Last Time

- We assumed that the link carries frames
  - FH Payload EDC
  - n bits k bits

- Error detecting code part contains bits that add redundancy

- Natural Questions:
  - How do physical media transport the frames?
  - Why are some links faster than others?
  - What limits the amount of information we can send on a link?
Today

- Link Functions and Components
- The role of Noise and Bandwidth in determining link rate
- Encoding: Converting bits to analog signals
  - Physical Layer Function
- Framing: Establishing the conventions that denote boundaries
  - Data Link Layer Function
Link Functions

- Functions
  1. Construct Frame with Error Detection Code
  2. Encode bit sequence into analog signal
  3. Transmit bit sequence on a physical medium (Modulation)
  4. Receive analog signal
  5. Convert Analog Signal to Bit Sequence
  6. Recover errors through error correction and/or ARQ

Adaptor: convert bits into physical signal and physical signal back into bits
Link Components

- Error Coding (e.g., parity)
- Channel Coding (e.g., NRZI)
- Modulation (e.g., OOK)
- Error Decoding
- Channel Decoding
- Demodulation

Data Flow:
- 0100011 → 01000111 → 1001010101 → Medium
Link Properties

- **Function**
  - Duplex/Half Duplex
  - One stream, multiple streams

- **Characteristics**
  - Bit Error Rate
  - Data Rate (this sometimes mistakenly called bandwidth!)
  - Degradation with distance

- **Cables and Fibers**
  - CAT 5 twisted pair: 10-100Mbps, 100m
  - Coax: 10-100Mbps, 200-500m
  - Multimode Fiber: 100Mbps, 2km
  - Single Mode Fiber: 100-2400Mbps, 40km

- **Wireless**
Example: Optical Links

- Source
- Coupler
- Splice
- Detector
- Transmitter
- Receiver

Total reflection

Cladding
Different modes of propagation
Core

Step index

One of multiple modes of propagation

GRIN

Unique mode of propagation

SMF

Diameter $\leq 8 \mu m$
Link rate and Distance

Links become slower with distance because of attenuation of the signal. Amplifiers and repeaters can help.
Noise

- A signal \( s(t) \) sent over a link is generally
  - Distorted by the physical nature of the medium
    - This distortion may be known and reversible at the receiver
  - Affected by random physical effects
    - Shot noise
    - Fading
    - Multipath Effects
  - Also interference from other links
    - Wireless
    - Crosstalk

- Dealing with noise is what communications engineers do
Noise limits the link rate

- Suppose there were no noise
  - E.g. Send $s(t)$ always receive $s(t+?)$
  - Take a message of $N$ bits say $b_1b_2\ldots b_N$, and send a pulse of amplitude of size $0.b_1b_2\ldots b_N$
  - Can send at an arbitrarily high rate
  - This is true even if the link distorts the signal but in a known way

- In practice the signal always gets distorted in an unpredictable (random) way
  - Receiver tries to estimate the effects but this lowers the effective rate

- One way to mitigate noise is to jack up the power of the signal
- Signal to Noise ratio (SNR) measures the extent of the distortion effects
Bandwidth affects the data rate

- There is usually a fixed range of frequencies at which the analog wave can traverse a link.
- The physical characteristics of the link might govern this.
- Example:
  - Voice Grade Telephone line 300Hz – 3300Hz
- The bandwidth is 3000Hz
- For the same SNR, a higher bandwidth gives a higher rate.
Sampling Result (Nyquist)

- Suppose a signal $s(t)$ has a bandwidth $B$.
- Sampling Result: Suppose we sample it (accurately) every $T$ seconds.

- If $T = 1/2B$ then it is possible to reconstruct the $s(t)$ correctly
  - Only one signal with bandwidth $B$ has these sample points
  - There are multiple signals with these sample points for signals with bandwidth greater than $B$
- Increasing the bandwidth results in a richer signal space
- No noise allowed in the sampling result
Sampling Continued

- But now assume noise that is distributed uniformly over the frequency band.
- Then the richer signal space will enable more information to be transmitted in the same amount of time.
- Higher bandwidth $\rightarrow$ Higher rate (for the same SNR)
The Frequency Spectrum is crowded...
Fundamental Result

- The affect of noise on the data is modeled probabilistically.
- It turns out that there is a maximum possible reliable rate for most channels called the capacity C:
  - There is a scheme to transmit at C with almost no errors
  - Finding this scheme is tricky but it exists
- For a commonly observed kind of noise called Additive White Gaussian Noise (AWGN) the capacity is given by:
  - $C = W \log_2(1 + S/N)$ bits/sec (Shannon)
  - Example: Voice grade line: $S/N = 1000$, $W=3000$, $C=30$Kbps
  - Technology has improved $S/N$ and $W$ to yield higher speeds such as 56Kb/s
Encoding

- Goal: send bits from one node to another node on the same physical media
  - This service is provided by the physical layer
- Problem: specify a robust and efficient encoding scheme to achieve this goal
Assumptions

- We use two discrete signals, high and low, to encode 0 and 1.
- The transmission is synchronous, i.e., there is a clock used to sample the signal.
  - In general, the duration of one bit is equal to one or two clock ticks.
- If the amplitude and duration of the signals is large enough, the receiver can do a reasonable job of looking at the distorted signal and estimating what was sent.
Non-Return to Zero (NRZ)

- 1 $\rightarrow$ high signal; 0 $\rightarrow$ low signal
- Disadvantages: when there is a long sequence of 1’s or 0’s
  - Sensitive to clock skew, i.e., difficult to do clock recovery
  - Difficult to interpret 0’s and 1’s (baseline wander)
Non-Return to Zero Inverted (NRZI)

- 1 → make transition; 0 → stay at the same level
- Solve previous problems for long sequences of 1’s, but not for 0’s
Manchester

- 1 $\rightarrow$ high-to-low transition; 0 $\rightarrow$ low-to-high transition
- Addresses clock recovery and baseline wander problems
- Disadvantage: needs a clock that is twice as fast as the transmission rate
  - Efficiency of 50%
4-bit/ 5-bit (100Mb/ s Ethernet)

- Goal: address inefficiency of Manchester encoding, while avoiding long periods of low signals
- Solution:
  - Use 5 bits to encode every sequence of four bits such that no 5 bit code has more than one leading 0 and two trailing 0’s
  - Use NRZI to encode the 5 bit codes
  - Efficiency is 80%

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<tr>
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</tr>
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Modulation

- The function of transmitting the encoded signal over a link, often by combining it with another (carrier signal)
  - E.g. Frequency Modulation (FM)
    - Combine the signal with a carrier signal in such a way that the instantaneous frequency of the received signal contains the information of the carrier
  - E.g. Frequency Hopping (OFDM)
    - Signal transmitted over multiple frequencies
    - Sequence of frequencies is pseudo random
Framing

- **Goal:** send a block of bits (frames) between nodes connected on the same physical media
  - This service is provided by the **data link** layer
- **Use a special byte (bit sequence) to mark the beginning (and the end) of the frame**
- **Problem:** what happens if this sequence appears in the data payload?
Byte-Oriented Protocols: Sentinel Approach

- STX – start of text
- ETX – end of text
- Problem: what if ETX appears in the data portion of the frame?
- Solution
  - If ETX appears in the data, introduce a special character DLE (Data Link Escape) before it
  - If DLE appears in the text, introduce another DLE character before it

- Protocol examples
  - BISYNC, PPP, DDCMP
Byte-Oriented Protocols: Byte Counting Approach

- **Sender**: insert the length of the data (in bytes) at the beginning of the frame, i.e., in the frame header.

- **Receiver**: extract this length and decrement it every time a byte is read. When this counter becomes zero, we are done.
Bit-Oriented Protocols

- Both start and end sequence can be the same
  - E.g., 01111110 in HDLC (High-level Data Link Protocol)
- Sender: inserts a 0 after five consecutive 1s
- Receiver: when it sees five 1s makes decision on the next two bits
  - if next bit 0 (this is a stuffed bit), remove it
  - if next bit 1, look at the next bit
    - If 0 this is end-of-frame (receiver has seen 01111110)
    - If 1 this is an error, discard the frame (receiver has seen 01111111)
Clock-Based Framing (SONET)

- SONET (Synchronous Optical NETwork)
- Developed to transmit data over optical links
  - Example: SONET ST-1: 51.84 Mbps
  - Many streams on one link
- SONET maintains clock synchronization across several adjacent links to form a path
  - This makes the format and scheme very complicated
SONET Multiplexing

- STS-3c has the payloads of three STS-1’s byte-wise interleaved.
- STS-3 is a SONET link w/o multiplexing
- For STS-N, frame size is always 125 microsec
  - STS-1 frame is 810 bytes
  - STS-3 frame is 810x3 = 2430 bytes
First two bytes of each frame contain a special bit pattern that allows to determine where the frame starts.

- No bit-stuffing is used.
- Receiver looks for the special bit pattern every 810 bytes.
  - Size of frame = 9x90 = 810 bytes.
Clock-Based Framing (SONET)

Details:

- Overhead bytes are encoded using NRZ
- To avoid long sequences of 0’s or 1’s the payload is XOR-ed with a special 127-bit pattern with many transitions from 1 to 0
Summary

- Links are subject to random noise
- For a given probabilistic model of the noise it may be possible to compute its capacity
  - Generally depends on SNR and Bandwidth
- Encoding – specifies how bits are represented on in the analog signal
  - Challenge – achieve:
    - Efficiency – ideally, bit rate = clock rate
    - Robust – avoid de-synchronization between sender and receiver when there is a large sequence of 1’s or 0’s
- Framing – specify how blocks of data are transmitted
  - Challenge
    - Decide when a frame starts/ends
    - Differentiate between the true frame delimiters and delimiters appearing in the payload data