The 802 Class of Standards

- List on next slide
- Some standards apply to all 802 technologies
  - E.g. 802.2 is LLC
  - Important for inter operability
- Some standards are for technologies that are outdated
  - Not actively deployed anymore
  - E.g. 802.6
Overview

- Link layer challenges and WiFi
- WiFi
  - Basic WiFi design
  - Some deployment issues
  - WiFi version
- Cellular

Wireless Communication

- Wireless communication is based on broadcast
  - A, B, and C can all hear each other’s signal
  - Looks like Ethernet!
  - Why not use CSMA/CD?
    - Carrier-sense Multiple Access / Collision Detection
    - Well, it is not that easy

What is the Problem?
There are no Wires!

- Attenuation is very high!
- Signal is not contained in a wire
- Attenuation is $1/D^2$ for distance D
- In addition, there is significant noise and interference
  - No wire to protect the signal
  - Much higher error rates
- Not all nodes in the wireless network can hear each other
  - Wireless communication range is shorter
  - Standard cannot limit the length of the wires

Implications for Wireless Ethernet

- Collision detection is not practical
  - Ratio of transmitted signal power to received power is way too high at the transmitter
  - Transmitter cannot detect colliding transmissions (deaf while transmitting)
  - So how do you detect collisions?
  - Not all nodes can hear each other
    - “Listen before you talk” often fails
    - Hidden and exposed terminals
    - Made worse by fading
    - Changes over time!
Hidden Terminal Problem

- Lack signal between S1 and S2 and cause collision at R1
- Severity of the problem depends on the sensitivity of the carrier sense mechanism
  - Clear Channel Assessment (CCA) threshold

Exposed Terminal Problem

- Carrier sense prevents two senders from sending simultaneously although they do not reach each other’s receiver
- Severity again depends on CCA threshold
  - Higher CCA reduces occurrence of exposed terminals, but can create hidden terminal scenarios

History

- Aloha wireless data network
- Car phones
  - Big and heavy “portable” phones
  - Limited battery life time
  - But introduced people to “mobile networking”
  - Later turned into truly portable cell phones
- Wireless LANs
  - Originally in the 900 MHz band
  - Later evolved into the 802.11 standard
  - Later joined by the 802.15 and 802.16 standards
- Cellular data networking
  - Data networking over the cell phone
  - Many standards – throughput is the challenge

Spectrum Allocation in US
Spectrum Use Comments

- Each country is in charge of spectrum allocation and use internally
- Federal Communication Commission (FCC) and National Telecommunication and Information Administration in the US
- Spectrum allocation differs quite a bit – implications for mobile users?
- Broadly speaking two types of spectrum
- Licensed spectrum: allocated to licensed user(s)
- Unlicensed spectrum: no license needed but device must respect rules

Some IEEE 802.11 Standards

- IEEE 802.11a
  - PHY Standard: 8 channels: up to 54 Mbps: some deployment
- IEEE 802.11b
  - PHY Standard: 3 channels: up to 11 Mbps: widely deployed
- IEEE 802.11d
  - MAC Standard: support for multiple regulatory domains (countries)
- IEEE 802.11e
  - MAC Standard: QoS support: supported by many vendors
- IEEE 802.11f
  - Inter-Access Point Protocol: deployed
- IEEE 802.11g
  - PHY Standard: 3 channels: OFDM and PBCC: widely deployed (as b/g)
- IEEE 802.11h
  - Suppl. MAC Standard: spectrum managed 802.11a (TPC, DFS): standard
- IEEE 802.11i
  - Suppl. MAC Standard: Alternative WEP: standard
- IEEE 802.11n
  - MAC Standard: MIMO: significant improvements in throughput
- IEEE 802.11ac
  - Support for multi-user MIMO
- IEEE 802.11ad
  - WiFi in the 60 GHz band

Frequency Bands

- Industrial, Scientific, and Medical (ISM) bands
- Generally called “unlicensed” bands

IEEE 802.11 Overview

- Adopted in 1997 with goal of providing
- Giving wireless users access to services in wired networks
- High throughput and reliability
- Continuous network connection, e.g. while mobile
- The protocol defines
  - MAC sublayer
  - MAC management protocols and services
  - Several physical layers: IR, FHSS, DSSS, OFDM
- Wi-Fi Alliance is industry group that certifies interoperability of 802.11 products
Features of 802.11 MAC protocol

- Supports MAC functionality
  - Addressing – based on 48-bit IEEE addresses
  - CSMA/CA
  - Error detection (checksum)
  - Error correction (ACK frame)
  - Flow control: stop-and-wait
  - Fragmentation (More Frag)
  - Collision Avoidance (RTS-CTS)

Infrastructure and Ad Hoc Mode

- Infrastructure mode: stations communicate with one or more access points which are connected to the wired infrastructure
  - What is deployed in practice
  - Two modes of operation:
    - Distributed Control Functions - DCF
    - Point Control Functions – PCF
  - PCF is rarely used - inefficient
  - Alternative is “ad hoc” mode: multi-hop, assumes no infrastructure
  - Rarely used, e.g. military
  - Hot research topic!

802.11: Infrastructure Mode

- Station (STA)
  - terminal with access mechanisms to the wireless medium and radio contact to the access point
- Access Point
  - station integrated into the wireless LAN and the distribution system
- Basic Service Set (BSS)
  - group of stations using the same AP
- Portal
  - bridge to other (wired) networks
- Distribution System
  - interconnection network to form one logical network (ESS: Extended Service Set) based on several BSS

Wireless Collision Avoidance

- Problem: two nodes, hidden from each other, transmit complete frames to base station
  - Collision detection not reliable: "listen before talking" can fail
  - Solution: rely on ACKs instead to detect packet loss
  - Collisions waste bandwidth for long duration!
    - Plus also exponential back off before retransmissions – collisions are expensive!
  - Solution: “CA” using small reservation packets
    - Nodes track reservation interval with internal “network allocation vector” (NAV)
    - This is called “virtual carrier sense”
  - Note that nodes still do “physical” carrier sense
    - “Listen before you talk” often works and is cheap
Collision Avoidance: RTS-CTS Exchange

- Explicit channel reservation
  - Sender: send short RTS: request to send
  - Receiver: reply with short CTS: clear to send
  - CTS reserves channel for sender, notifying (possibly hidden) stations
- RTS and CTS are short:
  - collisions are less likely, of shorter duration
  - end result is similar to collision detection
- Avoid hidden station collisions
  - Not widely used (not used really)
    - Overhead is too high!
    - Not a serious problem in typical deployments

IEEE 802.11 MAC Protocol

- RTS/CTS implemented using NAV: Network Allocation Vector
- NAV is also used with data packets
  - 802.11 data frame has transmission time field
  - Others (hearing data header) defer access for NAV time units
- But why do you need NAV if you can hear the header?
  - Fading?
  - Header is sent at lower bit rate

How About Exposed Terminal?

- Exposed terminals result in a lost transmission opportunity
  - Reduces capacity – no collisions
  - Exposed terminals are difficult to deal with
    - Even hard to detect them!
  - Good news – they are very rare!
  - So we live with them

DCF mode transmission without RTS/CTS

- Not used in Ethernet
- WiFi is more concerned about collisions
Exponential Backoff

- Force stations to wait for random amount of time to reduce the chance of collision
  - Backoff period increases exponential after each collision
  - Similar to Ethernet
- Also used when the medium is sensed as busy:
  - Wait for medium to be idle for a DIFS (DCF IFS) period
  - Pick random number in contention window (CW) = backoff counter
  - Decrement backoff timer until it reaches 0
    - But freeze counter whenever medium becomes busy
  - When counter reaches 0, transmit frame
  - If two stations have their timers reach 0 at same time; collision will occur;
- After every failed retransmission attempt:
  - Increase the contention window exponentially
  - \(2^{i-1}\) starting with \(CW_{\text{min}}\) up to \(CW_{\text{max}}\) e.g., 7, 15, 31

Now What about PCF?

- IEEE 802.11 combines random access with a “taking turns” protocol
  - DCF (Distributed Coordination Mode) – Random access
    - CP (Contention Period): CSMA/CA is used
    - PCF (Point Coordination Mode) – Polling
    - CFP (Contention-Free Period): AP polls hosts
  - Basestation can control who access to medium
    - Can offer bandwidth guarantees
  - Rarely used in practice

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Association Management

- Stations must associate with an AP before they can use the wireless network
  - AP must know about them so it can forward packets
  - Often also must authenticate
- Association is initiated by the wireless host – involves multiple steps:
  1. Scanning: finding out what access points are available
  2. Selection: deciding what AP (or ESS) to use
  3. Association: protocol to “sign up” with AP – share configuration info
  4. Authentication: needed to gain access to secure APs – many options
- Disassociation: station or AP can terminate association
“Static” Channel – Bitrate Adaptation

- 1 Mbps
- 2 Mbps
- 5.5 Mbps
- 11 Mbps

Lower signal rates enable coverage of large additional area.

Mobile Channel – Pedestrian

- 1 Mbps
- 2 Mbps
- 5.5 Mbps
- 11 Mbps
- 18 Mbps
- 24 Mbps
- 36 Mbps
- 48 Mbps
- 54 Mbps

Infrastructure Deployments

Frequency Reuse in Space

- Set of cooperating cells with a base stations must cover a large area
- Cells that reuse frequencies should be as distant as possible to minimize interference and maximize capacity
  - Minimizes hidden and exposed terminals
  - 3D problem!
  - Lots of measurements

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IEEE 802.11 Family

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Release</th>
<th>Freq</th>
<th>Rate (typical)</th>
<th>Rate (max)</th>
<th>Range (indoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Legacy</td>
<td>1997</td>
<td>2.4 GHz</td>
<td>1 Mbps</td>
<td>2 Mbps</td>
<td>?</td>
</tr>
<tr>
<td>802.11a</td>
<td>1999</td>
<td>5 GHz</td>
<td>25 Mbps</td>
<td>54 Mbps</td>
<td>~30 m</td>
</tr>
<tr>
<td>802.11b</td>
<td>1999</td>
<td>2.4 GHz</td>
<td>6.5 Mbps</td>
<td>11 Mbps</td>
<td>~30 m</td>
</tr>
<tr>
<td>802.11g</td>
<td>2003</td>
<td>2.4 GHz</td>
<td>25 Mbps</td>
<td>54 Mbps</td>
<td>~30 m</td>
</tr>
<tr>
<td>802.11n</td>
<td>2008</td>
<td>2.4/5 GHz</td>
<td>200 Mbps</td>
<td>600 Mbps</td>
<td>~50 m</td>
</tr>
<tr>
<td>802.11ac</td>
<td>2013</td>
<td>5 GHz</td>
<td>100s Mbps per user</td>
<td>1.3 Gbps</td>
<td>~50 m</td>
</tr>
<tr>
<td>802.11ad</td>
<td>2016</td>
<td>60 GHz</td>
<td>Gbps</td>
<td>7 Gbps</td>
<td>Short - room</td>
</tr>
</tbody>
</table>

A Factor of 1000+ Speedup?
- 802.11b: first WiFi to be standardized and widely deployed
  - Used 20MHz channels, 2.4 GHz only, inefficient modulation
- 802.11a and g: increases rates from 11 to 54Mbit/sec
  - Key factor is better modulation (“OFDM”)
  - They are the same standard, but 802.11a runs in 5GHz band
    - 5GHz band is wider and has lower utilization – more capacity!
- 802.11n: runs in both 5 and 2.4GHz bands – significant speed up
  - How? Better modulation, channel bonding, and MIMO

Channel Bonding
- Why only use 20Mhz channels per user?
  - Remember Shannon?
- What changes are needed?
  - Radios need to use a wider channel: adds complexity, cost
  - Interoperability between 20 and 40 MHz devices – messy
  - Mostly useful in 5 GHz band – more spectrum

How do we Go Faster?
- Wired world:
  Pull more wires!
- Wireless world:
  How about if we could do the same thing and simply use more antennas?
MIMO: Multiple In – Multiple Out

- Key idea: use multiple antenna pairs to send parallel data streams
- Should give us linear capacity increase (just like the wired world)
- Problem: the different transmissions interfere!
  - Each receiving antenna receives (weighted) sum of all transmissions
  - Could be viewed as noise – low S/N ratio in Shannon
- Solution: interference is not random but can be subtracted

How Do We Go Even Faster?

- 802.11ac: faster, mostly by more aggressive modulation and MIMO
  - Also uses multi-user MIMO: AP can send packets to multiple stations simultaneously (don’t worry about the details)
  - 802.11ad: first WiFi to use the 60 GHz band
    - Lots of bandwidth available, mostly unused
    - Transmission only over short distances
    - Signal does not penetrate objects, i.e., mostly LOS
  - In practice, need to use beam forming
  - While standardized, lots of open questions remain

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Cellular versus WiFi

<table>
<thead>
<tr>
<th></th>
<th>Cellular</th>
<th>WiFi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>Licensed</td>
<td>Unlicensed</td>
</tr>
<tr>
<td>Service model</td>
<td>Provisioned “for pay”</td>
<td>Unprovisioned “free” – no SLA</td>
</tr>
<tr>
<td>MAC services</td>
<td>Fixed bandwidth SLAs</td>
<td>Best effort no SLAs</td>
</tr>
</tbody>
</table>
Implications WiFi

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<tr>
<th>Spectrum</th>
<th>WiFi</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlicensed</td>
<td>No control – open, diverse access</td>
<td></td>
</tr>
<tr>
<td>Unprovisioned</td>
<td>No guarantees maximize throughput, fairness</td>
<td></td>
</tr>
<tr>
<td>Free</td>
<td>Best effort no SLAs</td>
<td></td>
</tr>
<tr>
<td>Spectrum</td>
<td>FCC rules to avoid collapse</td>
<td></td>
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</tbody>
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Implications Cellular

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<th>Cellular</th>
<th>Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Licensed</td>
<td>Provider has control over interference</td>
<td></td>
</tr>
<tr>
<td>Provisioned</td>
<td>Provisioned “for pay” Can and must charge + make commitments</td>
<td></td>
</tr>
<tr>
<td>Fixed bandwidth SLAs</td>
<td>TDMA, FDMA, CDMA; access control</td>
<td></td>
</tr>
</tbody>
</table>

But There are Many Similarities

- Cellular and WiFi face the same fundamental physical layer challenges
  - Interference, attenuation, multi-path, …
  - Spatial frequency reuse based on “cells”
    - Adjacent cells use different frequencies
  - Over time, they use similar modulation schemes
    - Each generation uses the best technology available at that time
  - Rapid improvements in throughputs
    - Better modulation and coding, increasingly aggressive MIMO, …

Early Cellular Networks

- Mobile radio telephone system was based on:
  - High power transmitter/receivers
  - Could support about 25 channels
  - in a radius of 80 Km
- To increase network capacity:
  - Multiple low-power transmitters (100W or less)
  - Small transmission radius -> area split in cells
  - Each cell with its own frequencies and base station
  - Adjacent cells use different frequencies
  - The same frequency can be reused at sufficient distance
Cellular Standards

- 1G systems: analog voice
  - Not unlike a wired voice line (without the wire)
  - Pure FDMA: each voice channel gets two frequencies
- 2G systems: digital voice
  - Many standards
  - Example: GSM - FDMA/TDMA, most widely deployed, 200 countries, a billion people
- 2.5G systems: voice and data channels
  - Example: GPRS - evolved from GSM, packet-switched, 170 kbps (30-70 in practice)
  - Use some of the “voice slots” for data

How to Increase Capacity?

- Adding new channels
  - More spectrum – spectrum auctions
- Frequency borrowing
  - More flexible sharing of channels across cells
- Sectoring antennas
  - Split cell into smaller cells using directional antennas – 3-6 per cell
- Microcells, picocells, …
  - Antennas on top of buildings, lamp posts
  - Form micro cells with reduced power
  - Good for city streets, roads and inside buildings

3G: voice (circuit-switched) and data (packet-switched)
- Several standards
- Most use Code Division Multiple Access (CDMA)

4G: 10 Mbps and up, seamless mobility between different cellular technologies
- LTE the dominating technology
- Completely packet switched, voice sent as packets
- Uses Orthogonal Frequency Division Multiplexing (OFDM) for increased robustness wrt. frequency selective fading and mobility
Old Slides