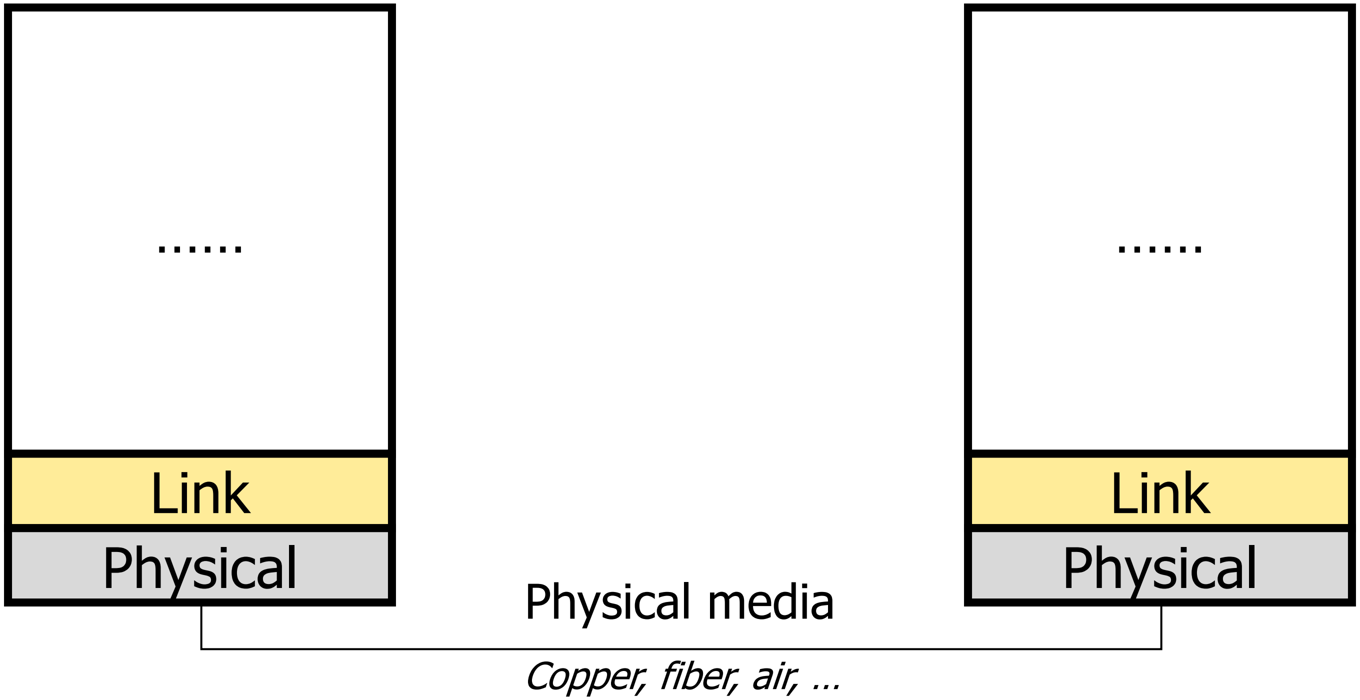
Physical Layer

CSC/ECE 570 Computer Networks
Fall 2024

Agenda

1. PHY Layer Functionalities
2. Modulation
3. Theoretical Limits of Noiseless/Noisy Channel
4. Media

Where is PHY?

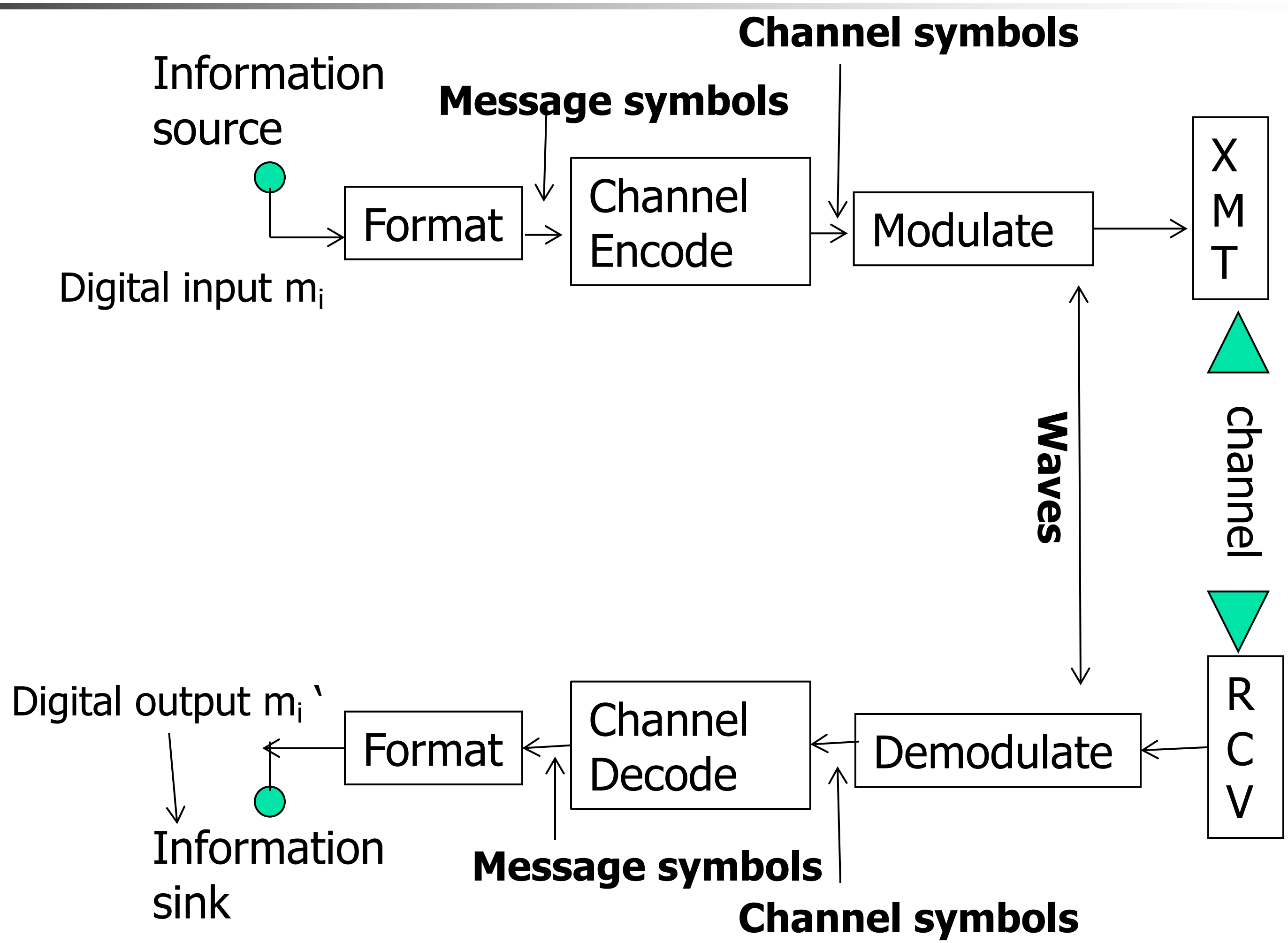


……
……
Link
Link
Physical
Physical
Physical media
Copper, fiber, air, …

PHY Layer Functionalities

- Input: digital signals from DLC layer
- Output: analog signals transmitted via wire / wireless
- Basic Processes:
  - Formatting: group of bits => symbols
  - Encoding: message symbols => channel symbols
  - Modulation: symbols => analog signals (waveforms)
  - Multiplexing: merging waveforms of multiple users
    - TDM, FDM, (CDM), …
- Theoretical foundation:
  - Information theory and Shannon capacity

Block Diagram of a Digital Communication System (DCS)



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Modulation of EM Waves

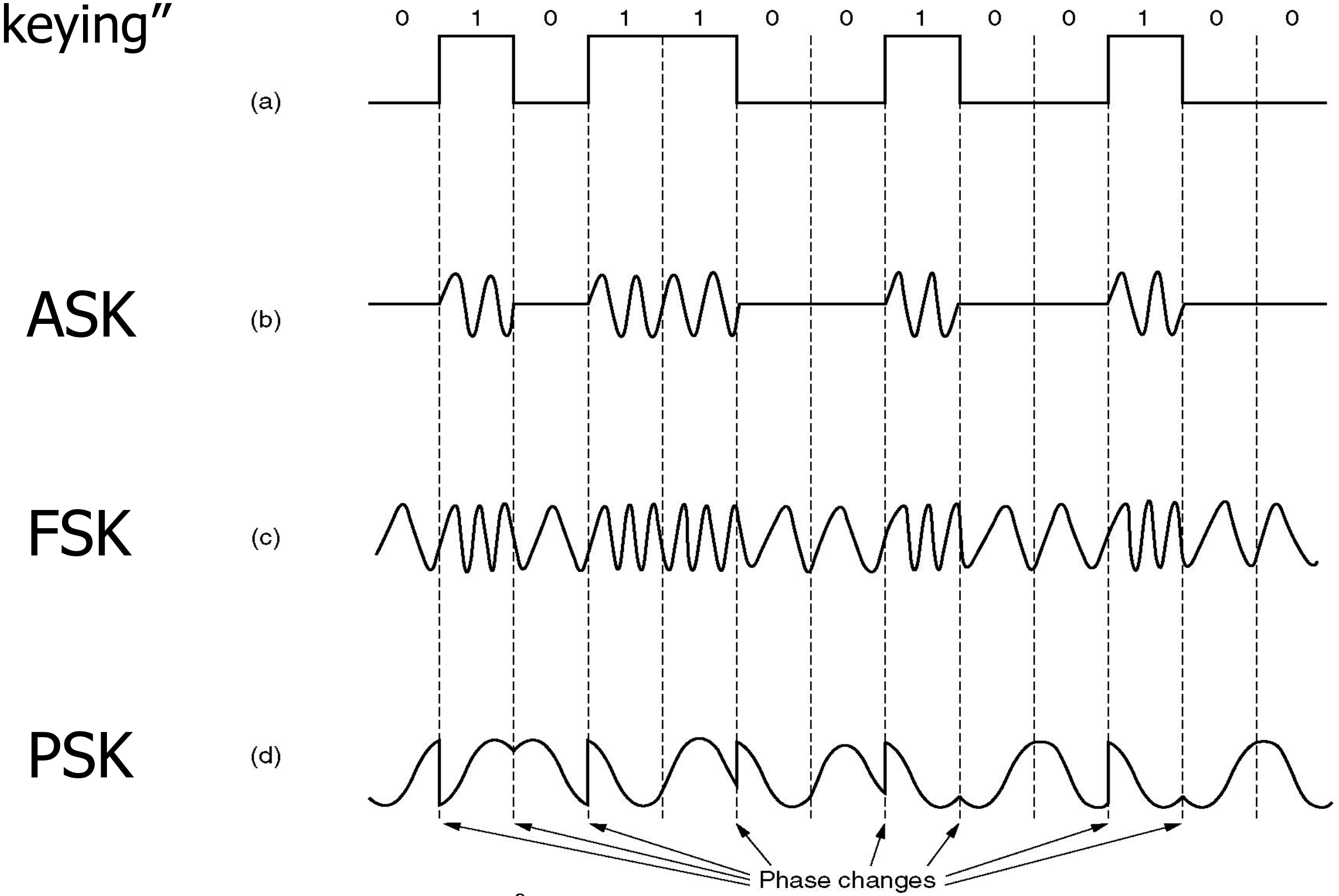
- Zeros and ones (digital bits)
- A “carrier” wave may first be realized on medium
  - Described by amplitude (A), frequency (F), phase (P)
  - Base energy pattern – no information (zero A, F, P)
  - Analog Signals
- A “signal” needs to be transmitted
  - Time varying
  - The value of the signal from instant to instant is used to change the energy pattern of the carrier

Injection

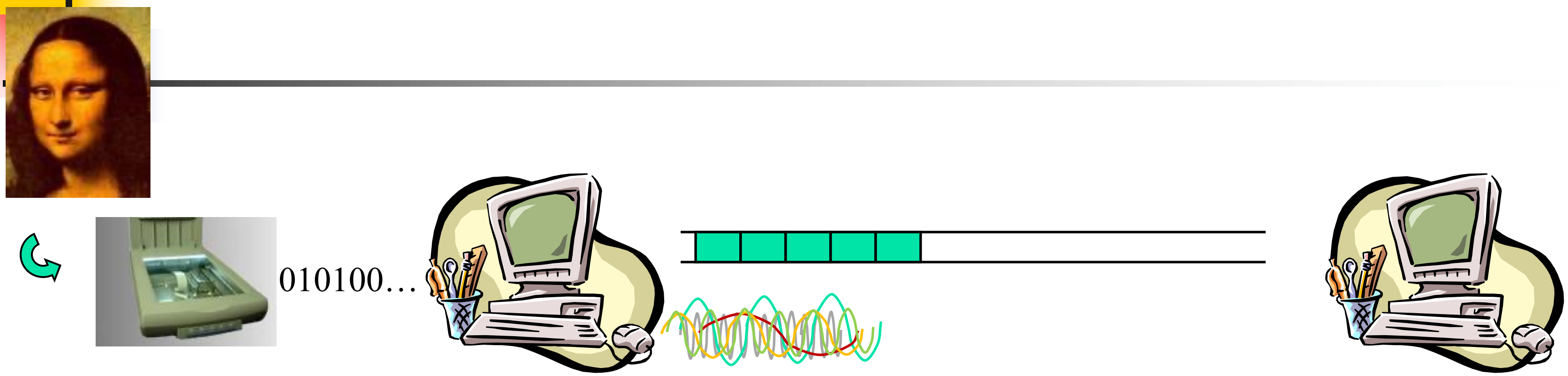
- Baseband Modulation
  - No carrier/low-frequency carrier
  - State of the medium (voltage) is made to follow signal one-to-one
  - Uses “entire” medium
- Broadband / Passband Modulation
  - Modulation of a carrier
  - Carriers at different frequencies can carry different signals
  - Sinusoidal advantages – remember harmonic analysis
  - Natural frequencies of transmission

Broadband injection

- Amplitude, Frequency, or Phase may be modulated
  - "Shift keying"

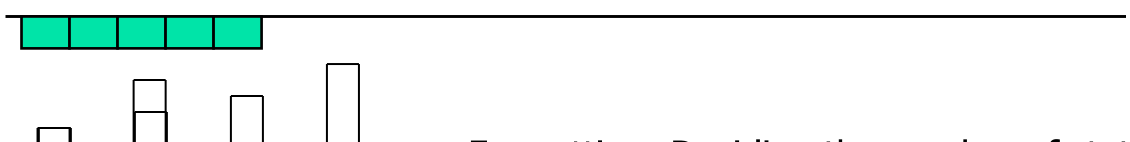


Physical Layer Communication



- Digital – 0, 1 …
  - Information can be analog or digital
- Electromagnetic (EM) waves – analog by definition
- Analog EM signal can be made to transfer digital data
- Digital-to-analog, analog-to-digital, there's the possibility of error happening all over.

The Issue of Bit Rate



--> Formatting: Deciding the number of states, V

- Consider simple AM (ASK)
  - Transmit one of two distinct amplitudes (voltages) → transmission of one bit
- How soon after can we transmit another bit? Depends on …
  - How fast can transmitter change its state?
  - How fast can receiver recognize line state? (decode)
  - Appears to limit bit rate (bandwidth)
- Does not have to be just two states
  - Why not transmitting one of four distinct amplitudes?
  - Why not more? → Limited by noise

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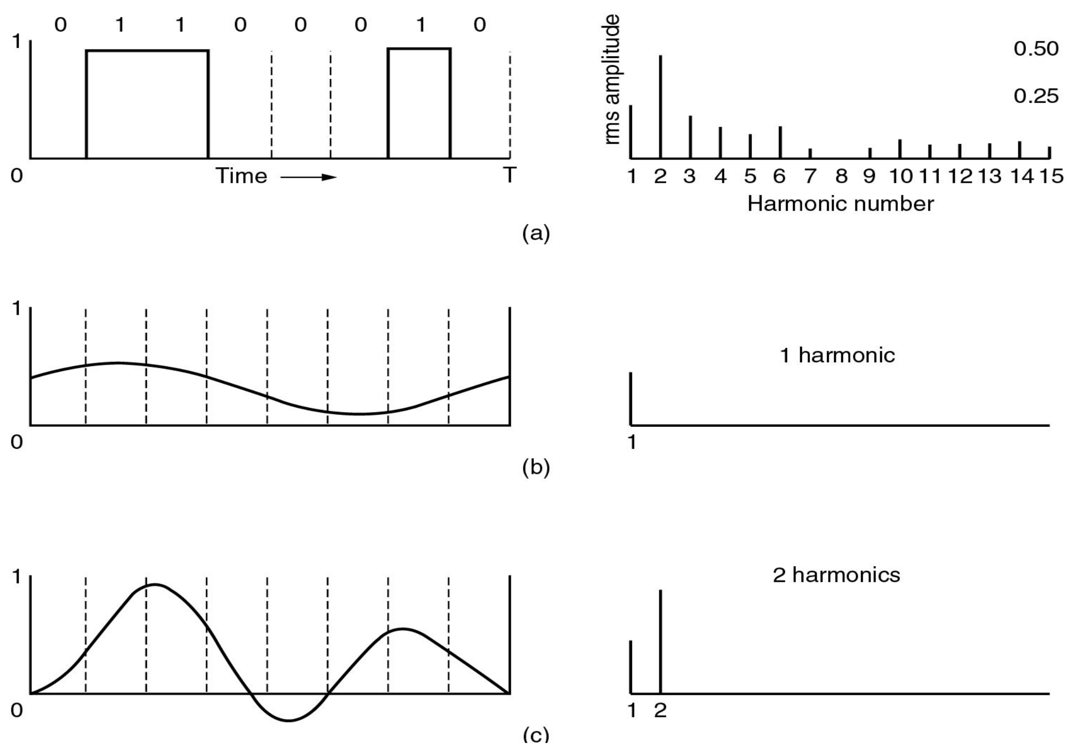
A Little Communication Theory

- The road to EM transmission:
  - Fourier: Harmonic analysis
  - Nyquist: Sampling theorem – bit rate
  - Shannon: Bit rate in presence of noise
- Briefly,
  - Most signals can be represented by sinusoid combinations
  - Discrete time sampling can reconstruct signals
  - Noiseless channel has limited maximum bit rate
  - Noise reduces maximum bit rate

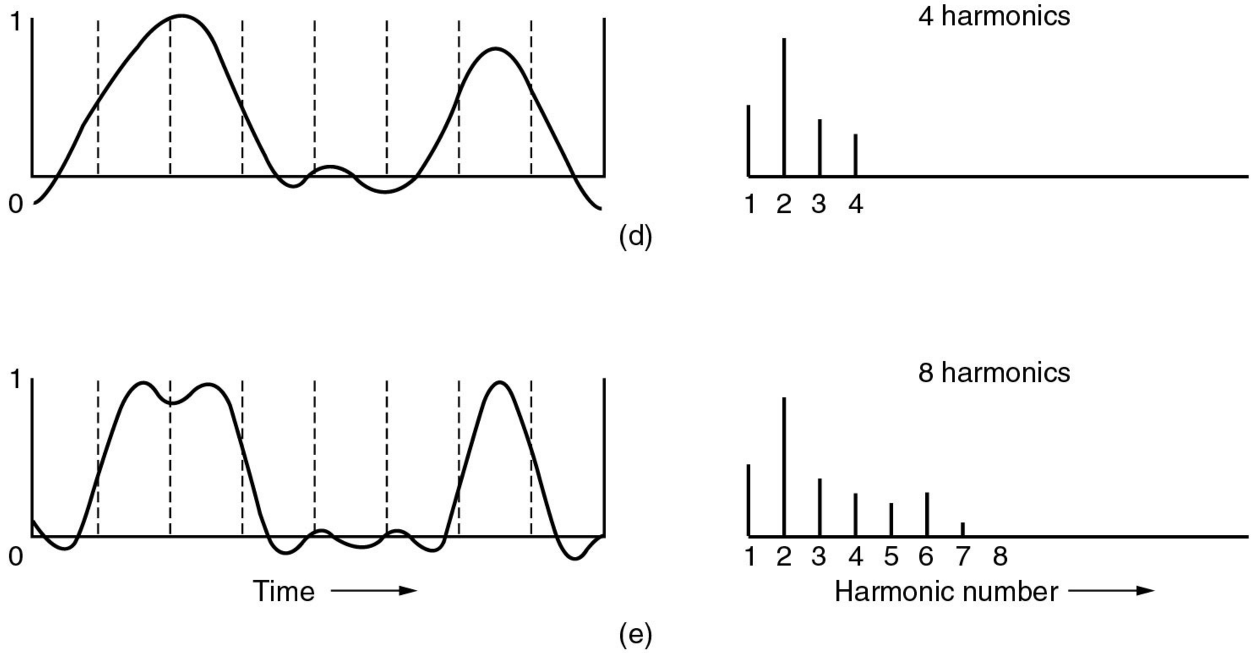
Bandwidth-Limited Signals

(a) A binary signal and its root-mean-square Fourier amplitudes, (b-c) successive approximations



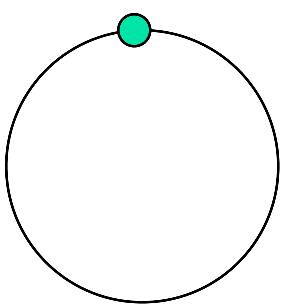
Bandwidth-Limited Signals (2)

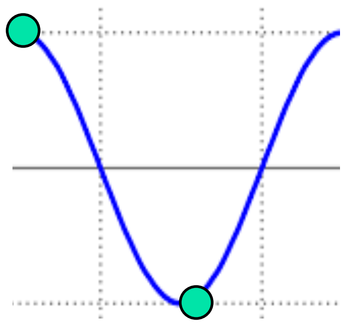
- (d) – (e) Successive approximations to the original signal

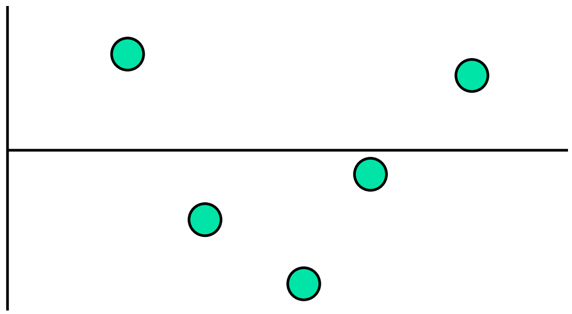


Sinusoid – Interesting Stuff

- A natural oscillation pattern
  - Obtained observing uniform circular motion by from one orthogonal direction
- Sampling
  - Sinusoid under strobe light
  - Could you unmistakably conclude what the sinusoid really is, if you only saw it momentarily at periodic intervals?



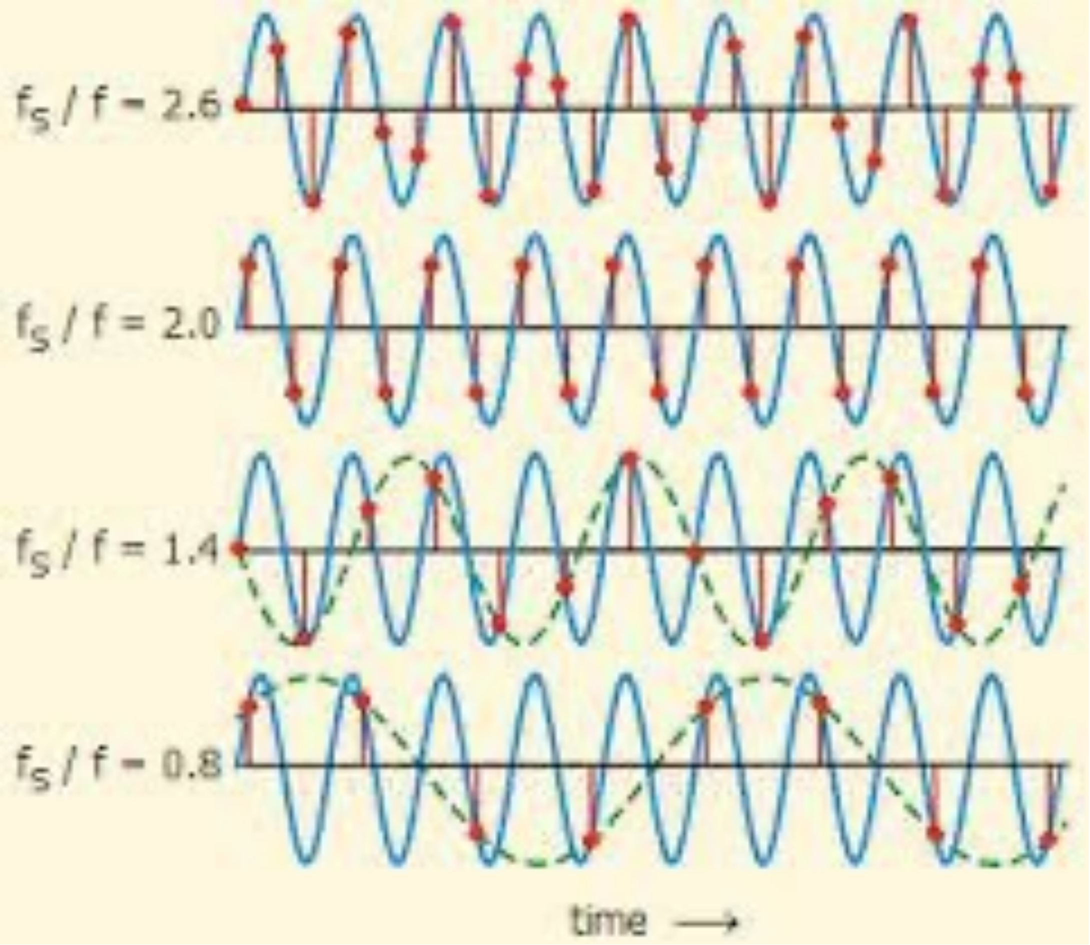




Nyquist's Result – Intuitive View

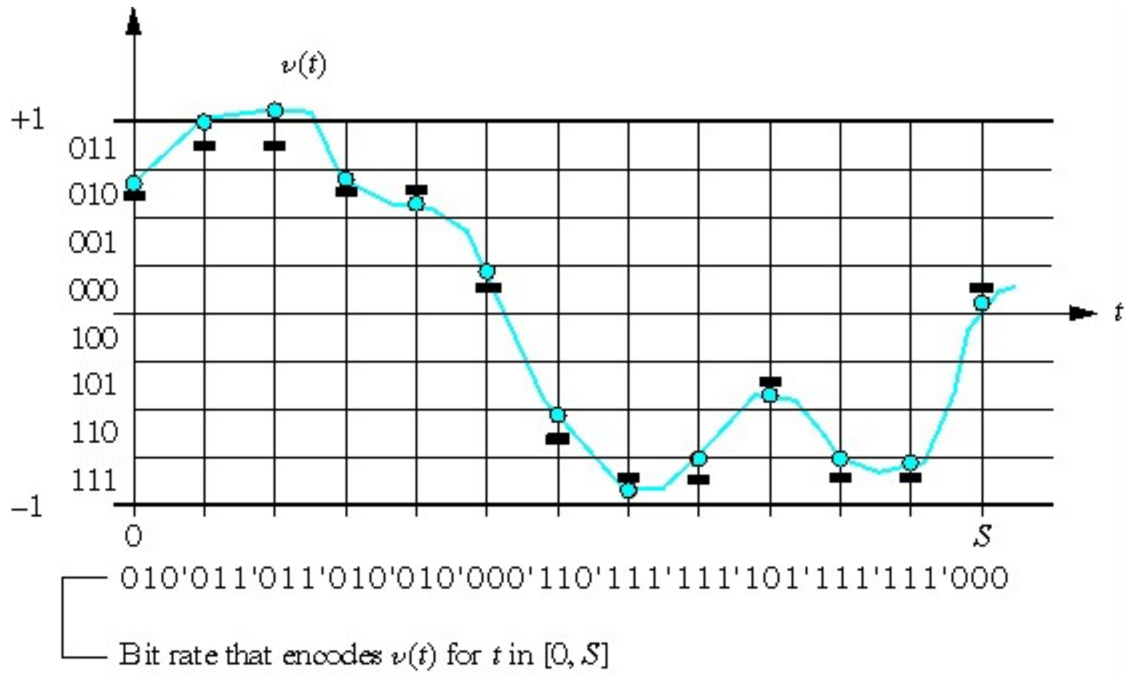
- Fitting a sinusoid
  - Low-rate sampling → wrong sinusoid
  - Half-rate sampling → wrong sinusoid
  - Full-rate sampling → still could be wrong
  - Double rate → no possibility of wrong sinusoid
- "Highest frequency"
  - Naturally introduced by device characteristics
  - Medium carries all frequencies between a lowest and highest frequencies ("frequency band")
  - Hence "band" "width"

Example



Sampling – Nyquist's Theorem

- Twice the highest frequency → no reconstruction loss



Bandwidth limited Bit rate

- Nyquist's theorem
  - Maximum bit rate = $2H \log_2 V$ bits/sec
  - H = bandwidth
  - V = number of discrete states
- Shannon's theorem
  - Maximum bit rate = $H \log_2 (1 + S/N)$ bits/sec
  - Introduces signal-noise ratio
  - Insight: random characteristic limits bit rate
  - Note on application
    - SNR in Shannon's theorem - ratio of power content (P_S/P_N)
    - Usual unit of SNR - dB, a logarithmic unit
    - dB = $10 \log_{10} (P_S/P_N)$

Bandwidth limited Bit rate

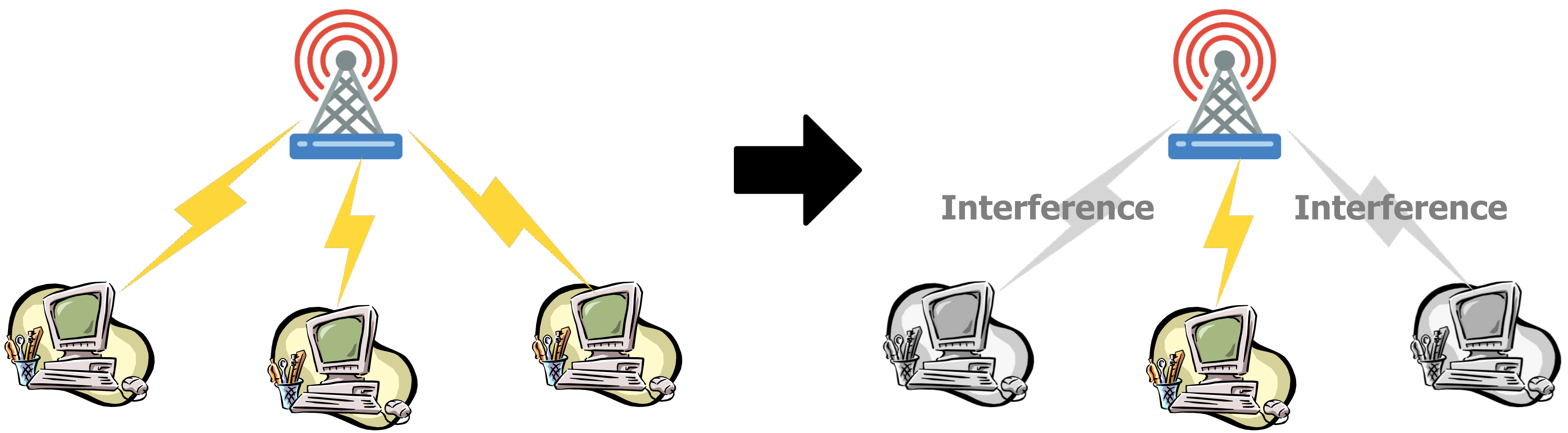
- Shannon's theorem
  - Maximum bit rate = $H \log_2 (1 + S/N)$ bits/sec
  - S is the signal strength at receiver side
  - How to get S?

  - Friis Transmission Equation:

    $S\ (dB) = P_{tr} + G_t + G_r + 20\log_{10}(\lambda/4\pi d)$

SNR vs. SINR

- Noise in SNR refers to any background signal not part of the transmitted (modulated) one
  - White noise, device error, …, and **interference**!
  - => Signal-to-Interference-and-Noise Ratio (SINR)



Comparing Results

- Both results give bitrates, but
  - With different assumptions and input
- Nyquist's theorem
  - Bit rate ***IF*** exactly V states are successfully used
    - Mo-Dem equipment already decided
  - Noise must allow V states
    - Often stated as perfect channel assumption
- Shannon's result
  - Estimation of what value of V will be successful
    - Noise level decides, so need noise level as input
- Either might be larger, depending on inputs V and N

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Media Types

1. Guided Transmission Media
   - Signals transmitted through wires

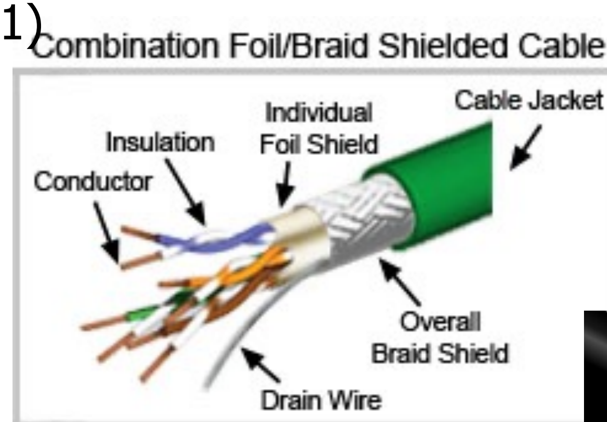
2. Unguided Transmission Media
   - No wires

- A link of some media types connects any pair of communicating devices

Guided Transmission Media

1. Twisted pairs
2. Coaxial cable
3. Power lines
4. Fiber cables

(1)



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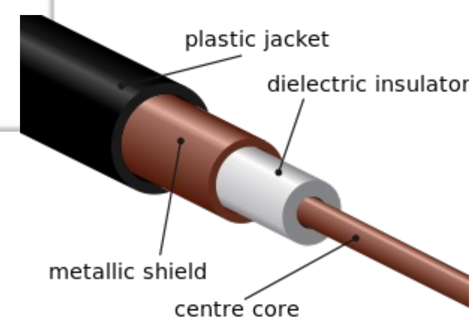

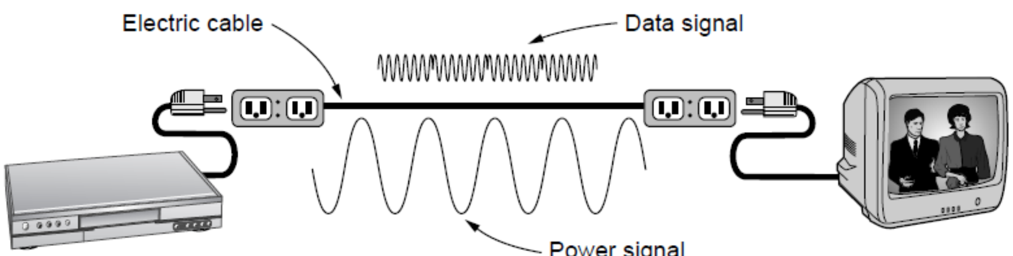

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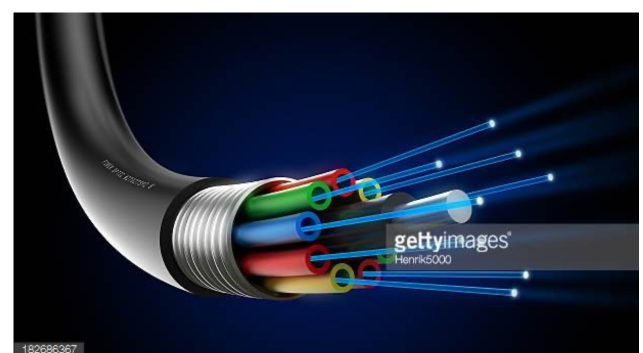


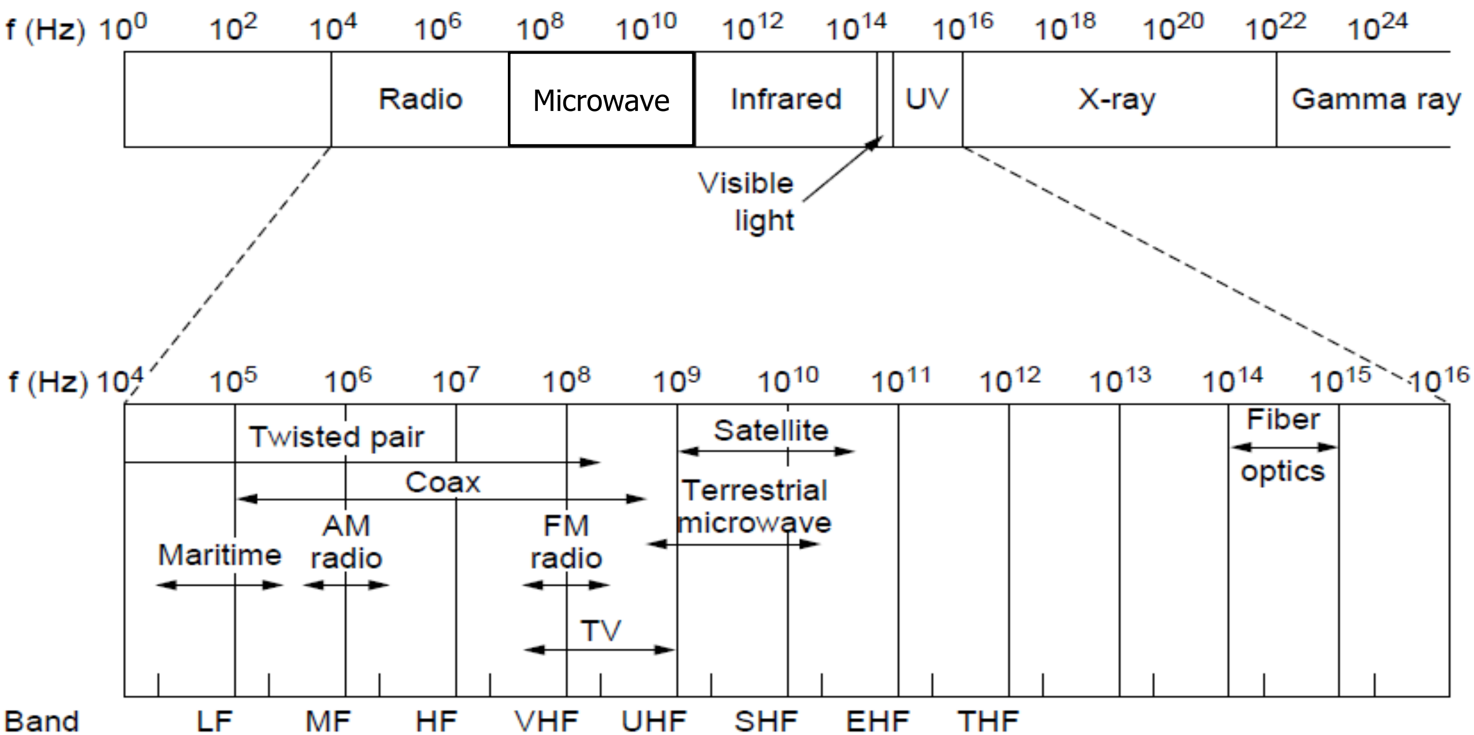
Copper vs Fiber Cables

Property	**Wires**	**Fiber**
Distance	Short (100s of m)	Long (tens of km)
Bandwidth	Moderate	Very High
Cost	Inexpensive	Less cheap
Convenience	Easy to use	Less easy
Security	Easy to tap	Hard to tap

Unguided transmission Media

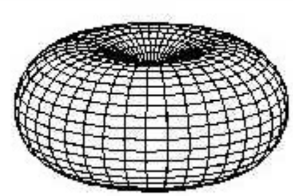
1. Radio Transmission
2. Microwave Transmission
3. Infrared Transmission
4. Light Transmission

Electromagnetic Spectrum



Wireless Characteristics

- *decreased signal strength:* radio signal attenuates as it propagates through matter (path loss)
- *interference from other sources:* standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., wireless phone); devices (motors, microwaves) interfere as well
- *multipath propagation:* radio signal reflects off objects, arriving at destination at slightly different times



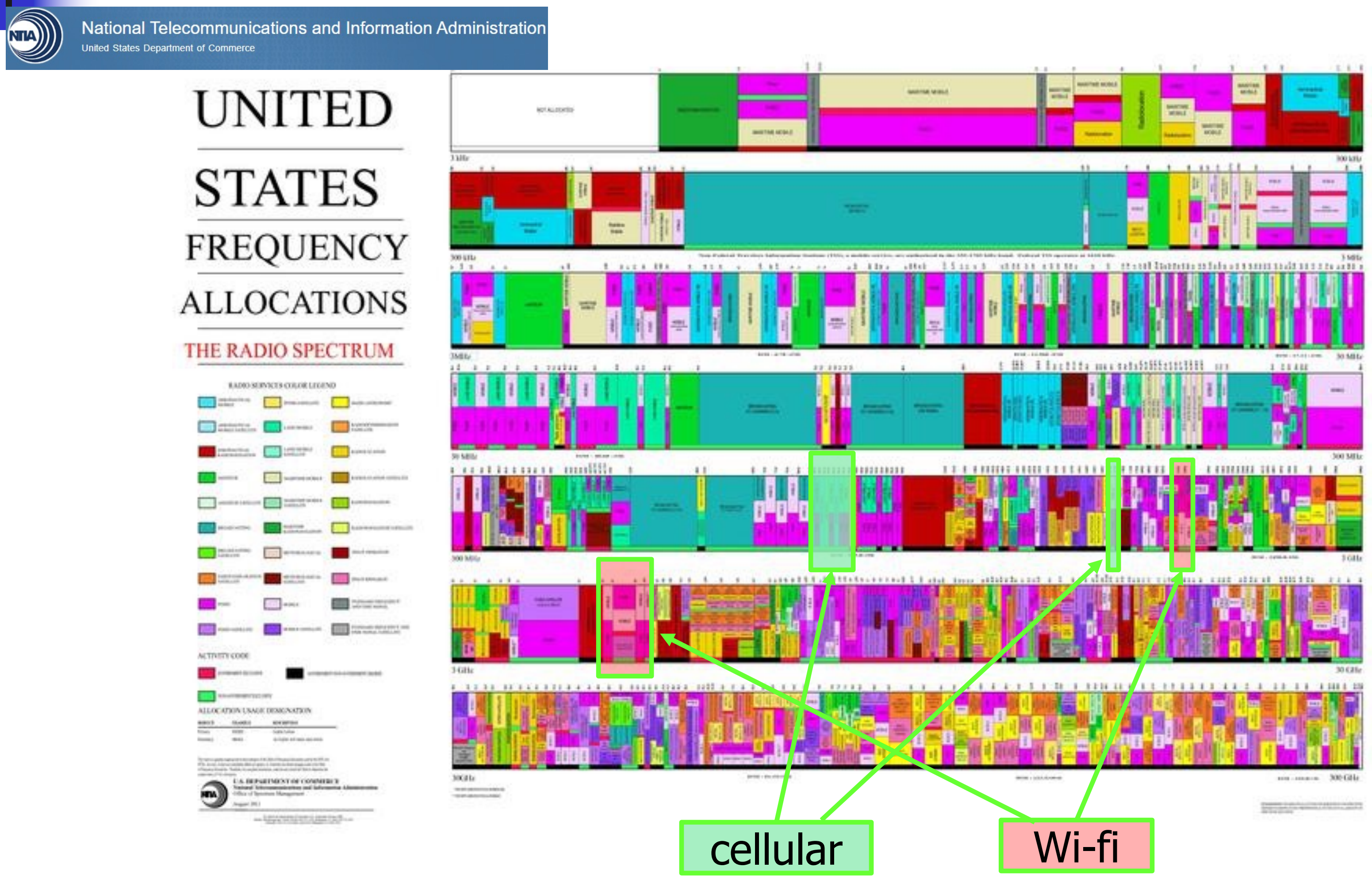
Bit errors are more common in wireless links than in wired links

Wireless Protocols – use powerful CRC error detection and reliable-data-transfer

Properties are **frequency-dependent**:

- High-frequency spectrum (e.g., 5G, mmWave): higher capacity, shorter distance
- Low-frequency spectrum (e.g., AM/FM radio): lower capacity, longer distance

US Spectrum Allocation



Question

Shannon Capacity

Show Correct Answer

Based on the Shannon capacity formula, a client device sending application data to a server via a direct wireless link can always achieve H log2 $(1 + S/N)$ bits/sec of application throughput, where H is the bandwidth, S is the signal strength, and N is the background noise.

A	TRUE
B	FALSE

Question (consider Shannon Capacity)

Which of the following affect the theoretical limit of information that can be transmitted via a channel?

A Bandwidth

B Modulation

C Noise

D Interference

E Overhead

F Protocol

G Distance

Next Lecture

1. DLC Layer Basics