Week 2: Data Communications Fundamentals

EE3017/IM2003 Computer Communications

School of Electrical and Electronic Engineering

Dr. SHAO Xuguang, Michelle

Email: XGSHAO@ntu.edu.sg

Room: S1-B1a-10

Phone: 6513-7648

Topic Outline

Introduction to Computer Communications 01

Data Communications Fundamentals 02

Data Transmission and channel capacity,
Line coding

Data Link Layer 03

Application

Transport

Network

Link

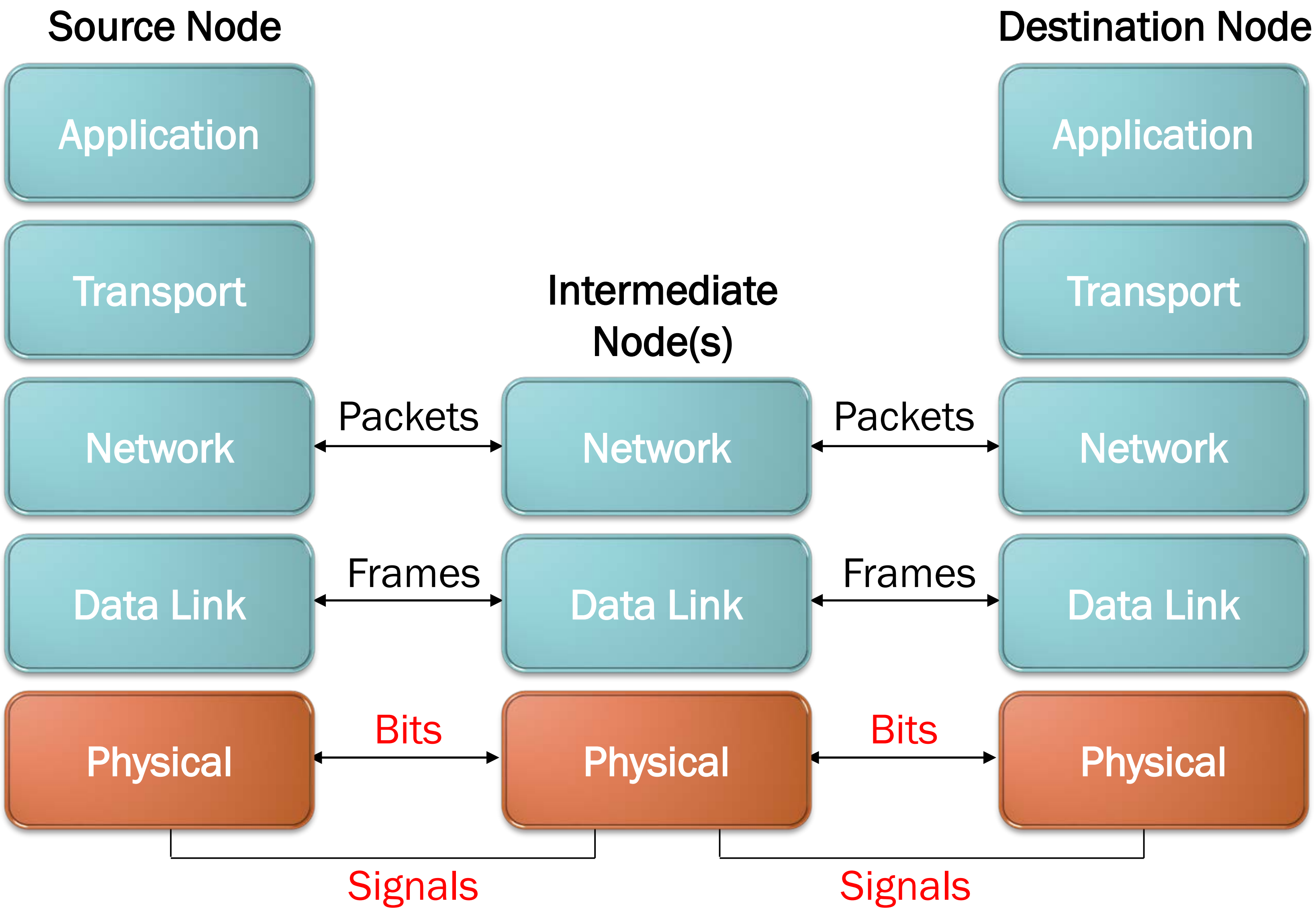
Physical

Learning Objectives

By the end of this topic, you should be able to:

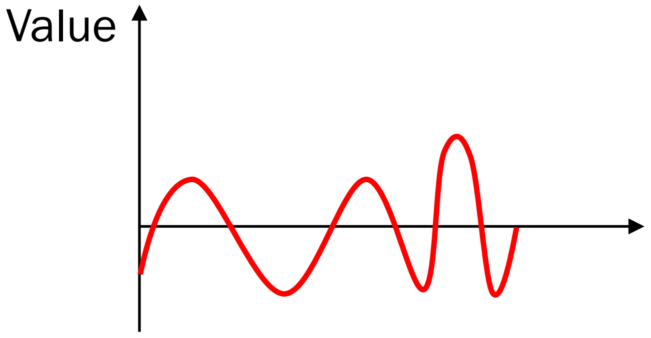
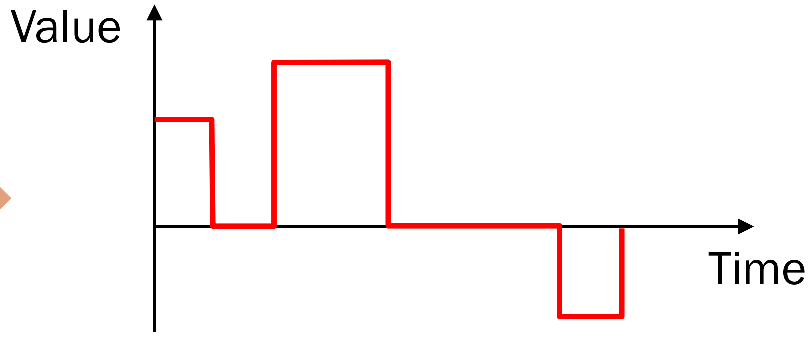
- Differentiate the data encoding and modulation techniques.
- Identify and analyse the channel characteristics in data communication.
- Build the correct channel capacity models based on the conditions given, then calculate and analyse the results.

Where are we?


Source Node
Intermediate Node(s)
Destination Node
Application
Application
Transport
Transport
Network
Packets
Network
Packets
Network
Data Link
Frames
Data Link
Frames
Data Link
Physical
Bits
Physical
Bits
Physical
Signals
Signals

Data Transmission and Channel Capacity

Analog vs. Digital

Analog	VS	Digital
Information is continuous.	Data	Information has discrete states.
	Signals	
Analog signal has infinitely many levels of intensity over a period of time.		A digital signal can have only a limited number of defined values.

Transmission System

Transmitter → Communication Channel → Receiver

Converts digital data into signal suitable for transmission and sends the signal over the communication channel.

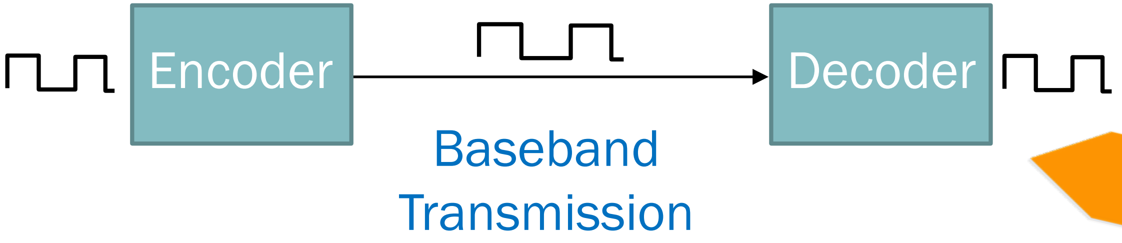
Receives the signal and converts it back into digital data to be delivered to the user.

Depending on the transmission medium, the data may be encoded directly and sent to the medium **(Baseband Transmission, Line Coding)** or it may be modulated on to an analog carrier and then transmitted **(Modulation)**.

Encoding and Modulation Techniques

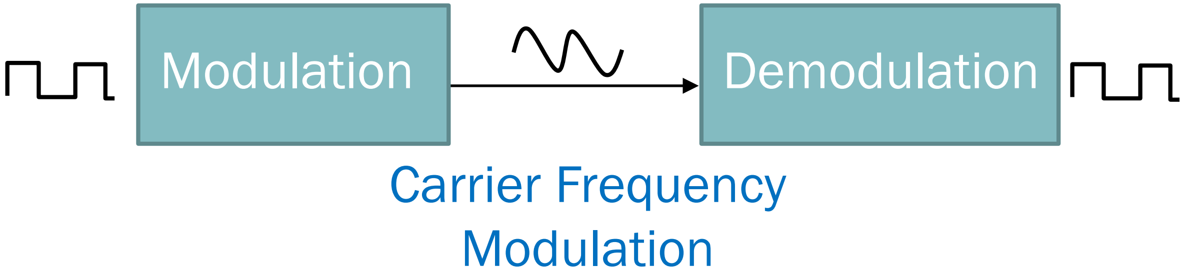
Data Encoding:

Mapping of information into sequence of digital signals.

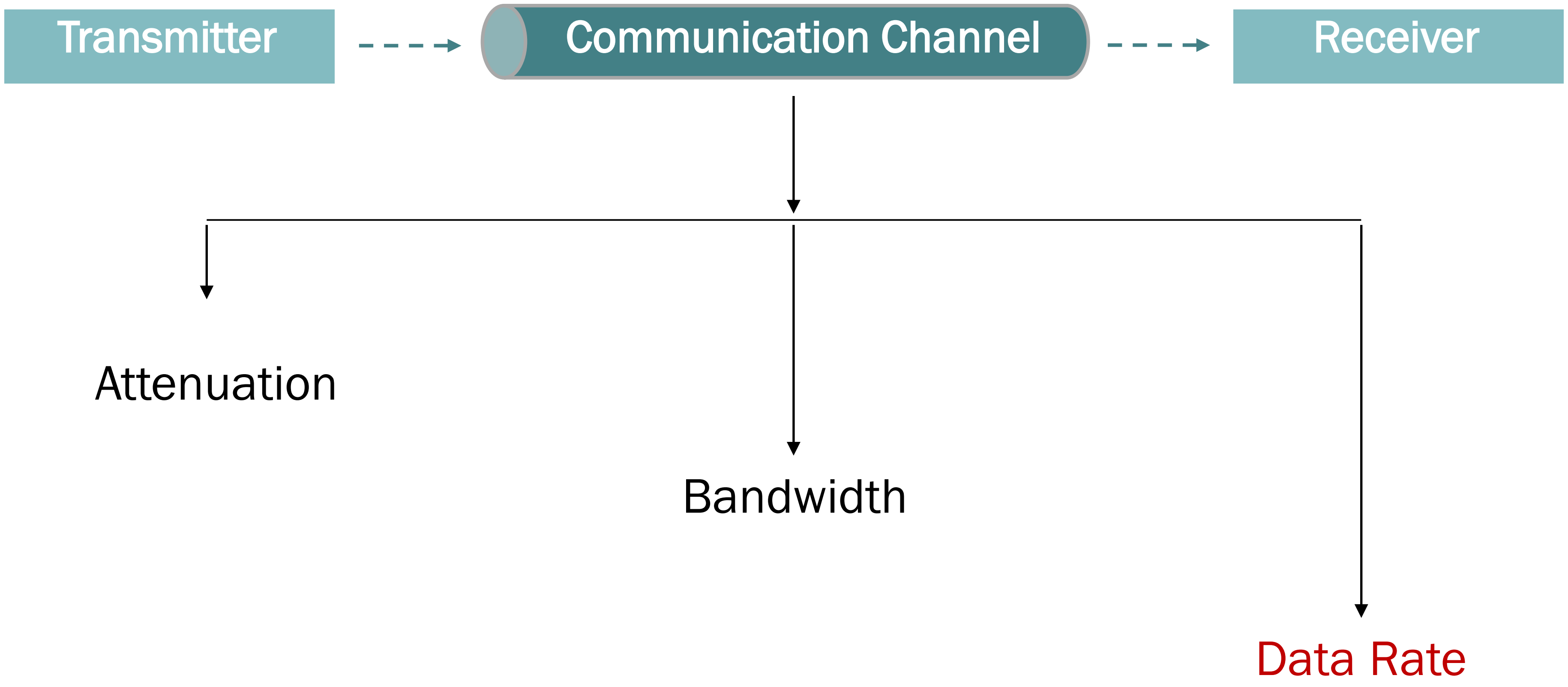


Modulation:

Embedding of information into sinusoidal waveforms.



Channel Characterisation Parameters



Channel Attenuation

Transmitted Signal $x(t)$ → Communication Channel → Received Signal $y(t)$

If	Transmitted Power = P_{in} watts
and	Received Power = P_{out} watts
Then	Channel Attenuation (Loss) = P_{in}/P_{out}
	= $10 \log_{10}(P_{in}/P_{out})$ dB

Channel Bandwidth

$x(t) = a\cos(2\pi f t)$ - - - → **Channel** - - - → $y(t) = a\,A(f)\cos(2\pi f t)$

$A(f)$ Frequency Characterisation of Channel

If input is sinusoid of frequency f, then

- Output also sinusoid of same frequency f
- Output attenuated by an amount $A(f)$ that depends on f

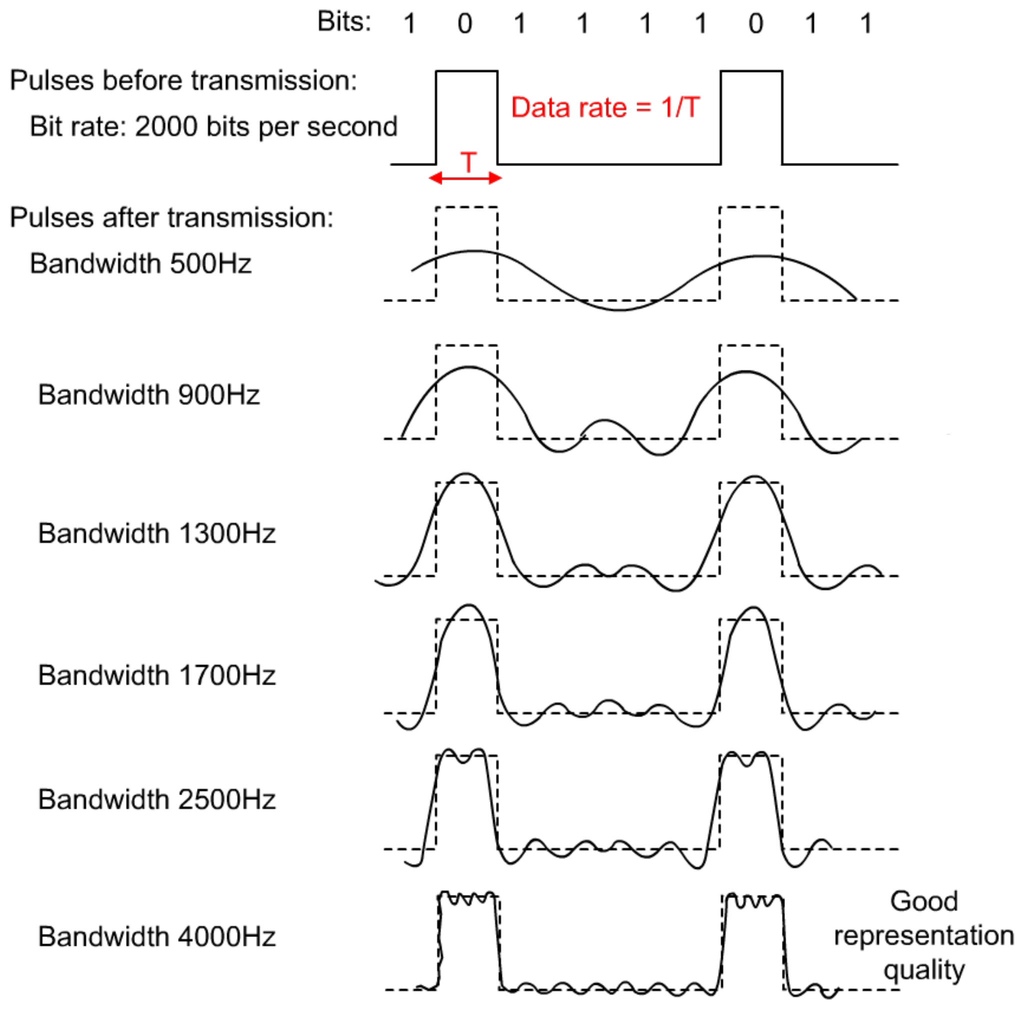
Data Rate and Bandwidth

A transmission system can only carry a limited band of frequencies. This limits the data rate that it can carry.

? What is the bandwidth required to carry a digital signal of 101111011?

A That will depend on the level of acceptable reception quality.

In general, a digital signal of **R bps** can be carried by a signal bandwidth of **2R Hz** with good accuracy although a bandwidth of **0.5R Hz** is sufficient for successful transmission.



Effect of Bandwidth on a Digital Signal

Nyquist Signalling Rate

Consider a noise free, ideal baseband channel:

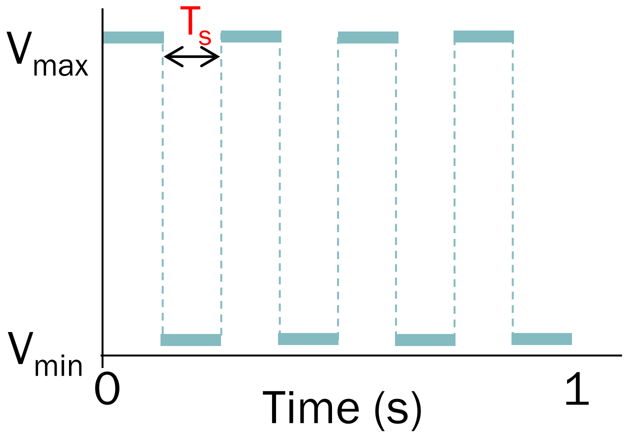
If the channel bandwidth is B Hz, then the maximum signalling rate achievable through this channel will be $2B$ pulses/second.

Nyquist Signalling Rate, $N_R = 2B$

- Special pulse shapes will be required to achieve the Nyquist Rate (i.e. pulses with zero inter-symbol interference).
- For real (non-ideal channels) we can only achieve pulse rates less than the Nyquist Rate.
- Note that the pulses can have any amplitude.

Symbol Rate

- A symbol is a state of the communication channel that persists for a fixed period of time.
  - Symbol duration, T_s.
- Symbol rate (also known as baud rate, pulse rate, or modulation rate) is the number of symbol changes per second.



$$S = \frac{1}{T_s}$$

[baud, symbols/s, pulses/s]

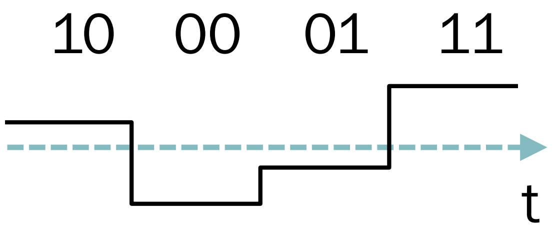
Bit Rate

- Bit rate (noted as R_b), also known as gross bit rate, raw bit rate, gross data transfer rate, is the total number of physically transferred bits per second over a communication link, including useful data as well as protocol overhead.

$$R_b(bits/s) = symbol\ rate(symbols/s) \times bits\ per\ symbol$$

$$= S \times \log_2 M \text{ [bits/s]}$$

M is the number of modulation levels.



For example M = 4, bits carried by each symbol equals $\log_2 M = 2$

$$R_b = S \times \log_2 4 = 2S$$

Multilevel Pulse Transmission

- With an ideal channel of bandwidth B, we can transmit $2B$ pulses/sec without interference. (i.e. Nyquist Signalling Rate)
- If pulses amplitudes are either $-A$ or $+A$, then each pulse conveys 1 bit of information (1 or 0), so

Bit Rate = 1 bit/pulse × *2B* pulses/sec = *2B* bps

- By going to $M = 2^m$ amplitude levels, we achieve

Bit Rate = *m* bits/pulse × *2B* pulses/sec = *2mB* bps

- For *M*-ary signals (M signal levels per symbol)

Nyquist Bit Rate, $\boldsymbol{R_M = 2B \log_2 M}$ **bps**

It would appear that in the absence of noise, the bit rate can be increased without limit by increasing M.
Not really feasible in channels with noise, as we will see later!

Bandwidth, Data Rate and Channel Capacity

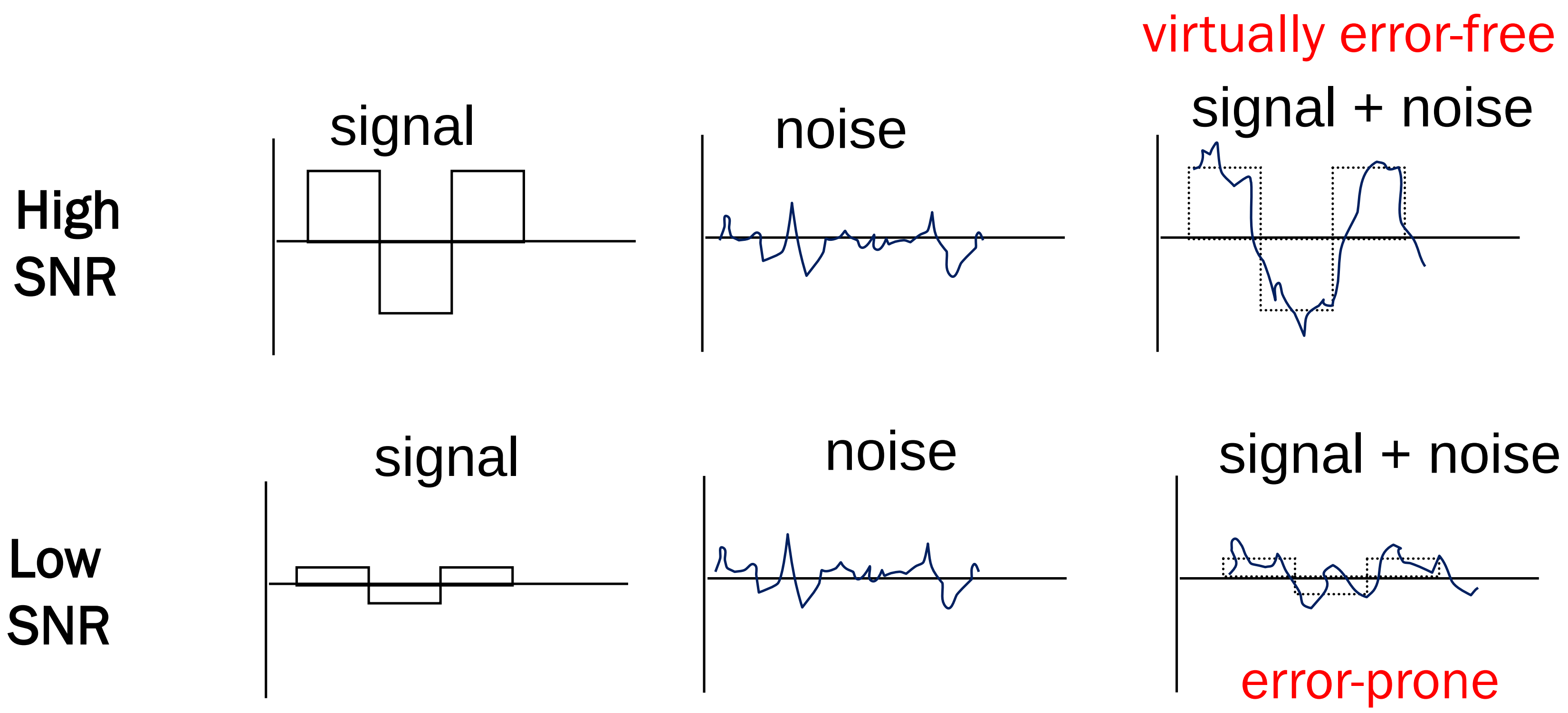
Any transmission system can only pass a limited band of analog frequencies, called Bandwidth (Hertz).

Together with noise, this limits the data rate that can be carried over the transmission system.

Data rate represents the number of bits per second (bps) that is to be carried over the transmission system.

Channel capacity is the maximum number of bits per second (bps) the transmission system can sustain given the bandwidth, signal power and noise power.

Effect of Noise



Signal-to-Noise Ratio (SNR)

Shannon Channel Capacity

Consider a noisy channel:

- Shannon's channel capacity formulation relates data rate, noise, and bandwidth
- Shannon channel capacity: $\boldsymbol{C = B\log_2(1 + \mathrm{SNR})}$

SNR: Signal-to-Noise Ratio

$$\left(\frac{\text{signal power}}{\text{noise power}}\right)$$

Represented in decibel

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(\frac{\text{signal power}}{\text{noise power}}\right)$$

Shannon Channel Capacity

$$\boxed{\boldsymbol{C} = \boldsymbol{B}\,\mathbf{log_2}(\mathbf{1} + \mathbf{SNR})}$$

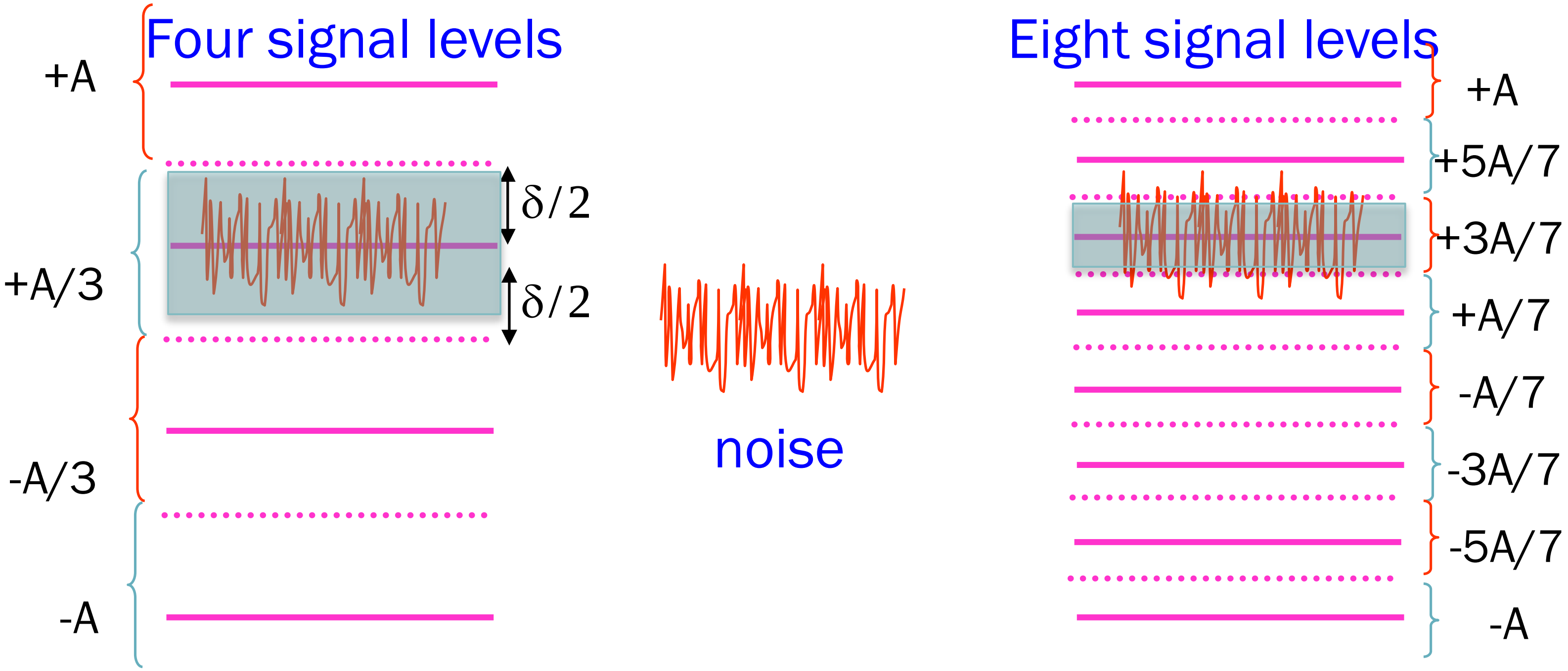
Arbitrarily reliable communications is possible if the transmission rate $R < C$.

The formal statement of Shannon's Capacity theorem says that as long as the channel is required to carry information at bit rates lower than C, it is possible to find a way of doing so.

In practice, this means that if a channel has a certain B and SNR, it can only be used to carry data at rates lower than C bits/second.

Effect of Noise

- Receiver makes decision based on received pulse level + noise.
- Error rate depends on relative value of noise amplitude and spacing between signal levels.
- If transmitted power is limited, then as M increases, spacing between levels decreases, causing more frequent errors to occur.



Multi-Level Amplitude Signalling

- **Nyquist's theorem** dictates the data rate of an encoding scheme given the bandwidth, *B* of the transmission channel and *M*, the maximum number of signalling states.
- **Shannon's theorem** dictates the maximum data rate of a transmission channel given the bandwidth, *B* of the transmission channel and the **SNR** of the channel.
- Now, given the SNR what is the maximum value for M?

Nyquist signal bit rate ≤ Shannon channel capacity

$$2B\log_2(M) \leq B\log_2(1+\mathrm{SNR}) \text{ where, } \mathrm{SNR} = \frac{\text{signal power}}{\text{noise power}} = \frac{S}{N}$$

$$\log_2(M^2) \leq \log_2\left(\frac{S+N}{N}\right) \Rightarrow M_{\max} = \sqrt{\left\lfloor\frac{S+N}{N}\right\rfloor}$$

Exercises: Multi-Level Amplitude Signalling

Exercise 1:

Determine the maximum number of signal levels, *M* for encoding a signal and transmitting at a signal power of 2.6 watts over a noisy channel with noise power of 10 mWatts.

Solution:

$$M_{\max} = \sqrt{\left[\frac{S+N}{N}\right]} = \sqrt{\frac{2.6+0.01}{0.01}} = 16.16 \approx 16$$

Exercises: Multi-Level Amplitude Signalling

Exercise 2:

Alternatively, given the channel bandwidth of 1 MHz and SNR_{dB} of 24.1 dB, what will be the channel capacity and what will be the maximum number of signal levels that will be needed?

Solution:

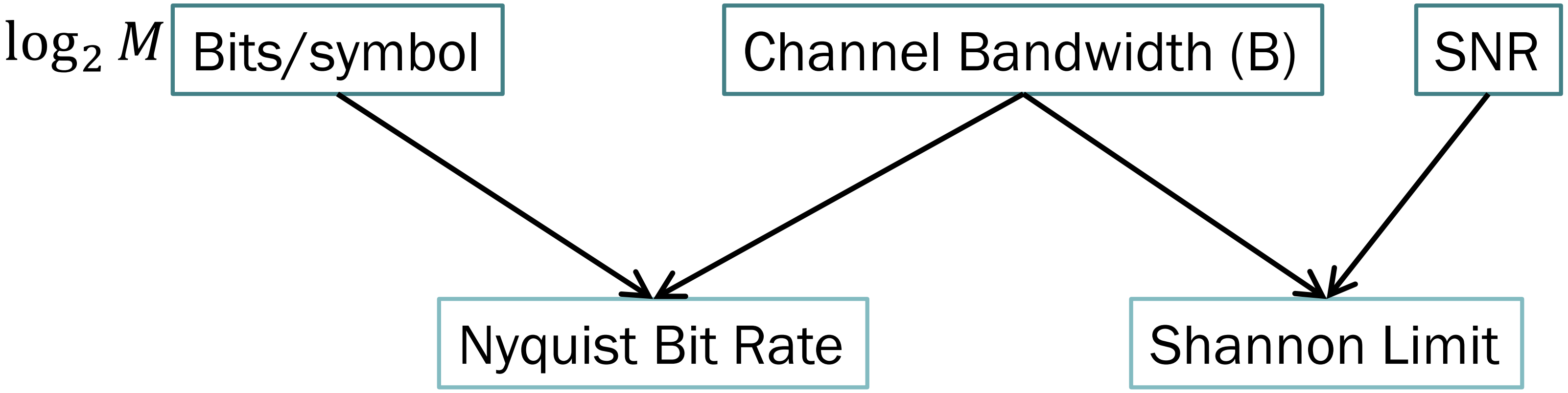
$$\mathrm{SNR_{dB}} = 10\log_{10}(\mathrm{SNR})\,;\mathrm{SNR} = 257$$

Shannon capacity, $C = B\log_2(1+\mathrm{SNR}) = 8.011 \approx 8\ \mathrm{Mbps}$

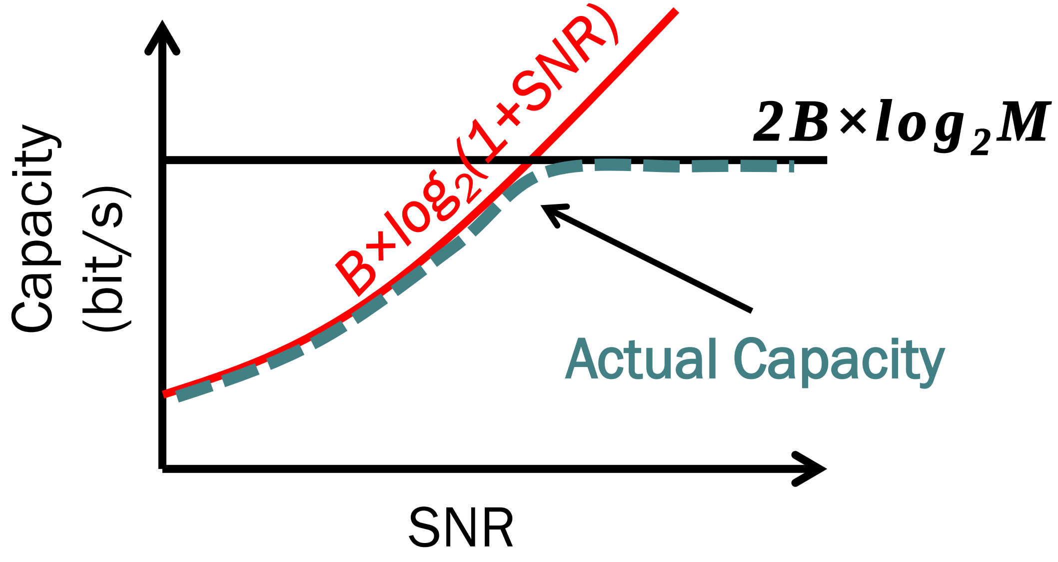
Nyquist signal bit rate, $R = 2B\log_2 M$

$$R \le C \;\Rightarrow\; M_{\max} = 16$$

Nyquist Bit Rate vs. Shannon Limit



$$R_{Nyquist} = 2B \times \log_2 M \qquad C = B \times \log_2(1 + SNR)$$



Summary

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Key points discussed in this topic:

- Data could be in analogue format or digital format. We are interested in digital data, where information has discrete states.
- An analog signal has infinitely many levels of intensity over a period of time whereas a digital signal can have only a limited number of defined values.
- In a data transmission system, the transmitter converts digital data into signal suitable for transmission and sends the signal over the communication channel. The receiver receives the signal and converts it back into digital data to be delivered to the user.

Summary

Key points discussed in this topic (cont'd):

- Data encoding maps information bits into sequence of digital signals.
- Channel attenuation is a measure of the loss of signal strength.
- A transmission system can only carry a limited band of frequencies. This limits the data rate that it can carry.
- The two common approaches to calculating data rate are the Nyquist and Shannon theorem:

Nyquist Bit Rate, $R_M = 2B \log_2 M$ bps

Shannon channel capacity: $C = B \log_2(1 + \mathrm{SNR})$