Wireless Networks: Sharing the Wireless Medium

COS 316, Lecture 15

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Today

1. How do wireless and wired networks differ?

2. Medium access control: Provisioned protocols

3. Contention-based medium access control
Wireless is less reliable

- In wired networks, link bit error rate is $10^{-12}$ and less
- Wireless networks are far from that target
  - Bit error rates of $10^{-6}$ and above are common!
- Why?
• **Wired networks:**
  Alice and Bob’s conversation is independent of Cathy and Eve’s conversation

• **Wireless networks:**
  Close by wireless conversations share the same wireless medium
Medium access: The Problem

- Receiver must hear ≤1 strong transmission at a time, else collision (transmissions are lost)

- Two questions:
  1. **How** should the shared medium be **divided**?
  2. **Who** gets to use each such unit of division, and **when**?

- A *medium access control (MAC) protocol* specifies the above
**Physical Limitation: Finite speed of light**

**From Princeton to...**

- **Mobile Base station**: 3–30 m
- **Wi-Fi AP**: 300 m
- **Trenton**: 30 km
- **Washington, D.C.**: 300 km
- **Yellowstone**: 3,000 km
- **Geosynchronous Satellite (one way)**: 30,000 km

- **Wi-Fi AP**: 10–100 ns
- **300 m**: 1 μs
- **30 km**: 1 ms
- **300 km**: 10 ms
- **3,000 km**: 100 ms
- **30,000 km**: 100 ms
Vastly Different Timescales, Same Medium Access Protocol!

- 3G/4G Cellular Data
- Wi-Fi
- Packet Radio (ALOHA net)
- Satellite Communications

Timescales:
- 100 ms
- 1 ms
- 1 μs
- 10–100 ns
- 3–30 m
- 300 m
- 300 km
- 30,000 km
1. How do wireless and wired networks differ?

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3. Contention-based medium access control
TDMA: Time Division Multiple Access

- Channel time is divided into fixed-period, repeating **rounds**
- Each user gets a fixed-length **slot** (packet time) in each round
  - Send across all frequencies during this slot
  - Unused slots are wasted
- **Out-of-band**: Mechanism for allocating/de-allocating slots
- **e.g.**: six stations, only 1, 3, and 4 have data to send

![Diagram of TDMA slot allocation](image)
FDMA: Frequency Division Multiple Access

- Channel’s frequency range (for all time) divided into frequency bands
  - Each user gets a fixed frequency band (unused frequency slots are wasted)

- e.g.: six stations, only #1, #3, and #4 have data to send
TDMA and FDMA: Considerations

• Advantages
  1. Users are guaranteed to be able to send bits, continuously (FDMA) or periodically (TDMA)

• Disadvantages
  1. Unused time slots or frequency bands reduce channel utilization

  2. An out-of-band mechanism is needed to allocate slots or bands (which requires another channel)

  3. Guard bands or guard times reduce channel utilization
CDMA: Code Division Multiple Access

• All users transmit over the **same frequencies, and at the same time**: 

  ![Diagram of CDMA network with Cathy, Alice, and Bob]

  Okay!

  Cathy (CDMA)

  Bob

• Allows multiple users to coexist and transmit simultaneously with **no interference**
Representing bits as binary levels

• Let’s represent bits with two (binary) levels as follows:
  0 bit \leftrightarrow +1 level  \quad 1 bit \leftrightarrow -1 level

• **Scenario:** Alice receives data from Bob and Cathy:

  Cathy \quad Alice \quad Bob

  – **TDMA e.g.:** Bob sends bits 101, Cathy sends 001:
Assign each user a unique binary sequence of bits: code
- Call each code bit a chip (convention)
- Call the code length $M$

CDMA example:

Bob’s code $c^{bob}$

Cathy’s code $c^{cathy}$
Suppose Cathy alone sends message bits 001:

**Algorithm (CDMA encoding):**
For each message bit \( m \):
Send \( m \times c^{user} \)

L data bits \( \rightarrow M \times L \) CDMA chips
Bit rate: Factor of \( M \) slower
CDMA: Assumptions

- Let’s assume we have a way of:
  - Synchronizing Cathy’s and Bob’s data bits in time
  - Synchronizing Cathy’s and Bob’s CDMA chips in time
  - Estimating and correcting the effect of the wireless channel between Cathy and Bob to Alice
What Alice Hears

Bob’s transmitted CDMA signal:

\[ + \]

Cathy’s transmitted CDMA signal:

\[ = \]

What Alice hears:

\[ +2 \]

\[ -2 \]

Result: Neither Bob nor Cathy’s signal – interference!
Tool: Correlation

Algorithm (correlation):
1. **Multiply** two signals pointwise, across time
2. **Sum** the result across time
3. **Normalize** (divide) by the signal length

Bob’s code $c^{bob}$

Cathy’s code $c^{cathy}$

Sum: 0 $\rightarrow$ Correlation: 0

1. Multiply pointwise:
2. Sum across time
3. Normalize ($\div 2$)
Tool: Correlation

Algorithm (correlation):
1. Multiply two signals pointwise, across time
2. Sum the result across time
3. Normalize (divide) by the signal length

Cathy's code $c^{cathy}$

1. Multiply pointwise:

Sum: 2 $\rightarrow$ Correlation: 1

2. Sum across time

3. Normalize $(\div 2)$
Correlating Cathy’s Code with Cathy’s CDMA transmission

Cathy’s transmission

\[ \text{corr} \]

Cathy’s code \( c^{\text{cathy}} \)

Correlation

Cathy sent: 0 0 1
Listening to Cathy

Alice hears a mixture

Bob’s transmission

Cathy’s transmission

Zero-correlation with Bob’s code cancels Bob’s transmission from the mixture
CDMA: Conclusions

- Communicate **collision-free** over the **same time and same frequency**

- **Tradeoff**: Lowered the bit rate

- *Was it a good tradeoff?*
1. How do wireless and wired networks differ?

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Idea: Use a single, shared channel

- Spread transmission across whole 100 MHz of spectrum
  - Remove constraints assoc. w/one channel per user
  - Robust to multi-path fading
    - Some frequencies likely to arrive intact
  - Supports peer-to-peer communication

- Collisions: Receiver must hear ≤1 strong transmission at a time

- So adopt deference from Ethernet
  - Listen (carrier sense, CS) before sending, defer to ongoing
Concurreny versus Taking Turns

- Far-apart links should send concurrently (spatial reuse)
- Nearby links should take turns:
When Does CS Work Well?

- Two transmission pairs are far away from each other
  - Neither sender carrier-senses the other

B transmits to A, while D transmits to C.
When Does CS Work Well?

- Both transmitters can carrier sense each other
  - Carrier sense uses thresholded correlation value (like CDMA) to determine if medium occupied

But what about cases in between these extremes?

B transmits to A, D transmits to C, taking turns.
Hidden Terminal Problem

- C can’t hear A, so C will transmit while A transmits
  - Result: Collision at B

- Carrier Sense insufficient to detect all transmissions on wireless networks!

- **Key insight:** Collisions are spatially located at receiver
Exposed Terminal Problem

- If C transmits, does it cause a collision at A? No!
  - Yet C cannot transmit while B transmits to A
- Same insight: Collisions spatially located at receiver
• Exchange of two short messages: *Request to Send (RTS)* and *Clear to Send (CTS)*

• Algorithm

  1. A sends an **RTS** (tells B to prepare) with message length $k$
  2. B replies an **CTS** (echoes message length)
  3. A sends its **Data**

```
1. “RTS, k bits”
A  3. “Data”
    B
2. “CTS, k bits”
    C
```
Deference to CTS

- Hear CTS → Defer for length of expected data transmission time

- Solves hidden terminal problem

1. “RTS, k bits”
2. “CTS, k bits”
3. “Data”

A → B → C (defers)
Deference to RTS, but not CS

- Hear RTS $\rightarrow$ Defer one CTS-time *(why?)*

- **MACA:** No carrier sense before sending!
  - Useless because of hidden terminals

- So exposed terminals **B, C** can transmit concurrently:

  1. “RTS, k bits”
  2. “CTS, k bits”
  3. “Data”

  (No deference after Step 2)
Contention-Based Protocols: Timeline

<table>
<thead>
<tr>
<th>Packet radio</th>
<th>Wireless LAN</th>
<th>Wired LAN</th>
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<tbody>
<tr>
<td>ALOHAnet</td>
<td></td>
<td>1960s</td>
</tr>
<tr>
<td>Amateur packet radio</td>
<td></td>
<td>Ethernet</td>
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Contestion-Based Protocols: Timeline

Packet radio → Wireless LAN → Wired LAN

ALOHA.net → Amateur packet radio → Ethernet

MACA → MACAW → IEEE 802.11 Wi-Fi

1960s
1970s
1980s
1990s
2000s
2010s
Final Thoughts

• Contention-based protocols are widely used
  – Less administrative overhead, no planning a priori

• Provisioned protocols can be much more efficient
  – Nowadays we see a mixture
    • Contention-based to set up the provisioning