Wireless Communication Fundamentals

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Suggested Reading

• Chapter 2 “Wireless Communications” by T. S. Rappaport, 2001 (version 2)

Mobile Devices

Pager
• receive only
• tiny displays
• simple text messages

PDA
• simpler graphical displays
• character recognition
• simplified WWW

Laptop
• fully functional
• standard applications

Mobile phones
• voice, data
• simple graphical displays

Palmtop
• tiny keyboard
• simple versions of standard applications

Sensors, embedded controllers
Frequencies for Mobile Communication

<table>
<thead>
<tr>
<th>RADIO</th>
<th>IR</th>
<th>VISIBLE</th>
<th>UV</th>
<th>X-RAYS</th>
<th>GAMMA RAYS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300GHz</td>
<td></td>
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<table>
<thead>
<tr>
<th>VLF</th>
<th>LF</th>
<th>MF</th>
<th>HF</th>
<th>VHF</th>
<th>UHF</th>
<th>SHF</th>
<th>EHF</th>
</tr>
</thead>
<tbody>
<tr>
<td>3k</td>
<td>30k</td>
<td>300k</td>
<td>3M</td>
<td>30M</td>
<td>300M</td>
<td>3G</td>
<td>30G</td>
</tr>
</tbody>
</table>

**VLF**: Very Low Frequency
**MF**: Medium Frequency
**VHF**: Very High Frequency
**SHF**: Super High Frequency
**LF**: Low Frequency
**HF**: High Frequency
**UHF**: Ultra High Frequency
**EHF**: Extremely High Frequency
Some US Frequency Allocations

Submarine Communications: 30 kHz
Navigation (Loran C): 100 kHz
AM Radio: 540 – 1,600 kHz (medium wave)
Tactical Comms/Radio Amateur: 3 – 30 MHz (short wave)
Cordless Phones: 46 - 49 MHz (FM) or 902-928 MHz &
2.4 - 2.4835 GHz (Spread Spectrum)
FM Radio: 88 – 108 MHz
TV: 54 – 216 MHz (VHF) & 420 – 890 MHz (UHF) [not contiguous]
Cellular: 824 - 894 MHz (UHF) [not contiguous]
PCS: 1.85- 1.99 GHz (UHF) [not contiguous]
Satellite Comms: SHF
Wireless LAN’s: ISM bands
ISM = Industry, Science & Medicine - transmit power of 1 watt or less.
ISM Bands:
902 --- 928 MHz
2.4 --- 2.4835 GHz
5.725 --- 5.850 GHz
Time-Domain View of Signals

• A generic sine wave

\[ s(t) = A \cdot \sin(2\pi ft + \phi) \]

  – Amplitude A: Peak value of a signal at any time.

  – Frequency f: Inverse of the period (f = 1/T) represents number of cycles per second (measured in Hertz (Hz)) i.e., this is the rate at which the signal repeats.

  – Phase \( \phi \): Relative position within a signal period.
Frequency and Amplitude

• Measure of frequency
• 1 Hertz = 1 cycle/sec
  – Unit of bandwidth for analog device
  – Frequency of sine wave in diagram: 4Hz
Phase

- Difference, measured in degrees, from a reference sine wave

Reference waveform
Phase-shifted 90°
Phase-shifted 180°
Signal Propagation Ranges

- **Transmission range**
  - communication possible
  - low error rate
- **Detection range**
  - detection of the signal possible
  - no communication possible
- **Interference range**
  - signal may not be detected
  - signal adds to the background noise
Propagation Mechanisms

• **Reflection**: propagation wave reflected by object larger than wavelength

• **Diffraction**: wave obstructed by surface with sharp, irregular edges

• **Scattering**: wave hits loose objects smaller than wavelength; signal scattered in bunch of outgoing weaker signals
Multipath Propagation

• Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction

• Time dispersion: signal is dispersed over time
  - interference with “neighbor” symbols, Inter Symbol Interference (ISI)
  - the transmission rate $R$ is limited by the delay spread
Propagation Models

- **Large scale propagation model**
  - Predict the mean signal strength over the distance between transmitter and receiver (path loss)

- **Small scale propagation model**
  - Characterize the fluctuations of signal strength over very short travel distances or very short time period (multipath fading)
Large Scale Propagation Models

• Propagation in free space:
  – Friis free space equation:
    \[ P_r = P_t \left( \frac{\lambda}{4\pi d} \right)^2 g_t g_r \]
    \( P_t = \) transmit power
    \( g_t, g_r = \) transmit/receive antenna gains
    \( d = \) distance between the antennas

• Propagation along the earth’s surface:
  – 2-ray model
    \[ P_r = P_t \left( \frac{h_t h_r}{d^2} \right) g_t g_r \]
    \( h_t, h_r = \) transmit/receive antenna height
Path Loss

- **Path Loss (PL)**
  - \( PL = P_t/P_r \)
  - \( PL_{dB} = 10 \times \log(PL) = 10 \times \log(P_t/P_r) \)

- **Path Loss Model**
  
  \[
  \bar{PL}(d) \propto \left( \frac{d}{d_0} \right)^n 
  \]

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

- **Log-normal Shadowing Model**

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

  \( n \): path loss exponent
  \( d_0 \): close-in reference distance
  \( X_\sigma \): zero mean Gaussian random variable

<table>
<thead>
<tr>
<th>Path loss exponents</th>
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<tbody>
<tr>
<td>Free space</td>
</tr>
<tr>
<td>Urban area</td>
</tr>
<tr>
<td>In building line-of-sight</td>
</tr>
<tr>
<td>Obstructed in building</td>
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<tr>
<td>----------------------------------------</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>4 to 6</td>
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Example for Path Loss

Path loss from source to d2 = 70dB

\[ \text{dB} = 10 \log \left( \frac{P_1}{P_2} \right) \]
Doppler Effect

• Caused by
  – the speed of mobile
  – speed of surrounding objects
    • If the surrounding objects move at a greater speed than the mobile, this effect dominates, otherwise it can be ignored

• Doppler shift
  – Mobile moving towards the transmitter with speed $v$: a maximum positive Doppler shift
  – The $n$-th path, moving within an angle $\alpha_n$, has a Doppler shift of
    \[ f_d^{\text{max}} = \frac{v}{\lambda} \]
    \[ f_d = \frac{v}{\lambda} \cos(\alpha_n) \]
  – If mobile moves away from transmitter, the frequency of received signal will be $f_r = f_c - f_d$
  – If mobile moves towards transmitter, the frequency of received signal will be $f_r = f_c + f_d$
Classification of Small Scale Fading

Small Scale Fading (Based on multipath delay spread)

- **Flat Fading**
  - Delay Spread $<$ Symbol period

- **Frequency Selective Fading**
  - Delay Spread $>$ Symbol period

Small Scale Fading (Based on Doppler spread)

- **Fast Fading**
  - $1/$Doppler Shift $<$ Symbol period

- **Slow Fading**
  - $1/$Doppler Shift $>$ Symbol period
Two Commonly Used Small Scale Channel Fading Models

**β Rayleigh** Fading Model (Multi paths without LOS signal path)

\[
p(r) = \begin{cases} 
\frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) & \text{for } r \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]

- \(r\): envelope amplitude of received signal
- \(2\sigma^2\): \(E(r^2)\) mean power of multipath signal

**β Rician** Fading Model (Multi paths contains one LOS signal path)

\[
p(r) = \begin{cases} 
\frac{r}{\sigma^2} \exp\left(-\frac{r^2 + a^2}{2\sigma^2}\right) I_0\left(\frac{a r}{\sigma^2}\right) & \text{for } r \geq 0 \\
0 & \text{otherwise}
\end{cases}
\]

- \(a\): peak amplitude of the dominant signal
- \(I_0\): Zero ordered modified Bessel Function
Digital Modulation

- Modern wireless systems use digital modulation
- Three types of digital modulation
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)
Modulation Examples

• M-ary Phase Shift Keying (MPSK)
  – Phase modulation
    \[ S_i(t) = A \cos(2\pi ft + \theta_i), \ 0 \leq t \leq T, \ i = 1,2,\ldots, M \]
  – \( \log_2 M \) bits encoded into one symbol

  – Examples
    • BPSK: \( \theta_1 = 0, \ \theta_2 = \pi \)
    • QPSK: \( \theta_1 = 0, \ \theta_2 = \pi / 2, \ \theta_3 = \pi, \ \theta_4 = 3\pi / 2 \)

• M-ary Quadrature Amplitude Modulation (M-QAM)
  – Combining phase modulation and amplitude modulation
    \[ S_i(t) = A_i \cos(2\pi ft + \theta_i), \ 0 \leq t \leq T, \ i = 1,2,\ldots, M \]
Examples for M-QAM

4-QAM
1 amplitude, 4 phases

8-QAM
2 amplitudes, 4 phases

bases functions

\[ \phi_1 = \sin(2\pi ft) \]
\[ \phi_2 = \cos(2\pi ft) \]

16-QAM
3 amplitudes, 12 phases

16-QAM
4 amplitudes, 8 phases

16-QAM
2 amplitudes, 8 phases