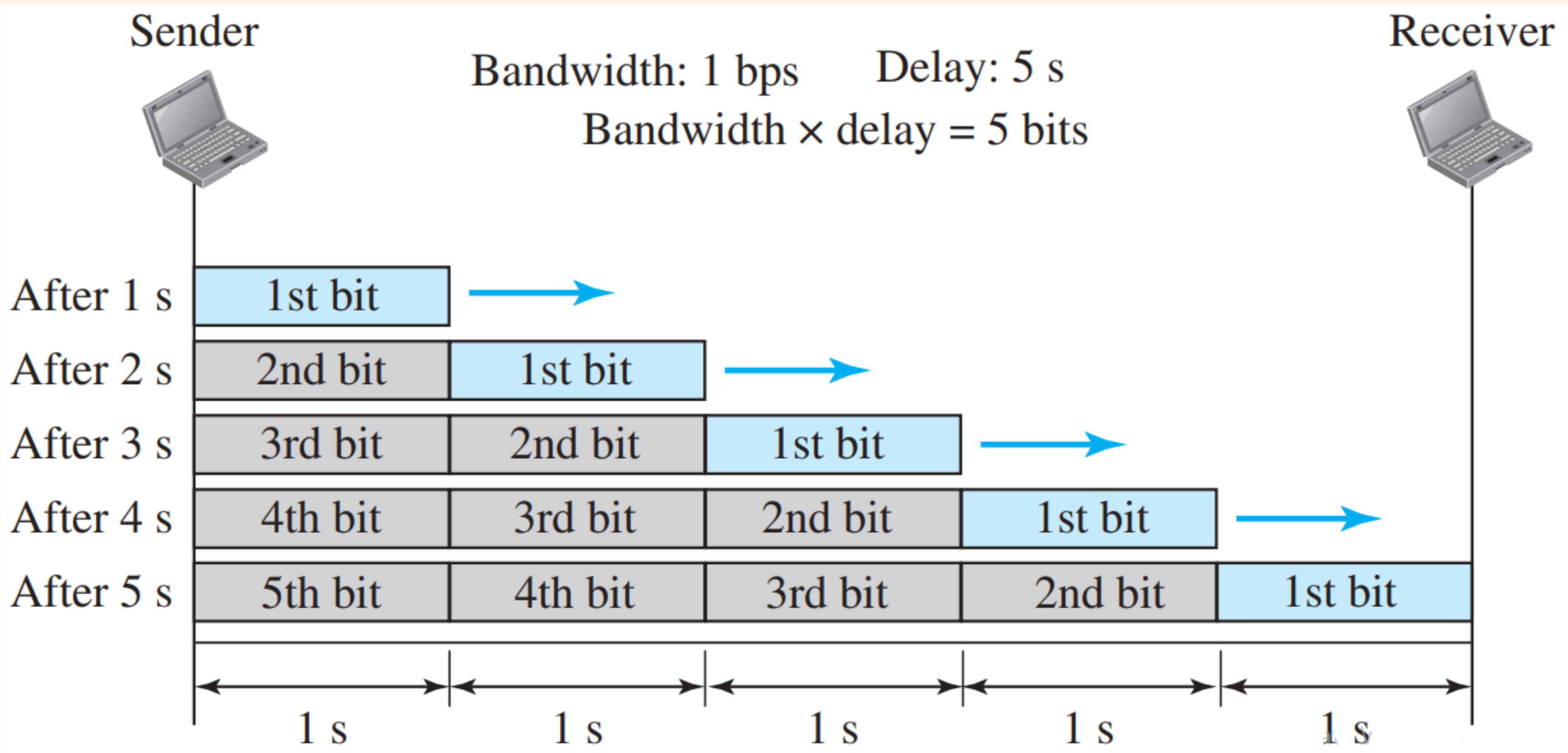
The **latency** or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source. We can say that latency is made of four components: propagation time, transmission time, queuing time and processing delay.

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

Bandwidth-Delay Product

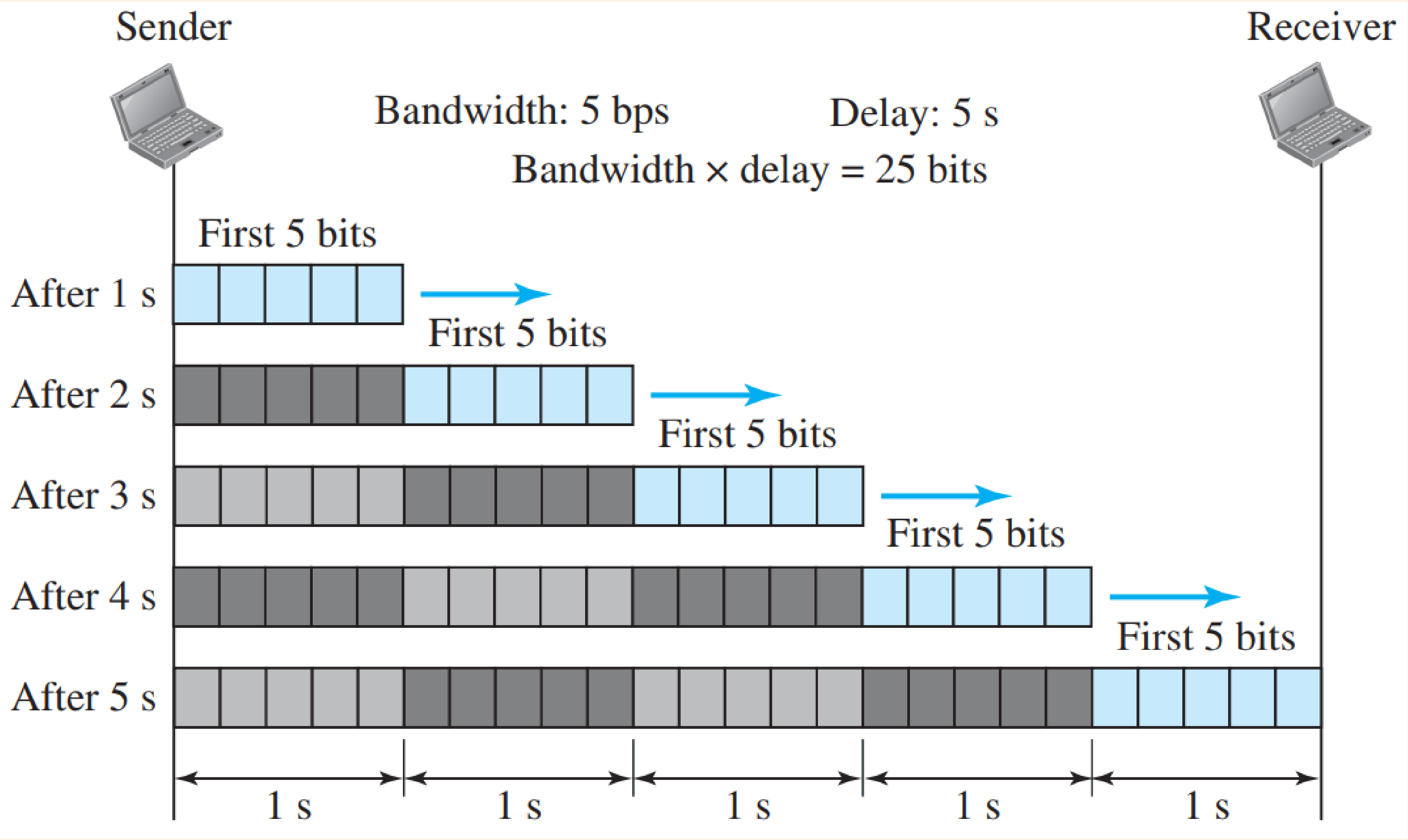
Bandwidth and **delay** are two performance metrics of a link. However, a very important performance metrics in data communications is the product of the two, the **bandwidth-delay product**. We will elaborate on this issue, using two hypothetical cases as examples in next slides.

Case 1



Sender
Receiver
Bandwidth: 1 bps
Delay: 5 s
Bandwidth × delay = 5 bits
After 1 s
1st bit
After 2 s
2nd bit
1st bit
After 3 s
3rd bit
2nd bit
1st bit
After 4 s
4th bit
3rd bit
2nd bit
1st bit
After 5 s
5th bit
4th bit
3rd bit
2nd bit
1st bit
1 s
1 s
1 s
1 s
1 s

Case 2


Sender
Receiver
Bandwidth: 5 bps
Delay: 5 s
Bandwidth × delay = 25 bits
First 5 bits
After 1 s
First 5 bits
After 2 s
First 5 bits
After 3 s
First 5 bits
After 4 s
First 5 bits
After 5 s
1 s
1 s
1 s
1 s
1 s

Case Study Outcome

Looking at case 1, we can say that this product 1 x 5 or 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.

Looking at case 2, we can say that this product 5 x 5 or 25 is the maximum number of bits that can fill the link. There can be no more than 25 bits at any time on the link.

The **bandwidth-delay product** defines the number of bits that can fill the link.

Books

1. Forouzan, B. A. "Data Communication and Networking. Tata McGraw." (2005).

References

1. Prakash C. Gupta, “Data communications”, Prentice Hall India Pvt.
2. William Stallings, "Data and Computer Communications”, Pearson
3. Forouzan, B. A. "Data Communication and Networking. Tata McGraw." (2005).