Radio Propagation Theory Basics
Figure 5.10 Sketch of Three Important Propagation Mechanisms:
Reflection (R), Scattering (S), Diffraction (D) [ANDE95]
Multipath Propagation

- Reflection - occurs when signal encounters a surface that is large relative to the wavelength of the signal
- Diffraction - occurs at the edge of an impenetrable body that is large compared to wavelength of radio wave
- Scattering – occurs when incoming signal hits an object whose size in the order of the wavelength of the signal or less
Wave Propagation Models

- **Fading:** is used to describe fluctuations in the envelope of the transmitted radio signal, when speaking of such fluctuations, one should consider two cases:

- **Small-Scale Fading (or Multipath):**
  - Short observation interval (or small distance), shows rapid fluctuations in the signal`s envelop

- **Large-Scale path loss:**
  - Long observation interval (large distance), shows rapid slow fluctuations; an averaged view.

- Received Power or path loss is the most important parameter predicted by large scale propagation models.
• **Effect of Mobility**
  - Channel varies with user location and time
  - Radio propagation is very complex
    » Multipath scattering from nearby objects
    » Shadowing from dominant objects
    » Attenuation effects
  - Results in rapid fluctuations of received power

Less variation the slower you move

For cellular telephony:
-30 dB, 3 μsec delay spread
• **Large scale fades**
  - Attenuation: in free space, power degrades by $1/d^2$
  - Shadows: signals blocked by obstructing structures

• **Small scale fades**
  - Multipath effects:
    » Rapid changes in signal strength over a small area or time interval
    » Random frequency modulation due to varying Doppler shifts on different multipath signals
    » Time dispersion (echoes) caused by multipath propagation delays
  - Even when mobile is stationary, the received signals may fade due to movement of surrounding objects!
• Delay Spread
  – Multipath propagation yields signal paths of different paths with different times of arrival at the receiver
  – Spreads/smears the signal, could cause inter-symbol interference, limits maximum symbol rate
  – Typical values (μs): Open < 0.2, Suburban = 0.5, Urban = 3
Factors Influencing Fading

- multipath propagation
- speed of mobile
- speed of surrounding objects
- transmission bandwidth of signal
Complete modeling for mobile radio

✓ Shadowing
✓ Path-loss
✓ Fast fading
✓ Correlation among sub-bands
Definition of path loss:

The path loss is the difference (in dB) between the transmitted power and the received power.

- Represents signal level attenuation caused by free space propagation, reflection, diffraction and scattering.

⇒ Necessary to calculate link budget.
Large-Scale Path Loss

• The main propagations mechanisms that determine the path loss:
  
  » **Reflection:**
  Occurs when the radio waves collid with an object which is very large in dimension compared to the wavelength of the propagating wave- e.g., surface of the earth, buildings, walls, ...

  » **Diffraction:**
  Occurs when the path between the transmitter/receiver is obstructed by a surface with sharp edges. A second wave can be generated. This phenomenon is dependent on: frequency, amplitude, phase and the angle of arrival of the incident wave.
» **Scattering:**

Occurs when the radio wave travels through medium consisting of objects with small dimensions compared to the wave`s wavelength. Typical scattered waves arise when the radio wave meets rough surfaces.
Three kinds of models

- **Empirical models**: based on measurement data, simple (few parameters), use statistical properties, not very accurate

- **Semi-deterministic models**: based on empirical models + deterministic aspects

- **Deterministic models**: site-specific, require enormous number of geometry information about the site, very important computational effort, accurate
Different types of cells:

- Each model is defined for a specific environment.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Typical cell radius</th>
<th>Location</th>
<th>Typical base station antenna installation height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large macro cell</td>
<td>1 km to 30 km</td>
<td>outdoor</td>
<td>Above medium roof-top level, all surrounding buildings are below antenna height</td>
</tr>
<tr>
<td>Small macro cell</td>
<td>0.5 km to 3 km</td>
<td>outdoor</td>
<td>Above medium roof-top level, heights of some surrounding buildings are above antenna height</td>
</tr>
<tr>
<td>Micro cell</td>
<td>up to 1 km</td>
<td>outdoor</td>
<td>Below medium roof top level</td>
</tr>
<tr>
<td>Pico cell</td>
<td>up to 500 m</td>
<td>indoor/outdoor</td>
<td>Below roof-top level</td>
</tr>
</tbody>
</table>
2. Macrocell path loss models
2.1 Empirical models

Why empirical models, so called “simplified models”? 

- Purely theoretical treatment of urban and suburban propagation is very complicated

  - Not all required geometric descriptions of coverage area are available (e.g. description of all trees, buildings etc...)

  - Excessive computational effort

Important parameter for cells designer: overall area covered

NOT the specific field-strength at particular locations
Free Space Path Loss Model

- The free space model is the simplest because we ignore the effects of all obstacles.
- Assuming the antenna is radiating isotropically-uniformly in all directions
- The path loss tells us the amount of received power at the receiver antenna a distance \( r \) meters away from the transmitting antenna with \( P_t \) power
- The transmitted antenna can be considered to be at the center of a sphere of radius \( r \)
The power density on the sphere (flux density) can be written as:

\[ P_d = \frac{EIRP}{4\pi r^2} = \frac{P_t}{4\pi r^2} \quad \text{Watts/m}^2 \]

Where: \textit{EIRP} is the effective radiated power from the isotropic source, \textit{4\pi r} is the surface area of the sphere, and \( P_d \) is the received power (a function of the transmitted power and antenna characteristics).
• Multiplying the last equation by the effective aperture of the receiving antenna $A_e$:

$$P_r = P_d A_e = \frac{P_t A_e}{4\pi r^2} \text{ Watts}$$  \hspace{1cm} (2)

• The received power is inversely proportional to square of the distance.

• The effective aperture of the antenna is related to its gain $G$ as:

$$G = \frac{4\pi A_e}{\lambda^2}$$  \hspace{1cm} (3)
\[ \therefore P_r = \frac{P_t G \lambda^2}{(4\pi r)^2} = \frac{P_t G_T G_R \lambda^2}{(4\pi r)^2} \]  

(4)

Where: \( G_T \) and \( G_R \) are the transmitter and receiver gains, respectively. Equation (4) is referred to as the Friis free space equation.

The choice of dBm (dB normalized to 1.0 mW – as mobile systems usually employ low-power devices- orders of milliwatts) leads to:

\[ P_L(dBm) = 10\log_{10} \left( \frac{P_t}{0.001P_r} \right) = -10\log_{10} \left( \frac{G_T G_R \lambda^2}{0.001(4\pi r)^2} \right) \]  

(5)
Propagation model for near earth`s surface

- A more realistic model which considers direct waves, ground waves, and ground reflected wave component

Propagation close to the earth`s surface
\[ P_r = \frac{4\pi P_t A_e (h_1 h_2)^2}{\lambda^2 r^4} \]  

(16)

- Equation (16) expresses the path loss near the Earth’s surface. \( h_1 \) and \( h_2 \) are the transmitter and receiver antenna heights, respectively, and \( r \) is the distance between the transmitter and receiver.
- For propagation close to the earth’s surface, the received power of the signal is inversly proportional to \( r^4 \).
- Comparing this fourth order decay with the second order decay for the free space model means that the power decays more rapidly with distance once the realistic model is in place.
- This equation is independent of the carrier frequency, this analysis is very simple and enough for estimation purposes.
Outdoor Propagation

Received Power $P_r = Kd^{-n}$,
$n = 2$ in free space, $3 \leq n \leq 4$ typically

BER = $f$(signal strength)

Error rates increase as SNR decreases
Propagation Models

- **Analytical model**
  \[ P(R) = N(R_0, \sigma) + 10\gamma \log\left(\frac{R}{R_0}\right) + x_\sigma \]

- **Empirical model**
  - **Hata-Okumura model**
    \[ L_{\text{mean}} = 69.55 + 26.16 \log(f_c) - 13.82 \log(h_b) - a(h_m) \]
    \[ + (44.9 - 6.55 \log(h_b)) \log R \text{ dB} \]
  - **Walisch-Ikegami model (Cost 231 model)**
    \[ L_{\text{mean}} = L_f + L_{\text{rots}} + L_{\text{ms}} \]
    mean path-loss = free-space loss + rooftop-to-street and scatter loss + multiscreen loss
Empirical Path Loss Models for Macrocells

- Macrocells are large enough to provide a coverage range on the order of kilometers, used for outdoor communications.
- Two models will be discussed here, Hata’s model which is based on graphical path loss data provided by Okumura and Lee’s model.
- Hata’s model was based on empirical data from measurements in Tokyo, Japan.
- Claimed to give accurate estimate of the path loss to within 1.0 dB compared with the measurements.
**Okumura-Hata model [1]**

Most popular model

Based on measurements made in and around Tokyo in 1968

- between 150 MHz and 1500 MHz
- Predictions from series of graphs ➔ approximate in a set of formulae (Hata)
- Output parameter: mean path loss (median path loss) \( L_{dB} \)
- Validity range of the model:
  - Frequency \( f \) between 150 MHz and 1500 Mhz
  - \( T_X \) height \( h_b \) between 30 and 200 m
  - \( R_X \) height \( h_m \) between 1 and 10 m
  - \( T_X - R_X \) distance \( r \) between 1 and 10 km
Okumura-Hata model cont.

3 types of prediction area:

- Open area: open space, no tall trees or building in path

- Suburban area: Village Highway scattered with trees and house
  Some obstacles near the mobile but not very congested

- Urban area: Built up city or large town with large building and houses
  Village with close houses and tall
Okumura-Hata model cont.

Definition of parameters:

- $h_m$: mobile station antenna height above local terrain height [m]
- $d_m$: distance between the mobile and the building
- $h_0$: typically height of a building above local terrain height [m]
- $h_b$: base station antenna height above local terrain height [m]
- $r$: great circle distance between base station and mobile [m]
- $R = r \times 10^{-3}$: great circle distance between base station and mobile [km]
- $f$: carrier frequency [Hz]
- $f_c = f \times 10^{-6}$: carrier frequency [MHz]
- $\lambda$: free space wavelength [m]
Okumura-Hata model cont.

- Okumura takes urban areas as a reference and applies correction factors

Urban areas: \( L_{dB} = A + B \log_{10} R - E \)

Suburban areas: \( L_{dB} = A + B \log_{10} R - C \)

Open areas: \( L_{dB} = A + B \log_{10} R - D \)

\[
A = 69.55 + 26.16 \log_{10} f_c - 13.82 \log_{10} h_b \\
B = 44.9 - 6.55 \log_{10} h_b \\
C = 2 \left( \log_{10} \left( \frac{f_c}{28} \right) \right)^2 + 5.4 \\
D = 4.78 \left( \log_{10} f_c \right)^2 + 18.33 \log_{10} f_c + 40.94 \\
E = 3.2 \left( \log_{10} \left( 11.7554 h_m \right) \right)^2 - 4.97 \quad \text{for large cities, } f_c \geq 300\text{MHz} \\
E = 8.29 \left( \log_{10} \left( 1.54 h_m \right) \right)^2 - 1.1 \quad \text{for large cities, } f_c < 300\text{MHz} \\
E = (1.1 \log_{10} f_c - 0.7) h_m - (1.56 \log_{10} f_c - 0.8) \quad \text{for medium to small cities}
\]
COST 231-Hata model [1][5]

Okumura-Hata model for medium to small cities has been extended to cover 1500 MHz to 2000 MHz (1999)

\[ L_{dB} = F + B \log_{10} R - E + G \]

\[ F = 46.3 + 33.9 \log_{10} f_c - 13.82 \log_{10} h_b \]

\[ E \] designed for medium to small cities

\[ G = \begin{cases} 
0 \text{ dB medium sized cities and suburban areas} \\
3 \text{ dB metropolitan areas} 
\end{cases} \]
COST 231-Hata model cont.

Accuracy

Extensive measurement in Lithuania [8] at 160, 450, 900 and 1800MHz :
• Standard deviation of the error = 5 to 7 dB in urban and suburban environment
• Best precision at 900 MHz in urban environment
• In rural environment: standard deviation increases up to 15 dB and more

Measurements in Brazil at 800 / 900 MHz :
• mean absolute error = 4.42 dB in urban environment
• standard deviation of the error = 2.63 dB

⇒ path loss prediction could be more accurate
⇒ but models are not complex and fast calculations are possible
⇒ precision greatly depends on the city structure
2.2 Semi-empirical models

COST 231-Walfisch-Ikegami [2][5]

Cost 231-WI takes the characteristics of the city structure into account:

- Heights of buildings \( h_{\text{Roof}} \)
- Widths of roads \( w \)
- Building separation \( b \)
- Road orientation with respect to the direct radio path \( \Phi \)

 Rue increases accuracy of the propagation estimation

 More complex

N.B. allows estimation from 20 m (instead of 1 km for Okumura-Hata model)

Output parameter: mean path loss
COST 231-Walfisch-Ikegami cont.

Restrictions:

- Frequency $f$ between 800 MHz and 2000 MHz
- $T_x$ height $h_{Base}$ between 4 and 50 m
- $R_x$ height $h_{Mobile}$ between 1 and 3 m
- $T_x - R_x$ distance $d$ between 0.02 and 5 km
COST 231-Walfisch-Ikegami cont.

2 cases: LOS and NLOS

**LOS:**

\[ L_{LOS} \text{[dB]} = 42.6 + 26 \log_{10} d \text{[km]} + 20 \log_{10} f \text{[MHz]} \]

**NLOS:**

\[ L_{NLOS} \text{[dB]} = L_{FS} + L_{rts} (w_r, f, \Delta h_{Mobile}, \Phi) + L_{MSD} (\Delta h_{Base}, h_{Base}, d, f, b_s) \]

\[ L_{FS} = \text{free space path loss} = 32.4 + 20 \log_{10} d \text{[km]} + 20 \log_{10} f \text{[MHz]} \]

\[ L_{rts} = \text{roof-to-street loss} \]

\[ L_{MSD} = \text{multi-diffraction loss} \]
COST 231-Walfisch-Ikegami cont.

\[ L_{rts} = -8.8 + 10 \log_{10}(f \text{[MHz]}) + 20 \log_{10}(\Delta h_{\text{Mobile}} \text{[m]}) - 10 \log_{10}(w \text{[m]}) + L_{ori} \]

\[ L_{ori} = \text{street orientation function} \]

\[ L_{ORI} = \begin{cases} 
-10 + 0.35 \Phi & 0 \leq \Phi < 35^\circ \\
2.5 + 0.075(\Phi - 35) & 35^\circ \leq \Phi < 55^\circ \\
4.0 - 0.114(\Phi - 55) & 55^\circ \leq \Phi < 90^\circ 
\end{cases} \]

\[ L_{MSD} = L_{bsh} + k_a + k_d \log_{10}(d \text{[km]}) + k_f \log_{10}(f \text{[MHz]}) - 9 \log_{10}(b) \]

Where \[ L_{bsh} = \begin{cases} 
-18 \log_{10}(1 + \Delta h_{\text{Base}}) & h_{\text{Base}} > h_{\text{Roof}} \\
0 & h_{\text{Base}} \leq h_{\text{Roof}} 
\end{cases} \]
COST 231-Walfisch-Ikegami cont.

\[ k_d = \begin{cases} 
  54 & \text{if } h_{\text{Base}} > h_{\text{Roof}} \\
  54 - 0.8 \Delta h_{\text{Base}} & d \geq 0.5 \text{ km, } h_{\text{Base}} \leq h_{\text{Roof}} \\
  54 - 0.8 \Delta h_{\text{Base}} d \text{ [km]} / 0.5 & d < 0.5 \text{ km, } h_{\text{Base}} \leq h_{\text{Roof}} 
\end{cases} \]

\[ k_d = \begin{cases} 
  18 & \text{if } h_{\text{Base}} > h_{\text{Roof}} \\
  18 - 15 \Delta h_{\text{Base}} / h_{\text{Roof}} & h_{\text{Base}} \leq h_{\text{Roof}} 
\end{cases} \]

\[ k_f = -4 + \begin{cases} 
  0.7 (f / 925 - 1) & \text{medium sized city} \\
  1.5 (f / 925 - 1) & \text{metropolitan center} 
\end{cases} \]
Ray tracing [6][7]

- based on geometrical optics (GO)

- used to modelling reflection and refraction of optical rays.
  - if $f < 10$ GHz: diffraction has to be taken into account
  - different diffraction models are added to GO as extensions

- Two methods for ray tracing: ray imaging and ray launching
Ikegami model [1]

⇒ entirely deterministic prediction of field strengths at specified points

• Using detail map of building heights, shapes and positions ⇒ trace ray paths
  Restriction: only single reflection from wall accounted for

• Diffraction calculated using single edge approximation

• Wall reflection are assumed to be fixed at constant value

⇒ two ray (reflected, diffracted) are power summed:

\[ L_E = 10 \log_{10} f_c + 10 \log_{10} (\sin \phi) + 20 \log_{10} (h_0 - h_m) - 10 \log_{10} w - 10 \log_{10} \left(1 + \frac{3}{L_r^2}\right) - 5.8 \]

Φ = angle between the street and the direct line from base to mobile

\( L_r = \) reflection loss = 0.25

38
Ikegami model cont.

- model tends to underestimate loss at large distance
- Variation of frequency is underestimated compared with measurement
3. Microcell path loss models
3.1 Empirical model

Dual slope empirical model [1]
Motivation: simple power law path loss model not accurate enough

⇒ Dual slop model

⇒ Two separate path loss exponents are used to characterize the propagation

⇒ breakpoint distance of a few hundred meters

Path loss: \( L = \begin{cases} 10n_1 \log_{10} r + L_1 & \text{for } r \leq r_b \\ 10n_2 \log_{10} \left( \frac{r}{r_b} \right) + 10n_1 \log_{10} r_b + L_1 & \text{for } r > r_b \end{cases} \)

\( L_1 = \) reference path loss at \( r = 1 \) m
\( r_b = \) breakpoint distance
\( n_1 = \) path loss exponent for \( r \leq r_b \)
\( n_2 = \) path loss exponent for \( r > r_b \)
3.2 deterministic model

Two-ray model [1]

→ valid for line of sight

↓ at least 1 direct ray and 1 reflected ray

Similar approach as plane earth loss but two path lengths not necessarily equal

\[
\frac{1}{L} = \left( \frac{\lambda}{4\pi} \right)^2 \left| \frac{e^{-jk_{r_1}}}{r_1} + R \frac{e^{-jk_{r_2}}}{r_2} \right|^2
\]

\[R = \text{Fresnel reflection coefficient}\]
Signal Propagation through Wireless Channels

- It is common to model the received signal strength in the form

\[ P_r[dB] = \overline{P_r(d)} + X + Y(t) \quad \text{where} \]

- \( \overline{P_r(d)} \): Average received power level as a function of distance, \( d \)

\[ \overline{P_r(d)} = P_t - L(d) \quad L(d) : \text{Large-scale (long-term) path loss} \]

- \( X \): Large-scale (long-term) shadowing
  
  Random variable to represent long-term variations in the average received power level due to different transmitter/receiver location geometries and terrain structure (e.g. forest area vs. open area)

- \( Y(t) \): Small-scale (short-term) fading
  
  Random process to represent short-term variations in the received power due to "multipath propagation" environment, (i.e. multiple delayed versions of the transmitted signal is received due to the reflections off of buildings, hills, cars and other obstacles, etc.)
As the mobile moves away from the transmitter, the local average received signal will gradually decrease as a function of the distance and it is this local average signal that is predicted by the "large-scale" propagation models.

When the mobile moves away from the transmitter by only a fraction of a wavelength, the received signal experiences fluctuations as a result of "small-scale" fading. These fluctuations can be severe and received signal power may vary by ~30-40dB. In deep fades, it is probable that the connection is lost unless some effective fading-mitigation techniques are employed.
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.
Link Budget Design Using Path Loss Models:

- Bit-error-rate is a function of SNR (signal-to-noise ratio), or equivalently CIR (carrier-to-interference ratio), at the receiver
  - the "function" itself depends on the modulation scheme!

- Link budget calculations allow one to compute SNR or CIR
  - requires estimate of power received from transmitter at a receiver
    - Tx antenna, Rx antenna, Rx amplifier, path loss (free space, shadowing)
  - also, estimate of noise and power received from "interferers"
    \[ SNR(dB) = P_r(d) \text{ dBm} - N \text{ dBm} \]
    where, \( N = KT_0BF \) or, \( N \text{ dBm} = -174 \text{ dBm} + 10 \log B \text{ (in Hz)} + F \text{ (dB)} \)
    where is the Boltzmann's constant, and \( F \) is the noise figure of the receiver

- Many different path loss models
  - analytical, empirical (fitting curves to measured data), combination
  - typically a slope-intercept approximation for far field radios (> 1m)
    \[ L(dB) = C + 10\gamma \log R \]

- Classical (large scale) path loss models
Example: Link Budget Calculation

- Maximum separation distance vs. transmitted power (with fixed BW)

Given:
- cellular phone with 0.6W transmit power
- unity gain antenna, 900 MHz carrier frequency
- SNR must be at least 25 dB for proper reception
- receiver BW is $B = 30$ KHz, and noise figure $F = 10$ dB

What will be the maximum distance?

Solution:

$N = -174 \text{ dBm} + 10 \log 30000 + 10 \text{ dB} = -119 \text{ dBm}$

For SNR > 25 dB, we must have $P_t > (-119+25) = -94 \text{ dBm}$

$P_t = 0.6W = 27.78 \text{ dBm}$

This allows path loss $\overline{PL}(d) = P_t - P_r < 122 \text{ dB}$

$\lambda = c/f = 1/3 \text{ m}$

Assuming $d_0 = 1 \text{ km}$, $\overline{PL}(d_0) = 91.5 \text{ dB}$

For free space, $n = 2$, so that: $122 > 91.5 + 10*2*\log(d/(1 \text{ km}))$

or, $d < 33.5 \text{ km}$

Similarly, for shadowed urban with $n = 4$, $122 > 91.5 + 10*2*\log(d/(1 \text{ km}))$

or, $d < 5.8 \text{ km}$
Path loss is directly proportional to the square of the carrier frequency and inversely to $d^n$. 

\[ \text{mean pathloss} \propto \frac{1}{d^m} \quad m < n \]

Large-scale fading (Lognormal fading)
• Assume average power (in dB) decreases proportional to \( \log \) of distance

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

• Justification?
  - measurements
  - intuition/theory... recall: free-space, ground-reflection model

• 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 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>

• Problem: “Environment clutter” may differ at two locations at same \( d \)
  - measured \( PL(d) \) may differ substantially from \( \overline{PL}(d) \)
Indoor Propagation

- **Physical Effects:**
  - Signal decays much faster
  - Coverage contained by walls, etc.
  - Walls, floors, furniture attenuate/scatter radio signals

- **Path loss formula:**
  
  \[ \text{Path Loss} = \text{Unit Loss} + 10 \, n \, \log(d) = k \, F + I \, W \]

  where:

  - Unit loss = power loss (dB) at 1m distance (30 dB)
  - \( n \) = power-delay index
  - \( d \) = distance between transmitter and receiver
  - \( k \) = number of floors the signal traverses
  - \( F \) = loss per floor
  - \( I \) = number of walls the signal traverses
  - \( W \) = loss per wall
Indoor Propagation

• Other Effecting Factors
  – People moving around:
    » Additional multipath induced attenuation of 10 dB
  – Buildings with few metal and hard partitions: RMS delay spread of 30 to 60 ns (several mbps w/o equalization)
  – Buildings with metal/open aisles: RMS delay spread of up to 300 ns (100s kbps w/o equalization)
  – Between floors:
    » Concrete/steel flooring yields less attenuation than steel plate flooring
    » Metallic tinted windows yield greater attenuation
    » 15 dB for first floor separation, 6 - 10 dB for next four floors, 1 - 2 dB for each additional floor of separation
Indoor Measurements

- Received signal strength depends on:
  - Open plan offices, construction materials, density of personnel, furniture, etc.

- Path loss exponents:
  - Narrowband (max delay spread < bit period)
    » Vary between 2 and 6, 2.5 to 4 most common
    » Wall losses: 10 dB to 15 dB
    » Floor losses: 12 dB to 27 dB
  - Wideband (max delay spread > bit period)
    » Delay spread varies between 15 ns and 100 ns
    » Can vary up to 250 ns
    » Requires sophisticated equalization techniques to achieve acceptable bit error rates
Outdoor-to-Indoor Measurements

• Penetration/“Building Loss”
  – Depends on building materials, orientation, layout, height, percentage of windows, transmission frequency
    » Received signal strength increases with increasing height of building (less urban clutter at upper floors)
    » Penetration loss decreases with increasing frequency
    » 6 dB less loss through windows

• Rate of decay/distance power law: 3.0 to 6.2, with average of 4.5

• Building attenuation loss: between 2 dB and 38 dB
Figure 4.28 Scatter plot of path loss as a function of distance in Office Building 1 [from [Sei92b] © IEEE].
Error Mechanisms

• **Average Duration of a Fade**

\[
ADF = \frac{\sqrt{2\pi} \left[ e^{R^2} - 1 \right]}{\beta v R}
\]

- Fade depth (ratio of RMS in dB)
- Depends on \( f \), Speed of mobile (m/s)

• **Some examples:**
  - 900 MHz, 50 km/hr -- undergoes ave fade depth of 20 dB
  - ADF = 0.962 ms
  - 0.5 m/s, ADF becomes 26.7 ms
  - Portables reside in fades for much longer time periods
  - Renders FEC techniques inoperative
Error Mechanisms

- **Average Duration of a Fade (approximation)**

\[ \tau(R) = \frac{\lambda}{v} \frac{\rho}{\sqrt{2\pi}} \quad \rho = \frac{R}{R_{\text{RMS}}} \]

- **Some examples:**

<table>
<thead>
<tr>
<th>Frequency (Mhz)</th>
<th>Wavelength</th>
<th>Avg Duration of Fade (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>0.33</td>
<td>0.957</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>Speed (m/s)</td>
<td>Rho</td>
</tr>
<tr>
<td>50</td>
<td>13.9</td>
<td>0.1</td>
</tr>
<tr>
<td>-20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (Mhz)</th>
<th>Wavelength</th>
<th>Avg Duration of Fade (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>0.33</td>
<td>23.94</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>Speed (m/s)</td>
<td>Rho</td>
</tr>
<tr>
<td>2</td>
<td>0.56</td>
<td>0.1</td>
</tr>
<tr>
<td>-20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (Mhz)</th>
<th>Wavelength</th>
<th>Avg Duration of Fade (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>900</td>
<td>0.33</td>
<td>6.308</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>Speed (m/s)</td>
<td>Rho</td>
</tr>
<tr>
<td>24</td>
<td>6.67</td>
<td>0.32</td>
</tr>
<tr>
<td>-10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Error Mechanisms

• Strategies for Overcoming Errors
  – Antenna diversity (+10 dB)
    » Dual antennas placed a λ/2 separation
  – Forward error correction (FEC)
    » Improve fade margin through coding gain
    » Coding gain = signal energy per bit-to-noise ratio required to attain a particular error rate with and without coding
    » Not very effective in slowly varying radio channels
    » Block vs. Convolutional Codes, Interleaved vs. Non-Interleaved
  – Automatic Repeat Request (ARQ)
    » Retransmission protocol for blocks in error
    » Stop and Wait, Go Back N, Selective Repeat
4. Picocell path loss models

Base station antenna located inside building
4.1 Empirical model

Propagation within buildings

Wall and floor factor models [1]

Characterize indoor path loss by:

- a fixed exponent of 2 (as in free space) + additional loss factors relating to number of floors \( n_f \) and walls \( n_w \) intersected by the straight-line distance \( r \) between terminals

\[
L = L_I + 20 \log r + n_f \ a_f + n_w \ a_w
\]

- \( a_f \) = attenuation factor per floor
- \( a_w \) = attenuation factor per wall
- \( L_I \) = reference path loss at \( r = 1 \) m
Wall and floor factor models - ITU-R models. [1]

⇒ Similar approach except:

- only floor loss is accounted explicitly

- loss between points on same floor included implicitly by changing path loss exponent

\[ L_T = 20 \log_{10} f_c [\text{MHz}] + 10 n \log_{10} r [\text{m}] + L_f(n_f) - 28 \]
Wall and floor factor models - ITU-R models cont.

\[ L_T = 20 \log_{10} f_c [\text{MHz}] + 10n \log_{10} r [\text{m}] + L_f (n_f) - 28 \]

Table 13.1: Path loss exponents \( n \) for the ITU-R model (13.2)*

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Residential</th>
<th>Office</th>
<th>Commercial</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td></td>
<td>3.3</td>
<td>2.0</td>
</tr>
<tr>
<td>1.2–1.3</td>
<td></td>
<td>3.2</td>
<td>2.2</td>
</tr>
<tr>
<td>1.8–2.0</td>
<td>2.8</td>
<td>3.0</td>
<td>2.2</td>
</tr>
<tr>
<td>4.0</td>
<td></td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>60.0</td>
<td></td>
<td>2.2</td>
<td>1.7</td>
</tr>
</tbody>
</table>

*The 60 GHz figures apply only within a single room for distances less than around 100 m, since no wall transmission loss or gaseous absorption is included.

Table 13.2: Floor penetration factors, \( L_f (n_f) [\text{dB}] \) for the ITU-R model (13.2)*

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential</td>
</tr>
<tr>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1.8–2.0</td>
<td>4 ( n_f )</td>
</tr>
</tbody>
</table>

*Note that the penetration loss may be overestimated for large numbers of floors, for reasons described in Section 13.4.1. Values for other frequencies are not given.
4.2 Semi-empirical model

Propagation into buildings

COST231 line-of-sight model [1]

Total path loss: $L_T = L_F + L_e + L_g (1 - \cos \theta)^2 + \max(L_1, L_2)$

$L_F$ = free space loss for total path length $(r_i + r_e)$
$L_e$ = path loss through external wall at normal incidence ($\theta = 0^\circ$)
$L_g$ = additional external wall loss incurred at grazing incidence ($\theta = 90^\circ$)

$L_1 = n_w L_i \text{ and } L_2 = \alpha (r_i - 2)(1 - \cos \theta)^2$

$N_w$ = number of wall crossed by the internal path $r_i$
$L_i$ = loss per internal wall

$\alpha$ = specific attenuation which applies for unobstructed internal path
COST231 line-of-sight model cont.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Material</th>
<th>Approximate value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_e$ or $L_l$ [dB m$^{-1}$]</td>
<td>Wooden walls</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Concrete with</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>non-metallised windows</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Concrete without windows</td>
<td>10–20</td>
</tr>
<tr>
<td>$L_s$ [dB]</td>
<td>Unspecified</td>
<td>20</td>
</tr>
<tr>
<td>$\alpha$ [dB m$^{-1}$]</td>
<td>Unspecified</td>
<td>0.6</td>
</tr>
</tbody>
</table>
5. Conclusion

Empirical models:
- not always accurate enough
- can be used only over parameter ranges included in the original measurement set

Deterministic models:
- require an enormous amount of data to describe fully the cover area
- very important computational effort
Adjusting Antenna to Reduce Co-Channel Interference

- lowering antenna (effective in a valley but not in a hill)
- tilting down antenna
- umbrella antenna pattern
Typical Ways to Overcome Fading

- diversity, which may be the most useful technique
- equalization
- forward error correcting codes and interleaving
- increasing power
- RAKE receiver
Doppler effect

- The receiver moves with constant velocity $v$ relative to source $S$.
- Path lengths to $X$ and $Y$ differ by $\Delta l = d \cos \theta = v \Delta t \cos \theta$.
- Phase change in received signal is $\Delta \phi = \frac{2\pi \Delta l}{\lambda}$.
- Doppler shift (apparent frequency change) is then $f_d = \frac{1}{2\pi} \frac{\Delta \phi}{\Delta t} = \frac{v}{\lambda} \cos \theta$. 
Choices for Base Antenna Location:

- **At Average Building Height**
  - Cheap (licensing, site availability, zoning)
  - Limits range of antennae

- **Above Average Building Height**
  - Expensive
  - Best reception (least occlusion) (closest to LOS)

- **Below Building Height**
  - Cheapest
  - Increases in Network capacity from smaller cells
Antenna Height and Coverage:

- Base antenna height has a strong effect on coverage patterns (8 m Bldg)

(a) Antenna=6 m

(b) Antenna=10 m

- $0 - 120$ dB
- $120 - 130$ dB
- $130 - 140$ dB
Detailed path loss modelling for antenna mounting height:
• Near Rooftop

\[ L = 40 \log(R) + 30 \log(f) + 49 \text{ dB} \]

• Above Rooftop

\[ L = 38 \log(R) + 21 \log(f) - 18 \log(\Delta h_b) + 71.7 \text{ dB} \]

• Below Rooftop

\[ L = 40 \log(R) + 40 \log(f) + 35 \text{ dB} \]

• Line of Sight (LOS)

- 20 dB/decade \( R \) and 20 dB/decade \( f \)
**Homework:**

1) What are the advantages and defaults of empirical models, what is the most widely used empirical model?

2) Using the ITU-R model, calculate the path loss at 0.9 GHz in an office environment, where the distance between Tx and Rx is 10 m, and they are separated by 1 floor.