**Outline**

- Admin. and recap
- Improve mesh capacity
  - Reduce L (infrastructure "blackholes", mobility for delay tolerant networks)
  - MIMO: Use multiple antennas
  - Cognitive radio: use more spectrum
- Radio resource management for energy management of mobile devices

**Admin.**

- Project meeting slots to be posted on classesv2

**Recap: Constraints in Capacity Analysis**

Radio interface constraint
- a single half-duplex transceiver at each node

Interference constraint
- transmission successful if there are no other transmitters within a distance \((1+\Delta)r\) of the receiver

\[
\sum_{b \neq i} h(b) \leq WT \frac{n}{2}
\]

\[
\sum_{b \neq i} (r_{bi})^2 \leq 16WT \frac{n}{\pi \Delta^2}
\]

**Recap: Capacity Bound**

Note: \[\sum_{x_i} x_i^2 = n \sum x_i^2\]

Let \(L\) be the average (direct-line) distance for all

\[\lambda TL \leq \sum_{i=1}^{\lambda T} \sum_{h=1}^{n} h^2\]

\[\lambda TL \leq \frac{\lambda T W T n}{2 \sqrt{\Delta \lambda}} \leq \sqrt{\frac{8WT}{\pi \lambda}} \sqrt{n}\]

rate*distance capacity: \[\lambda L \leq \sqrt{\frac{8W}{\pi \lambda n}}\]

**Improving Wireless Mesh Capacity**

- Reduce L
- Increase \(W\)
- Multiple transceivers
- Approx. optimal
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**MIMO Basics**

\[
y_1 = h_{11}x_1 + h_{12}x_2 \\
y_2 = h_{21}x_1 + h_{22}x_2
\]

Solve two variables from two equations.

**Multiple Input Multiple Output (MIMO)**

- 4x4 MIMO
- LTE
- Kindle Fire HD

**MIMO Benefit: Concurrency using Interference Nulling**

tx2: for every symbol \( q \), transmits \( q \) on first antenna and \( aq \) on second antenna.

interference at rx1:

\[
(h_{11} + ah_{31})q
\]

if tx2 picks \( \alpha = -\frac{h_{31}}{h_{32}} \)

NO interference at rx1.

**Using MIMO for more Concurrency: Motivation**

Assume tx1 is sending to rx1

Can tx2 transmit in 802.11 using carrier sensing?

**Problem**

- rx2 hears \( p \) from tx1
- Can rx2 decode?
Decoding at rx2:

Observation

- for different symbols p from tx1, the received signal at rx2 moves along a 1-d vector $h_{tx1}$

\[
\hat{y} = (\begin{bmatrix} h_{12} \\ h_{13} \end{bmatrix}) p = \hat{h}_{tx1} p
\]

- rx2 projects received signal orthogonal to $h_{tx1}$

Decoding at rx2:

Removing tx1 signal by Projection

- rx2 picks w2 and w3:

\[
w_2^* h_{12} + w_3^* h_{13} = 0
\]

to compute

\[
w_2^* y_2 + w_3^* y_3
\]

Decoding at rx2:

Projection Details

- rx2 can estimate channels $h_{12}, h_{13}$ from preamble

Decoding at rx2:

Projection Details

\[
y_2 = h_{12}p + (h_{22} + h_{32}\alpha)q
\]
\[
y_3 = h_{13}p + (h_{23} + h_{33}\alpha)q
\]
\[
w_2^* h_{12} + w_3^* h_{13} = 0
\]
\[
\Rightarrow
\]
\[
w_2 y_2 + w_3 y_3 = [w_2(h_{22} + \alpha h_{23}) + w_3(h_{23} + \alpha h_{23})]q
\]

Summary: MIMO allows concurrency w/ interference nulling.

Problem of Only Nulling

- Assume both tx1 and tx2 are transmitting.

If only nulling, tx3 cannot transmit

Key idea: rx2 ignores interference from tx1 by projection. If tx3 aligns tx3 $\rightarrow$ rx2 interference along the same direction as that of tx1 $\rightarrow$ rx2, then rx2 can remove it too.

Solution: MIMO using Interference Alignment

- Assume both tx1 and tx2 are transmitting.
MIMO with Nulling and Alignment

\[ y_2 = h_{12}p + (h_{32} + \alpha h_{32})q + (\alpha' h_{42} + \beta' h_{32} + \gamma' h_{42})r \]

\[ y_3 = h_{13}p + (h_{33} + \alpha h_{33})q + (\alpha' h_{43} + \beta' h_{33} + \gamma' h_{43})r \]

tx3 picks \( \alpha', \beta', \gamma' \)

rx2 sees:

\[ y_2 = h_{12}p + (h_{32} + \alpha h_{32})q \]

\[ y_3 = h_{13}p + (h_{33} + \alpha h_{33})q \]

Because rx2 projects to orthogonal to \( \hat{h}_{31} \), no interference from tx3 to rx2.

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Spectrum Allocation Chart

- Opportunity: unlicensed spectrum is large and has low utilization
  - US unlicensed freq:
    - 2.400-2.4835 G
    - 902-928 M
    - 5.15-5.25 G (200 mw)
    - 5.25-5.35 G (1 w)
    - 5.725-5.825 (4w)

Problem of Using Unlicensed

- Unlicensed spectrum may have occupants and is fragmented

- Requirement: Coexistence with dynamic and unknown narrowband devices in the unlicensed spectrum

Existing Solutions

1. Operate below noise-level

   Limits range

   Wideband

   Unlicensed Spectrum

   Zigbee

   802.11a

   Others
**Existing Solutions**

1. Operate below noise-level
   - Limits range
2. Pick a contiguous unoccupied band
   - Limits throughput

**Unlicensed Spectrum**

- Zigbee
- 802.11a
- Others

**Swift: Cognitive Aggregation**

- **Cognition:** Detect unoccupied bands
- **Aggregation:** Weave all unoccupied bands into one link

**Research Issues**

- How to detect available frequency bands?
- How to operate across chunks of non-contiguous frequencies?
- How do sender and receiver establish communication when their perceived available frequency bands differ?

**Aggregating Non-Contiguous Bands**

- **Leverage OFDM**
  - Divided frequency band into multiple sub-bands that can be treated independently

- **Transmitter:** Puts power and data only in OFDM bands not occupied by narrowband devices
- **Receiver:** Extracts data only from OFDM bands used by transmitter

**Cognition: How to detect occupied bands?**

- Unlicensed → Can’t assume known narrowband devices
- Typical solution: Power threshold

<table>
<thead>
<tr>
<th>Baseband Frequencies (MHz)</th>
<th>Narrowband Power in dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faraway 802.11</td>
<td>Ideal Threshold</td>
</tr>
</tbody>
</table>
Cognition: How to detect occupied bands?

- Unlicensed → Can’t assume known narrowband devices
- Typical solution: Power threshold

Typical solution: Power threshold

Problem: No Single Threshold Works Across All Locations

Adaptive Sensing

Unlicensed devices typically react to interference
Carrier sense in 802.11, TCP backoff, etc.

Intuitively:
- Poke the narrowband device, putting power in ambiguous bands
- If the narrowband device reacts, back away

Reasonable for unlicensed spectrum, which operates as best-effort

Adaptive Sensing: Alg

- Continuously sense the medium when not sending a packet
- Detect appearance of narrowband device when narrowband power exceeds noise level
- Detect reaction from changes in narrowband power profile

Adaptive Sensing in Action

- Start with a conservative choice of bands
- Keep tightening as long as narrowband is unaffected

Narrowband Reaction | Detection Metric
---|---
**Carrier Sense (e.g., 802.11):** Will not transmit when sensing a SWIFT packet | Probability of narrowband power immediately after a SWIFT packet
**Back-off (e.g., TCP, MAC):** Will send less often | Inter-arrivals of narrowband power
**Autorate:** Will use lower modulation, increasing packet size | Duration of narrowband power

Look for statistically significant change in metric using standard tests (e.g. t-test)
Adaptive Sensing in Action

- Start with a conservative choice of bands
- Keep tightening as long as narrowband is unaffected

Adaptive Sensing in Action

Wideband

Metric

Time

Adaptive Sensing in Action

Tighten

Metric

Time

Adaptive Sensing in Action

Loosen

Metric

Time

Wideband Throughput and Range

Baseline that operates below the noise of 802.11
Wideband Throughput and Range

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Baseline</th>
<th>SWIFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>9</td>
<td>150</td>
<td>150</td>
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<tr>
<td>12</td>
<td>200</td>
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<td>18</td>
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<td>300</td>
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<tr>
<td>21</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>24</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>

Other Work

- Cognitive Radios
  - 802.22, KNOWS, CORVUS, DIMSUMNet etc.
- Wideband systems
  - Intel, Chandrakasan et al., Mishra et al., Sodini et al.

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Recall: GSM Logical Channels and Request

- Many link layers use a hybrid approach
  - Mobile device uses random access to request radio resource
  - Device holds radio resource during a session

Radio Resource Control Setup for Data in 3G

RRC Statement in UMTS

- Given the large overhead to set up radio resources, UMTS implements RRC state machine on mobile devices for data connection

Recall: GSM Logical Channels and Request

- Call setup from an MS
  - RACH (request signaling channel)
  - AGCH (assign signaling channel)
  - SDCCH (request call setup)
  - SDCCH message exchange
  - SDCCH (assign TCH)
  - Communication

Source: Erran Li.

**RRC of a Large Commercial 3G Net**

- **DCH**: High Power State (high throughput and power consumption)
- **FACH**: Low Power State (low throughput and power consumption)
- **IDLE**: No radio resource allocated

**Promo Delay**: 2 sec

**DCH Tail**: 5 sec

**FACH Tail**: 12 sec

---

**Case Study: Pandora Streaming**

**Problem**: High resource overhead of periodic audience measurements (every 1 min)

**Recommendation**: Delay transfers and batch them with delay-sensitive transfers

---

**Case Study: Fox News**

**Problem**: Scattered bursts due to scrolling

**Recommendation**: Group transfers of small thumbnail images in one burst

---

**Case Study: BBC News**

**Problem**: Scattered bursts of delayed FIN/RST packets

**Recommendation**: Close a connection immediately if possible, or within tail time

---

**Case Study: Google Search**

**Problem**: High resource overhead of query suggestions and instant search

**Recommendation**: Balance between functionality and resource when battery is low

---

**RRC Effects on Device/Network**

- Wasted Radio Energy: 34%
- Wasted Channel Occupation Time: 33%
RRC State Transitions in LTE

RRC_CONNECTED
- Timer expiration

RRC_IDLE
- Data transfer

Continuous Reception

Short DRX
- Ti

Long DRX
- Ti

RRC_IDLE
- Data transfer

RRC_CONNECTED
- Timer expiration

Continuous Reception

Short DRX
- Ti

Long DRX
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RRC_IDLE
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RRC_IDLE
- Data transfer

RRC_CONNECTED
- Timer expiration

Continuous Reception

Short DRX
- Ti

Long DRX
- Ti

RRC_IDLE
- Data transfer

Summary

- App developers may not be aware of interactions with underlying network radio resource management
- A good topic to think about as a part of your project