CS649
Sensor Networks
Lectures 7-8: Physical Layer Characterization

Andreas Terzis
http://hinrg.cs.jhu.edu/wns06/
Outline

- (Simple) Radio Power loss models
- Reality
- (More) Radio Power loss models
Motivation

• Communication between nodes over wireless channel
• Characteristics of wireless channel have impact on all upper layer protocols
  • Transmission range
  • Loss rate (BER is determined by SNR at the receiver)
• Would like to model those characteristics
  • Guide design of future systems
  • Help analysis of future systems
We are Computer Scientists

- EE “stuff” has a lot of math
- Math is hard!
- Presented as a play with three acts
Are there any models for wireless channels?

Quite many, starting from simple to very complex
Friss Free-Space Propagation Model

\[
\frac{P_R}{P_T} = G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2
\]

- Models **average power** received
- Assume no obstructions between source and receiver (LOS path)
- Isotropic antennas
- Perfect Power match

\(P_T\) and \(P_R\) - power values at the receiving and transmitting antennas (in watts)
\(G_T\) and \(G_R\) are the power gains for the transmitting and receiving antenna
\(\lambda\) - wavelength in meters
\(d\) - distance between receiver and transmitter
Propagation Mechanisms in Space with Objects

- **Reflection**
  - Radio wave impinges on an object $>> \lambda$ (30 cm @1 GHz)
  - Earth surface, walls, buildings, atmospheric layers

- **Diffraction**
  - Radio path is obstructed by an impenetrable surface with sharp irregularities (edges)
  - Secondary waves “bend” around the obstacle
  - Explains how RF energy can travel without LOS

- **Scattering**
  - When medium has large number of objects $< \lambda$ (30 cm @1 GHz)
  - Similar principles as diffraction, energy reradiated in many directions
  - Rough surfaces, small objects (e.g. foliage, lamp posts, street signs)

- **Other:** Fading and multi-path
Example: Ground Reflection (2-Ray) Model

- Model found to be good predictor for large-scale signal strength over distances of several kilometers for mobile systems with tall towers (h>50m)
- Can show that for large \( d \) \( d \gg \sqrt{h_t h_r} \)

\[ P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \]
Log-distance Path Loss Model

- Assume average power (in dB) decreases proportional to the log of distance

$$\overline{PL}(d) = \overline{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right)$$

- Path-loss exponent $n$, depends on propagation environment

<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</td>
<td>2.7-3.5</td>
</tr>
<tr>
<td>Shadowed Urban</td>
<td>3-5</td>
</tr>
<tr>
<td>In-building LOS</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstruction in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstruction in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>
A more realistic model: Log-Normal Shadowing Model

\[ \overline{PL}(d) = \overline{PL}(d_0) + 10n \log \left( \frac{d}{d_0} \right) + X_\sigma \]

\( X_\sigma \) is zero - mean Gaussian r.v (in dB) with standard deviation \(\sigma\) (in dB)

- Statistically describes random shadowing effects
- values of \(n\) and \(\sigma\) are computed from measured data using linear regression
- Model typically derived from measurements
- Log normal model found to be valid in indoor environments
- All these models describe signal strength variations over large distances and large time scales
Back in the class...

I don’t really know what this old guy is saying. Plus it seems complicated. Can’t I just use the simple free scale model?

But wait! There’s more
Second Act

• Assuming that the old guy is exaggerating about the need of extra models, our friend sets out to verify that experimental results match the simple model
Complex Behavior at Scale: An Experimental Study of Low-Power Sensor Networks

- Motivating Scenario
  - Expected vs. Obtained results
- Platform
- Methodology
Packet Reception Statistics

- Radio range is not uniform
  - Why?
- 10%-15% of links are asymmetric
  - Why?
Radio Channel Features

- Asymmetrical links: the connectivity of node a to node b (a->b) might be significantly different than from node b to node a (b->a).
- Non-isotropical connectivity: the connectivity is not necessary the same in all the directions (same distance) from the source.
- Non-monotonical distance decay: nodes that are geographically far away from the source may get better connectivity than nodes that are geographically closer.
Parameters

- **Transmission gain control**: most of the low power radios used in sensor networks have some form TX gain control.
- **Antenna height**: the relative distance of the antenna with respect to the reference ground.
- **Radio frequency and modulation type**: as defined by the radio hardware used.
- **Packet size**: the number of bits transmitted per packet can affect the likelihood of receiving the packet with no errors.
- **Data rate**: the number of packet per second transmitted.
- **Environment type**: difficult to completely classify. We could differentiate between indoors or outdoors, with or w/o LOS, different levels of physical interference (furniture, walls, trees, etc.), and different materials (sand, grass, concrete, etc.).
SCALE: A tool for Simple Connectivity Assessment in Lossy Environments

Alberto Cerpa, Naim Busek and Deborah Estrin
Locations

- Outdoors Forest: Will Rogers Park. Dense vegetation and trees with open area in a valley.
- Outdoors Urban: Boelter Hall Court Yard. Open area with some vegetation surrounded by buildings.
- Indoors: LECS Ceiling and Lab. Office type of environment with cubicles, desks, etc.
Non-isotropic connectivity

Received Signal Strength
Another view of directionality
Reception rate as a function of distance (low power)
Effect of tx power on link quality
Spatial Characteristics

- Great variability over distance (50 to 80% of radio range)
  - Reception rate is not normally distributed around the mean and std. dev. (more later)
  - Real communication channel is not isotropic
- Low degree of correlation between distance and reception probability; lack of monotonicity and isotropy
- The region of highly variable reception rates is 50% or more of the radio range, and it is not confined to the limit of the radio range (explain)
Link Asymmetries

![Graph showing cumulative distribution function of link asymmetry difference for different power levels.](image)
Percentage of asymmetric links as a function of tx power

- No correlation between power setting and asymmetry
Percentage of asymmetric links as a function of distance

- No clear correlation between distance and existence of asymmetric links

(a) Outdoor Habitat, Mica 2
Asymmetric Links

- Found 5 to 30% of asymmetric links
- No simple correlation between asymmetric links and distance or TX output power
- They tend to appear at multiple distances from the radio range, not at the limit.
What is the main cause of asymmetric links?

<table>
<thead>
<tr>
<th>Node Type</th>
<th>Location Type</th>
<th>Asymmetric link-pairs before swapping</th>
<th>Inverted link-pairs after swapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mica 2</td>
<td>Outdoor Urban</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Mica 2</td>
<td>Indoor Office</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Mica 1</td>
<td>Indoor Office</td>
<td>24</td>
<td>22</td>
</tr>
</tbody>
</table>

- When swapping the asymmetric links node pairs, the asymmetric links were inverted (91.1% ± 8.32)
- Link asymmetries are primarily caused by differences in hardware calibration.
Temporal signal variation
Variation in reception rate is weakly correlated to distance

Indoor LECS Lab - mica1

- Low Power (-7 dBm)
- Medium Power (-5 dBm)
Correlation between avg reception rate and reception rate variation

Indoor LECS Lab - Mica 1

- Low Power (-7 dBm)
- Medium Power (-5 dBm)
Temporal Characteristics

- Time variability is correlated with mean reception rate
- Time variability is not correlated with distance from the transmitter
Effect of packet size on reception rate
Optimal Packet Size?

- Larger packets produce a slight decrease in reception rate...
- BUT, larger packets reduce start symbol and header overhead.
- Efficiency:

\[
\frac{Useful\ BitRX}{Total\ BitTX} = \frac{PayloadSize_i}{TotalPacketSize_i} \times P_i(s)
\]
Efficiency Metric
In a Nutshell

• Great variability over distance (50 to 80% of radio range)
  • Reception rate is not normally distributed around the mean and std. dev.
  • Real communication channel is not isotropic
• Found 5 to 30% of asymmetric links
  • Not correlated with distance or transmission power
  • Primary cause: differences in hardware calibration (rx sensitivity, energy levels)
• Time variability is correlated with mean reception rate and not correlated with distance from the transmitter
• It is possible to optimize your performance by adjusting the coding schemes and packet sizes to the operating conditions
Underlying distribution looks like?

Reception Rate (%)

Distance (meters)

Sample Population (%)

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So the simple model is obviously insufficient. The log-normal shadow model can explain variations in space, but what about variations in time?

If only you would have let me finish
Small scale effects

- Variation of the received signal strength about a local mean over small travel distances (few λ’s) and short time intervals.
- Due to Fading
  - Multipath propagation
  - Speed of node and surroundings
Multipath Propagation

Radio channel impulse response is the sum of all the paths the rays take:

\[ h(t) = \sum_{i=1}^{k} a_i e^{g_i} \delta(t - \tau_i) \]

Result is **Rayleigh** distribution (NLOS)

\[ f(x) = \frac{x}{\alpha^2} e^{-x^2/2\alpha^2}, x \geq 0, \alpha \geq 0 \]

or **Rician** distribution (LOS)