L-9 Wireless

Wireless Intro
- TCP on wireless links
- Wireless MAC
- Assigned reading
  - [BPSK97] A Comparison of Mechanism for Improving TCP Performance over Wireless Links
  - [BM09] In Defense of Wireless Carrier Sense
- Optional
  - [BDS+94] MACAW: A Media Access Protocol for Wireless LAN’s

Wireless Challenges
- Force us to rethink many assumptions
- Need to share airwaves rather than wire
  - Don’t know what hosts are involved
  - Host may not be using same link technology
- Mobility
- Other characteristics of wireless
  - Noisy → lots of losses
  - Slow
  - Interaction of multiple transmitters at receiver
    - Collisions, capture, interference
    - Multipath interference

Overview
- Wireless Background
- Wireless MAC
  - MACAW
  - 802.11
- Wireless TCP
Transmission Channel Considerations

• Every medium supports transmission in a certain frequency range.
  • Outside this range, effects such as attenuation, .. degrade the signal too much
• Transmission and receive hardware will try to maximize the useful bandwidth in this frequency band.
  • Tradeoffs between cost, distance, bit rate
• As technology improves, these parameters change, even for the same wire.
  • Thanks to our EE friends

The Nyquist Limit

• A noiseless channel of width $H$ can at most transmit a binary signal at a rate $2 \times H$.
  • E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  • Assumes binary amplitude encoding

Past the Nyquist Limit

• More aggressive encoding can increase the channel bandwidth.
  • Example: modems
    • Same frequency - number of symbols per second
    • Symbols have more possible values

Capacity of a Noisy Channel

• Can’t add infinite symbols - you have to be able to tell them apart. This is where noise comes in.

  • Shannon’s theorem:
    • $C = B \times \log(1 + S/N)$
    • $C$: maximum capacity (bps)
    • $B$: channel bandwidth (Hz)
    • $S/N$: signal to noise ratio of the channel
      • Often expressed in decibels (db). $10 \log(S/N)$.
  • Example:
    • Local loop bandwidth: 3200 Hz
    • Typical $S/N$: 1000 (30db)
    • What is the upper limit on capacity?
      • Modems: Teleco internally converts to 56kbit/s digital signal, which sets a limit on $B$ and the $S/N$. 
Free Space Loss

\[ \text{Loss} = \frac{P_t}{P_r} = \frac{(4\pi d)^2}{(G_t G_r \lambda^2)} \]

- Loss increases quickly with distance \((d^2)\).
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss depends on frequency: higher loss with higher frequency.
  - But careful: antenna gain depends on frequency too
    - For fixed antenna area, loss decreases with frequency
    - Can cause distortion of signal for wide-band signals

Cellular Reuse

- Transmissions decay over distance
  - Spectrum can be reused in different areas
  - Different “LANs”
  - Decay is \(1/R^2\) in free space, \(1/R^4\) in some situations

Multipath Effects

- Receiver receives multiple copies of the signal, each following a different path
  - Copies can either strengthen or weaken each other.
    - Depends on whether they are in our out of phase
  - Small changes in location can result in big changes in signal strength.
    - Short wavelengths, e.g. 2.4 GHz \(\rightarrow 12\) cm
  - Difference in path length can cause inter-symbol interference (ISI).

Fading - Example

- Frequency of 910 MHz or wavelength of about 33 cm
Overview

- Wireless Background
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  - MACAW
  - 802.11
- Wireless TCP

Medium Access Control

- Think back to Ethernet MAC:
  - Wireless is a shared medium
  - Transmitters interfere
  - Need a way to ensure that (usually) only one person talks at a time.
    - Goals: Efficiency, possibly fairness

Example MAC Protocols

- Pure ALOHA
  - Transmit whenever a message is ready
  - Retransmit when ACK is not received
- Slotted ALOHA
  - Time is divided into equal time slots
  - Transmit only at the beginning of a time slot
  - Avoid partial collisions
  - Increase delay, and require synchronization
- Carrier Sense Multiple Access (CSMA)
  - Listen before transmit
  - Transmit only when no carrier is detected

CSMA/CD Does Not Work

- Carrier sense problems
  - Relevant contention at the receiver, not sender
  - Hidden terminal
  - Exposed terminal
- Collision detection problems
  - Hard to build a radio that can transmit and receive at same time
MACA (RTS/CTS)

RTS = Request-to-Send

assuming a circular range

MACA (RTS/CTS)

NAV = remaining duration to keep quiet

MACA (RTS/CTS)

CTS = Clear-to-Send

MACA (RTS/CTS)

NAV = 8
MACA (RTS/CTS)

- DATA packet follows CTS. Successful data reception acknowledged using ACK.

MACAW: Additional Design

- ACK (needed for faster TCP transfers)
- DS (needed since carrier sense disabled)

RRTS

- Problem:
MACAW: Conclusions

- 8% extra overhead for DS and ACK
- 37% improvement in congestion

<table>
<thead>
<tr>
<th>Protocol</th>
<th>RTS-CTS-DATA</th>
<th>MACAW</th>
<th>RTS-CTS-DS-DATA-ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>59.99</td>
<td>48.97</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: The throughput, in packets per second, achieved by a unattended single stream.

Overview

- Wireless Background
- Wireless MAC
  - MACAW
  - 802.11
- Wireless TCP

IEEE 802.11 Overview

- Adopted in 1997

Defines:
- MAC sublayer
- MAC management protocols and services
- Physical (PHY) layers
  - IR
  - FHSS
  - DSSS

802.11 particulars

- 802.11b (WiFi)
  - Frequency: 2.4 - 2.4835 Ghz DSSS
  - Modulation: DBPSK (1Mbps) / DQPSK (faster)
  - Orthogonal channels: 3
    - There are others, but they interfere. (!)
  - Rates: 1, 2, 5.5, 11 Mbps
- 802.11a: Faster, 5Ghz OFDM. Up to 54Mbps
- 802.11g: Faster, 2.4Ghz, up to 54Mbps
- 802.11n: 2.4 or 5Ghz, multiple antennas (MIMO), up to 450Mbps (for 3x3 antenna configuration)
802.11 details

- Preamble
  - 72 bits @ 1Mbps, 48 bits @ 2Mbps
  - Note the relatively high per-packet overhead
- Control frames
  - RTS/CTS/ACK/etc.
- Management frames
  - Association request, beacons, authentication, etc.

Overview, 802.11 Architecture

802.11 modes

- Infrastructure mode
  - All packets go through a base station
  - Cards associate with a BSS (basic service set)
  - Multiple BSSs can be linked into an Extended Service Set (ESS)
    - Handoff to new BSS in ESS is pretty quick
      - Wandering around CMU
    - Moving to new ESS is slower, may require re-addressing
      - Wandering from CMU to Pitt
- Ad Hoc mode
  - Cards communicate directly.
  - Perform some, but not all, of the AP functions

802.11 Management Operations

- Scanning
- Association/Reassociation
- Time synchronization
- Power management
Scanning & Joining

- Goal: find networks in the area

- Passive scanning
  - No require transmission → saves power
  - Move to each channel, and listen for Beacon frames

- Active scanning
  - Requires transmission → saves time
  - Move to each channel, and send Probe Request frames to solicit Probe Responses from a network

Association in 802.11

1: Association request
2: Association response
3: Data traffic

Client → AP

Time Synchronization in 802.11

- Timing synchronization function (TSF)
  - AP controls timing in infrastructure networks
  - All stations maintain a local timer
  - TSF keeps timer from all stations in sync

- Periodic Beacons convey timing
  - Beacons are sent at well known intervals
  - Timestamp from Beacons used to calibrate local clocks
  - Local TSF timer mitigates loss of Beacons

Power Management in 802.11

- A station is in one of the three states
  - Transmitter on
  - Receiver on
  - Both transmitter and receiver off (dozing)

- AP buffers packets for dozing stations
- AP announces which stations have frames buffered in its Beacon frames

- Dozing stations wake up to listen to the beacons
- If there is data buffered for it, it sends a poll frame to get the buffered data
IEEE 802.11 Wireless MAC

- Support broadcast, multicast, and unicast
  - Uses ACK and retransmission to achieve reliability for unicast frames
  - No ACK/retransmission for broadcast or multicast frames

- Distributed and centralized MAC access
  - Distributed Coordination Function (DCF)
  - Point Coordination Function (PCF)

802.11 DCF (CSMA)

- Distributed Coordination Function (CSMA/CA)
- Sense medium. Wait for a DIFS (50 µs)
- If busy, wait ‘till not busy. Random backoff.
- If not busy, Tx.
- Backoff is binary exponential

- Acknowledgements use SIFS (short interframe spacing). 10 µs.
  - Short spacing makes exchange atomic

802.11 DCF ([RTS/CTS/]Data/ACK)

- RTS/CTS/Data/ACK vs. Data/ACK
  - Why/when is it useful?
  - What is the right choice
  - Why is RTS/CTS not used?

Discussion
802.11 Rate Adaptation

- 802.11 spec specifies rates not algorithm for choices
  - 802.11b 4 rates, 802.11a 8 rates, 802.11g 12 rates
  - Each rate has different modulation and coding

Transmission Rate ↑ then Loss Ratio ↑
Transmission Rate ↓ then Capacity Utilization ↓

throughput decreases either way – need to get it just right

Auto Bit Rate (ABR) Algorithms

- Probe Packets
  - ARF
  - AARF
  - SampleRate
- Consecutive successes/losses
  - ARF
  - AARF
  - Hybrid Algorithm
- Physical Layer metrics
  - Hybrid Algorithm
  - RBAR
  - OAR
- Long-term statistics
  - ONOE

Commercially Deployed: ARF, SampleRate and ONOE

Carrier Sense

Desired result: concurrency

Desired result: time-multiplexing

Desired result: ???

Maybe Carrier Sense is Fine?

- “Far” interference:
  - Small distance variation: \( \Delta r_1 = \Delta r_2 \)

- “Near” interference:
  - Nobody wants concurrency,
    \( \text{SINR}_{\text{concurrent}} \ll \text{SINR}_{\text{multiplexing}} \)

- In both cases, all receivers agree on preferring either multiplexing or concurrency
  - “Agreement” means CS can perform well
  - Intermediate distance will be the hard case
  - Also, shadows and obstacles?
**Single Receiver, Sender and Interferer**

- Receiver preference vs. position:
  - Excellent agreement on multiplexing
  - Disagreement??
  - Excellent agreement on concurrency

**ABR Helps in Disagreements**

- Intermediate distance can mean poor agreement! But...
- Does “mistaken” multiplexing mean 50%-reduced throughput? No. Adapts with higher bitrate.
- “Exposed” and “hidden” terminals are not very useful concepts with ABR

**Carrier Sense + ABR Works Well**

- Inefficiency is small
- Optimal
- Multiplexing
- Concurrency
- Carrier Sense (D_{max} = 55)
Key Assumptions

• ABR == Shannon
  • ABR is rarely this good

• Interference and ABR are both stable
  • Interference may be bursty/intermittent

Overview

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  • MACAW
  • 802.11

• Wireless TCP

Wireless Challenges

• Force us to rethink many assumptions
• Need to share airwaves rather than wire
  • Don’t know what hosts are involved
  • Host may not be using same link technology
• Mobility
• Other characteristics of wireless
  • Noisy \(\rightarrow\) lots of losses
  • Slow
  • Interaction of multiple transmitters at receiver
    • Collisions, capture, interference
    • Multipath interference

TCP Problems Over Noisy Links

• Wireless links are inherently error-prone
  • Fades, interference, attenuation
  • Errors often happen in bursts
• TCP cannot distinguish between corruption and congestion
  • TCP unnecessarily reduces window, resulting in low throughput and high latency
• Burst losses often result in timeouts
• Sender retransmission is the only option
  • Inefficient use of bandwidth
Constraints & Requirements

- Incremental deployment
  - Solution should not require modifications to fixed hosts
  - If possible, avoid modifying mobile hosts
- Probably more data to mobile than from mobile
  - Attempt to solve this first

Challenge #1: Wireless Bit-Errors

Burst losses lead to coarse-grained timeouts
Result: Low throughput

Performance Degradation

2 MB wide-area TCP transfer over 2 Mbps Lucent WaveLAN

Proposed Solutions

- End-to-end protocols
  - Selective ACKs, Explicit loss notification
- Split-connection protocols
  - Separate connections for wired path and wireless hop
- Reliable link-layer protocols
  - Error-correcting codes
  - Local retransmission
Approach Styles (End-to-End)

- Improve TCP implementations
  - Not incrementally deployable
  - Improve loss recovery (SACK, NewReno)
  - Help it identify congestion (ELN, ECN)
    - ACKs include flag indicating wireless loss
    - Trick TCP into doing right thing \(\rightarrow\) E.g. send extra dupacks
  - What is SMART?
    - DUPACK includes sequence of data packet that triggered it

Approach Styles (Split Connection)

- Split connections
  - Wireless connection need not be TCP
  - Hard state at base station
    - Complicates mobility
    - Vulnerable to failures
    - Violates end-to-end semantics

Approach Styles (Link Layer)

- More aggressive local retransmit than TCP
  - Bandwidth not wasted on wired links
- Adverse interactions with transport layer
  - Timer interactions
  - Interactions with fast retransmissions
  - Large end-to-end round-trip time variation
- FEC does not work well with burst losses
Hybrid Approach: Snoop Protocol

- Shield TCP sender from wireless vagaries
  - Eliminate adverse interactions between protocol layers
  - Congestion control only when congestion occurs
- The End-to-End Argument [SRC84]
  - Preserve TCP/IP service model: end-to-end semantics
  - Is connection splitting fundamentally important?
- Eliminate non-TCP protocol messages
  - Is link-layer messaging fundamentally important?

Fixed to mobile: transport-aware link protocol
Mobile to fixed: link-aware transport protocol

Snoop Overview

- Modify base station
  - to cache un-acked TCP packets
  - … and perform local retransmissions
- Key ideas
  - No transport level code in base station
  - When node moves to different base station, state eventually recreated there

Snoop Protocol: CH to MH

- Snoop agent: active interposition agent
  - Snoops on TCP segments and ACKs
  - Detects losses by duplicate ACKs and timers
  - Suppresses duplicate ACKs from MH

Transfer of file from CH to MH
Current window = 6 packets
- Transfer begins

- Snoop agent caches segments that pass by

- Packet 1 is Lost

- Packet 1 is Lost
  - Duplicate ACKs generated
• Packet 1 is Lost
  • Duplicate ACKs generated
  • Packet 1 retransmitted from cache at higher priority

• Duplicate ACKs suppressed

• Clean cache on new ACK

• Clean cache on new ACK
Snoop Protocol: CH to MH

- Active soft state agent at base station
- Transport-aware reliable link protocol
- Preserves end-to-end semantics

Performance: FH to MH

- Snoop+SACK and Snoop perform best
- Connection splitting not essential
- TCP SACK performance disappointing

Discussion

- Real link-layers aren’t windowed
  - Out of order delivery not that significant a concern

- TCP timers are very conservative

MACAW

- 4 design details
  1. Contention is at the receiver
  2. Congestion is location dependent
  3. Fairness
  4. Propagate synchronization information about contention periods
Fairness in MACAW

- Channel capture in MACA
  - Backoff doubled every collision
  - Reduce backoff on success
- Solution: Copy backoffs
  - This does not always work as wanted

MACAW: Additional Design

- Multiple Stream Model

<table>
<thead>
<tr>
<th></th>
<th>Single Stream</th>
<th>Multiple Stream</th>
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</thead>
<tbody>
<tr>
<td>B-P1</td>
<td>11.42</td>
<td>15.07</td>
</tr>
<tr>
<td>B-P3</td>
<td>13.34</td>
<td>15.02</td>
</tr>
<tr>
<td>P3-B</td>
<td>22.74</td>
<td>15.64</td>
</tr>
</tbody>
</table>

- ACK (TCP transfer!)

<table>
<thead>
<tr>
<th>Error Rate</th>
<th>RTS/CTS/DATA</th>
<th>RTS/CTS/DATA-ACK</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>40.41</td>
<td>36.76</td>
</tr>
<tr>
<td>0.001</td>
<td>36.18</td>
<td>36.67</td>
</tr>
<tr>
<td>0.01</td>
<td>16.65</td>
<td>35.52</td>
</tr>
<tr>
<td>0.1</td>
<td>2.48</td>
<td>9.93</td>
</tr>
</tbody>
</table>

802.11 Glossary

- Station
- BSS - Basic Service Set
  - IBSS: Infrastructure BSS
- ESS - Extended Service Set
  - A set of infrastructure BSSs.
  - Connection of APs
  - Tracking of mobility
- DS – Distribution System
  - AP communicates with another

802.11 Frame Priorities

- Short interframe space (SIFS)
  - For highest priority frames (e.g., RTS/CTS, ACK)
- DCF interframe space (DIFS)
  - Minimum medium idle time for contention-based services
SIFS/DIFS
SIFS makes RTS/CTS/Data/ACK atomic

\[
\begin{array}{c|c|c|c|c}
\text{RTS} & \text{Data} & \text{Time} \\
\hline
\text{Sender1} & \text{SIFS} & \text{CTS} & \text{SIFS} & \text{SIFS/ACK} & \text{DIFS} & \text{Time} \\
\hline
\text{Receiver1} & \text{SIFS} & \text{CTS} & \text{SIFS} & \text{SIFS/ACK} & \text{DIFS} & \text{Time} \\
\hline
\text{Sender2} & \text{DIFS} & \text{RTS} & \text{Time} \\
\end{array}
\]

802.11 RTS/CTS
- RTS sets “duration” field in header to
  - CTS time + SIFS + CTS time + SIFS + data pkt time
- Receiver responds with a CTS
  - Field also known as the “NAV” - network allocation vector
  - Duration set to RTS dur - CTS/SIFS time
  - This reserves the medium for people who hear the CTS

IEEE 802.11
RTS = Request-to-Send

assuming a circular range

IEEE 802.11
RTS = Request-to-Send

\[\text{NAV} = \text{remaining duration to keep quiet}\]
IEEE 802.11

CTS = Clear-to-Send

A  B  C  D  E  F

DATA packet follows CTS. Successful data reception acknowledged using ACK.

IEEE 802.11

CTS = Clear-to-Send

A  B  C  D  E  F

IEEE 802.11

NA V = 8

IEEE 802.11

A  B  C  D  E  F

IEEE 802.11
IEEE 802.11

Reserved area

Snoop Performance Improvement

Benefits of TCP-Awareness

- 30-35% improvement for Snoop: LL congestion window is small (but no coarse timeouts occur)
- Connection bandwidth-delay product = 25 KB
- Suppressing duplicate acknowledgments and TCP-awareness leads to better utilization of link bandwidth and performance
Other Issues

• What about mobility?
• What about mobile-to-fixed communication?

Handling Mobility

Correspondent Host

Router

Base Station

Mobile Host

Send packets to multiple base stations

Resend missed packets from Snoop cache on handoff

Outline

• Bluetooth
Bluetooth basics
- Short-range, high-data-rate wireless link for personal devices
  - Originally intended to replace cables in a range of applications
  - e.g., Phone headsets, PC/PDA synchronization, remote controls
- Operates in 2.4 GHz ISM band
  - Same as 802.11
  - Frequency Hopping Spread Spectrum across ~80 channels

Bluetooth Basics cont.
- Maximum data rate of up to 720 Kbps
  - But, requires large packets (> 300 bytes)
- Class 1: Up to 100mW (20 dBm) transmit power, ~100m range
  - Class 1 requires that devices adjust transmit power dynamically to avoid interference with other devices
- Class 2: Up to 2.4 mW (4 dBm) transmit power
- Class 3: Up to 1 mW (0 dBm) transmit power

Usage Models
- Wireless audio
  - e.g., Wireless headset associated with a cell phone
  - Requires guaranteed bandwidth between headset and base
  - No need for packet retransmission in case of loss
- Cable replacement
  - Replace physical serial cables with Bluetooth links
  - Requires mapping of RS232 control signals to Bluetooth messages
- LAN access
  - Allow wireless device to access a LAN through a Bluetooth connection
  - Requires use of higher-level protocols on top of serial port (e.g., PPP)
- File transfer
  - Transfer calendar information to/from PDA or cell phone
  - Requires understanding of object format, naming scheme, etc.

Lots of competing demands for one radio spec!
### Piconet Architecture
- One master and up to 7 slave devices in each Piconet:
  - Master controls transmission schedule of all devices in the Piconet:
    - Time Division Multiple Access (TDMA): Only one device transmits at a time
    - Frequency hopping used to avoid collisions with other Piconets
      - 79 physical channels of 1 MHz each, hop between channels 1600 times a sec

### Scatternets
- Combine multiple Piconets into a larger Scatternet:
  - Device may act as master in one Piconet and slave in another
  - Each Piconet using different FH schedule to avoid interference
  - Can extend the range of Bluetooth, can route across Piconets

### Baseband Specification
- 79 1-MHz channels defined in the 2.4 GHz ISM band
  - Gaussian FSK used as modulation, 115 kHz frequency deviation
- Frequency Hopping Spread Spectrum
  - Each Piconet has its own FH schedule, defined by the master
  - 1600 hops/sec, slot time 0.625 ms
- Time Division Duplexing
  - Master transmits to slave in one time slot, slave to master in the next
  - TDMA used to share channel across multiple slave devices
    - Master determines which time slots each slave can occupy
    - Allows slave devices to sleep during inactive slots

### Time slots
- Each time slot on a different frequency
  - According to FH schedule
  - Packets may contain ACK bit to indicate successful reception in the previous time slot
    - Depending on type of connection...
    - e.g., Voice connections do not use ACK and retransmit
  - Packets may span multiple slots – stay on same frequency
Physical and Logical Links

- Bluetooth supports two types of physical links.
  - Synchronous Connection Oriented (SCO):
    - Slave assigned to two consecutive slots at regular intervals
    - Just like TDMA...
    - No use of retransmission... why??
  - Asynchronous Connectionless (ACL)
    - Allows non-SCO slots to be used for “on demand” transmissions
    - Slave can only reply if it was addressed in previous slot by master

Packet Formats

- Bluetooth supports 14 different payload formats!
  - Different formats for control, voice, and data packets
  - Frames can span 1, 3, or 5 slots
  - Different levels of error coding: No coding, 1/3, or 2/3 FEC

<table>
<thead>
<tr>
<th>Access code</th>
<th>Header</th>
<th>Payload</th>
</tr>
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<tbody>
<tr>
<td>72</td>
<td>54</td>
<td>232</td>
</tr>
<tr>
<td>624</td>
<td>624</td>
<td>624</td>
</tr>
<tr>
<td>624</td>
<td></td>
<td>624</td>
</tr>
</tbody>
</table>

- What is the maximum bandwidth that Bluetooth can achieve?
  - Counting only application payload bytes, no CRC or FEC
  - 5-slot packet, no protection: 341 payload bytes
  - Total time = 5 * (0.625) ms = 3.125 ms
  - But... need to count an extra slot from the master for ACK!
  - Total bandwidth is therefore 341 bytes / (6 * 0.625 ms) = 721 kbps

Discussion

- Nice points
  - A number of interesting low power modes
  - Device discovery
    - Must synchronize FH schemes
    - Burden on the searcher

- Some odd decisions
  - Addressing
    - Somewhat bulky application interfaces
  - Not just simple byte-stream data transmission
  - Rather, complete protocol stack to support voice, data, video, file transfer, etc.
    - Bluetooth operates at a higher level than 802.11 and 802.15.4