CMPE 257: Wireless and Mobile Networking

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Lecture 2

CMPE 257 Winter'10
Announcements

• Updates to the Web page.
• Projects.
• Project proposal.
• Class mailing list.
Today

• Finish covering lecture 1 slides.
• PHY: wireless link, capacity.
Some Relevant Conferences and Journals

• MONET, WINET, IEEE JSAC
• IEEE Trans Mobile Computing
• IEEE Trans Wireless Comm.
• ACM Mobicom, ACM Mobihoc
• ACM Sensys, ACM mobsys
• IEEE SECON, IEEE MASS, IEEE ICNP
• IEEE Infocom, IEEE WCNC, IEEE Globecom
Elements of a Wireless Network

- **Wireless hosts**
  - laptop, PDA, IP phone
  - run applications
  - may be stationary (non-mobile) or mobile

- Wireless does **not** always mean mobility
Elements of a Wireless Network

- base station
  - typically connected to wired network
  - relay - responsible for sending packets between wired network and wireless host(s) in its “area”
  - e.g., cell towers, 802.11 access points
Elements of a Wireless Network

- **Wireless link**
  - typically used to connect mobile(s) to base station
  - also used as backbone link
  - multiple access protocol coordinates link access
  - various data rates, transmission distance

- **Network infrastructure**
Characteristics of selected wireless link standards

Indoor: 10-30m
Outdoor: 50-200m
Mid-range outdoor: 200m – 4 Km
Long-range outdoor: 5Km – 20 Km

Data rate (Mbps): 200, 54, 5-11, 4, 1

- **802.15**
- **802.11b**
- **802.11a,g**
- **802.11n**
- **802.16 (WiMAX)**
- **UMTS/WCDMA-HSPDA, CDMA2000-1xEVDO**
- **UMTS/WCDMA, CDMA2000**
- **IS-95, CDMA, GSM**
- **2G**
- **3G cellular enhanced**
- **3G**
- **data**
Elements of a wireless network

- **infrastructure mode**
  - base station connects mobiles into wired network
  - handoff: mobile changes base station providing connection into wired network
Elements of a wireless network

**ad hoc mode**

- no base stations
- nodes can only transmit to other nodes within link coverage
- nodes organize themselves into a network: route among themselves
## Wireless Network Taxonomy

<table>
<thead>
<tr>
<th>infrastructure (e.g., APs)</th>
<th>single hop</th>
<th>multiple hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>host connects to base station (WiFi, WiMAX, cellular) which connects to larger Internet</td>
<td>host may have to relay through several wireless nodes to connect to larger Internet: <em>mesh net</em></td>
<td></td>
</tr>
<tr>
<td>no base station, no connection to larger Internet (Bluetooth, ad hoc nets)</td>
<td>no base station, no connection to larger Internet. May have to relay to reach other a given wireless node</td>
<td>MANET, VANET</td>
</tr>
</tbody>
</table>

**Mobile Adhoc Networks**

**Vehicular Adhoc Networks**
Wireless versus Wired Networking

What complicates wireless networking vs. wired networking?

What are the challenges raised by wireless communications?
Wireless Networking Challenges

- Wireless channel:
  - E.g., for satellite we get extended propagation delays.
  - High bit error rate ‘BER’ (higher than optical fiber and coax.).
  - Asymmetry in bandwidth and delay.
  - Wireless channel impairments: effects of wave propagation, attenuation,… etc.

- Mobility: introduces topology dynamics.

- Power constraints.
Wireless Link Characteristics (1)

Differences from wired link . . .

- decreased signal strength: radio signal attenuates as it propagates through matter (path loss)
- interference from other sources: standardized wireless network frequencies (e.g., 2.4 GHz) shared by other devices (e.g., phone); devices (motors) interfere as well
- multipath propagation: radio signal reflects off objects ground, arriving at destination at slightly different times

. . . make communication across (even a point to point) wireless link much more “difficult”
Wireless Link Characteristics (2)

• SNR: signal-to-noise ratio
  – larger SNR – easier to extract signal from noise (a “good thing”).

• SNR versus BER tradeoffs
  – given physical layer: increase power -> increase SNR->decrease BER.
  – given SNR: choose physical layer that meets BER requirement.
The Wireless Link
Wireless Spectrum of Interest

Frequency in Hz

<table>
<thead>
<tr>
<th>LF</th>
<th>10^4</th>
<th>10^6</th>
<th>10^8</th>
<th>10^10</th>
<th>10^12</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VHF</td>
<td></td>
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<td></td>
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<tr>
<td>UHF</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Radio

<table>
<thead>
<tr>
<th>IR</th>
<th>10^14</th>
<th>10^16</th>
<th>10^18</th>
<th>10^20</th>
<th>10^22</th>
<th>10^24</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-Ray</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cosmic Rays</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Frequency in MHz

- Cordless (CT-1): 46 - 49 MHz
- Cellular (AMPS, IS-136, IS-95): 824 - 849 MHz, 869 - 894 MHz, 902 - 928 MHz
- ISM: 1850 - 1990 MHz
- PCS: 2400 - 2483 MHz
- LMDS: 28 - 31 GHz (1.3 GHz)

5.15 - 5.35 GHz & 5.725 - 5.825 GHz

U-NII ISM

Mani Srivastava, UCLA
Noise and Interference

The signal received by the receiver is a composite of

- Signal of interest
- Noise
- Interference

Interference contains information of interest to some other receiver
Signal Propagation
Radio Channel Propagation Effects

- Diffraction
- Reflection
- Scattering, …
Path Loss: Wireless Channel Impairments

• Spatial and temporal effects.
• Radio propagation models:
  – Indoor versus outdoor.
  – Large-scale versus small-scale.
Large- and Small-Scale Propagation Models

• Large-scale models:
  – Large T-R distances (100s or 1000s of meters) and long time scales
  – Captures average channel conditions.

• Small-scale models:
  – Short T-R distances and short time scales (seconds).
Large-Scale Path Loss Models
Free-Space Propagation

Valid for large distances.

- Used when Transmitter and Receiver have a clear, unobstructed, line-of-sight (LOS) path
  - e.g. satellite channels, microwave LOS radio links

- Free space power at a receiver antenna at a distance \( d \) from transmitter antenna is:
  \[
  P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}
  \]
  where,
  - \( G_t \) and \( G_r \) are antenna gains
  - \( L \geq 1 \) is the system loss factor not related to propagation
    (e.g. loss due to filter losses, hardware etc.)

- Path loss = signal attenuation as a positive quantity in dB
  \[
  PL(dB) = 10\log \frac{P_t}{P_r} = -10\log \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L}
  \]
“Non” Free-Space Propagation

• Reflection:
  – Earth surface, atmosphere, buildings, walls, etc.
  – Reflection amount is function of material, angle of incidence, frequency, etc.

• Diffraction:
  – Radio path obstructed by impenetrable surfaces with edges.
  – Secondary waves “bend” around object (Huyge’s principle).
  – Aka, shadowing.

• Diffusion (or scattering):
  – Medium with large number of objects.
  – Similar to diffraction but with many (smaller) objects, e.g., foliage, lamp posts, street signs, etc.
Reflection, Diffraction, and Scattering in Real-Life

- Received signal often a sum of contributions from different directions
  - random phases make the sum behave as noise (Rayleigh Fading)
Example: Ground Reflection (2-Ray) Model

- Model found a good predictor for large-scale signal strength over distances of several kilometers for mobile systems with tall towers (heights > 50m) as well as for LOS microcell channels.

- Can show (physics) that for large $d \gg \sqrt{h_t h_r}$

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

- Much more rapid path loss than expected due to free space.
Signal Strength at Receiving Antenna(s)

- Path loss
- Small-scale fading
- Shadowing

Graph showing Signal Strength (S(dB)) vs. Distance, with Receiver Sensitivity indicated.
Path loss depends on environment

\( n \) is the path-loss exponent.

<table>
<thead>
<tr>
<th>Environment</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 - 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In-building LOS</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>
More on Large Scale Path Loss

• RF signal penetration into buildings
  - depends on building material, height, percentage of windows, height, orientation, transmission frequency
    e.g. signal strength inside the building increases with height (LOS to upper floor walls)
    e.g. metallic tints can provide 3 to 30 dB attenuation in a single glass pane
  - $n$ is between 3.0 and 6.2, with average of 4.5
Small-Scale Fading (over small temporal and spatial scales)

- In urban areas, mobile antenna heights << height of buildings
  - usually no LOS from basestation
- Mobile receiver may stop in a deep fade (null)
- Moving surrounding objects also cause time-varying fading

Fading affects available channel data rate
Factors Influencing Small-Scale Fading

- **Multipath propagation**
  - multiple waves arriving at random delays (phases), angles, & amplitudes
  - causes signal strength fluctuation, signal distortion, and signal smearing (due to “inter-symbol interference”)

- **Speed of mobile**
  - causes random frequency modulation due to different Doppler shifts on each multipath component

- **Speed of surrounding objects**
  - time varying Doppler shift on multipath components
Multipath Fading Example

\[ \delta(t) \]

\[ \begin{array}{c}
\text{TX} \\
\text{path1} \\
\text{path2} \\
\text{path3} \\
\text{path4} \\
\text{RX}
\end{array} \]

Received Power

\[ \begin{array}{c}
\text{path1} \\
\text{path2} \\
\text{path3} \\
\text{path4}
\end{array} \]

Delay Spread

\[ t \]
Combating the Channel Impairments

- Increase transmitter power
  - counters flat fading, but costly
- (Adaptive) Equalization
  - compensates for intersymbol interference due to time dispersion
- Antenna or space diversity for "multipath"
  - usually, two (or more) receiving antennas, separated by $\lambda/2$
  - selection diversity vs. scanning diversity vs. combining diversity
  - also, "adaptive antenna arrays" or "smart antennas"
- Forward error correction
  - transmit redundant data bits - "coding gain" provides "fading margin"
  - not very effective in slowly varying channels or long fades
- Automatic Repeat Request (ARQ)
  - retransmission protocol for blocks of data (e.g. packets) in error
  - stop-and-wait, go-back-N, selective-repeat etc.
- Other: packet length adaptation, spreading gain adaptation etc.
Indoor Path Loss Models (e.g. for WLANs, WPBXs)

- Two characteristics of indoor environments:
  - small distances
  - much greater environmental variability even for small T-R separations
    e.g. doors closed vs. opens, ceiling vs. desk mounted antennas
    walls, floors, furniture, people moving around

- Partition losses on same floor
  - wide variety of partitions.... with different electrical & physical characteristics
  - hard partitions (to the ceiling) vs soft partitions
  - extensive databases of measurements

- Partition losses between floors
  - depends on construction material, number of windows, presence of tinting...
  - characterized by “Floor Attenuation Factors” (FAF)
# Indoor Path Loss

<table>
<thead>
<tr>
<th>Building</th>
<th>Frequency (MHz)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retail Stores</td>
<td>914</td>
<td>2.2</td>
</tr>
<tr>
<td>Grocery Store</td>
<td>914</td>
<td>1.8</td>
</tr>
<tr>
<td>Office, hard partition</td>
<td>1500</td>
<td>3.0</td>
</tr>
<tr>
<td>Office, soft partition</td>
<td>900</td>
<td>2.4</td>
</tr>
<tr>
<td>Office, soft partition</td>
<td>1900</td>
<td>2.6</td>
</tr>
<tr>
<td>Factory LOS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textile/Chemical</td>
<td>1300</td>
<td>2.0</td>
</tr>
<tr>
<td>Textile/Chemical</td>
<td>4000</td>
<td>2.1</td>
</tr>
<tr>
<td>Paper/Cereals</td>
<td>1300</td>
<td>1.8</td>
</tr>
<tr>
<td>Metalworking</td>
<td>1300</td>
<td>1.6</td>
</tr>
<tr>
<td>Suburban Home</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor Street</td>
<td>900</td>
<td>3.0</td>
</tr>
<tr>
<td>Factory OBS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Textile/Chemical</td>
<td>4000</td>
<td>2.1</td>
</tr>
<tr>
<td>Metalworking</td>
<td>1300</td>
<td>3.3</td>
</tr>
</tbody>
</table>
Model versus Reality

• Models don’t capture reality exactly.
• But still useful for performance estimation.
  – E.g., network simulators.
Error Control

Errors can occur during transmission.

• Proactive versus reactive error control.
  – Proactive error control: anticipate errors.
  – Reactive error control: act if errors occurred.
Error Control Codes

- Error control codes (ECC) can be used to detect and/or correct such errors.

- Error control capabilities of a code depend on the redundancy introduced by the code.

- \((n,k)\) code: \(k\) bits of data, \(n-k\) checkbits

Error detection versus error correction.
Error Control Functionality

- ECC may not be able to correct or detect all errors
- Higher layers cannot rely on lower layers to detect/correct all errors
- Different protocol layers incorporate different ECC mechanisms, depending on the reliability requirements
- Ultimate responsibility for reliability at the application layer
SINR-Threshold Model

• Errors are non-deterministic phenomenon.
• SINR: Signal to Interference-plus-Noise Ratio.
• Deterministic approximation:
  – If SINR exceeds a threshold, assume reliable transmission.
Capacity of Wireless Networks
Fundamental Limits

• What’s the best we can do in a wireless network?
  – Can optimal capacity be achieved?
  – What’s the best achievable performance?
Addressing Fundamental Limits in Ad Hoc Networks

- **Really** hard problem!
- **Solution:** approximations.

What we are trying to model

The model

JJ’s CE 257
Spring’09

CMPE 257 Winter’10
Capacity of Wireless Networks

[Gupta-Kumar]

• Multi-hop ad-hoc networks.
  – Stationary.
• 2 network models:
  – Arbitrary and
  – Random network.
Arbitrary Networks

- $n =$ number of nodes in a unit area
- $W =$ rate of successful transmission
  (interpreted as a measure of "bandwidth")

- Arbitrary

  ➔ Place $n$ nodes wherever desired

  ➔ Choose any flows as desired
  (each flow has a source & a destination)

  ➔ Schedule transmissions as desired
  (under interference constraint)
Arbitrary Networks:
Interference Constraint: “Protocol Model”

- \( d(i, j) = \text{distance between nodes } i \& j \)

- \( \Delta (\text{constant}) \)

- \( i \rightarrow j \) (node \( i \) is transmitting to node \( j \))

- If node \( k \) transmits simultaneously (interference) then \( i \rightarrow j \) transmission is reliable iff

\[
d(k, j) \geq (1 + \Delta)d(i, j), \quad \Delta > 0
\]
Protocol Model

\[ d(k, j) \geq (1 + \Delta) d(i, j), \quad \Delta > 0 \]
Arbitrary Networks: Interference Constraint

- Interference model is an approximation of reality

- Approximation adequate to derive results on “trends” in capacity as a function of number of nodes

⇒ How does network capacity change when number of nodes is increased?
Random Network

- Nodes placed randomly over unit area:
  Expected number of nodes in area $A = nA$

- Each node picks as destination the node closest to
  a randomly chosen location (uniform distribution)

- Transmission "range" = $r$

- $i \rightarrow j$ reliable if interferers not too close to $j$

\[ d(k, j) \geq (1 + \Delta)r \]
Results

• Bad news:
  • Multiple access interference (MAI) kills wireless ad hoc networks!
  • As the number of nodes ($n$) increases, the throughput per node ($\lambda(n)$) decreases and average delay ($D(n)$) increases.

$$\lambda(n) = \Theta\left(\frac{1}{\sqrt{n \log(n)}}\right) \xrightarrow{n \to \infty} 0$$

$$D(n) = \Theta\left(\frac{n}{\sqrt{\log(n)}}\right) \xrightarrow{n \to \infty} \infty$$
Using Mobility and Relaying [Grossglauser and Tse]

• 2-phase algorithm:
  – Phase 1: source sends packet to relay (or destination).
  – Phase 2: relay sends packet to destination.
Multi-User Diversity

- Goal: find “additional routes” between S-D.
  - At steady-state, packets from every source distributed across network.
  - Ensures nodes always data to send when scheduled.
Result

- Mobility: $\theta (1)$.
- Only two relay hops needed to achieve optimum capacity.
- MAI is avoided by using relaying storage in nodes
  - The equivalent of establishing a new line in a wired network.
Using Multi-Packet Reception
[Challenges, Mobicom07]

• MPR eliminates the negative effect of MAI.

• Order capacity is $\Theta(r(n))$
  – Where $r(n)$ is receiver’s reception range.

• Order capacity increases with $r(n)$ !!!