Lecture 12: Wireless Physical and Link Layers

Static Routing is due today
Ethernet: 802.3

• Dominant wired LAN technology
  - 10BASE5 (vampire taps)
  - 10BASE-T, 100BASE-TX, 1000BASE-T

• Frame format:

<table>
<thead>
<tr>
<th>Physical</th>
<th>Link</th>
<th>Layer 3</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
<td>SFD</td>
<td>Src</td>
<td>Dest</td>
</tr>
<tr>
<td>7 x 10101010</td>
<td>10101011</td>
<td>6 bytes</td>
<td>6 bytes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type/ Len</th>
<th>Payload</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 bytes</td>
<td>46-1500 bytes</td>
<td>4 bytes</td>
</tr>
</tbody>
</table>

Gap: 96 ns, 960 ns, 9600 ns
Physical Layer (Layer 1)

• Responsible for specifying the physical medium
  - Category 5 cable (Cat5): 8 wires, twisted pair, RJ45 jack
  - WiFi wireless: 2.4GHz

• Responsible for specifying the signal
  - 100BASE-T: 5-level pulse amplitude modulation (PAM-5)
  - 802.11b: Binary and quadrature phase shift keying (BPSK/QPSK)

• Responsible for specifying the bits
  - 100BASE-T: 4-to-6 bit-to-chip encoding, 3 chip symbols
  - 802.11b: Barker code (1-2Mbps), complementary code keying (5.5-11Mbps)
Wireless is Different

- Variable: signal attenuates over space
- Interference: other RF sources can interfere with signal
- Multipath: signal can self-interfere
- Distributed: nodes cannot detect collisions
- To address these differences, wireless link layers use slightly different mechanisms
Attenuation Over Space

- Signal weakens as distance from transmitter increases
- Reflections, obstructions, etc. complicate the attenuation
- Depending on the antenna, not uniform in all directions
- Much more complex than the wired model
Signal Strength Over Space
Directional Antennas
Interference

- In unlicensed bands (e.g., 802.11), there are lots of transmitters
  - 802.11 cards
  - 802.15.1 (Bluetooth)
  - 802.15.4 (ZigBee)
  - 2.4GHz phones
  - Microwave ovens

- This interference can be stronger or weaker than the signal, and can prevent successful reception
Analog Signals

Amplitude

Wavelength
Specifying the Signal: Modulation

On-Off Keying (OOK)

1 0 1

Amplitude Shift Keying (ASK)

1 0 1

On-Off Keying (OOK)

Amplitude Shift Keying (ASK)
Modulation, Continued

1 0 1
Frequency Shift Keying (FSK)

1 0 1
Phase Shift Keying (PSK)
I/Q Modulation

• I: in-phase, Q: quadrature
• Sum of two sines is a sine
• Show what the carrier looks like compared to a simple, unmodulated signal
• Use I/Q because this is how it’s actually done in hardware
Modulation in I/Q Plots

OOK  ASK  FSK  BPSK  QPSK
Signal, Noise, and Interference

- **Signal**: energy of desired transmission
- **Noise/Noise floor**: energy of hardware thermal effects
- **Interference**: energy of other transmitters
- **Usually measured in dBm/dBW**: $0 \text{dBm} = 1 \text{mW}$, $0 \text{dBW} = 30 \text{dBm} = 1 \text{W}$
  - Note dB is a logarithmic scale: $10 \text{dBm} = 10 \text{mW}$, $20 \text{dBm} = 100 \text{mW}$
Signal Plus Noise
SINR

- **Signal to Interference-and-Noise Ratio**

- **Measured in dB:** $\frac{|S|}{|N+I|}$
  - $S = -50\text{dBm}, N+I = -95\text{dBm}, \text{SINR} = 35\text{dB}$
  - $S = -89\text{dBm}, N+I = -93\text{dBm}, \text{SINR} = 4\text{dB}$
Bit Error Rates

- There is a theoretical limit on how much information a channel can carry.
- Bit error rate depends on the SINR and the modulation.
- This is why wireless link layers use more complex chip/bit encoding.
After the signal is received and digitized, it is fed through a series of adaptive delay stages which are summed together via feedback loops. This technique is particularly effective in slowly changing environments such as transmission over telephone lines, but is more difficult to implement in rapidly changing environments like factory floors, offices and homes where transmitters and receivers are moving in relation to each other. The main drawback is the impact on system cost and complexity. Adaptive equalizers can be expensive to implement for broadband data links.

Spread spectrum systems are fairly robust in the presence of multipath. Direct Sequence Spread Spectrum (DSSS) systems will reject reflected signals which are significantly delayed relative to the direct path or strongest signal. This is the same property which allows multiple users to share the same bandwidth in Code Diversity Multiple Access (CDMA) systems. Frequency Hopping Spread Systems (FHSS) also exhibit some degree of immunity to multipath. Because a FHSS transmitter is continuously changing frequencies, it will always hop to some frequencies which experience little or no multipath loss. In a severe fading environment, throughput of an FHSS system will be reduced, but it is unlikely that the link will be lost completely. The performance of DSSS systems in the presence of multipath is described further in a separate section below.

Modulation Technique

Modulation technique is a key consideration. This is the method by which the analog or digital information is converted to signals at RF frequencies suitable for transmission. Selection of modulation method determines system bandwidth, power efficiency, sensitivity, and complexity. Most of us are familiar with Amplitude Modulation (AM) and Frequency Modulation (FM) because of their widespread use in commercial radio. Phase Modulation is another important technique. It is used in applications such as Global Position System (GPS) receivers and some cellular telephone networks.

For the purposes of link budget analysis, the most important aspect of a given modulation technique is the Signal-to-Noise Ratio (SNR) necessary for a receiver to achieve a specified level of reliability in terms of BER. A graph of $\frac{E_b}{N_0}$ vs BER is shown in Figure 4. $\frac{E_b}{N_0}$ is a measure of the required energy per bit relative to the noise power. Note that $\frac{E_b}{N_0}$ is independent of the system data rate. In order to convert from $\frac{E_b}{N_0}$ to SNR, the data rate and system bandwidth must be taken into account as shown below:

$$\text{SNR} = \left( \frac{E_b}{N_0} \right) \times \left( \frac{R}{B_T} \right)$$

Where:
- $E_b$ = Energy required per bit of information
- $N_0$ = thermal noise in 1Hz of bandwidth
- $R$ = system data rate
- $B_T$ = system bandwidth

Spread Spectrum Radios

The term "spread spectrum" simply means that the energy radiated by the transmitter is spread out over a wider amount of the RF spectrum than would otherwise be used. By spreading out the energy, it is far less likely that two users sharing the same spectrum will interfere with each other. This is an important consideration in an unlicensed band, which why the regulatory authorities imposed spread spectrum requirements on radios which transmit over -1dBm (about 0.75mW) in the following bands:

![Figure 3. Adaptive Equalizer](image)

![Figure 4. Probability of Bit Error for Common Modulation Methods](image)

Table 1. Typical Bandwidths for Various Digital Modulation Methods

<table>
<thead>
<tr>
<th>MODULATION METHOD</th>
<th>TYPICAL BANDWIDTH (NULL-TO-NULL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK, DQPSK</td>
<td>1.0 x Bit Rate</td>
</tr>
<tr>
<td>MSK</td>
<td>1.5 x Bit Rate</td>
</tr>
<tr>
<td>BPSK, DBPSK, OFSK</td>
<td>2.0 x Bit Rate</td>
</tr>
</tbody>
</table>

Application Note 9804
Example: 802.11b

- 11-chip Barker sequence: 10110111000
- Binary Phase Shift Keying (BPSK)
- SYNC, SFD, signal, service, length, CRC, data
- Service field reserved, length is in us
Variable Bit Rates

- 802.11b supports 1, 2, 5.5, and 11Mbps
- 2, 5.5Mbps and 11Mbps are QPSK
- To support this, the signal field says what the data rate is
  - 00001010: 1Mbps (11 chips/bit, barker code)
  - 00010100: 2Mbps (11 chips/bit, barker code)
  - 00110111: 5.5Mbps (2 chips/bit, CCK)
  - 01101110: 11Mbps (1 chip/bit, CCK)
- So the header is still at 1Mbps, even if the data is at 11Mbps
- CCK is rather complex: don’t worry about it
802.11 Packet Loss Rates
• How does this affect TCP?
Wireless PHY Summary

• Can’t control or limit the channel

• Need to deal with weak signals, interference, etc.

• Many different kinds of modulation: amplitude, frequency, phase

• Use robust encodings when needed, use fast speeds when possible

• Lots of intermediate packet delivery ratios
2 minute break
MAC Layer Responsibilities

- Arbitrate control of the channel
- One node should be able to use 100%
- Multiple nodes should get a fair share
- Want high utilization under contention
CA versus CD

- Collision detect (CD) is hard in wireless
- Local signal is much stronger than anything received
- Protocols use collision avoidance (CA) by sensing the channel
Simple MAC: CSMA/CA

- 1) Wait a small random period, check the channel
- 2) If the channel is busy, go to 1 (maybe longer wait)
- 3) Transmit packet
802.11b MAC: CSMA/CA

- Maintain a waiting counter \( c \)
- For each time step channel is idle, \( c \rightarrow \)
- When \( c = 0 \), transmit
- If packet is not acknowledged (layer 2), pick a new, larger \( c \)
  - Use lack of layer 2 ack as collision detect

![Diagram showing data transmission and acknowledgment]
Problems with CSMA/CA

• Want to know state of channel at receiver, not transmitter

• But wireless is not transitive!
  - A hears B
  - A hears C
  - B and C may not hear each other
  - B and C can only sense their channel, but need to know if A’s channel is clear
Hidden Terminal Problem
Exposed Terminal Problem
RTS/CTS

- Request-to-send, Clear-to-send (RTS/CTS)
- Allows transmitter to check availability of channel at receiver
- Transmitter sends an RTS
- If it hears a CTS, sends data
- If not, retries RTS some time later
- If you hear a CTS for someone else, don’t transmit
Data
Network Allocation Vector (NAV)

- 802.11b supports RTS/CTS
- NAV is data structure node uses to know when channel may be clear
- NAV is in terms of *time*: variable bit rates, RTS, etc.
RTS/CTS Benefits

- Solves the hidden terminal problem (assuming CTS not corrupted)
- Improves packet delivery ratio
- Does it solve the exposed terminal problem? What about ACKs?
RTS/CTS Drawbacks

- 3 packets per packet: RTS/CTS/DATA
- RTS still go through CSMA: they can be lost
- CTS losses cause lengthy retries
- 33% of IP packets are TCP ACKs: is it worth it?
- In practice, WiFi doesn’t use RTS/CTS