(1)

Mobile Radio Propogation

Large-Scale Path Loss:

Modeling the radio channel is typically done in a statistical fashion, based on measurements made specifically for an intended communication system or spectrum allocation.

Radio Wave Propogation:

- Propogation models have traditionally focused on predicting the average received signal strength at a given distance from the transmitter, as well as the variability of the signal strength in close proximity to a particular location

large scale propogation models:

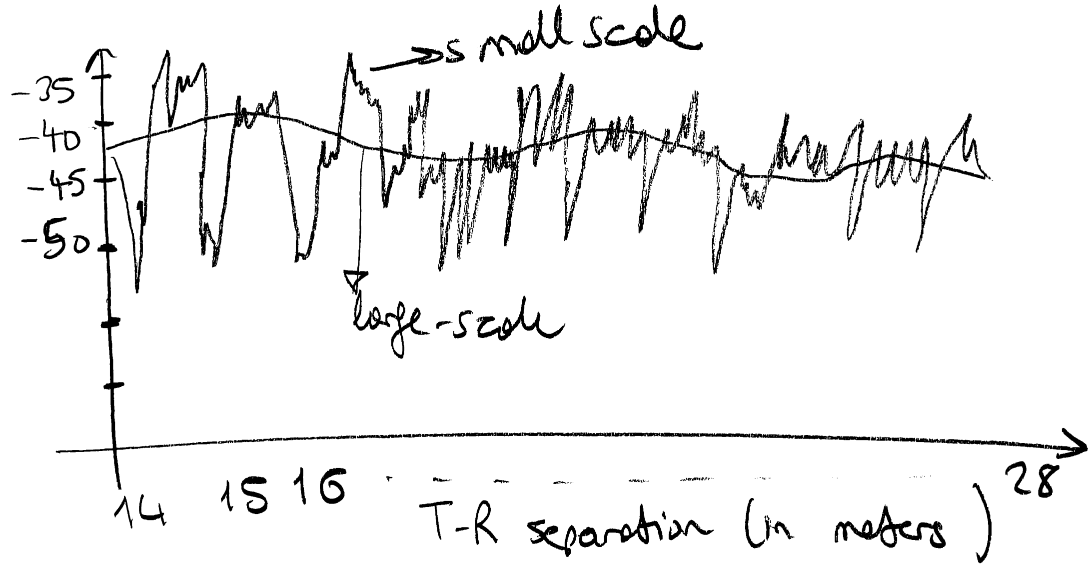
Propogation models that predict the mean signal strength for an arbitrary transmitter-receiver separation distance are useful in estimating the radio coverage area of a transmitter and are called large-scale propogation models.

2

small-scale fading models:

propagation models that characterize the rapid fluctuations of the received signal strength over very short travel distances (a few wavelengths) or short time durations (on the order of seconds) are called small-scale or fading models.

Ex:



In this ~~lecture~~ large-scale propagation models will be studied.

Free Space Propagation Model:

- The free space propagation model is used to predict received signal strength when the transmitter and receiver have a clear, un-obstructed line-of-sight path between them

(3)

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$ → Friis free space equation

P_t → transmitted power

$P_r(d)$ → received power at distance d

G_t → transmitter antenna gain

G_r → receiver antenna gain

d → T-R separation in meters

L → system loss factor not related to propagation ($L \geq 1$) ($L = 1$ indicates no loss in the system hardware)

λ → wavelength in meters

Gain of the antenna is related to its effective aperture, A_e, by

$$G = \frac{4\pi A_e}{\lambda^2}$$

A_e is related to the physical size of the antenna

λ is related to the carrier frequency by

$$\lambda = \frac{c}{f_c} = \frac{2\pi c}{w_c}$$

$$w_c = 2\pi f_c$$

c → speed of light

f_c → carrier frequency in Hertz

w_c → " " " radians per second

G_t, G_r → are dimensionless

Path Loss:

The path loss for the free space model when antenna gains are included is given by

$$PL(dB) = 10\log\frac{P_t}{P_r} = -10\log\left[\frac{G_t G_r \lambda^2}{(4\pi)^2 d^2}\right]$$

Fraunhofer distance (Far-Field):

$$d_f = \frac{2D^2}{\lambda}$$ $D \rightarrow$ is the largest physical dimension of the antenna

The Friis free space model is valid for values of d which are in the far-field of the transmitting antenna.

To be in the far-field region, d_f must satisfy

$$d_f \gg D \rightarrow \frac{2D^2}{\lambda} \gg D \rightarrow D \gg \frac{\lambda}{2}$$

$$d_f \gg \lambda$$

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

$$P_r(d_0) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_0^2 L}$$

$\rightarrow$ Take ratio

$$\frac{P_r(d)}{P_r(d_0)} = \left(\frac{d_0}{d}\right)^2 \quad d \geq d_0 \geq d_f$$

5

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^2 \quad d \geq d_0 \geq d_f$$

$$\downarrow$$

$$10\log\left(\frac{P_r(d)}{0.001}\right) = 10\log\left(P_r(d_0)\left(\frac{d_0}{d}\right)^2 \cdot \frac{1}{0.001}\right)$$

$$P_r(d)\,dBm = 10\log\left(\frac{P_r(d_0)}{0.001W}\right) + 20\log\left(\frac{d_0}{d}\right) \quad d \geq d_0 \geq d_f$$

$P_r(d_0)$ → in Watts

$P_r(d)\,dBm$ ↓ expressed in mili-decibel

The reference distance d_0 for practical systems using low gain antennas in the 1-2 GHz region is typically chosen to be 1m in indoor environments and 100m or 1km in outdoor environments.

Ex 3: Find d_f for an antenna with maximum dimension of 1m and operating frequency of 900 MHz

S/n: $D = 1m \quad f_c = 900 MHz \quad \lambda = \frac{c}{f} \rightarrow \lambda = \frac{3\times10^8}{900\times10^6}$

$\rightarrow \lambda = \frac{1}{3} m$

$$d_f = \frac{2D^2}{\lambda} \rightarrow d_f = \frac{2}{1/3} = 6m$$

$d_f \gg D$ ✓ $\quad d_f \gg \lambda$ ✓

Ex:

$P_t = 50 \text{watts}$

Express P_t in dB and dBm

S/n:

$$P_t(\text{dBm}) = 10\log\left(\frac{P_t(\text{mW})}{1\text{mW}}\right)$$

$$= 10\log\left(\frac{50\times10^3\,\text{mW}}{1\text{mW}}\right)$$

$$= 47.0\,\text{dBm}$$

$$P_t(\text{dBW}) = 10\log\left(\frac{P_t(\text{W})}{1\text{W}}\right)$$

$$= 10\log 50$$

$$= 17.0\,\text{dBW}$$

Ex:

$P_t = 50 \text{watts}$ $\quad G_t = G_r = 1 \quad L = 1$

$f_c = 900\text{MHz}$

Find $P_r(d)$ $\quad$ a) $d = 100\text{m}$

b) $d = 10\text{km}$

S/n:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

a)

$$= \frac{50 \cdot 1 \cdot 1 \cdot (1/3)^2}{(4\pi)^2 \cdot 100^2 \cdot 1}$$

$$= 3.5\times10^{-6}\,\text{W}$$

(7) $P_r = 3.5\times10^{-6}\,W$

$= 3.5\times10^{-3}\,mW$

$P_r(dBm) = 10\log P_r(mW)$

$= 10\log(3.5\times10^{-3}\,mW)$

$= -24.5\,dBm$

b) $\underset{dBm}{P_r(d)} = \underbrace{P_r(d_0)}_{dBm} + 20\log\left(\frac{d_0}{d}\right)$

$P_r(10km) = -24.5dBm + 20\log\left(\frac{100}{10.000}\right)$

$= -24.5dBm - 40dB$

$= -64.5dBm$

The effective isotropic radiated power (EIRP)

$EIRP = P_t G_t$

represents the maximum radiated power available from a transmitter in the direction of maximum antenna gain

Power flux density P_d (W/m2) is given as

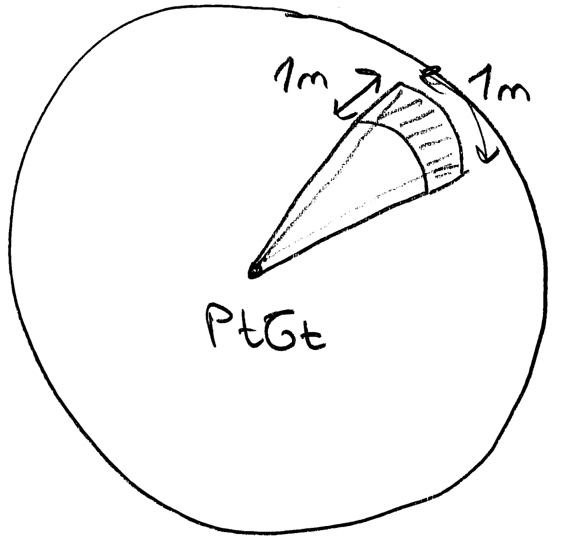
$P_d = \frac{EIRP}{4\pi d^2} \rightarrow P_d = \frac{P_t G_t}{4\pi d^2} = \frac{E^2}{\eta}$ $\quad \eta = 120\pi\,\Omega$
$= 377\,\Omega$

(8)

$$P_d = \frac{|E|^2}{377\Omega} \ \text{w/m}^2$$

$|E| \rightarrow$ magnitude of the radiating portion of the electric field in the far-field.

$$P_r(d) = P_d A_e$$
$$= \frac{|E|^2}{120\pi} A_e$$
$$= \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2}$$



Three Basic Propogation Mechanisms:

Reflection, diffraction, and scattering are the three basic propogation mechanisms which impact propogation in a mobile communication system.

- Reflection occurs when a propogating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propogating wave.

- Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that has sharp irregularities.

9

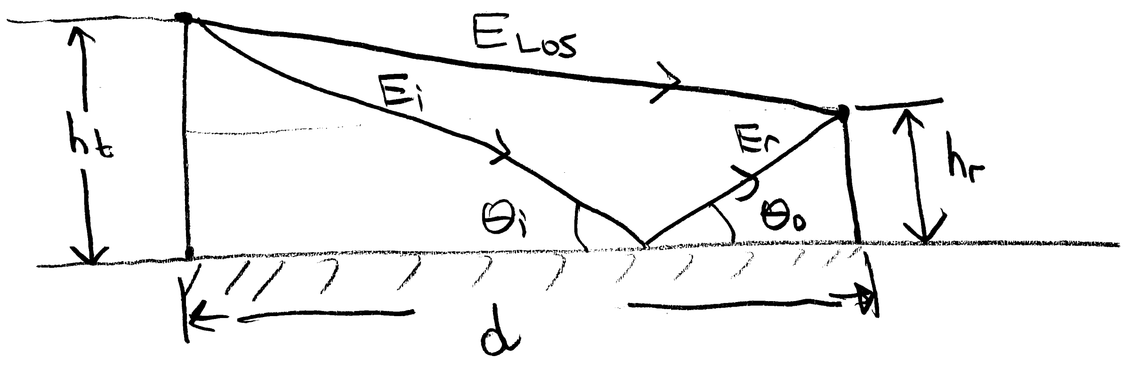
The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line-of-sight path does not exist between the transmitter and receiver.

- Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large

Note: Electromagnetic energy cannot pass through a perfect conductor a plane wave incident on a conductor has all of its energy reflected

Ground Reflection (2-ray Model)

This model has been found to be reasonably accurate for predicting the large-scale signal strength over distances of several kilometers for mobile radio systems that use tall towers (over 50m), as well as LOS microcell channels in urban environments.



10

If E_0 is the free space E-field at a reference d_0 from the transmitter, then for $d > d_0$ the free space propagating E-field is given by

$$E(d,t) = \frac{E_0 d_0}{d} \cos\left(\omega_c\left(t - \frac{d}{c}\right)\right) \quad d > d_0$$

$|E(d,t)| = E_0 \frac{d_0}{d}$ represents the envelope of the E-field at d meters from the transmitter

For 2-ray model

The received power at a distance d from the transmitter can be expressed as

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

The path loss for the 2-ray model can be expressed in dB as

$$PL(dB) = 40\log d - (10\log G_t + 10\log G_r + 20\log h_t + 20\log h_r)$$

Path Loss Models

By using path loss models to estimate the received signal level as a function of distance, it becomes possible to predict the SNR for a mobile communication system

11

– Long Distance Path Loss Model:

Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance whether in outdoor or indoor radio channels.

The average large-scale path loss for an arbitrary T-R separation is expressed as

$$\overline{PL}(d) \propto \left(\frac{d}{d_0}\right)^n$$

or

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

$n \rightarrow$ path loss exponent

$d_0 \rightarrow$ close-in reference distance

$d \rightarrow$ T-R separation

– Log-normal Shadowing:

Equation (A) is not valid for every environment. Measurements have shown that at any value of d the path loss $PL(d)$ at a particular location is random and distributed log-normally (normal in dB) about the mean distance dependent value

That is

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

and

$$P_r(d)(dBm) = P_t(dBm) - PL(d)(dB)$$

$X_\sigma \rightarrow$ zero-mean Gaussian distributed RV in dB with standard deviation σ (also in dB)

- Simply put, log-normal shadowing implies that measured signal levels at a specific T-R separation have Normal distribution about the distance dependent mean of eqn. (A) where the measured signal levels have values in dB units.

- The log-normal distribution describes the random shadowing effects which occur over a large number of measurement locations which have the same T-R separation, but have different levels of clutter on the propagation path. This phenomenon is referred to as log-normal shadowing

(13) Since $PL(d)$ is a random variable with a normal distribution in dB about $\overline{PL}(d)$, so is $P_r(d)$.

The prob. that the received signal level will exceed a certain value z can be calculated from the cumulative density function of

$$P_r\left(P_r(d) > z\right) = Q\left(\frac{z - \overline{P_r}(d)}{\sigma}\right)$$

where
$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} \exp\left(-\frac{x^2}{2}\right) dx$$
$$= \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{z}{\sqrt{2}}\right)\right]$$

$$Q(z) = 1 - Q(-z)$$

Similarly
$$P_r\left(P_r(d) < z\right) = Q\left(\frac{\overline{P_r}(d) - z}{\sigma}\right)$$

Note: $\mathrm{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^{z} e^{-x^2} dx$ → error function

$\mathrm{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_z^{\infty} e^{-x^2} dx$ → complementary error function

14

$$\mathrm{erfc}(z) = 1 - \mathrm{erf}(z)$$

$$Q(z) = \int_z^{\infty} \frac{1}{\sqrt{2\pi}} e^{-y^2/2} \, dy$$

$$Q(z) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{z}{\sqrt{2}}\right)\right] = \frac{1}{2} \mathrm{erfc}\left(\frac{z}{\sqrt{2}}\right)$$

$$\mathrm{erfc}(z) = 2Q\left(\sqrt{2}\, z\right)$$

$$\mathrm{erf}(z) = 1 - 2Q\left(\sqrt{2}\, z\right)$$

Determination of Percentage of Coverage Area:

- It is clear that due to random effects of shadowing some locations within a coverage area will be below a particular desired received.
- It is often useful to compute how the boundary coverage relates to the percent of area covered within the boundary

Let R be radius of a circular coverage area from the base station

$\gamma \rightarrow$ desired received signal threshold

$U(\gamma) \rightarrow$ the percentage of area with a received signal that is equal or greater than γ

(15)

Let $d=r$ be the radial distance from the transmitter

$$U(\gamma)=\frac{1}{\pi R^2}\int \text{Prob}\{P_r(r)>\gamma\}\, dA$$

is the prob. that the random received signal at $d=r$ exceeds the threshold γ within an incremental area dA

$$U(\gamma)=\frac{1}{\pi R^2}\int_0^{2\pi}\int_0^{R} \text{Prob}\{P_r(r)>\gamma\}\, \overbrace{r\,dr\,d\theta}^{dA}$$

We know that $\text{Prob}\{P_r(r)>\gamma\}=Q\left(\dfrac{\gamma-\overline{P_r(r)}}{\sigma}\right)$

$$=\frac{1}{2}-\frac{1}{2}\,\text{erf}\left(\frac{\gamma-\overline{P_r(r)}}{\sigma\sqrt{2}}\right)$$

$$=\frac{1}{2}-\frac{1}{2}\,\text{erf}\left(\frac{\gamma-(P_t-(\overline{PL}(d_0)+10\,n\log(r/d_0)))}{\sigma\sqrt{2}}\right)$$

(A)

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

which is written as $\overline{PL}(r)=10\,n\log\left(\frac{R}{d_0}\right)+10\,n\log\left(\frac{r}{R}\right)$

$+\overline{PL}(d_0)$

16

and using eqn (A)

$$\text{Prob}\{P_r(r) > \gamma\} = \frac{1}{2} - \frac{1}{2}\,\text{erf}\left[\frac{\gamma - [P_t - (\overline{PL}(d_0) + 10n\log(R/d_0) + 10n\log(\frac{r}{R})]}{\sigma\sqrt{2}}\right]$$

Let $a = (\gamma - P_t + \overline{PL}(d_0) + 10n\log(R/d_0)) / \sigma\sqrt{2}$

and $b = (10n\log e) / \sigma\sqrt{2}$

then

$$U(\gamma) = \frac{1}{2} - \frac{1}{R^2}\int_0^R r\,\text{erf}\left(a + b\ln\frac{r}{R}\right)dr$$

by substituting $t = a + b\log\left(\frac{r}{R}\right)$ in the above equation

It can be shown that

$$\text{(B)} \quad U(\gamma) = \frac{1}{2}\left[1 - \text{erf}(a) + \exp\left(\frac{1-2ab}{b^2}\right)\left(1 - \text{erf}\left(\frac{1-ab}{b}\right)\right)\right]$$

By choosing the signal level such that $\overline{P_r}(R) = \gamma$

(i.e., $a = 0$)

$U(\gamma)$ can be shown to be

$$U(\gamma) = \frac{1}{2}\left[1 + \exp\left(\frac{1}{b^2}\right)\left(1 - \text{erf}\left(\frac{1}{b}\right)\right)\right]$$

Eqn. (B) can be evaluated for large values of σ and n.

Ex: The average large-scale path loss for an arbitrary T-R separation is

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

Let $d_o = 100m$ & $\overline{PL}(d_o) = 0dB$ $n = 4.4$

Find $\overline{PL}(dB)$ at $d = 2km$ $P_r(d_o) = 0$ dB.

Sln:

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

$$= 0 + 10 \times 4.4 \log\left(\frac{2000}{100}\right)$$

$$= 57.24dB$$

Note: $P_r(d)\,dBm = P_r(d_o)\,dBm + 10\log\left(\frac{d_o}{d}\right)^n$

$$= P_r(d_o)\,dBm - 10n\log\frac{d}{d_o}\ dB$$

$$\boxed{P_r(d)\,dBm = P_r(d_o)\,dBm - 10n\log\frac{d}{d_o}}$$

(18) Summary of the formulas:

$$PL(dB) = 10\log\frac{P_t}{P_r}$$

$$P_r(d) = P_r(d_0)\left(\frac{d_0}{d}\right)^n \qquad n=2 \quad d \geq d_0 \geq d_f$$

$$P_r(d)\,dBm = P_r(d_0)\,dBm - 10n\lg\left(\frac{d}{d_0}\right)$$

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

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

$$X_\sigma \sim N(0,\sigma^2)$$

$$P_r(d)\,dBm = P_t(dBm) - PL(d)\,dB$$

Ex:

Distance From Transmitter	Received Power
100m	0 dBm
200m	-20 dBm
1000m	-35 dBm
3000m	-70 dBm

$n = 4.4$

a) The received power wrt. distance is given above estimate the received powers taking reference $d_0 = 100m$

b) Compute the variance between estimated and measured values

(19)

Slno

$$Pr(d)_{dBm} = Pr(d_0)\, dBm - 10n\log\left(\frac{d}{d_0}\right)$$

$$\hat{P}_i = P(d_0) - 10n\log\frac{d_i}{100m} \qquad d_0 = 100m$$

a) $P(d_0) = 0\, dBm$ → use as a reference

$\hat{P}_1 = 0$ $\quad \hat{P}_2 = -3n$ $\quad \hat{P}_3 = -10n$ $\quad \hat{P}_4 = -14.77n$

$\hat{P}_1 = 0\, dBm$ $\quad \hat{P}_2 = -13.2\, dBm$ $\quad \hat{P}_3 = -44\, dBm$ $\quad \hat{P}_3 = -64.988\, dBm$

b) The received power

$P_1 = 0\, dBm$ $\quad P_2 = -20\, dBm$ $\quad P_3 = -35\, dBm$ $\quad P_3 = -70\, dBm$

The estimated received power

$\hat{P}_1 = 0\, dBm$ $\quad \hat{P}_2 = -13.2\, dBm$ $\quad \hat{P}_3 = -44\, dBm$ $\quad \hat{P}_3 = -64.988\, dBm$

Variance between estimated and measured values

is

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}(P_i - \hat{P}_i)^2 \qquad N = 4$$

$$\sigma^2 = \frac{1}{4}\left[(0+0) + (-20+13.2)^2 + (-35+44)^2 + (-70+64.98)^2\right]$$

$$= 38.09 \longrightarrow \boxed{\sigma = 6.17\, dB}$$

Ex: For the previous example estimate the received power at $d = 2km$ and predict the likelihood that the received signal level at 2km will be greater than $-60 dBm$

Slne

$$\bar{P}(d = 2km) = 0 - 10(4.4)\log\left(\frac{2000}{100}\right)$$

$$= -57.24 \ dBm$$

1)

A Gaussian R.V. having zero mean and $\sigma = 6.17$ could be added to this value to simulate random shadowing effects at $d = 2km$

2) The prob. that the received signal level will be greater than $-60 dBm$ is given by

$$Prob\{P_r(d) > -60 dBm\} = Q\left(\frac{\gamma - \overline{P_r(d)}}{\sigma}\right)$$

$$= Q\left(\frac{-60 + 57.24}{6.17}\right)$$

$$= 0.6727$$

$$= 67.3\ \%$$

(21)

Ex:

$R = 600\,m$ → Cell radius

$P_t = 100\,mW$ → Base station transmit power

$= 20\,dBm$

$n = 3.7$

$\gamma = P_{min} = -110\,dBm$ → Minimum received power requirements

$\gamma = P_{min} = -120\,dBm$

$\sqrt{2}.\sigma = 3.65\,dB$ $\overline{PL(d_0)} = + 31.54\,dB$ $d_0 = 1m$

Find the coverage area for a cell with the combined path-loss and shadowing models.

Sln:

$$\overline{P_r(R)} = P_t(dBm) - PL(d)\,dB$$

$$= P_t(dBm) - \overline{PL}(d_0) - 10\,n \log\left(\frac{d}{d_0}\right)$$

$$= 20 - 31.54 - 37.1 \log_{10} \frac{600}{1}$$

$$= -114.6\,dBm \neq \underbrace{-110\,dBm}_{P_{min}}$$

So we use

$$U(\gamma) = \frac{1}{2}\left[1 - erf(a) + exp\left(\frac{1-2ab}{b^2}\right)\left(1 - erf\left(\frac{1-ab}{b}\right)\right)\right]$$

$$a = \left(\overset{\gamma}{P_{min}} - P_t + \overline{P_L}(d_0) + 10\,n \log(d/d_0)\right) / \sigma\sqrt{2} \quad d = R$$

22

$$a = \left(\frac{-110 + 114.6}{3.65} \right)$$

$a = 1.26$

$$b = \left(\frac{10 n \log e}{\sigma \sqrt{2}} \right)$$

$$b = \frac{10 \times 3.7 \log e}{365}$$

$b = 4.41$

$$U(\gamma) = \frac{1}{2}\left[1 - \mathrm{erf}(a) + \exp\left(\frac{1 - 2ab}{b^2} \right)\left(1 - \mathrm{erf}\left(\frac{1 - ab}{b} \right) \right) \right]$$

$\gamma \downarrow P_{min} \downarrow -110\,dBm$

$= 0.58$

For $\gamma = P_{min} = -120\,dBm$

$U(\gamma) = 0.988 \rightarrow 98\%$ are covered.

a much more acceptable value for coverage area.

Outdoor Propogation Models:

- Radio transmission in a mobile communications system often takes place over irregular terrain. The terrain profile of a particular area needs to be taken into account for estimating the path loss. The terrain profile may vary from a simple curved earth profile to a highly mountainous profile.

A number of propogation models are available to predict path loss over irregular terrain.
↳ bölge, arazi

Most of these models are based on a systematic interpretation of measurement data obtained in the service area.

Some outdoor propogation models are:

1. Longley-Rice Model

This model is available as a computer program to calculate large-scale median transmission loss relative to free space loss over irregular terrain for frequencies between 20 MHz and 10 GHz. The program takes as input the transmission freq.

(24)

path length, polarization, antenna heights, surface refractivity, effective radius of earth ground conductivity, ground dielectric constant and climate.

2. Durkin's Model (Reading Assignment
Rappaport, Wireless Communications)

3. Okumura Model:

It is one of the most widely used models for signal prediction in urban areas
kentsel

applicable for frequencies in the range 150MHz - 1920 MHz
" " distances in the range 1km to 100km

can be used for base station antenna heights ranging from 30m to 1000m

- Okumura's model is wholly based on measured data and does not provide any analytical explanation.
- Okumura's model is considered to be among the simplest and best in terms of accuracy in path loss prediction
- The model is fairly good in urban and suburban areas, but not as good as in rural areas.
kırsal, köy

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

L_{50} → median value of propagation path loss

L_F → free space propagation loss

A_{mu} → median attenuation relative to free space

$G(h_{te})$ → base station antenna height gain factor

$G(h_{re})$ → mobile antenna height gain factor

G_{AREA} → gain due to the type of environment

Graphs of $A_{mu}(f,d)$ and G_{AREA} for a wide range of frequencies are available (see pg 117 Rappaport)

$$G(te) = 20\log\left(\frac{hte}{200}\right) \quad 1000_m > hte > 30_m$$

$$G(h_{re}) = 10\log\left(\frac{hre}{3}\right) \quad hre \leq 3m$$

$$G(h_{re}) = 20\log\left(\frac{hre}{3}\right) \quad 10m > hre > 3m$$

(26)

Ex:

Find the median path loss using Okumura's model

$d = 50\,km \quad h_{te} = 100\,m \quad h_{re} = 10\,m$

$EIRP = 1\,kW \quad f_c = 900\,MHz$.

Find the power at receiver (assume a unity gain receiving antenna)

S/n:

$$PL(dB) = 10\log\frac{P_t}{P_r}$$

$$= -10\log\frac{\overset{1}{G_t}\,\overset{1}{G_r}\,\lambda^2}{(4\pi)^2 d^2}$$

$$= -10\log\frac{\lambda^2}{(4\pi)^2 d^2}$$

$$L_F = 10\log\left(\frac{\lambda^2}{(4\pi)^2 d^2}\right) = 10\log\left(\frac{(3\times10^8/900\times10^6)^2}{(4\pi)^2\,(50\times10^3)^2}\right)$$

$$= 125.5\,dB$$

From Okumura curves

$A_{mu}(900\,MHz, 50\,km) = 43\,dB$

and $G_{AREA} = 9\,dB$

$$G(h_{te}) = 20\log\left(\frac{\overset{100}{h_{te}}}{200}\right) = -6\,dB$$

$$G(h_{re}) = 20\log\left(\frac{\overset{10}{h_{re}}}{200}\right) = 10.46\,dB$$

(27)

The total mean path loss is

$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

$$= 125.5\,dB + 43\,dB - (-6)\,dB - 10.46\,dB - 9\,dB$$

$$= 155.04\,dB$$

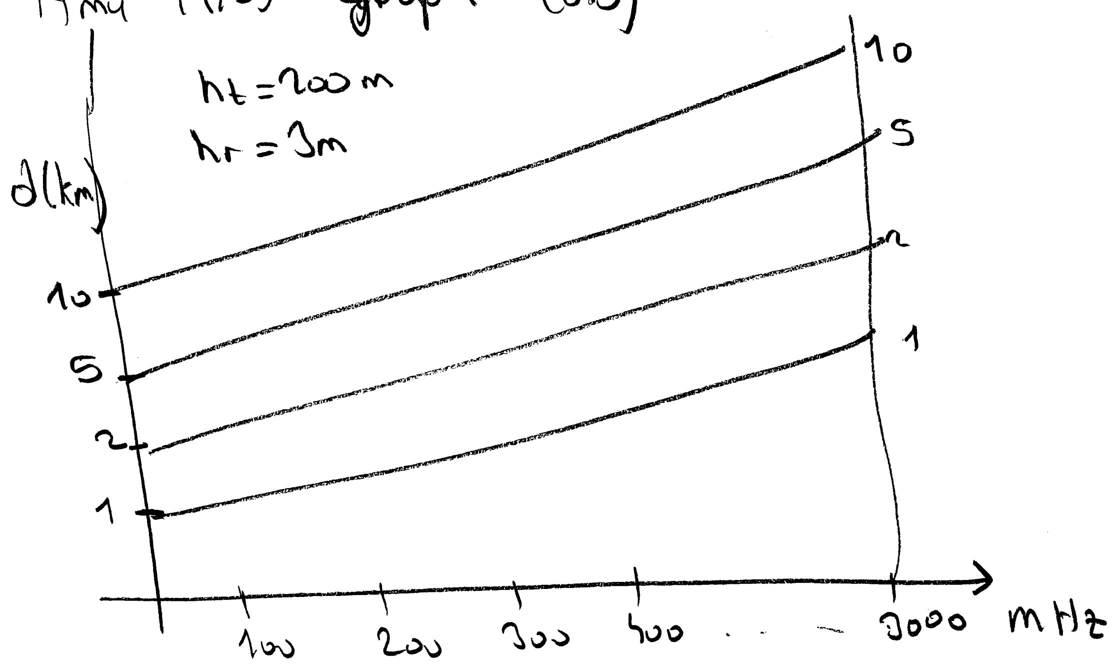
The median received power is

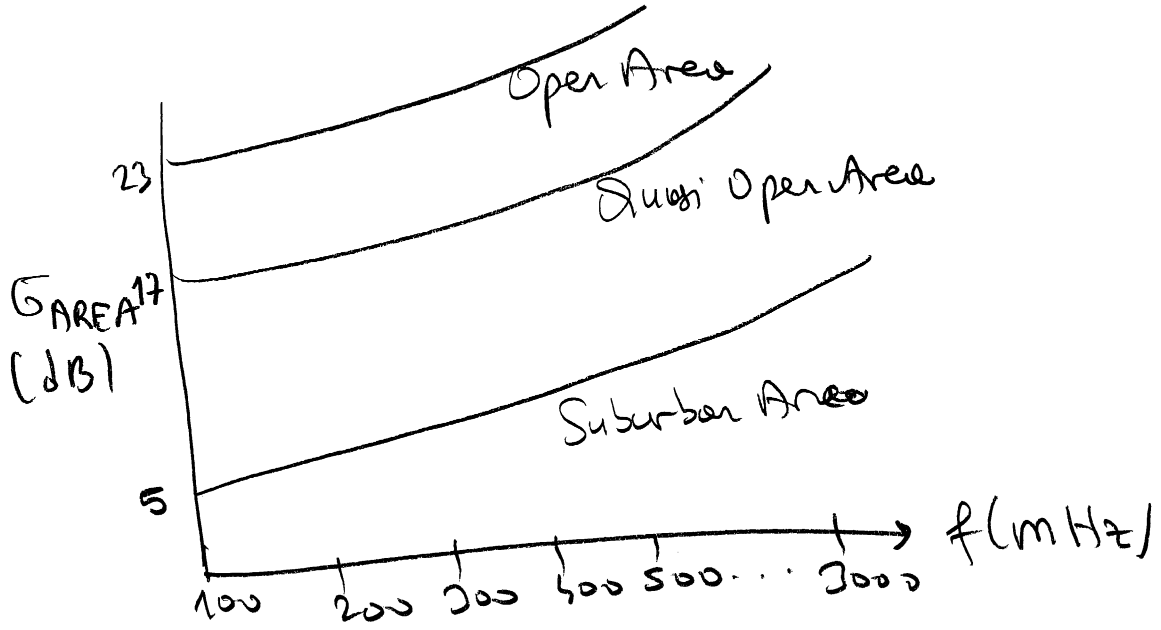
$$P_r(d) = \overset{P_t}{EIRP}(dBm) - L_{50}(dB) + G_r(dB)$$

$$= 60\,dBm - 155.04\,dB + 0\,dB$$

$$= -95.04\,dBm$$

$A_{mu}(f,d)$ Graph (dB)





G_{AREA} Graph for Okumura Model

Hata Models:

Median path loss in urban areas is given by

$$L_{50}(\text{urban})\,dB = 69.55 + 26.16 \log f_c - 13.82 \log h_{te} - a(h_{re}) + (44.9 - 6.55 \log h_{te}) \log d$$

$f_c \rightarrow$ carrier frequency in the range 150MHz–1500MHz

$h_{te} \rightarrow$ effective transmitter antenna height (in meters) ranging from 30m to 200m

$h_{re} \rightarrow$ effective receiver antenna height ranging from 1m to 10m

$d \rightarrow$ T-R separation distance (in km)

$a(h_{re}) \rightarrow$ correction factor which is a function of the size of the coverage area

For a medium sized city

$$a(h_{re}) = (1.1 \log f_c - 0.7) h_{re} - (1.56 \log f_c - 0.8) \text{ dB}$$

For a large city

$$a(h_{re}) = 8.29 (\log 1.54 h_{re})^2 - 1.1 \text{ dB} \quad f_c \leq 300 \text{MHz}$$

$$a(h_{re}) = 3.2 (\log 11.75 h_{re})^2 - 4.97 \text{ dB} \quad f_c \geq 300 \text{MHz}$$

For suburban areas

$$L_{50}(\text{dB}) = L_{50}(\text{urban}) - 2 [\log (f_c/28)]^2 - 5.4$$

For rural areas:

$$L_{50}(\text{dB}) = L_{50}(\text{urban}) - 4.78 (\log f_c)^2 + 18.33 \log f_c - 40.94$$

Hata model is well suited for large cell mobile systems, but not personal communication systems (PCS) which have cells on the order of 1km radius.

PCS extension to Hata Model:

COST-231 working committee developed an extended version of the Hata model

$$L_{50}(urban) = 46.3 + 33.9 \log f_c - 13.82 \log h_{te} - a(h_{re}) + (44.9 - 6.55 \log h_{te}) \log d + C_M$$

$$C_M = \begin{cases} 0 \text{ dB} & \text{for medium sized city and suburban areas} \\ 3 \text{ dB} & \text{for metropolitan centers} \end{cases}$$

Indoor Propagation Models:

The indoor radio channel differs from the traditional mobile radio channel in two aspects

1. The distances covered are much smaller, and the variability of the environment is much greater for a much smaller range of T-R separation
2. It has been observed that propagation within buildings is strongly influenced by specific features such as the layout of the building the construction material, and the building type

Indoor radio propagation is dominated by the same mechanisms of outdoor: reflection, diffraction, and scattering However, the conditions are much more variable

Some of the key models are given as follows:

Partition Losses (Same Floor)

Partitions that are formed as part of the building structure are called hard partitions, and partitions that may be moved and which do not span to the ceiling are called soft partitions

Researchers have formed extensive data bases of losses for a great number of partitions
See Table 3.3 in Rappaport

Material Type	Loss (dB)	Frequency
All metal	26	815 MHz
Concrete block wall	13	1300 MHz
Loss from one floor	20-30	1300 MHz
Light textile	3-5	1300 MHz
Dry plywood (3/4 in) 2 sheets	4	9.6 GHz
⋮	⋮	⋮

Partition losses between Floors:

The losses between floors of a building are determined by the external dimensions and materials of the building, as well as the type of construction used to create the floors and the external surroundings.

The attenuation between one floors of the building is greater than the incremental attenuation caused by each additional floor

	Building	(FAF) dB 915 MHz	LN	(FAF) dB 1800 MHz	LN
SF PacBell Building	One Floor	13.2	16	26.2	21
	Two Floors	18.1	10	33.4	21
	Three Floors	24.0	10	35.2	20
	Four Floors	27.0	10	38.4	20
	Five Floors	27.1	10	46.4	17

LN $\rightarrow$ Location Number
FAF $\rightarrow$ Floor attenuation factors

Path Loss Model for Indoor:

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

$n \rightarrow$ depend on the surroundings and building type

$X_\sigma \rightarrow$ normal R.V. in dB having standard deviation of σ dB

Signal Penetration into Buildings:

RF penetration has been found to be a function of frequency as well as height within the building.

Measurements showed that penetration loss decreases with increasing frequency

Ex:

Loss	Freq
16.4 dB	441 MHz
11.6 dB	896.5 MHz
7.6 dB	1400 MHz

↓ measurement in Liverpool

Loss	Freq
14.2 dB	900 MHz
13.4 dB	1800 MHz
12.8 dB	2300 MHz

↓ Measurements by Turkmani

- Measurements made in front of windows indicated 6 dB less penetration loss on average than did measurements made in parts of buildings without windows

- Walker measured radio signals into fourteen different buildings in Chicago from seven external cellular transmitters. Results showed that building penetration loss decreased at a rate of 1.9 dB per floor from the ground level up to the fifteenth floor and then began increasing above the fifteenth floor (due shadowing effects of adjacent buildings)