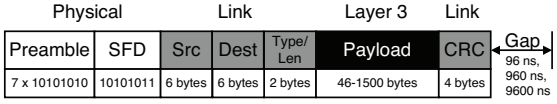
Lecture 11: Wireless Networking

Outline

- **Wireless physical layer challenges**
  - Signal, noise, modulation
  - A little bit of EE goes a long way
- **Wireless link layers**
  - Hidden terminals, exposed terminals
  - CSMA/CA
  - RTS/CTS
- **Wireless routing and throughput**

Ethernet: 802.3

- **Dominant wired LAN technology**
  - 10BASE5 (vampire taps)
  - 10BASE-T, 100BASE-TX, 1000BASE-T
- **Frame format:**



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)

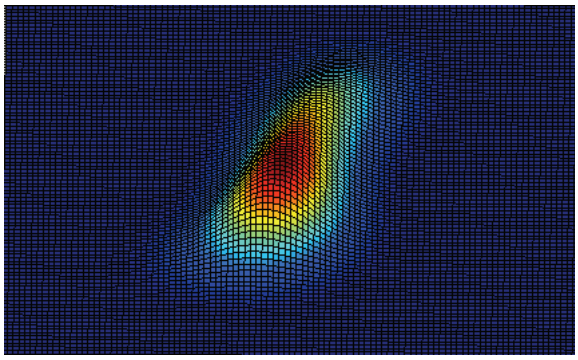
Wireless is Different

- **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**
- **Also, can't just abstract away the physical and link layers: need a brief introduction to underlying EE**

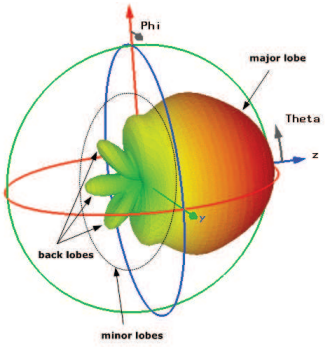
Attenuation Over Space

- **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



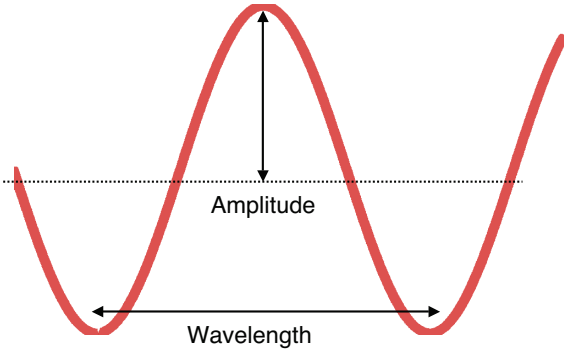
Directional Antennas



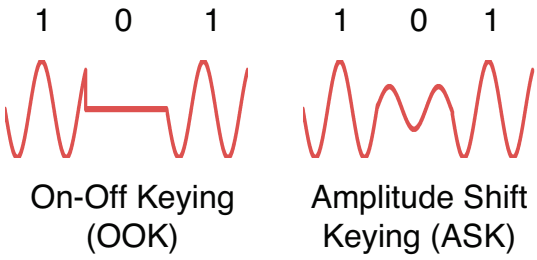
Interference

- **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**

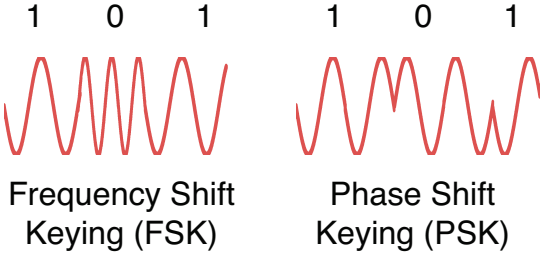
Analog Signals



Specifying the Signal: Modulation

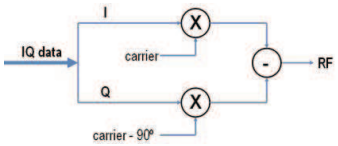


Modulation, Continued

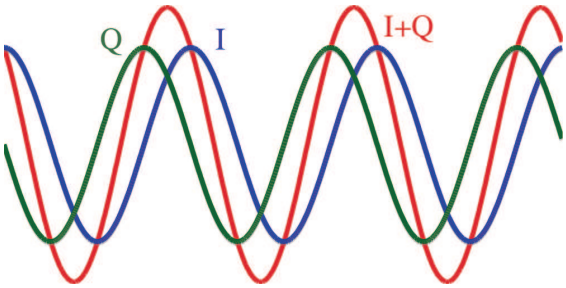


I/Q Modulation

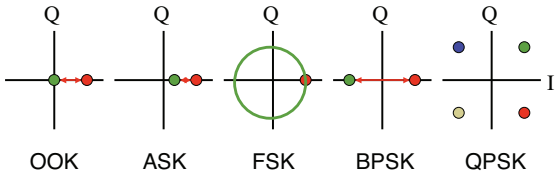
- I: in-phase, Q: quadrature
- Sum of two sines is a sine
- Show what the carrier looks like compared to a simple, unmodulated signal
- Use I/Q because this is how it's actually done in hardware



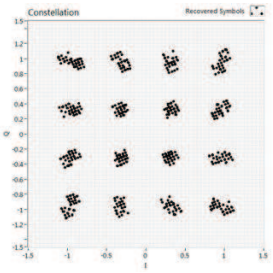
I+Q



Modulation in I/Q Plots



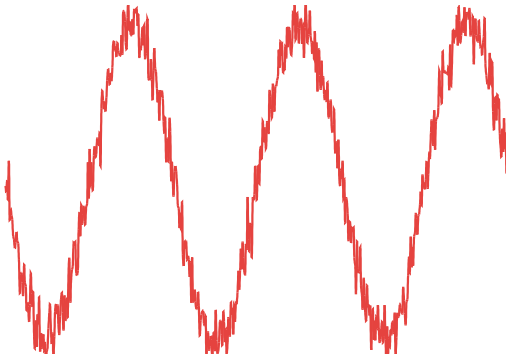
Example measurements from 16-QAM



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: 0dBm = 1mW, 0dBW = 30dBm = 1W
  - Note dB is a logarithmic scale: 10dBm = 10mW, 20dBm = 100mW

Signal Plus Noise



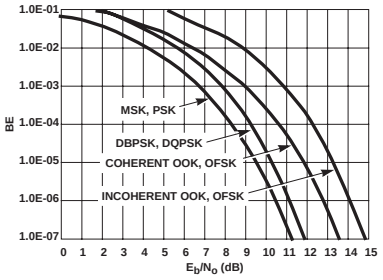
SINR

- **Signal to Interference-and-Noise Ratio**
- **Measured in dB:** $\frac{|S|}{|N+I|}$
  - S = -50dBm, N+I = -95dBm, SINR = 45dB
  - S = -89dBm, N+I = -93dBm, SINR = 4dB
- **SINR is particularly critical in wireless because of attenuation over space**

Bit Error Rates

- **There is a theoretical limit on how much information a channel can carry (Shannon limit)**
- **Bit error rate depends on the SINR and the modulation**
- **This is why wireless link layers use more complex chip/bit encoding**
  - If signal is strong (high SINR), have few chip errors, can use low encoding
  - If signal is weak (low SINR), have many chip errors, use higher encoding to recover from errors

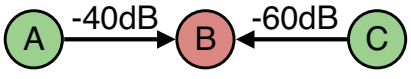
Example Theoretical Bit Error Rates



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**

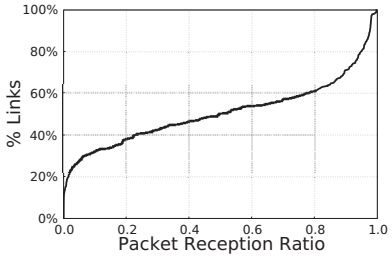
Collisions are not so simple



- **If A transmits first, B can still decode its packet**
- **If C transmits first, A will corrupt its packet and B can't decode C's packet**
- **What if AB and BC are both -60dB?**
- **Signal strength matters: this is the RF capture effect**

802.11 Packet Loss Rates

802.11 Packet Loss Rates (at 11Mbps)



- How does this affect TCP?

Wireless PHY Summary

- Can't control or limit the channel
- Need to deal with weak signals, interference, etc.
- Signal strength affects collisions
- 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

Wireless Link Layers

MAC Layer Responsibilities

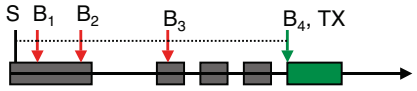
- Arbitrate control of the channel
- One node should be able to use 100%
- Multiple nodes should get a fair share
- Want high utilization under contention

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

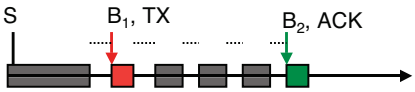
Simple MAC: CSMA/CA

- **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

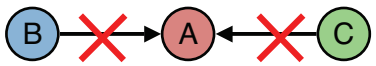
- **Maintain a waiting counter c**
- **For each time step channel is idle, $c--$**
- **When $c = 0$, transmit**
- **If packet is not acknowledged (layer 2), pick a new, larger c**
  - Use lack of layer 2 ack as collision detect



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



- **B and C can't hear each other, A can hear both**
- **B and C sense a clear channel, transmit, and collide at A**
- **B is a *hidden terminal* to C, and C is a *hidden terminal* to B**

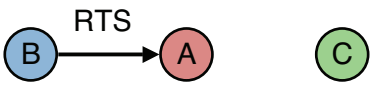
Exposed Terminal Problem

- **A transmits to B**
- **C hears the transmission, backs off, even if it wants to transmit to D**
- **C is an *exposed* terminal to A's transmission**

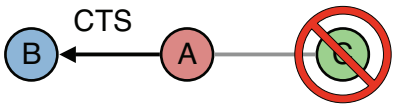
RTS/CTS

- **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**

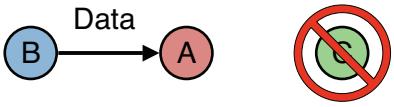
RTS



CTS



Data

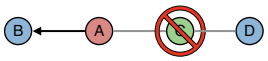


Network Allocation Vector (NAV)

- **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)**
  - In practice, not true: a node's CTS can collide with another node's RTS
  - In practice, can reduce but not solve the hidden terminal problem on data
  - Control packets still collide
- **Improves data packet delivery ratio**
- **Does it solve the exposed terminal problem? What about ACKs?**



RTS/CTS Drawbacks

- **3 packets per packet: RTS/CTS/DATA (4-22% overhead in 802.11b)**
- **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**

802.11 Association

- **Terminal hears beacon from AP (scan channels), or sends a** *probe request*
- **Terminal sends an** *authentication request*, **AP sends** *authentication response*
  - If security is enabled, use keys
  - Also "null" authentication
- **Terminal sends** *association request*, **AP sends** *association response*

Association Continued

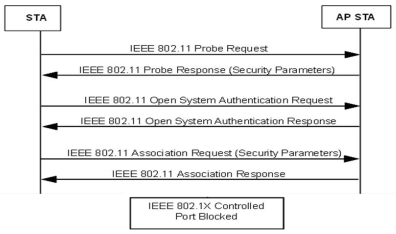
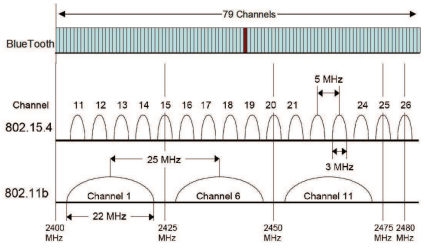


Figure 5-11—Establishing the IEEE 802.11 association

2.4GHz Band



Wireless Routing

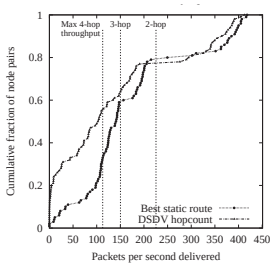
Wireless Routing

- **Network is much more dynamic**
- **Not constrained by physical topology**
- **Discovering and estimating links to neighbors**
- **Discovering and maintaining routes to nodes**
- **Rich area of study: we'll just touch on link cost**

Hopcount Considered Harmful

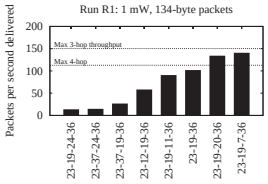
- **Minimizing hopcount causes protocol to choose long links**
- **Links are more likely to be on edge of SNR/PRR curve**
  - Less stable
  - Require more maintenance
- **One way wireless routing is different**
- **OLSRv2 adds the concept of link metrics**

DSDV and Hopcount on Roofnet



- **From DeCouto et al., "A High-Throughput Path Metric for Multi-Hop Wireless Routing."**

Variations Across Hopcounts



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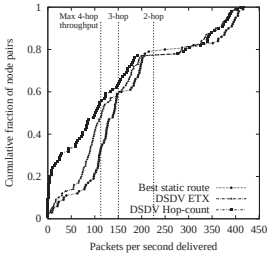
Expected Transmissions (ETX)

- **Proposed by DeCouto et al.**
- **Alternative metric: ETX, number of transmissions until you receive an ACK**
- **Cost of link is** $\frac{1}{PRR_{AB} \cdot ARR_{BA}}$
  - $PRR_{AB} = 75\%, ARR_{BA} = 66\%, ETX_{AB} = 2.0$
  - $PRR_{AB} = 50\%, ARR_{BA} = 50\%, ETX_{AB} = 4.0$
- **Cost of route is sum of ETX values of links on route**

ETX Benefits



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ETX Is Not Enough

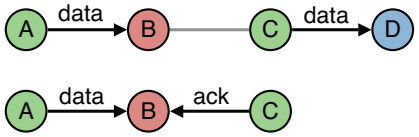
- **802.11b supports four different bit rates**
- **ETX can select the route, but not the bitrate**
- **One packet at 11Mbps $\neq$ one packet at 1Mbps**
- **Solution: Estimated Time of Transmission (ETT)**
  - Probe at different bit rates
  - Choose link bit rate based on minimum cost

Link Metrics Today

- **Rough consensus that ETX/ETT is the right metric**
  - Addresses intermediate links
  - Can be used across link layers
- **No consensus on how to estimate the value**
  - Several proposals
  - Still an active area of research
- **Issue: conflates hopcount and link quality, making loops very easy (100% $\rightarrow$ 33% can look like 2 more hops)**
- **Issue: minimizes delay, does not maximize throughput**

Throughput Dropoff

- **Only every third node can transmit, or you get the hidden terminal problem**
- **In TCP, data and ack packets cause the hidden terminal problem**



Wireless Routing

- **Maintaining consistent, distributed state on a dynamic system**
- **Preventing loops via serialization or source routing**
- **On-demand versus continuous**
- **ETX/ETT better metric than hopcount**