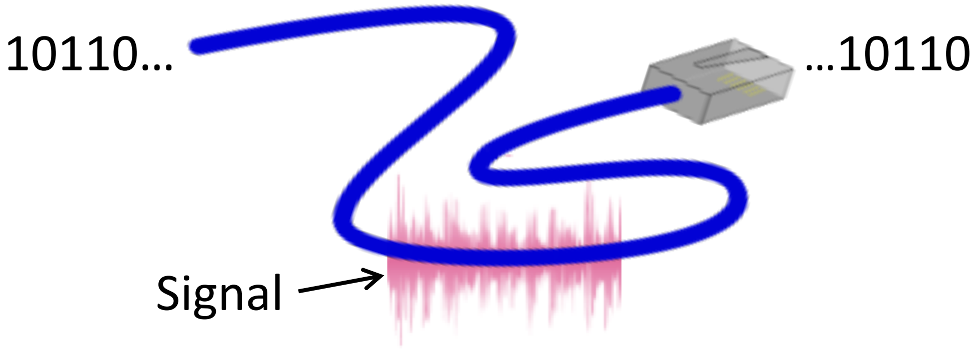
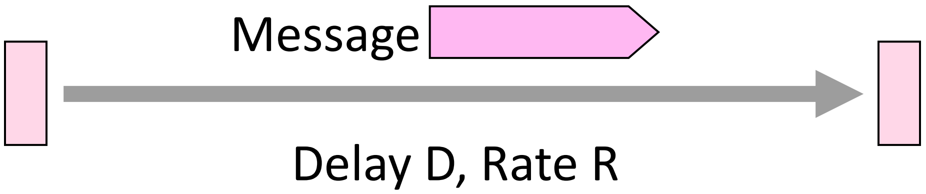
Scope of the Physical Layer

- Concerns how signals are used to transfer message bits over a link
  - Wires etc. carry <u>analog signals</u>
  - We want to send <u>digital bits</u>



Simple Link Model

- We'll end with an abstraction of a physical channel
  - Rate (or bandwidth, capacity, speed) in bits/second
  - Delay in seconds, related to length



- Other important properties:
  - Whether the channel is broadcast, and its error rate

Message Latency

- Latency is the delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"
  - Propagation delay: time for bits to propagate across the wire
  - Combining the two terms we have:

Message Latency (2)

- Latency is the delay to send a message over a link
  - Transmission delay: time to put M-bit message "on the wire"

    T-delay = M (bits) / Rate (bits/sec) = M/R seconds

  - Propagation delay: time for bits to propagate across the wire

    P-delay = Length / speed of signals = Length / ⅔c = D seconds

  - Combining the two terms we have: $L = M/R + D$

Metric Units

- The main prefixes we use:

Prefix	Exp.	prefix	exp.
K(ilo)	10^3	m(illi)	10^{-3}
M(ega)	10^6	μ(micro)	10^{-6}
G(iga)	10^9	n(ano)	10^{-9}

- Use powers of 10 for rates, 2 for storage
  - 1 Mbps = 1,000,000 bps, 1 KB = 2^{10} bytes
- “B” is for bytes, “b” is for bits

Latency Examples (2)

- "Dialup" with a telephone modem:

  D = 5 ms, R = 56 kbps, M = 1250 bytes

  $L = 5 \text{ ms} + (1250 \text{x} 8)/(56 \times 10^3) \text{ sec} = 184 \text{ ms}!$

- Broadband cross-country link:

  D = 50 ms, R = 10 Mbps, M = 1250 bytes

  $L = 50 \text{ ms} + (1250 \text{x} 8) / (10 \times 10^6) \text{ sec} = 51 \text{ ms}$

- A long link or a slow rate means high latency
  - Often, one delay component dominates

Bandwidth-Delay Product

- Messages take space on the wire!

- The amount of data in flight is the <u>bandwidth-delay (BD) product</u>

$$BD = R \times D$$

  – Measure in bits, or in messages
  – Small for LANs, big for “long fat” pipes

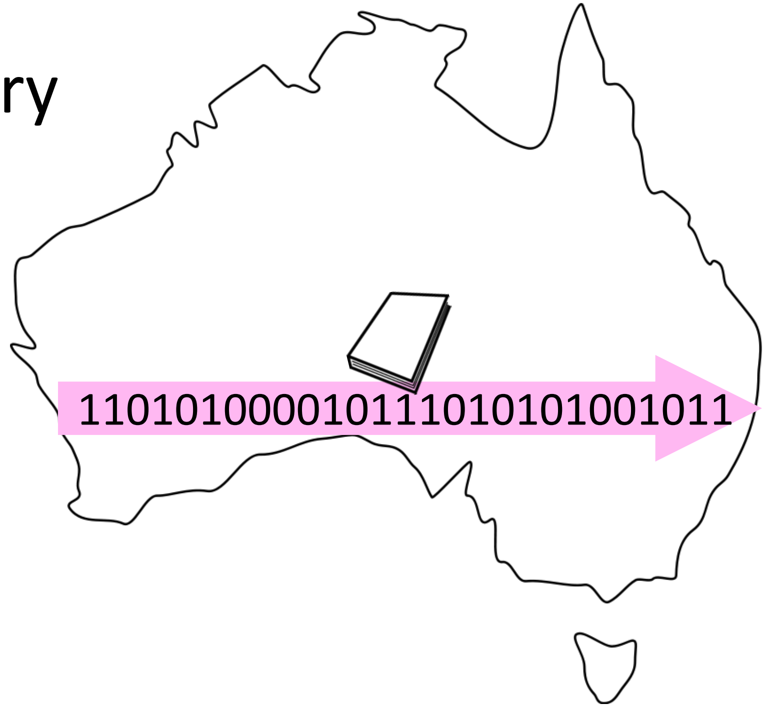
Bandwidth-Delay Example (2)

- Fiber at home, cross-country

  R=40 Mbps, D=50 ms

  $$BD = 40 \times 10^6 \times 50 \times 10^{-3} \text{ bits}$$
  $$= 2000 \text{ Kbit}$$
  $$= 250 \text{ KB}$$

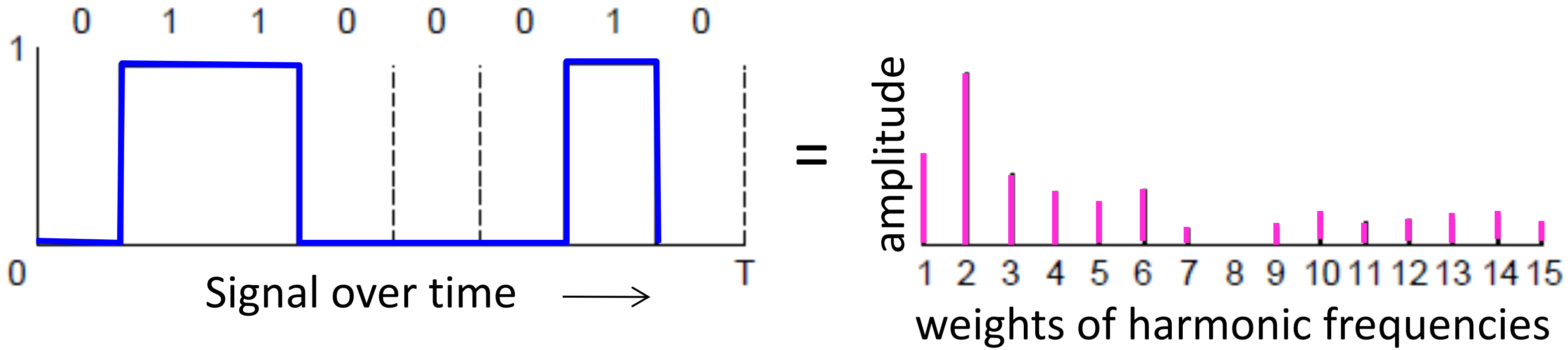
- That's quite a lot of data "in the network"!



Frequency Representation

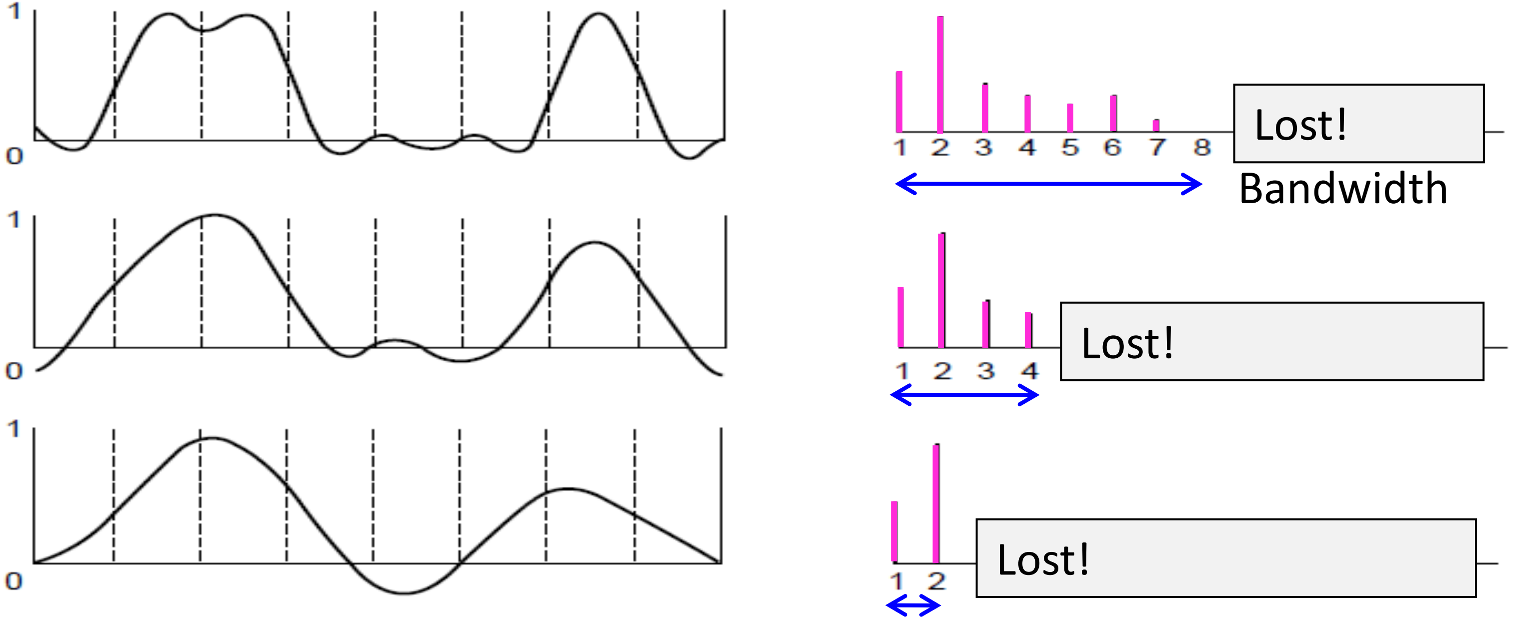
- A signal over time can be represented by its frequency components (called Fourier analysis)

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$



Effect of Less Bandwidth

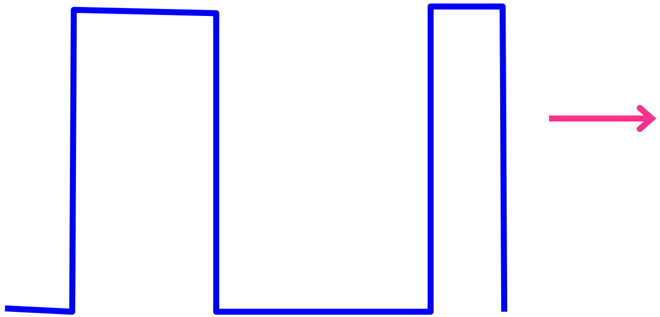
- Fewer frequencies (=less bandwidth) degrades signal



Signals over a Wire (2)

- Example:

Sent signal



2: Attenuation:

3: Bandwidth:

4: Noise:

Signals over Wireless

- Signals transmitted on a carrier frequency, like fiber
- Travel at speed of light, spread out and attenuate faster than $1/dist^2$
- Multiple signals on the same frequency interfere at a receiver

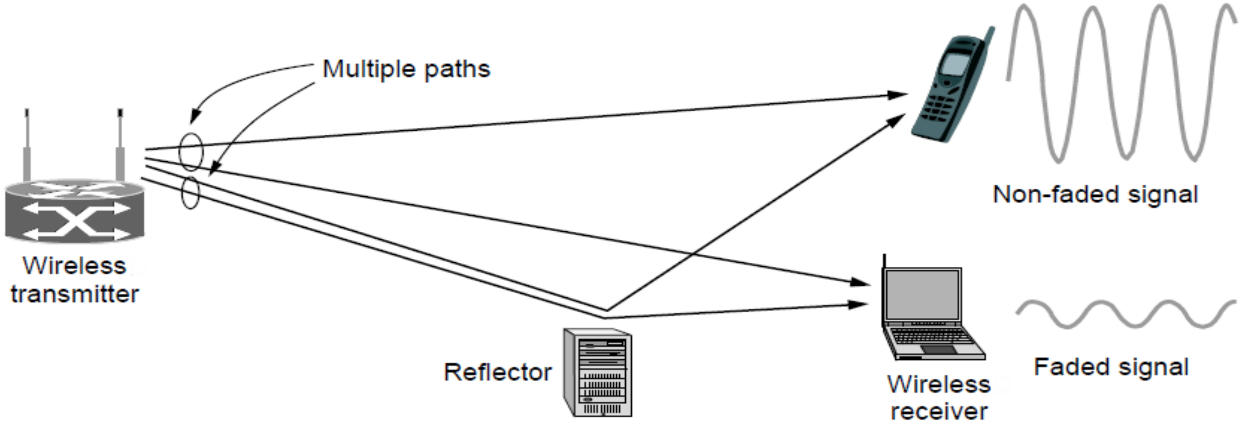
Signals over Wireless (5)

- Various other effects too!
  - Wireless propagation is complex, depends on environment

- Some key effects are highly frequency dependent,
  - E.g., multipath at microwave frequencies

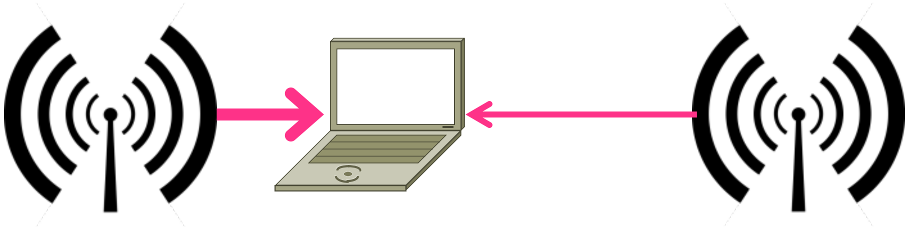
Wireless Multipath

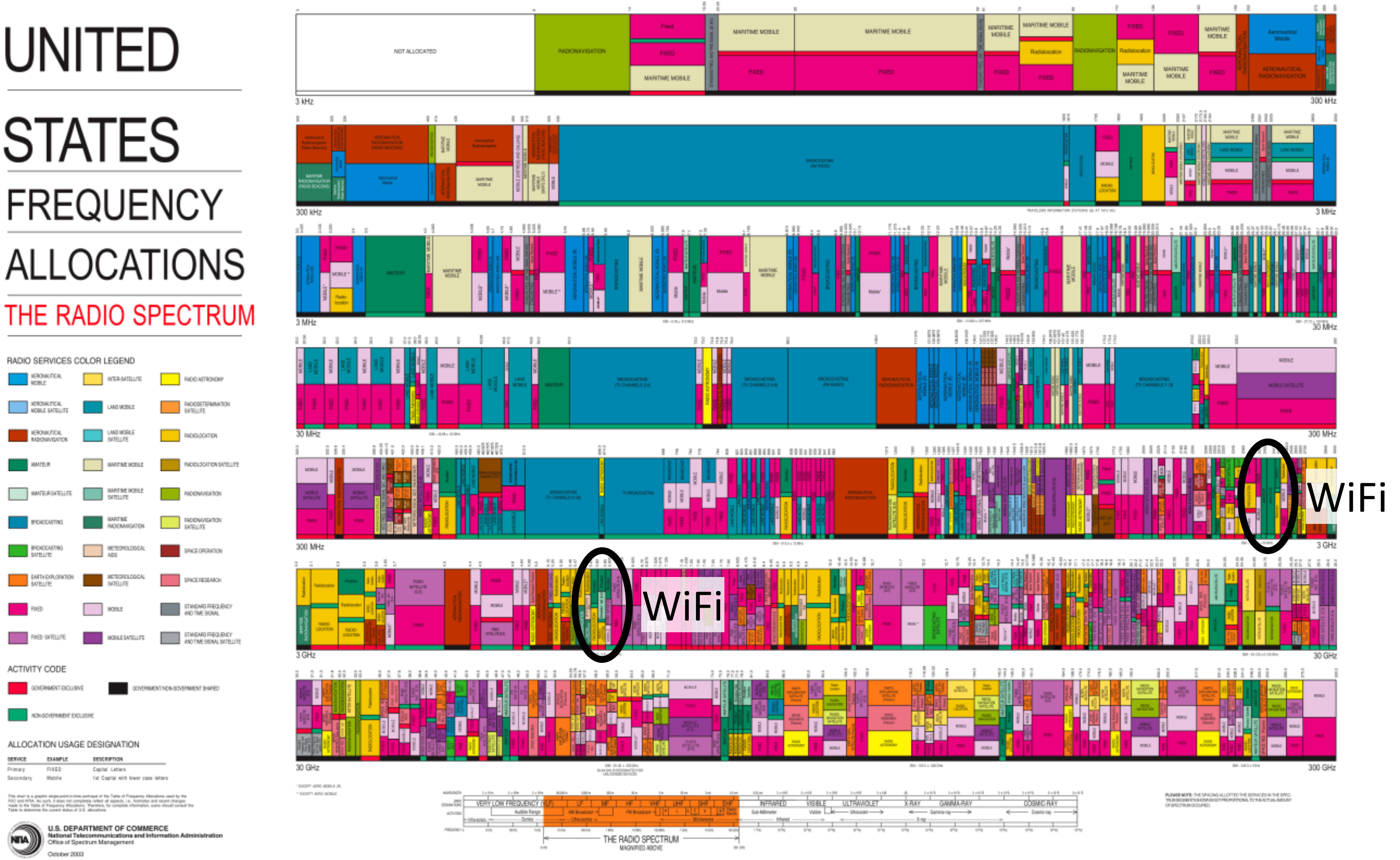
- Signals bounce off objects and take multiple paths
  - Some frequencies attenuated at receiver, varies with location
  - Messes up signal; handled with sophisticated methods (§2.5.3)



Wireless

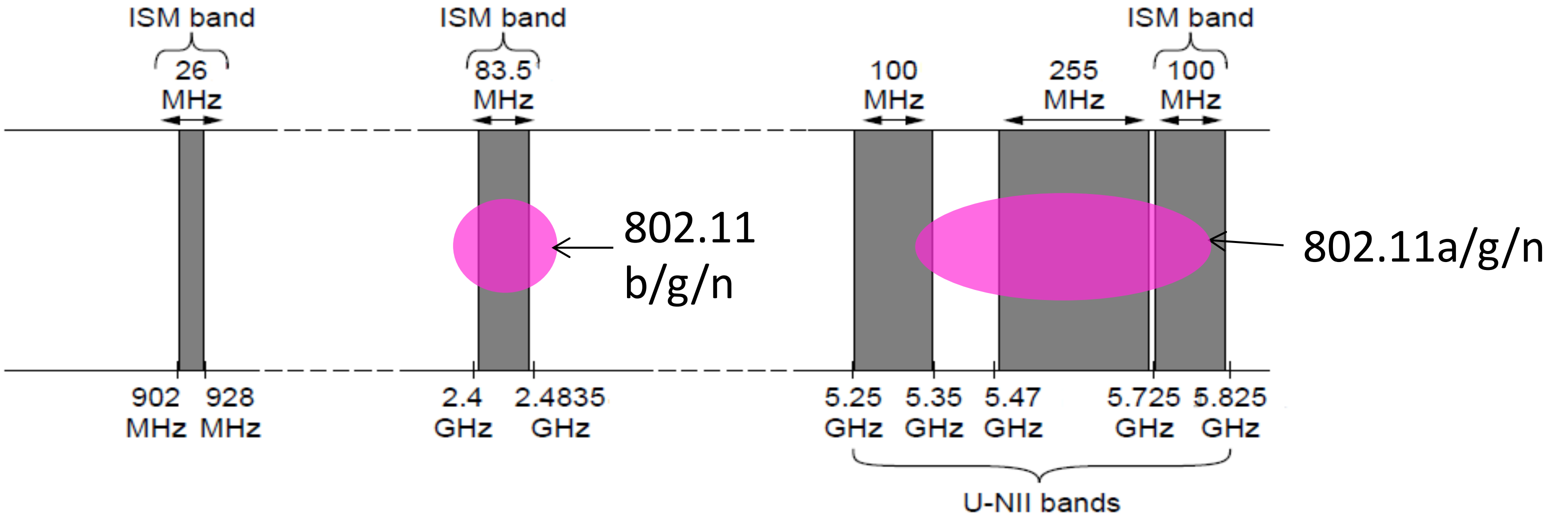
- Sender radiates signal over a region
  - In many directions, unlike a wire, to potentially many receivers
  - Nearby signals (same freq.) <u>interfere</u> at a receiver; need to coordinate use




UNITED
STATES
FREQUENCY
ALLOCATIONS
THE RADIO SPECTRUM
RADIO SERVICES COLOR LEGEND
ACTIVITY CODE
ALLOCATION USAGE DESIGNATION
U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
October 2003
3 kHz
300 kHz
3 MHz
30 MHz
300 MHz
3 GHz
30 GHz
300 GHz
WiFi
WiFi
THE RADIO SPECTRUM

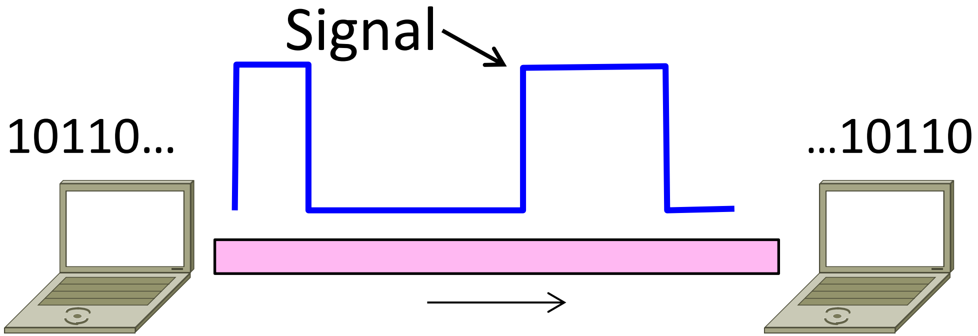
Wireless (2)

- Microwave, e.g., 3G, and unlicensed (ISM) frequencies, e.g., WiFi, are widely used for computer networking



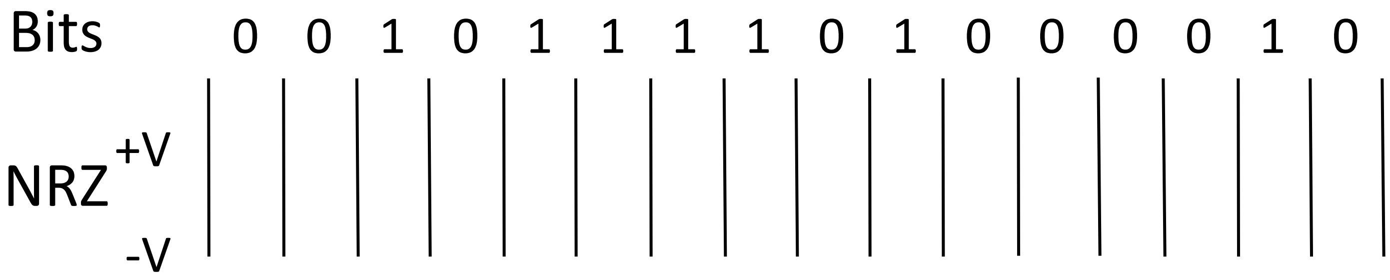
Topic

- We've talked about signals representing bits. How, exactly?
  - This is the topic of modulation



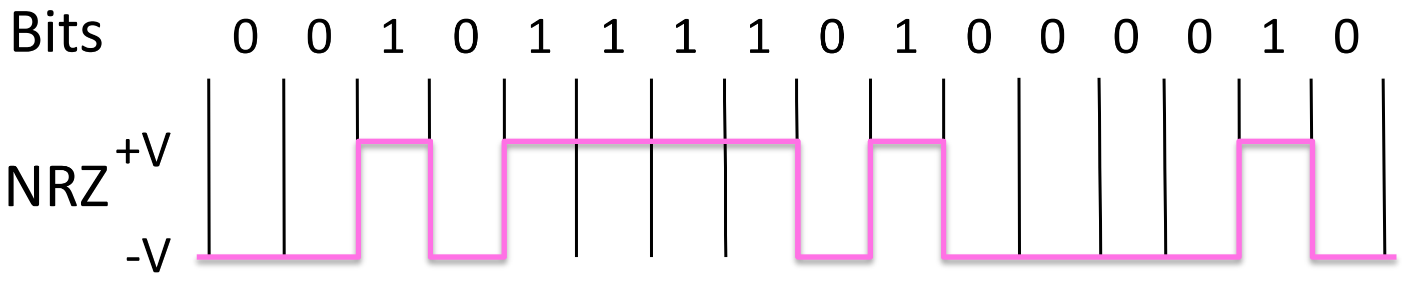
A Simple Modulation

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)



A Simple Modulation (2)

- Let a high voltage (+V) represent a 1, and low voltage (-V) represent a 0
  - This is called NRZ (Non-Return to Zero)



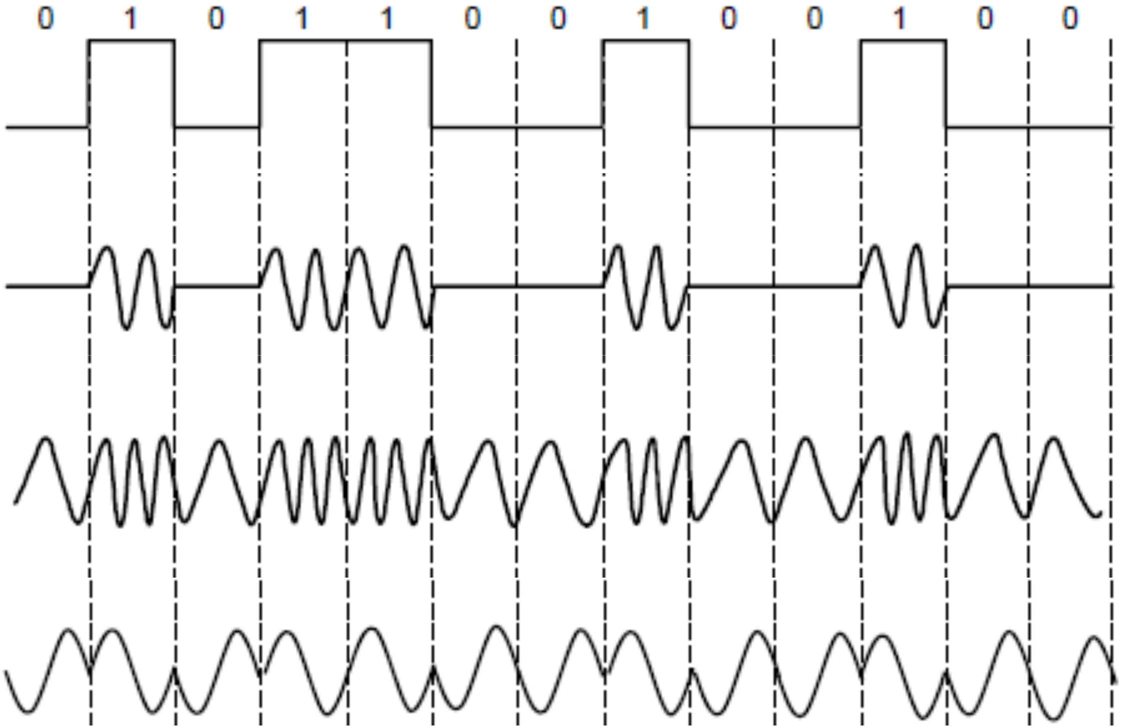
Modulation

NRZ signal of bits

Amplitude shift keying

Frequency shift keying

Phase shift keying



Topic

- How rapidly can we send information over a link?
  - Nyquist limit (~1924) »
  - Shannon capacity (1948) »

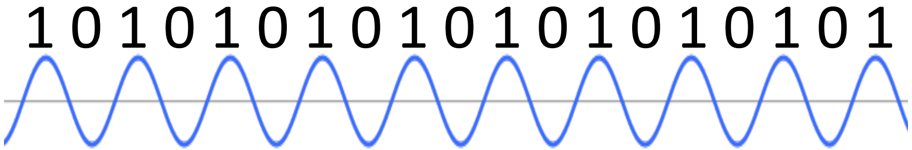
- Practical systems are devised to approach these limits

Key Channel Properties

- The bandwidth (B), signal strength (S), and noise strength (N)
  - B limits the rate of transitions
  - S and N limit how many signal levels we can distinguish

Nyquist Limit

- The maximum <u>symbol</u> rate is 2B



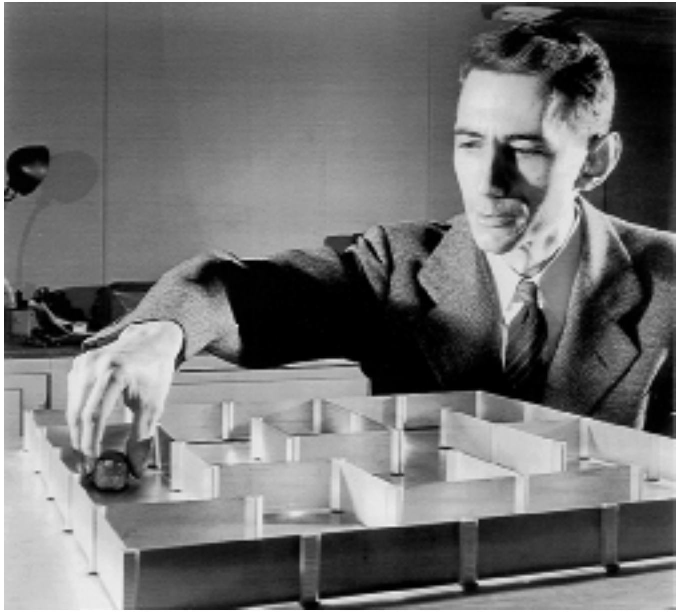
- Thus if there are V signal levels, ignoring noise, the maximum bit rate is:

$$R = 2B \log_2 V \text{ bits/sec}$$

Claude Shannon (1916-2001)

- Father of information theory
  - "A Mathematical Theory of Communication", 1948
- Fundamental contributions to digital computers, security, and communications

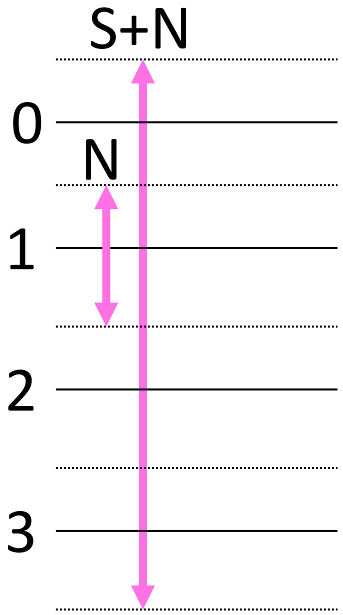
Electromechanical mouse that "solves" mazes!



Credit: Courtesy MIT Museum

Shannon Capacity

- How many levels we can distinguish depends on S/N
  - Or SNR, the Signal-to-Noise Ratio
  - Note noise is random, hence some errors
- SNR given on a log-scale in deciBels:
  - $SNR_{dB} = 10\log_{10}(S/N)$



Shannon Capacity (2)

- Shannon limit is for capacity (C), the maximum information carrying rate of the channel:

$$C = B \log_2(1 + S/(BN)) \text{ bits/sec}$$

Wired/Wireless Perspective

- Wires, and Fiber
  - Engineer link to have requisite SNR and B

  → Can fix data rate

- Wireless
  - Given B, but SNR varies greatly, e.g., up to 60 dB!

  → Can't design for worst case, must adapt data rate

Wired/Wireless Perspective (2)

- Wires, and Fiber
  - Engineer link to have requisite SNR and B

  →Can fix data rate

Engineer SNR for data rate

- Wireless
  - Given B, but SNR varies greatly, e.g., up to 60 dB!

  →Can't design for worst case, must adapt data rate

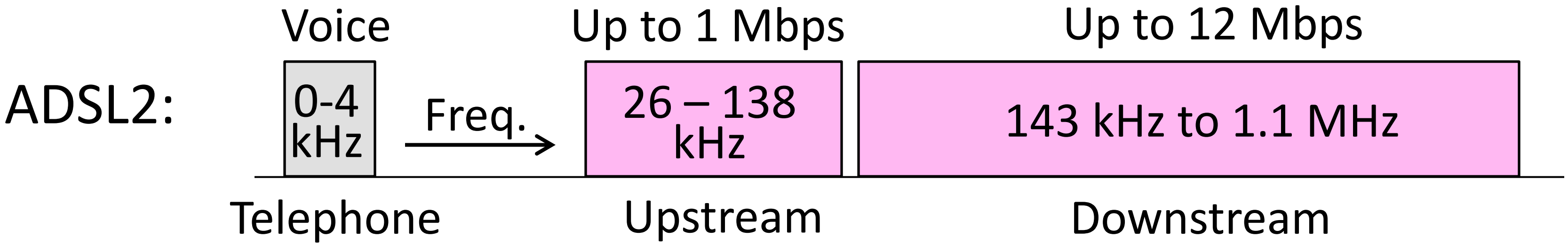
Adapt data rate to SNR

Putting it all together – DSL

- DSL (Digital Subscriber Line) is widely used for broadband; many variants offer 10s of Mbps
  - Reuses twisted pair telephone line to the home; it has up to ~2 MHz of bandwidth but uses only the lowest ~4 kHz

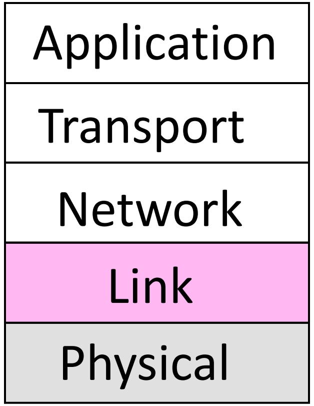
DSL (2)

- DSL uses passband modulation (called OFDM)
  - Separate bands for upstream and downstream (larger)
  - Modulation varies both amplitude and phase (called QAM)
  - High SNR, up to 15 bits/symbol, low SNR only 1 bit/symbol



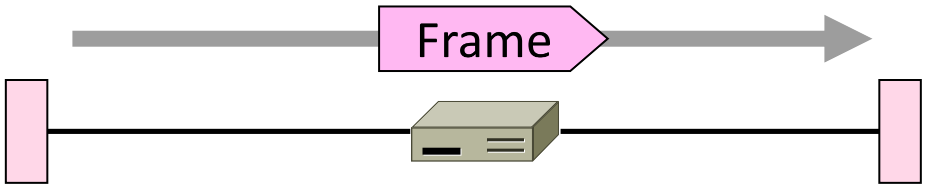
Where we are in the Course

- Moving on to the Link Layer!

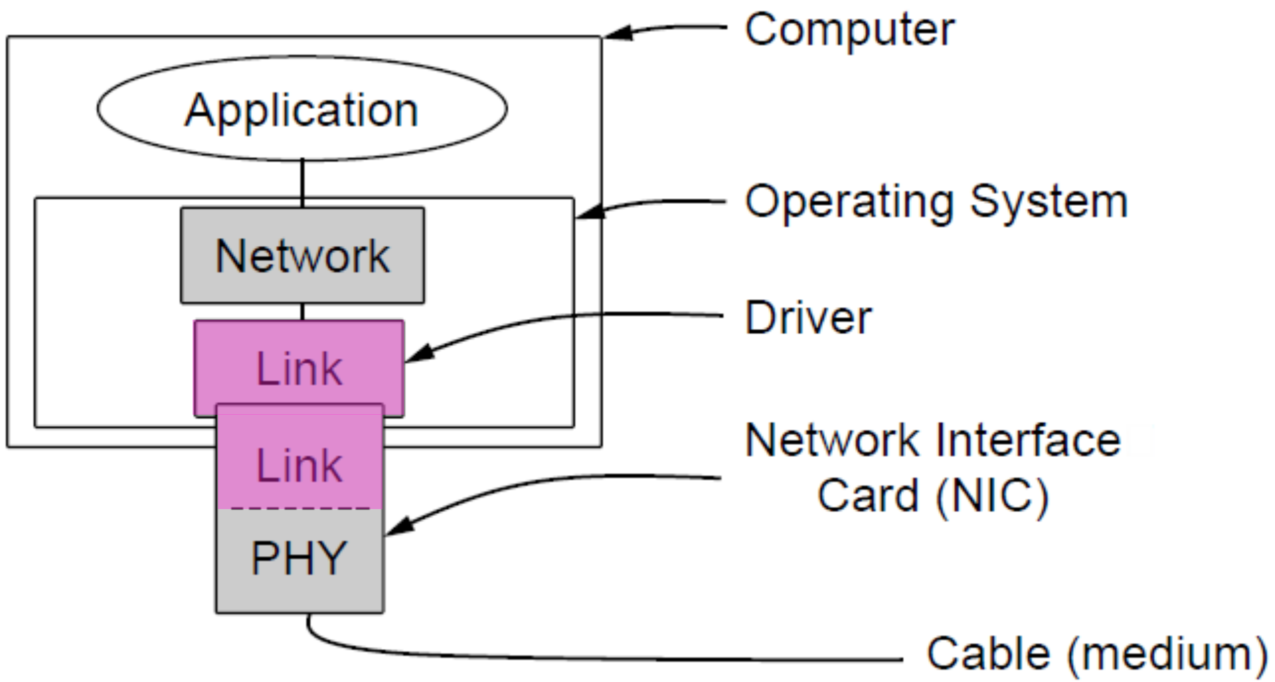


Scope of the Link Layer

- Concerns how to transfer messages over one or more connected links
  - Messages are frames, of limited size
  - Builds on the physical layer



Typical Implementation of Layers (2)

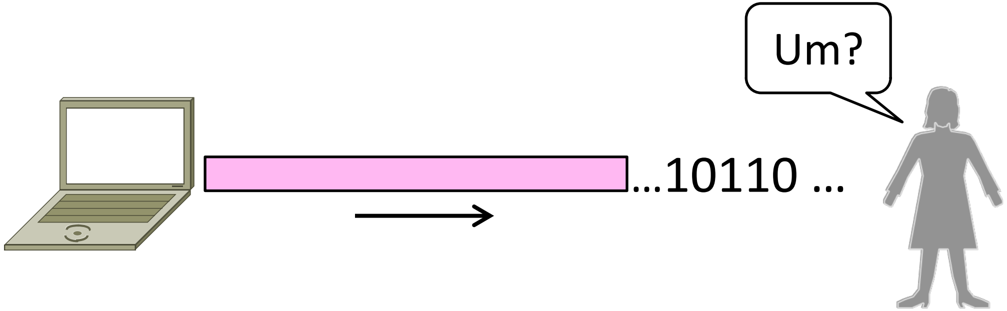


Functions of the Link Layer

1. Framing
   - Delimiting start/end of frames
2. Error detection and correction
   - Handling errors
3. Retransmissions
   - Handling loss
4. Multiple Access
   - 802.11, classic Ethernet
5. Switching
   - Modern Ethernet

Topic

- The Physical layer gives us a stream of bits. How do we interpret it as a sequence of frames?



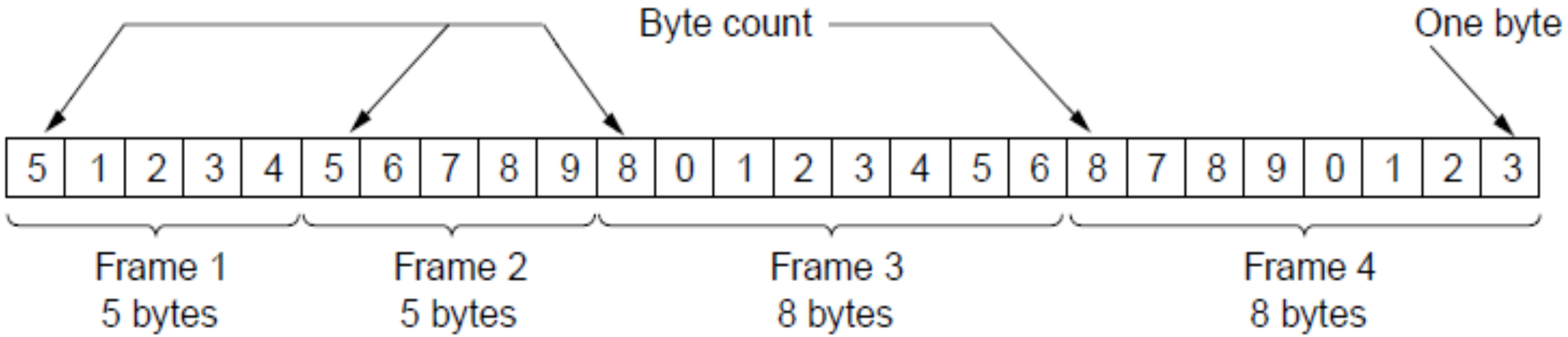
Framing Methods

- We'll look at:
  - Byte count (motivation) »
  - Byte stuffing »
  - Bit stuffing »
- In practice, the physical layer often helps to identify frame boundaries
  - E.g., Ethernet, 802.11

Byte Count

- First try:
  - Let’s start each frame with a length field!
  - It’s simple, and hopefully good enough …

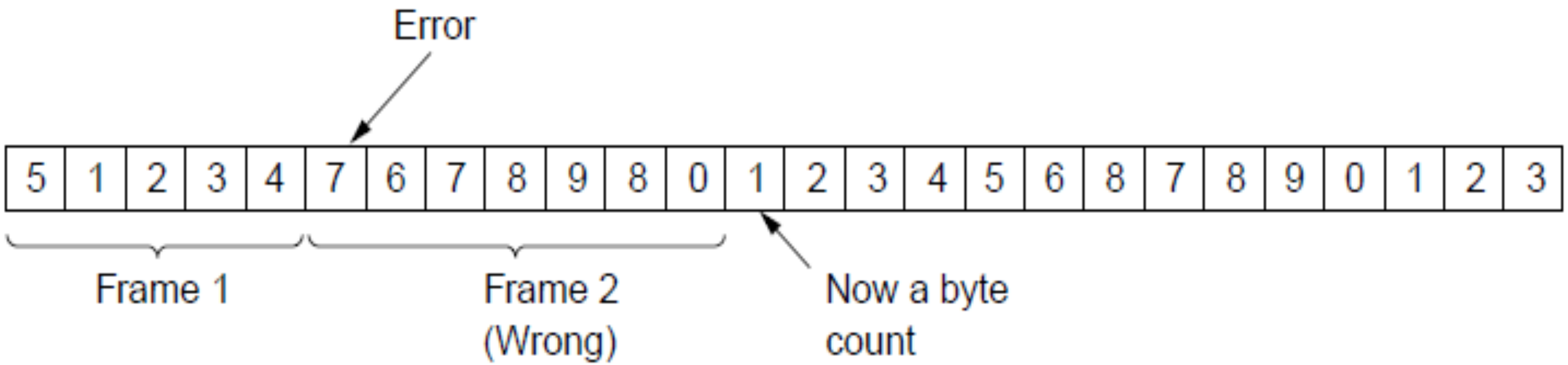
Byte Count (2)



- How well do you think it works?

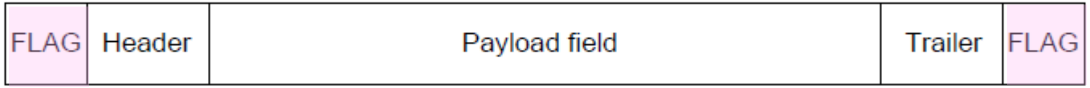
Byte Count (3)

- Difficult to re-synchronize after framing error
  - Want a way to scan for a start of frame



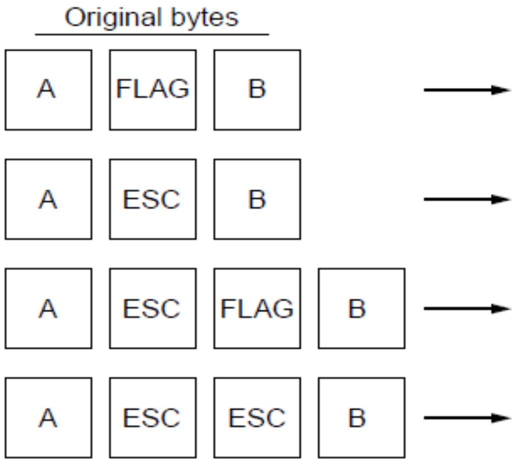
Byte Stuffing

- Better idea:
  - Have a special flag byte value that means start/end of frame
  - Replace ("stuff") the flag inside the frame with an escape code
  - Complication: have to escape the escape code too!



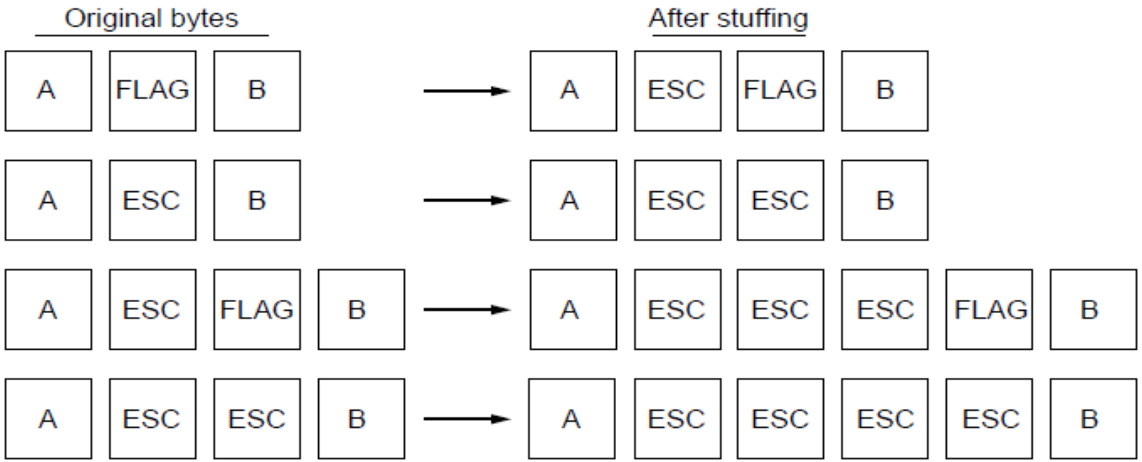
Byte Stuffing (2)

- Rules:
  - Replace each FLAG in data with ESC FLAG
  - Replace each ESC in data with ESC ESC



Byte Stuffing (3)

- Now any unescaped FLAG is the start/end of a frame



Bit Stuffing

- Can stuff at the bit level too
  - Call a flag six consecutive 1s
  - On transmit, after five 1s in the data, insert a 0
  - On receive, a 0 after five 1s is deleted

Bit Stuffing (2)

- Example:

Data bits	0 1 1 0	1 1 1 1	1 1 1 1	1 1 1 1	1 1 1 1	0 0 1 0
Transmitted bits with stuffing						

Bit Stuffing (3)

- So how does it compare with byte stuffing?

Data bits 0 1 1 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 1 0

Transmitted bits with stuffing 0 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0

Stuffed bits