Outline

- Modulation and Demodulation
- Signal to Interference and Noise Ratio
- Radio Power loss models
- Implications
- Experimental results
Motivation

- Communication between nodes over wireless channel
- Characteristics of wireless channel and transceiver have impact on all upper layer protocols
  - Transmission range
  - Loss rate
  - Energy consumption
- Would like to model those characteristics
  - Understand performance of existing systems
  - Guide design of future systems
  - Help analysis of future systems
Fundamental parameters that control rate and quality of information exchange are the channel bandwidth $B$ and the signal power $S$.

- Bandwidth: range of frequencies that the channel can transmit
- Increasing signal power reduces the effect of channel noise
- SNR
Relationships

- Channel bandwidth and signal power are interchangeable

\[ SNR_2 \approx SNR_1^{B_1/B_2} \]

- If we double the channel bandwidth, the new SNR is the square of the original

- Shannon’s Equation

\[ C = B \log_2 (1 + SNR) \]
Modulation and Demodulation

- Digital computers exchange digital data
  - Sequence of symbols from the channel alphabet
- Modulation translates symbols to waveforms of finite length
- Demodulation maps received waveforms to symbols
  - Received waveform is a distorted version of transmitted waveform
  - Leads to errors in detecting transmitted symbols
    - Symbol Error Rate (SER), Bit Error Rate (BER), Packet Error Rate (PER)
Bandpass Modulation

- Signal is modulated onto a periodic carrier wave
  - Center frequency $f_c$, Bandwidth $B$
  - $s(t) = A(t)\cos(\omega(t) + \varphi(t))$
- Three fundamental modulation schemes
  - Amplitude Shift Keying (ASK)
  - Phase Shift Keying (PSK)
  - Frequency Shift Keying (FSK)
- Binary vs. m-ary modulation
Noise and interference

- Received signal is sum of distorted transmitted signal with **noise** and **interference**

- **Thermal noise**
  - Caused by thermal motions of electrons in conducting media
  - Modeled by Gaussian distribution $N(0, \sigma^2)$ (AWGN)
  - $SNR = 10\log(P_{rcvd}/N_0)$

- **Interference**
  - Caused by signals coming from other transmitters
  - $SINR = 10\log(P_{rcvd}/(N_0+\sum I_i))$

- BER depends on modulation scheme and SINR
Path Loss calculations

- SINR-PRR curve tells us that packet error rate depends on received signal strength $P_R$
- How do we calculate $P_R$ from $P_T$ and knowledge of the environment?
Friss Free-Space Propagation Model

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

- \( P_T \) 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

- Models **average power** received
- Assume no obstructions between source and receiver (LOS path)
- Isotropic antennas
- Valid for values of \( d \) in the far-field of the transmitting antenna
Signal to Noise Ratio

- Noise of power $N_0$ arrives at the sensor
  - $\text{SNR} = \frac{P_r}{N_0}$
  - Usually measured in decibels: $\text{SNR}_{dB} = 10 \log_{10} \text{SNR}$
  - When SNR drops below threshold signal cannot be detected

- How can we increase detection range?
  - Quadrupling the power doubles the range
  - Double the carrier frequency by a factor of two
  - Improve detection algorithm
Propagation medium Losses

- Propagation medium usually introduces distortion, scattering, and attenuation
  - Propagation loss $L_p$
  - Absorption in uniform medium is a constant fractional loss per unit distance
  - Example: Fading due to rain as function of frequency

<table>
<thead>
<tr>
<th>$F$ (GHz)</th>
<th>$L_p$ (dB/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>0.048</td>
</tr>
<tr>
<td>9.4</td>
<td>0.093</td>
</tr>
<tr>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>34.9</td>
<td>2.34</td>
</tr>
</tbody>
</table>
Obstructions

- Obstructions, media changes, and reflective objects introduce further losses
  - Examined through a combination of geometric optics and diffraction
Reflection and refraction occur when wave passes through boundary of two media with different indexes of refraction.

\[ \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_1}{n_2} \]

Proportion of energy transferred depends on media and 
- Refraction does not always occur: waveguide effects.
Diffraction

- Huygen’s principle: Every point in the wavefront can be considered as the source of a new spherical front
  - Implies that waves go around corners: diffraction
- Intensity of diffracted wave is much less of the incident wave
  - Shadowing
- Scattering
  - When medium has large number of objects $< \lambda$ (30cm @1 GHz)
  - Similar principles as diffraction, energy reradiated in many directions
  - Rough surfaces, small objects (e.g. foliage, lamp posts, street signs)
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 $d$, $d >> \sqrt{h_t h_r}$

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

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

- \( X_\sigma \) 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
Multipath fading

- Combination of geometric optics and diffraction can be used to estimate propagation relations between two points in space
  - Ray launching and ray tracing
  - Require knowledge of space and reflective objects
  - Statistical models are used to account for uncertainty
- Sum of multiple rays model

\[ h(t; \tau) = \sum_{i} \alpha_i(t) e^{i\theta_i(t)} \delta(\tau - \tau_i(t)) \]

- Time variation due to motion of terminals and medium
- Multipath fading: variations due to different phase sums in short time and space scales
Putting it all together

- Large-scale variations are typically broken down into distance attenuation and shadow fading
  - Distance attenuation is modeled by range to some power
  - Shadowing is caused by objects that are multiples of $\lambda$
    - Lognormal statistics
- Multipath fading adds variation over small distances (and time)
  - Flat fading is modeled by Rayleigh or Ricean random variables

Distance loss
Shadowing added to distance loss
Sum of all losses including multipath
Radio environment models

- Simplified statistical models can be used to predict behavior in real environments
- For in-building propagation, losses due to particular obstructions must be accounted

<table>
<thead>
<tr>
<th>Environment</th>
<th>Distance Exponent</th>
<th>Shadowing Model</th>
<th>Multipath Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
<td>2</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Urban cellular</td>
<td>2.7-3.5</td>
<td>Lognormal</td>
<td>Rayleigh or Rice</td>
</tr>
<tr>
<td>Shadowing in urban cellular</td>
<td>3-5</td>
<td>Lognormal</td>
<td>Rayleigh</td>
</tr>
<tr>
<td>In building line of sight</td>
<td>1.6-1.8</td>
<td>Site-specific</td>
<td>Rayleigh or lognormal</td>
</tr>
<tr>
<td>Obstructed office building</td>
<td>4-6</td>
<td>Site-specific</td>
<td>Rayleigh or lognormal</td>
</tr>
</tbody>
</table>
Understanding Packet Delivery Performance in Dense Wireless Sensor Networks

J. Zhao R. Govindan
Presented at Sensys 2003
Goal

- Given the inherent uncertainty of wireless communication and the nature of low-power radios “it is imperative to get a quantitative understanding of wireless communication in sensor networks, however imperfect”

- Evaluation metric: *packet delivery*
  - Packet delivery translates to network lifetime
  - Especially important over multi-hop paths

- Parameters of interest
  - Range
  - Tx Power
  - Environment
Measurement methodology

- Place sixty motes in a chain topology
  - Single periodic transmitter, all else are receivers
- Three different environments
  - Office, natural habitat, parking lot
Aggregate Packet Delivery Performance

- At least 20% of the nodes have at least 10% packet loss
  - Indoor environment is harshest for delivery
- Reducing Tx power improves packet delivery
Spatial Characteristics of Packet Delivery

- Distinct reception regimes
  - Reception rate in the gray region varies significantly
  - Gray region is almost one third of the total communication range
Signal Strength and Packet Delivery

- Log distance path model can be used to approximate received signal strength.
- While high received signal strength corresponds to high reception rate, some links with low RSS are good.
Temporal Characteristics of Packet Delivery

- Links in the gray area exhibit high temporal variability
An Analysis of Unreliability and Asymmetry in Low-Power Wireless Links

M. Zuniga Zamalloa, B. Krishnamachari
ACM Transactions on Sensor Networks
Paper Goals

- Explain experimental results regarding packet delivery in low-power wireless links
- Model the behavior of low-power wireless links
Modeling the extent of the gray region

- PRR is a function of BER and packet size
- BER is a function of modulation scheme and SNR

\[
\gamma(d) = N(\mu(d), \sigma)
\]

\[
\mu(d) = P_t - 10n \log_{10} \left( \frac{d}{d_0} \right) - P_n
\]
Extent of the gray region

- Transitional region coefficient $\Gamma$: ratio of the extent of the transitional region to the connected region
Packet reception CDF

- Model can be used to provide the CDF of packet reception rate as a function of distance