15-744: Computer Networking

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
  - [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 or 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

• Wireless MAC
  • 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
MACAW

- 4 design details
  1. Contention is at the receiver
  2. Congestion is location dependent
  3. Fairness
  4. Proper propagation of contention

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

MACAW: Additional Design

- DS
  - Because carrier sense disabled

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<tr>
<th>Error Rate</th>
<th>Single Stream</th>
<th>Multiple Stream</th>
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<tr>
<td>0</td>
<td>11.32</td>
<td>15.90</td>
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<tr>
<td>0.001</td>
<td>12.34</td>
<td>15.92</td>
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<tr>
<td>0.01</td>
<td>22.74</td>
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<table>
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<th>Error Rate</th>
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<th>RTS-CTS-DATA-Ack</th>
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<tbody>
<tr>
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<td>20.11</td>
<td>30.70</td>
</tr>
<tr>
<td>0.001</td>
<td>30.50</td>
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<td>0.01</td>
<td>33.32</td>
<td>33.32</td>
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<tr>
<td>0.1</td>
<td>2.48</td>
<td>9.33</td>
</tr>
</tbody>
</table>

A CTS RTS B

C5 Hears RTS
DS

C2 Doesn’t hear CTS
Hears DS
**Overview**

- Wireless Background

- **Wireless MAC**
  - MACAW
  - 802.11

- Wireless TCP

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**IEEE 802.11 Overview**

- Adopted in 1997

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

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**MACAW: Conclusions**

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

![Table](image)

**Future work:**
- Multicast support
- Copying backoff

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**RRTS**

- **Problem:**

  ![Diagram](image)
### 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

### 802.11 details

- **Fragmentation**
  - 802.11 can fragment large packets (this is separate from IP fragmentation).
- **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

- **Existing Wired LAN**
- **ESS**
- **STA**
- **AP**
- **BSS**: Basic Service Set
- **ESS**: Extended Service Set

### 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

- Joining a BSS
  - Synchronization in TSF and frequency: Adopt PHY parameters: The BSSID: WEP: Beacon Period: DTIM

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)

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

Overview
• Wireless Background

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• 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
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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

![Diagram showing wireless network with losses leading to congestion]

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

Performance Degradation

![Graph showing TCP performance degradation]

Best possible TCP with no errors (1.30 Mbps)
TCP Reno (280 Kbps)

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 → 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

Split-Connection Congestion Window

- Wired connection does not shrink congestion window
- But wireless connection times out often, causing sender to stall
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 FH sender
  - 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

• Clean cache on new ACK

• Duplicate ACKs suppressed

• 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