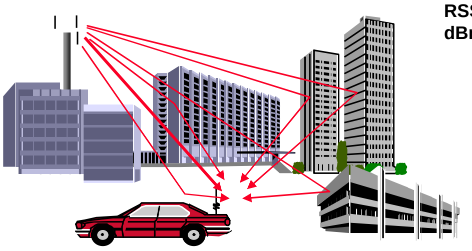
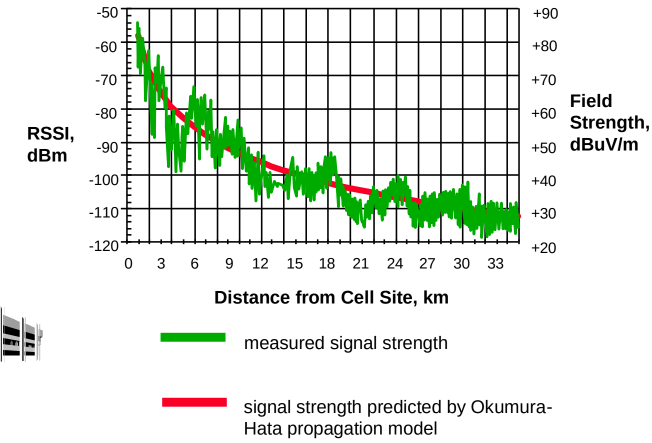
Chapter 4
Mobile Radio Propagation
(Large-scale Path Loss)

Multi-path Propagation

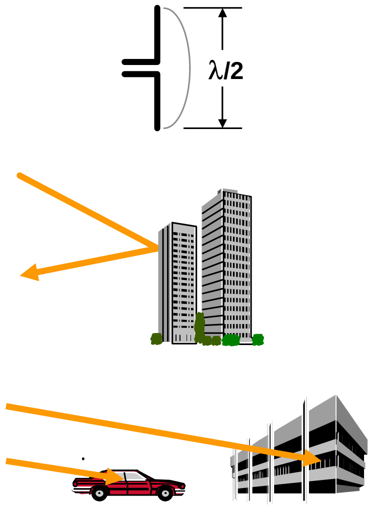




Objectives

- To refresh understanding of basic concepts and tools
- To discuss the basic philosophy of propagation prediction applicable to cellular systems
- To identify and explore key propagation modes and their signal decay characteristics
- To discuss the multi-path propagation environment, its effects, and a method of avoiding deep fades
- To survey key available statistical propagation models and become familiar with their basic inputs, processes, and outputs
- To understand application of statistical confidence levels to system propagation prediction
- To review and gain familiarity with general measurement and propagation prediction tools available commercially

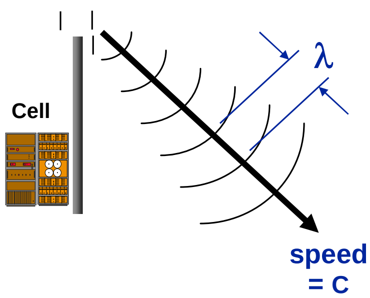
Wave Propagation Basics: Frequency and Wavelength



Wavelength is an important variable in RF propagation.

- **Wavelength determines the approximate required size of antenna elements.**
- **Objects bigger than roughly a wavelength can reflect or block RF energy.**
- **RF can penetrate into an enclosure if it has holes roughly a wavelength in size, or larger.**

Wave Propagation: Frequency and Wavelength



Examples:

AMPS cell site f = 870 MHz.
λ = 0.345 m = 13.6 inches

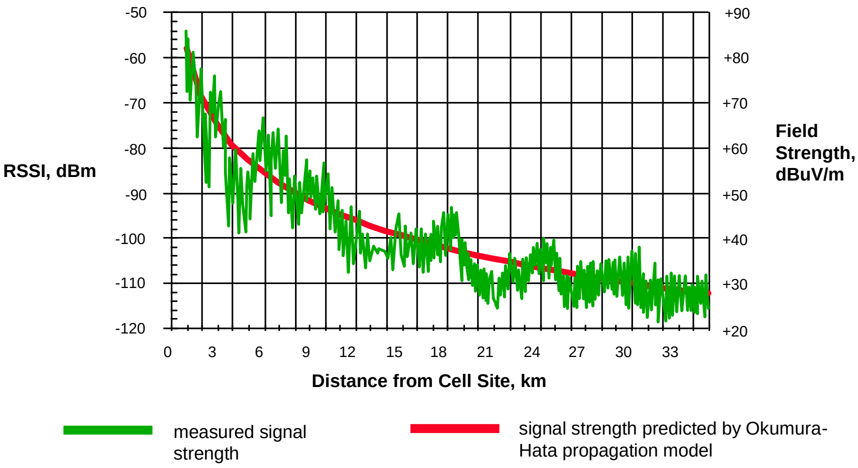
PCS-1900 site f = 1960 MHz.
λ = 0.153 m = 6.0 inches

- **Radio signals travel through empty space at the** speed of light (C)
  - **C** = 186,000 miles/second (300,000,000 meters/second)
- Frequency (F) **is the number of waves per second (unit: Hertz)**
- Wavelength (λ) **(length of one wave) is calculated:**
  - (distance traveled in one second) **/**(waves in one second)

$$\boxed{\lambda = C / F}$$

Statistical Propagation Models

- Prediction of Signal Strength as a function of distance without regard to obstructions or features of a specific propagation path



Radio Propagation

- **Mobile radio channel**
  - fundamental limitation on the performance of wireless communications.s
  - severely obstructed by building, mountain and foliage.
  - speed of motion
  - a statistical fashion
- **Radio wave propagation characteristics**
  - reflection, diffraction and scattering
  - no direct line -of-sight path in urban areas
  - multipath fading
- **Basic propagation types**
  - Propagation model: predict the average received signal strength
  - Large-scale fading: Shadowing fading
  - Small-scale fading: Multipath fading

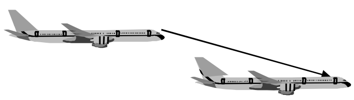
Propagation Model

- **To focus on predicting the average received signal strength at a given distance from the transmitter**
  - variability of the signal strength
  - is useful in estimating the radio coverage.
- **Large-scale propagation**
  - computed by averaging over 5λ ~ 40λ, 1m ~ 10m, for1GHz ~ 2GHz.
- **Small-scale fading**
  - received signal strength fluctuate rapidly, as a mobile moves over very small distance.
  - Received signal is a sum of multi-path signals.
  - Rayleigh fading distribution
  - may vary by 30 ~ 40 dB
  - due to movement of propagation related elements in the vicinity of the receiver.

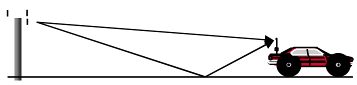
Deterministic Techniques
Basic Propagation Modes

- **There are several very commonly-occurring** modes of propagation**, depending on the environment through which the RF propagates. Three are shown at right:**
  - these are simplified, practically-calculable cases
  - real-world paths are often dominated by one or a few such modes
    - these may be a good starting point for analyzing a real path
    - you can add appropriate corrections for specific additional factors you identify
  - we're going to look at the math of each one of these

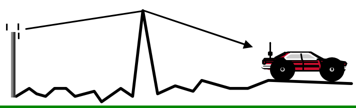
Free Space



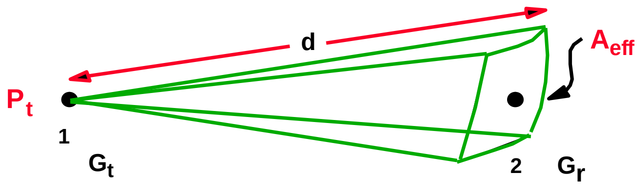
Reflection
with partial cancellation



Knife-edge
Diffraction



Free-Space Propagation



$$|S| = \frac{P_t}{4\pi d^2} G_t$$: power density

$$P_r = |S|\, A_{eff}$$: Received power

$$A_{eff} = \frac{\lambda^2}{4\pi} \cdot G_r \quad \Rightarrow \quad G = \frac{4\pi A_{eff}}{\lambda^2}$$

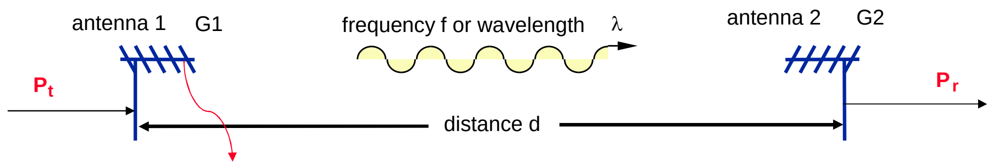
$$P_r = \frac{P_t}{4\pi d^2} \cdot G_t \cdot G_r \cdot \frac{\lambda^2}{4\pi}$$

$EIRP = P_t G_t$ (Effective isotropic radiated power)

- **Effective area (Aperture) $A_{eff} = \eta A$ ratio of power delivered to the antenna terminals to the incident power density**
  - η : Antenna efficiency
  - A : Physical area
- **Transmitter antenna gain = G_t**
- **Receiver antenna gain = G_r**
- **Propagation distance = d**
- **Wave length = λ**

Free-Space Propagation

- **A clear, unobstructed Line-of-sight path between them**
  - Satellite communication, Microwave Line-of-sight (Point-to-point)



EIRP= P_tG_t = effective isotropic radiated power (compared to an isotropic radiator) : dB_i
ERP = EIRP-2.15dB = effective radiated power (compared to an half-wave dipole antenna) : dB_d

Path Gain

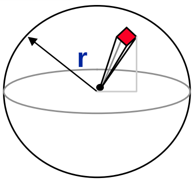
$$\text{gain} = \frac{P_r}{P_t} = G_1 G_2 \left(\frac{\lambda}{4\pi d}\right)^2 = G_1 G_2 \left(\frac{c}{4\pi d f}\right)^2 = G_1 G_2 \left(\frac{3\times 10^8}{4\pi d \cdot 1\times 10^3 \cdot f \cdot 1\times 10^6}\right)^2$$

for *d* in km, *f* in MHz

Path Loss = 1 / (P_r/P_t) when antenna gains are included

$$\text{loss(dB)} = 32.44 + 20\log d + 20\log f - G_1(\text{dB}) - G_2(\text{dB})$$

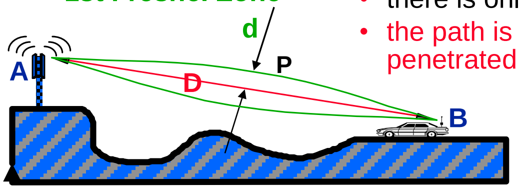
Free-Space Propagation



Free Space "Spreading" Loss
energy intercepted by the red square is proportional to **$1/r^2$**

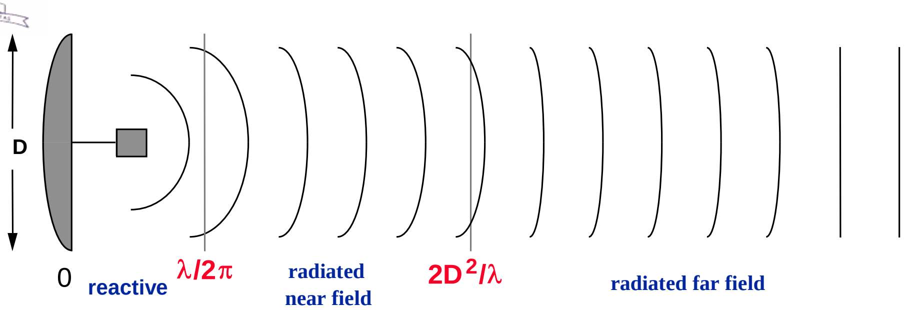
- The simplest propagation mode
  - Imagine a transmitting antenna at the center of an empty sphere. Each little square of surface intercepts its share of the radiated energy
  - Path Loss, db (between two *isotropic antennas*)
    $= 36.58 + 20 * Log_{10}(F_{MHZ}) + 20Log_{10}(Dist_{MILES})$
  - Path Loss, db (between two *dipole antennas*)
    $= 32.26 + 20 * Log_{10}(F_{MHZ}) + 20Log_{10}(Dist_{MILES})$
  - Notice the rate of signal decay:
  - **6 db per octave** of distance change, which is **20 db per decade** of distance change
- When does free-space propagation apply?
  - there is only one signal path (no reflections)
  - the path is unobstructed (first Fresnel zone is not penetrated by obstacles)

1st Fresnel Zone



First Fresnel Zone =
{Points P where AP + PB - AB $< \lambda/2$ }
Fresnel Zone radius d = 1/2 $(\lambda D)^{\wedge(1/2)}$

Near and Far fields



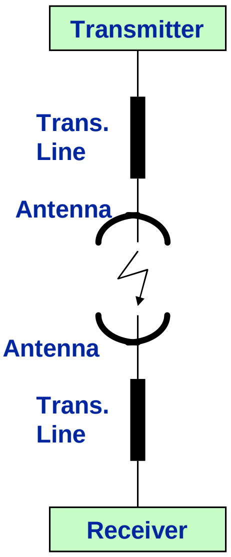
- **These distances are rough approximations!**
- **Reactive near field has substantial reactive components which die out**
- **Radiated near field angular dependence is a function of distance from the antenna (i.e., things are still changing rapidly)**
- **Radiated far field angular dependence is independent of distance**
- **Moral: Stay in the far field!**

An Example

- **An antenna with maximum dimension (D) of 1m, operating frequency (f) = 900 MHz.**
  - **$\lambda = c/f = 3\times10^8/900 \times10^6 = 0.33$**
  - **Far-field distance = $d_f = 2D^2/\lambda = 2 \times(1)^2 /0.33 = 6$m**

- **TX power, P_t = 50W, f_c = 900MHz, G_t** = 1 = **G_r**
  - **P_t (dBm) = 10log(50 $\times10^3$ mW) = 47 dBm = 10lon(50) = 17 dBW**
  - G_t **= 1 =** G_r = 0dB
  - Loss (100m)= 32.44 +20log(d_{km})+20log(f_{MHz}) = 32.44 + 20log (0.1)+20log(900) =71.525 dB
    - P_r (100m)= 47 +0 –71.525 +0 = -24.5 dBm
  - Loss (10km)= 32.44 +20log(d_{km})+20log(f_{MHz}) = 32.44 + 20log (10)+20log(900) =71.525 dB + 40 = 111.525 dB
    - P_r (100m)= 47 +0 –111.525 +0 = -64.5 dBm

A Tedious Tale of One Radio Link



- **Let's track the power flow from transmitter to receiver in the radio link we saw back in lesson 2. We're going to use real values that commonly occur in typical links.**

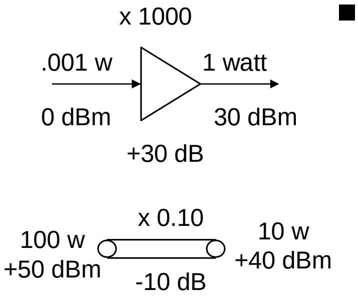
20 Watts TX output
x 0.50 line efficiency
= 10 watts to antenna
x 20 antenna gain
= 200 watts ERP
x 0.000,000,000,000,000,1585 path attenuation
= 0.000,000,000,000,031,7 watts **if intercepted by dipole antenna**

x 20 antenna gain
= 0.000,000,000,000,634 watts into line

x 0.50 line efficiency
= 0.000,000,000,000,317 watts to receiver

Did you enjoy that arithmetic? Let's go back and do it again, a better and less painful way.

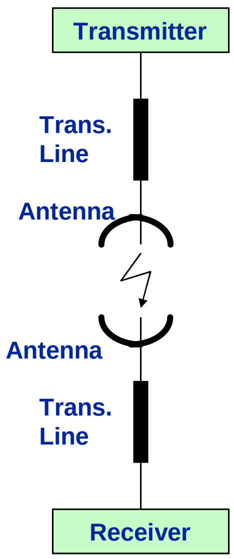
Decibels - A Helpful Convention



- dB are comfortable-size numbers
- rather than **multiply and divide** RF power ratios, in dB we can **just add & subtract**
- Given a number, convert to dB:
  db = 10 x Log_{10} (N)
- Given dB, convert to a number:
  N = $10^{\wedge(db/10)}$

- **Decibels normally refer to power ratios -- in other words, the numbers we represent in dB usually are a ratio of two powers. Examples:**
  - A certain amplifier amplifies its input by a factor of 1,000. (P_{out}/P_{in} = 1,000,000). That amplifier has 30 dB gain.
  - A certain transmission line has an efficiency of only 10 percent. (P_{out}/P_{in} = 0.1) The transmission line has a loss of -10 dB.
- **Often decibels are used to express an absolute number of watts, milliwatts, kilowatts, etc. When used this way, we always append a letter (W, m, or K) after "db" to show the unit we're using. For example,**
  - 20 dBK = 50 dBW = 80 dBm= 100,000 watts
  - 0 dBm = 1 milliwatt

A Much Less Tedious Tale
of that same Radio Link



- **Let's track the power flow again, using decibels.**

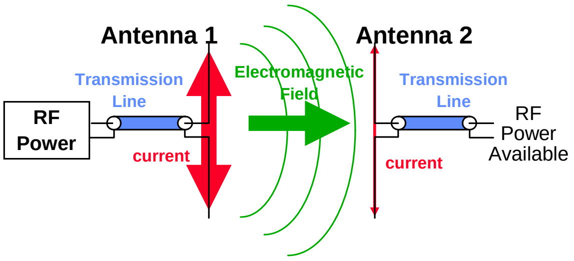
+43 dBm TX output
-3 dB line efficiency
= +40 dBm to antenna
+13 dB antenna gain
= +53 dBm ERP
-158 dB path attenuation
= -105 dBm **if intercepted by dipole antenna (+4.32dB for EIRP)**

+13 dB antenna gain
= -92 dBm into line

-3 dB line efficiency
= -95 dBm to receiver

- Wasn't that better?! Let's look at how dB work.

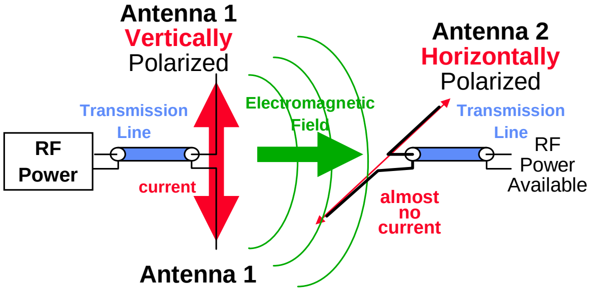
Introduction
The Function of an Antenna



An antenna **is a passive device (an arrangement of electrical conductors) which converts RF power into electromagnetic fields, or intercepts electromagnetic fields and converts them into RF power.**

- **RF power causes** current **to flow in the antenna.**
- **The current causes an** electromagnetic field **to radiate through space.**
- **The electromagnetic field induces small currents in any other conductors it passes. These currents are small, exact replicas of the original current in the original antenna.**

Antenna Polarization



- **The electromagnetic field is oriented by the direction of current flow in the radiating antenna.**
- **To intercept significant energy, a receiving antenna should be oriented parallel to the transmitting antenna.**

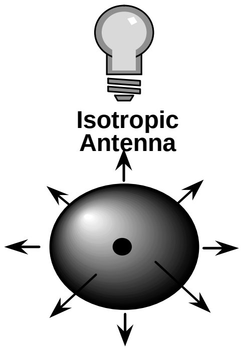
A receiving antenna oriented at right angles to the transmitting antenna will have very little current induced in it. This is referred to as cross-polarization**. Typical cross-polarization loss is 20 dB.**

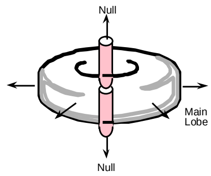
- **Vertical polarization is the norm in mobile telephony.**

Reference Antennas and Effective Radiated Power

Effective Radiated Power is always expressed in relation to the radiation produced by a reference antenna.

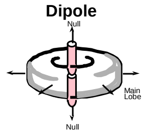
- **The flashlight example used a plain light bulb as a reference - producing the same light in all directions.**
- **The radio equivalent of a plain light bulb is called an** isotropic radiator**. It radiates the same in all directions. Unfortunately, it뭇 virtually impossible to build such an antenna.**
  - Radiation compared to an isotropic radiator is called **EIRP**, **E**ffective **I**sotropic **R**adiated **P**ower.
- **The simplest, most common, physically constructible reference antenna is a dipole.**
  - Radiation compared to a dipole is called **ERP**, **E**ffective **R**adiated **P**ower.



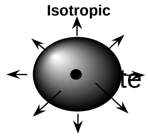


Wireless Communication

Reference Antennas, ERP and EIRP



HF



- ERP **is by comparison to a** Dipole
  - This is the tradition in **cellular**, land mobile, communications, and FM/TV broadcasting
- EIRP **is by comparison to an** Isotropic Radiator
  - This is the tradition in **PCS** at 1900 MHz., microwave, communications, and radar
- **ERP values can be converted to EIRP and vice versa.**
  - For a given amount of power input, a dipole produces 2.16 db more radiation than an isotropic radiator, due to the dipole뭇 slight directionality. A third antenna compared against both dipole and isotropic will have a bigger EIRP (vs. isotropic) than ERP (vs dipole). The difference is 2.16 db, a power ratio of 1.64. Therefore,

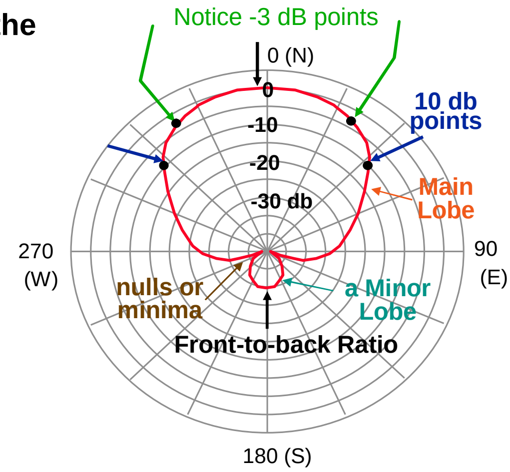
ERP = EIRP - 2.16 dB	and	**ERP = EIRP / 1.64**
EIRP = ERP + 2.16 dB	and	**EIRP = ERP x 1.64**

Radiation Patterns
Key Features and Terminology

Radiation patterns of antennas are usually plotted in polar form

- **The** Horizontal Plane Pattern **shows the radiation as a function of azimuth (i.e.,direction N-E-S-W)**
- **The** Vertical Plane Pattern **shows the radiation as a function of elevation (i.e., up, down, horizontal)**
- **Antennas are often compared by noting specific features on their patterns:**
  - -3 db (“HPBW”), -6 db, -10 db points
  - front-to-back ratio
  - angles of nulls, minor lobes, etc.

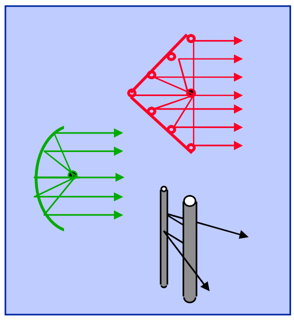
Typical Example
Horizontal Plane Pattern



Two Basic Methods of Obtaining Gain

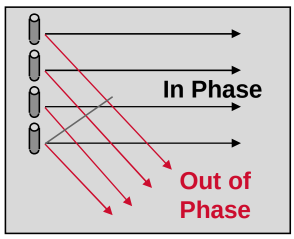
Quasi-Optical Techniques **(reflection, focusing)**

- Reflectors can be used to concentrate radiation
  - technique works best at microwave frequencies, where reflectors are small
- examples:
  - **corner reflector** used at cellular or higher frequencies
  - **parabolic reflector** used at microwave frequencies
  - **grid or single pipe** reflector for cellular



Array Techniques **(discrete elements)**

- power is fed or coupled to multiple antenna elements; each element radiates
- elements?radiations in phase in some directions
- in other directions, different distances to distant observer introduce different phase delay for each element, and create pattern lobes and nulls



Real-World Path Loss

Free space is, in general, NOT the real world. We must deal with:

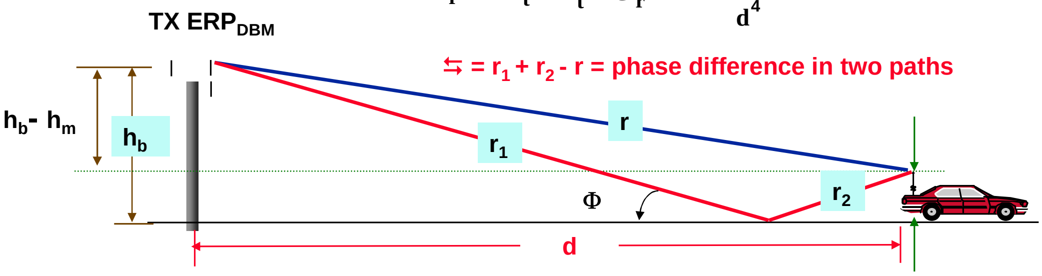
- reflections over flat or curved Earth
- reflections from smooth
- scattering from rough surfaces
- diffraction around/over obstacles
- absorption by vegetation and other lossy media, including buildings and walls
- multipath fading
- approximately fourth power propagation loss

Reflection

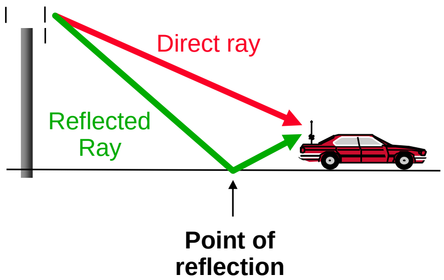
- **A propagating wave impinges upon an object with very large dimensions (>> λ)**
- **Reflections occur from surface of the earth and from building and wells $\rightarrow$ Flat surface**

Path Loss (dB) = 40Log(d) - [10Log(G_t)+10Log (G_r) +20Log (h_b) +20Log (h_m)]

$$P_r = P_t \cdot G_t \cdot G_r \frac{h_b^2 \cdot h_m^2}{d^4}$$



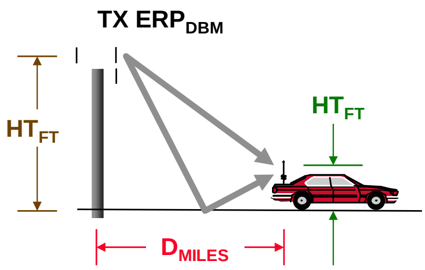
Reflection with Partial Cancellation



This reflection is at "grazing incidence". The reflection is virtually 100% efficient, and the phase of the reflected signal flips 180 degrees.

- **Assumptions:**
  - the cell is a mile away or more
  - the cell is not over a few hundred feet higher than the car
  - there are no other obstructions
- **If these assumptions are true, then:**
  - The point of reflection will be very close to the car -- at most, a few hundred feet away.
  - the difference in path lengths is influenced most strongly by the car antenna height above ground or by slight ground height variations
- **The reflected ray tends to cancel the direct ray, dramatically reducing the received signal level**

Reflection with Partial Cancellation



- Analysis:
  - physics of the reflection cancellation predicts signal decay approx. 40 db per decade of distance
    - twice as rapid as in free-space!
  - observed values in real systems range from 30 to 40 db/decade

Received Signal Level, dBm =

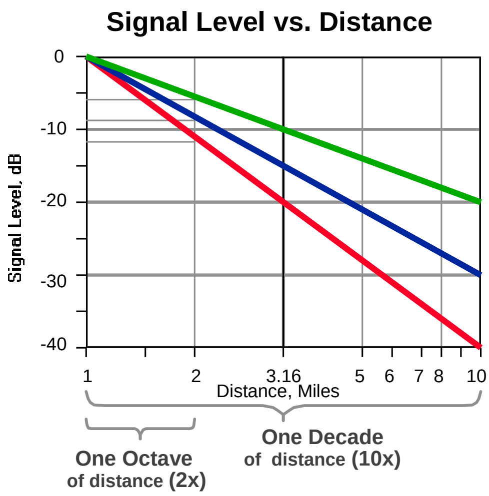
TX ERP$_{DBM}$ - 172
- 34 x Log$_{10}$ (D$_{MILES}$)
+ 20 x Log$_{10}$ (Base Ant. Ht$_{FEET}$)
+ 10 x Log$_{10}$ (Mobile Ant. Ht$_{FEET}$)

Comparison of Free-Space and Reflection Propagation Modes

Assumptions: Flat earth, TX ERP = 50 dBm, @ 870 MHz. Base Ht = 200 ft, Mobile Ht = 5 ft.

Distance$_{MILES}$	1	2	4	6	8	10	15	20
FS usingFree-Space$_{DBM}$	-45.3	-51.4	-45.3	-57.4	-63.4	-65.4	-68.9	-71.4
FS using Reflection$_{DBM}$	-69.0	-79.2	-89.5	-95.4	-99.7	-103.0	-109.0	-113.2

Observation on Signal Decay Rates



We've seen how the signal decays with distance in two simplified modes of propagation:

- Free-Space
  - 20 dB per decade of distance
  - 6 db per octave of distance
- Reflection Cancellation
  - 40 dB per decade of distance
  - 12 db per octave of distance
- **Real-life cellular propagation decay rates are typically somewhere between 30 and 40 dB per decade of distance**

Diffraction

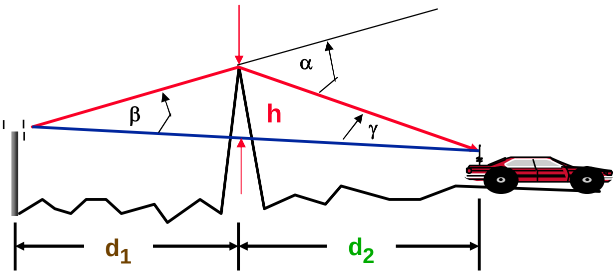
- **Diffraction allows radio signals to propagate around the curved surface of the earth, beyond the horizon, and to propagate behind obstructions.**
  - The diffraction field still exists and often has sufficient strength to produce a useful signal, as a receiver moves deeper into the obstructed (shadowed) region.
  - Caused by the propagation of secondary wavelets into a shadowed region.
  - Sum of the electric field components of all the secondary wavelets in the space around the obstacle.
- **Excess path length (⇆): the difference between the direct path and the diffracted path.**
  - A function of height and position of the obstruction, as well as the transmitter and receiver location.
- **Fresnel zones: successive receiver where ⇆ = $n\lambda/2$**
  - provide *constructive* and *destructive* interference to the total received signal.
  - Obstruction does not block the volume within the first Fresnel zone.

Diffraction parameter

- Excess path length (difference between direct path and diffracted path)

$$\Delta = \frac{h^2 (d_1 + d_2)}{2 \; d_1 d_2}$$

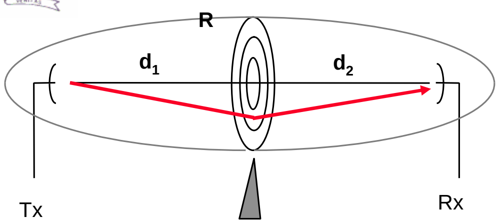
  - The corresponding phase difference $\phi = \frac{2\pi \Delta}{\lambda} = \frac{2\pi}{\lambda} \frac{h^2 (d_1 + d_2)}{2 \; d_1 d_2}$
  - $\alpha = \beta + \gamma \;\Rightarrow\; \alpha \approx h \left(\frac{d_1 + d_2}{d_1 d_2} \right)$
  - Fresnel-Kirchoff diffraction Parameter $\nu = \alpha \sqrt{\frac{2 \, d_1 d_2}{\lambda (d_1 + d_2)}}$



$$\phi = \frac{\pi}{2} \nu^2$$

Phase difference bet. LOS and diff. Path is a function of height and position of the obstruction, as well as TX and RX

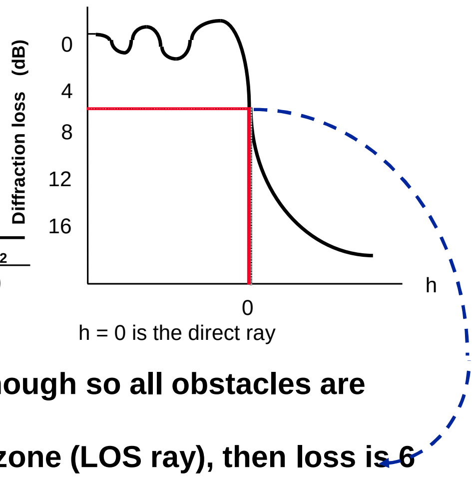
Fresnel Zones



Fresnel zones are the family of ellipsoids which are the loci of circles that indicate certain values of phase of the rays which pass through them

$$R_n = \sqrt{\frac{n\lambda \, d_1 d_2}{(d_1+d_2)}}$$

as $\phi = n \pi$
or $\Delta = n \lambda /2$

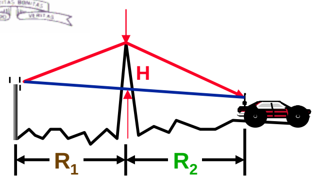


h = 0 is the direct ray

- Generally want antenna heights high enough so all obstacles are below first Fresnel zone (n = 1)
- If tip of obstacle is at center of Fresnel zone (LOS ray), then loss is 6 dB greater than free-space path loss

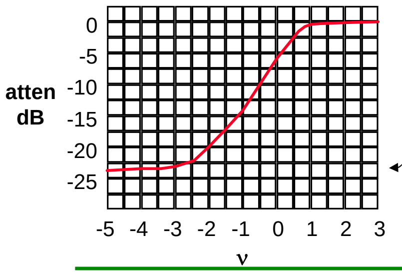
$R = 17.3 \sqrt{\frac{d_1 d_2}{(d_1+d_2) \, f}}$ *R* is 1st Fresnel Zone radius, d_1,d_2 in km, and *f* in GHz

Knife-Edge Diffraction



$$\nu = H\sqrt{\frac{2}{\lambda}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)}$$

$E_d / E_o = F(\nu)$, $G_{d,dB} = 20\log|F(\nu)|$



- Radio signals to propagate between Transmitter and Receiver is obstructed by a surface that has sharp irregularities (edges) such as hill or mountain.
- Sometimes a single well-defined obstruction blocks the path. This case is fairly easy to analyze and can be used as a manual tool to estimate the effects of individual obstructions.
- First calculate the parameter ν from the geometry of the path
- Next consult the table to obtain the obstruction loss in db
- Add this loss to the otherwise-determined path loss to obtain the total path loss.
- Other losses such as reflection cancellation still apply, but computed independently for the path sections before and after the obstruction.

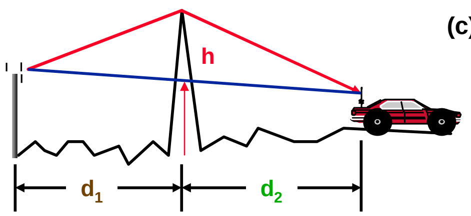
An Example of Diffraction

- $\lambda = 1/3$ m, $d_1 = 1$km, $d_2 = 1$km, and (a) h = 25m (b) h = 0 (c) h = -25m.

$$\nu = \alpha\sqrt{\frac{2\, d_1 d_2}{\lambda\,(d_1 + d_2)}}$$

$$\Delta = \frac{h^2 (d_1 + d_2)}{2\ d_1 d_2}$$

$\phi = n\,\pi$ or $\Delta = n\,\lambda/2$ for Fresnel Zones



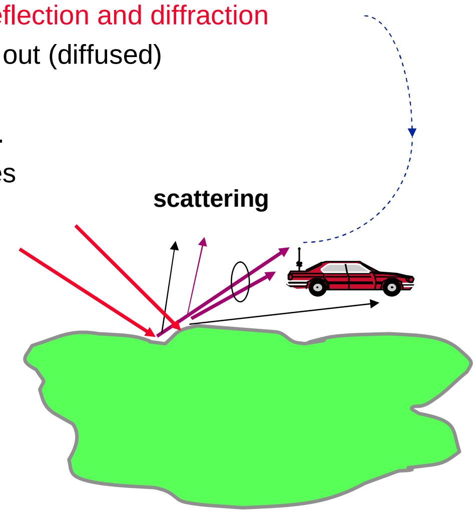
(a) h = 25m: $\nu = 2.74$, Loss = 22 dB from Figure 4.14. Approximation = 21.7 dB, $\Delta = 0.625$m, $\lambda = 1/3$, n = 3.75 $\Rightarrow$ the tip of the obstruction completely blocks the first three Fresnel zones.

(b) h = 0m: $\nu = 0$, Loss = 6 dB from Figure 4.14. Approximation = 6 dB, $\Delta = 0$m $\Rightarrow$ the tip of the obstruction lies in the middle of the first Fresnel zone.

(c) h = -25m: $\nu = -2.74$, Loss = 1dB from Figure 4.14. Approximation = 0dB, $\Delta = 0.625$m, $\lambda = 1/3$, n = 3.75 $\Rightarrow$ the tip of the obstruction completely blocks the first three Fresnel zones. However, the diffraction losses are negligible, since the obstruction is below the LOS.

Scattering

- **Why consider scattering**
  - Actual received signal > what predicted by reflection and diffraction
  - Rough surface → reflected energy is spread out (diffused)
  - Flat surface with dimensions > λ.
  - number of obstacles per unit volume is large.
  - Rough surfaces, small objects → irregularities
  - ex. Foliage, trees, , street signs, lamp post.



- **Rayleigh criterion**
  - Rough surface: $h > h_c$, $h_c = \lambda / 8\sin\theta_i$
  - reflection coefficient = flat coefficient $\times \rho_S$
    - $\Gamma_{rough} = \rho_S \times \Gamma$
    - ρ_S : scattering loss

Propagation Model

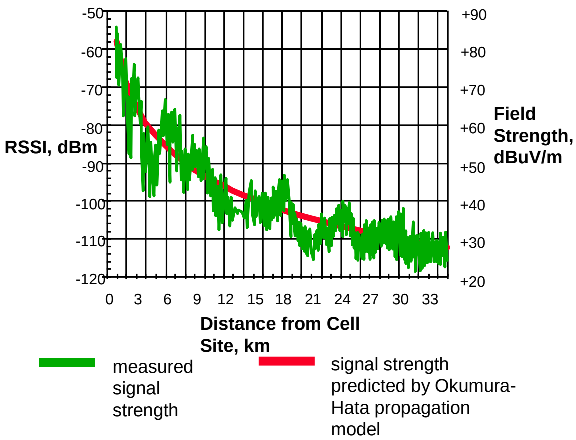
- **General types**
  - Outdoor
  - Indoor : conditions are much more variable.
- **Most of these models are based on a systematic interpretation of measurement data obtained in the service area.**
- **Parameters used in propagation model**
  - Frequency
  - Antenna heights
  - Environments : Large city, medium city, suburban, Rural (Open) Area.
- **Common models**
  - Hata Model : 20km > Range >1km
  - Walfisch and Bertoni Model :Range < 5km
  - Indoor propagation models : include scattering, reflection, diffraction
    - conditions are much more variable

Statistical Propagation Models

- Based on statistical analysis of large amounts of measurement data
- Predict signal strength as a function of distance and various parameters
- Useful for early network dimensioning, number of cells, etc.
- “Blind” to specific physics of any particular path -- based on statistics only
- Easy to implement as a spreadsheet on PC or even on hand-held programmable calculator
- Very low confidence level if applied as spot prediction method, but very good confidence level for system-wide generalizations

Statistical Propagation Models

- Prediction of Signal Strength as a function of distance without regard to obstructions or features of a specific propagation path



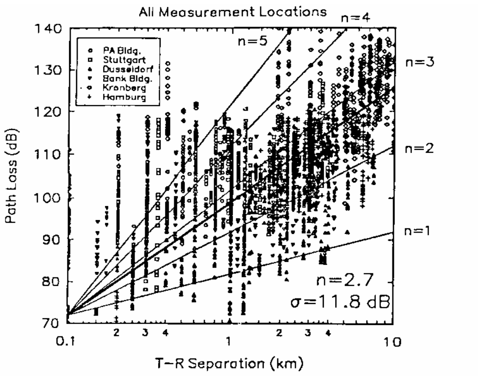


Figure 4.17 Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [from [Sei91] © IEEE].

Statistical Propagation Models:
Commonly-required Inputs

- **Frequency**
- **Distance from transmitter to receiver**
- **Effective Base Station Height**
- **Average Terrain Elevation**
- **Arbitrary loss allowances based on rules-of-thumb for type of area (Urban, Suburban, Rural, etc.)**
- **Arbitrary loss allowance for penetration of buildings/vehicles**
- **Assumptions of statistical distribution of variation of field strength values**

Okumura Model

$$L_{50}\,(dB) = L_F + A_{mu}\,(f,d) - G(h_t) - G(h_r) - G_{AREA}$$

- **Widely used model for signal prediction in urban areas**
- **is based on measured data and does not provide any analytical explanation**

Where:

L_{50} = The 50% (median) value of propagation path loss
L_F = The free space propagation loss
A_{mu} (f,d) = median attenuation relative to free space (see Fig. 3.23)
$G(h_t)$ = Base station antenna height gain factor (30m ~1000m)
$G(h_r)$ = mobile antenna height gain factor
G_{AREA} = Gain due to the type of environment (see Fig. 3. 24)

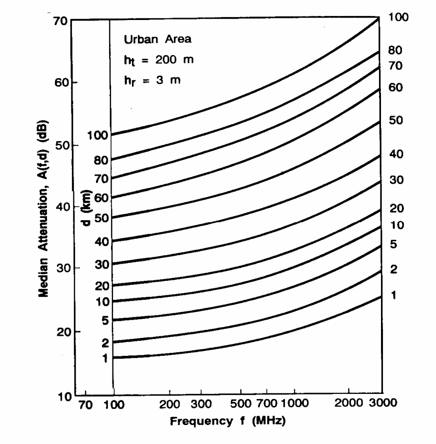
f : 150MHz ~ 1920MHz (up to 3000MHz), d: 1km ~ 100km

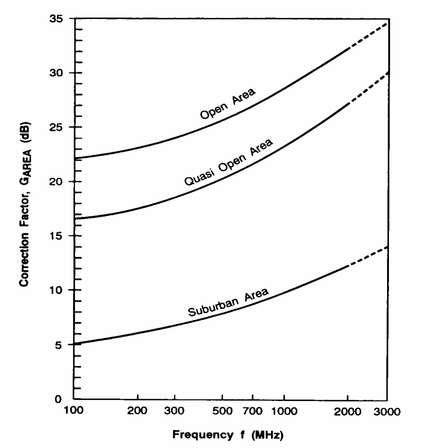
$G(h_t) = 20\log(h_t/200)$,	$G(h_r) = 10\log(h_r/3)$, $h_r \le 3m$ $G(h_r) = 20\log(h_r/3)$, $10m \ge h_r > 3m$

An Example
using Okumura Model

- D= 50 km, h_t = 100m, h_r = 10m, in an urban environment. EIRP = 1kW, f = 900 MHz, unit gain receiving antenna.

- L_F = 125.5dB
- A_{mu}(900MHz, 50 km)) = 43 dB
- G_{AREA} = 9dB
- $G(h_t)$ = -6dB
- $G(h_r)$ = 10.46 dB
- L_{50} = 155.04 dB
- $P_r(d)$ = 60-155.04 + 0 = -95.04 dBm





Hata Model

L_{50} *(Urban)* (dB) = 69.55 + 26.16 log (F) – 13.82 log(H_b) + (44. 9 – 6.55 log(H_b))*log (D) – a

Where:

A	=	Path loss
F	=	Frequency in mHz (150M-1500 MHz)
D	=	Distance between base station and terminal in km (1km ~20km)
H	=	Effective height of base station antenna in m (30m ~200m)
a	=	Environment correction factor for mobile antenna height (1m~10m)

a = (1.1 log (F) - 0.7) H_m - (1.56 log (F)- 0.8) dB = Small~medium sized city (urban)

8.29 (log (1.54 H_m)) ^{2} - 1.1 dB for F ≤ 300 MHz
3.2 log (F) (log (11.75 H_m)) ^{2} - 4.97 dB for F ≥ 300 MHz = Large city (Dense Urban)

- L_{50} *(Urban)* - 2(log(F/28)) ^{2} - 5.4 = Suburban
- L_{50} *(Urban)* - 4.78(log(F)) ^{2} - 18.33 (log(F)) - 40.98 = Rural (open)

- L_{90} = L_{50} + 10.32 dB : 90% QOS, L_{50} is the median value of propagation loss

COST-231 Hata Model

A (dB) = 46.3 + 33.9log (F) – 13.82 log(H_b) + (44. 9 – 6.55 log(H_b))*log (D) – a + c

Where:

A	=	Path loss
F	=	Frequency in MHz (**1500M-2000 MHz**)
D	=	Distance between base station and terminal in km (1km ~20km)
H	=	Effective height of base station antenna in m (30m ~200m)
a	=	Environment correction factor for mobile antenna height
c	=	Environment correction factor

C = **0 dB** **=** Small~medium sized city (urban), Suburban

3 dB **=** Dense Urban (metropolitan center)

A is defined in the Hata Model

Wireless Communication

Statistical Propagation Models
Okumura-Hata Model

A (dB) = 69.55 + 26.16 log (F) – 13.82 log(H) + (44. 9 – 6.55 log(H))*log (D) + C

Where:

A	=	Path loss
F	=	Frequency in MHz (**800-900 MHz**)
D	=	Distance between base station and terminal in km
H	=	Effective height of base station antenna in m
C	=	Environment correction factor

C =

0 dB	=	Dense Urban
- 5 dB	=	Urban
- 10 dB	=	Suburban
- 17 dB	=	Rural

Statistical Propagation Models
COST-231 HATA Model

A (dB) = 46.3 + 33.9*logF – 13.82*logH + (44.9 – 6.55*logH)*log D + C

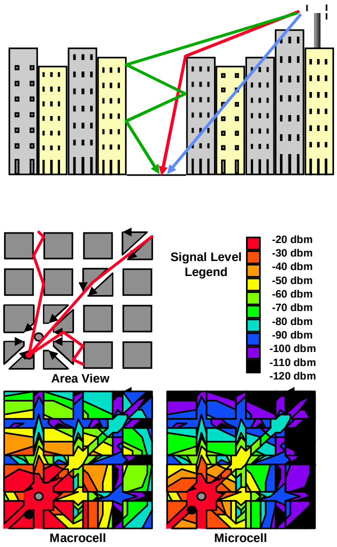
Where:

A	=	Path loss
F	=	Frequency in mHz (**between 1700 and 2000 mHz**)
D	=	Distance between base station and terminal in km
H	=	Effective height of base station antenna in m
C	=	Environment correction factor

C =

- 2 dB	=	for dense urban environment: high buildings, medium and wide streets
- 5 dB	=	for medium urban environment: modern cities with small parks
- 8 dB	=	for dense suburban environment, high residential buildings. wide streets
- 10 dB	=	for medium suburban environment. industrial area and small homes
- 26 dB	=	for rural with dense forests and quasi no hills

Statistical Propagation Models
Walfisch-Ikegami Model

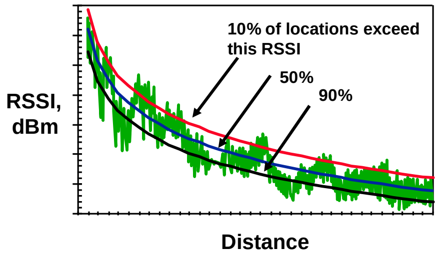


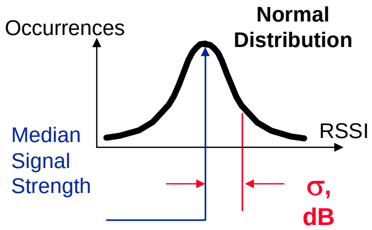
- **Useful only in dense urban environments, but often superior to other methods in this environment**
- **Based on "urban canyon" assumption**
  - a "carpet" of buildings divided into blocks by street canyons
  - Uses diffraction and reflection mechanics and statistics for prediction
  - Input variables relate mainly to the geometry of the buildings and streets
- **Useful for two distinct situations:**
  - macro-cell - antennas above building rooftops
  - micro-cell - antennas lower than most buildings
- **Available in both 2-dimensional and 3-dimensional versions**

Statistical Techniques
Practical Application of Distribution Statistics

- **Technique:**
  - use a model to predict RSSI
  - compare measurements with model
    - obtain median signal strength
    - obtain standard deviation
    - now apply correction factor to obtain field strength required for desired probability of service
- **Applications: Given**
  - a desired signal level
  - the standard deviation of signal strength measurements
  - a desired percentage of locations which must receive that signal level
  - We can compute a “cushion” in dB which will give us that % coverage

Percentage of Locations where Observed RSSI exceeds Predicted RSSI

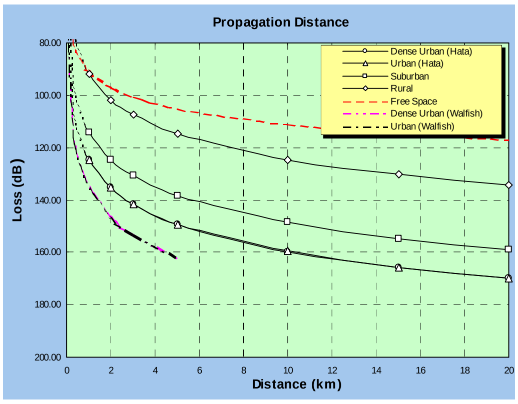




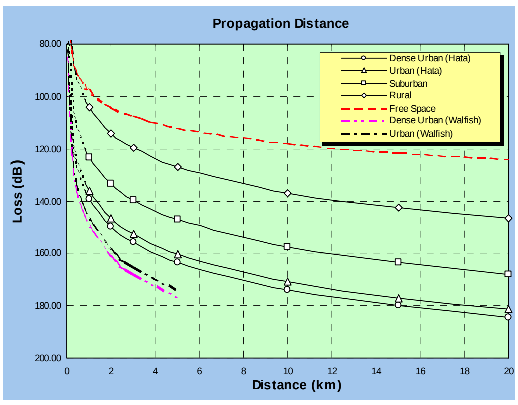
Propagation Loss

- **Comparison among models**
  - Free space
  - Hata Model (**Okumura + COST 231)**
  - Walfisch : considered by ITU-R in IMT-2000 standard.

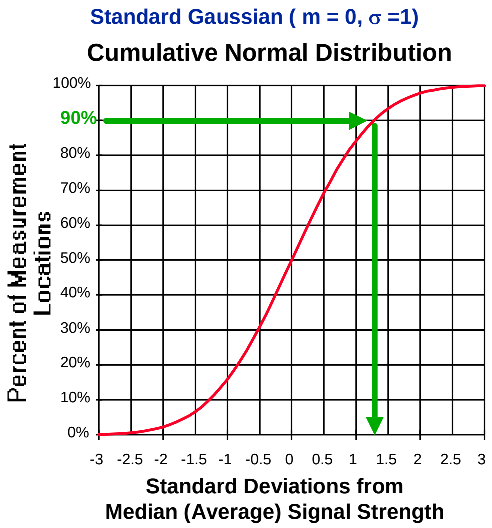
Cellular system, f = 850MHz



PCS system, f =1900 MHz

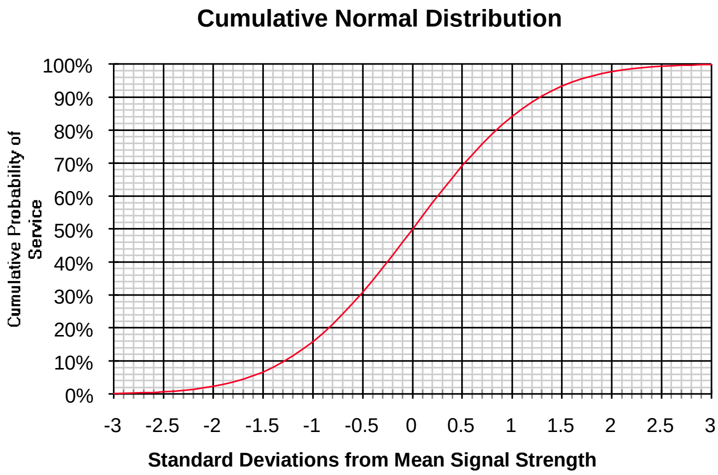


Statistical Techniques
Example of Application of Distribution Statistics



- **Suppose you want to design a cell site to deliver at least** -95 dBm to at least 90% **of the locations in an area**
- **Measurements you've made have a** 10 dB. standard deviation **above and below the average signal strength**
- **On the chart:**
  - to serve **90% of possible locations**, we must deliver an average signal strength 1.29 standard deviations stronger than -95 dBm, **σ = 10**
  - **-95 + (1.29 x 10) = - 82 dbm**
  - Design for an average signal strength of **- 82 dbm!**

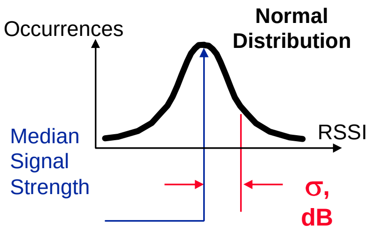
Statistical Techniques
Normal Distribution Graph & Table for Convenient Reference



Standard Deviation	Cumulative Probability
-3.09	0.1%
-2.32	1%
-1.65	5%
-1.28	10%
-0.84	20%
-0.52	30%
2.35	99%
0	50%
0.52	70%
0.84	80%
1.28	90%
1.65	95%
2.35	99%
3.09	99.9%

Log-normal Shadowing Fading

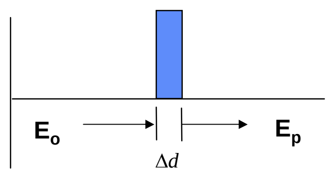
- **Long-term variation are due to propagation through obstructions, ets. And if the number of obstructions is large**
- **The loss in dB is respected as a Gaussian distribution with a m_R(dB) and variance σ (dB)**
  - m_R is the median loss of the path
- **We choose a specific coverage criteria such as 95%, 90%, 85% . To find 90% Loss**
  - Pr [Loss m_R + Loss (σ)] = 90%
- **In all these cases, σ itself is a function of the environment**
  - Large, medium city, suburban : $\sigma \approx$ 8dB
  - Rural area $\sigma \approx$ 4dB
    - for σ = 9 dB.and 90% coverage, Loss (σ)= 10.32 dB



Shadowing Fading statistics

- **Long-term variation is modeled by a log-normal distribution**

$$E_p = E_o\, e^{-(\alpha + j\beta)\Delta d} \Rightarrow |E_p| = |E_o|\, e^{-\alpha \Delta d}$$

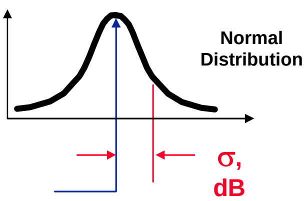


- at the receiver, the input signal will be given by

$$E_r = |E_i| \prod e^{-\alpha_i \Delta r_i} \Rightarrow |E_r| = |E_i|\, e^{-\Sigma \alpha_i \Delta r_i}$$

- if number of obstructions is large, $-\Sigma \alpha_i \Delta r_i$ is Gaussianly distributed for any α_i and r_i
- $y = e^{x}$, y is lognormally distributed if **x** is Gaussianly distributed.

101og(Y) = 10log(e)X



Percentage of Coverage

- The percentage of area with a received signal ≥ γ , I.e.

  Pr [Pr (R) ≥ γ]

  - γ : desired received signal threshold
  - radial distance from the transmitter
    - received signal at D = R exceeds the threshold γ
    - see Fig. 3.18 for different n and σ
- Ex: shadowing deviation σ = 8dB, 75% boundary coverage (QOS)
  - Loss exponent factor n = 4 → area coverage 94%
  - Loss exponent factor n = 2 → area coverage 91%

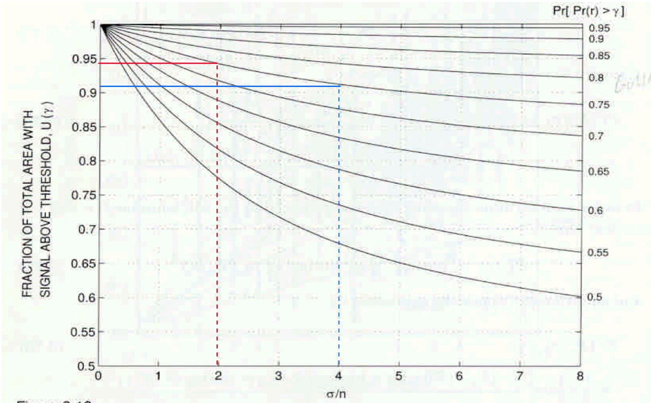


Figure 3.18
Family of curves relating fraction of total area with signal above threshold, $U(\gamma)$ as a function of probability of signal above threshold on the cell boundary.

Statistical Propagation Models Typical Results

Example of Model Results:
Typical Cell Range Predictions for Various Environments

F = 1900 mHz	Tower Height (meters)	EIRP (watts)	Range (km)
Dense Urban	30	200	1.05
Urban	30	200	2.35
Suburban	30	200	4.03
Rural	50	200	10.3

Building Penetration Losses

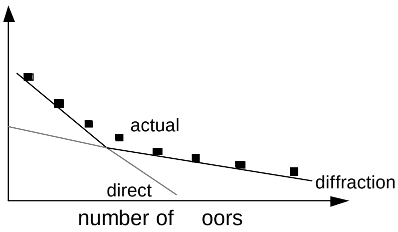
- Usual technique for path loss into a building: get median signal level in streets by some "normal" method add building penetration losses
- Loss α 1/h in general
- Small scale variation is Rayleigh
- Large scale variation is log-normal
- Loss α 1/f
- Each additional floor is about 2 dB difference in loss
- For primarily scattering paths, standard deviation is about 4 dB
- For paths with at least partial LOS, standard deviation is about 6 to 9 dB
- Windows of many new buildings have a thin layer of metal sputtered on the window glass; this increases attenuation

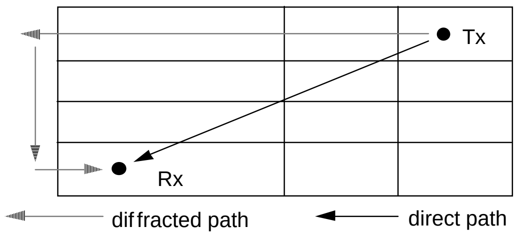
D. Molkdar, "Review on radio propagation into and within buildings," IEE Proc-H, Vol. 138, No. 1, Feb 1991, pp 61- 73.

Propagation Inside Buildings

- Indoor environment differs from mobile environment in
  - interference environment (usually higher, due to equipment)
  - fading rate (usually slower, due to reduced speeds)
- Limitations due to bandwidth
  - narrowband (e.g. TDMA) systems coverage limited by multipath and shadow fading
  - wideband systems experience ISI due to delay spread (less frequency diversity gain)
- Power as a function of distance varies over a range:
  - P α $1/d^2$ in a near-free-space environment (hallway)
  - P α $1/d^6$ in a high-clutter environment (room full of cubes)
- Loss: floors with structural metal > brick wall > plaster wall
- Office fading is usually more continuous /smaller dynamic range than mobile fading
- Stairwells and elevator shafts can act as waveguides and aid floor-to-floor propagation
- Presence of an LOS path reduces RMS delay spread

Propagation Inside Buildings - Prediction





- Combination of ray-tracing and diffraction can be very accurate at predicting inside propagation
- Direct rays (through floors): each floor increases loss
- Diffraction (windows and outside): large loss initially, but more floors do not add much loss
- 900 MHz band losses
- 10 dB/floor for reinforced concrete
- 13 dB/floor for precast slab floor
- 26 dB isolation for corrugated steel (diffraction path dominates)

Acceptable Cellular Voice Quality

- AMPS VOICE QUALITY IS ACCEPTABLE IF OVER 90% OF THE COVERAGE:
  1) VOICE S/N RATIO > 38 dB IN FADING ENVIRONMENT
  2) RF CARRIER-TO-INTERFERENCE RATIO (CIR) > 18 dB
- GIVEN 1) AND 2), 75% OF USERS GRADE THE SYSTEM AS "GOOD" OR "EXCELLENT"
- MATHEMATICALLY:

$$\frac{S}{N} = 10 \log_{10}\left[\frac{3\beta^2}{4}\ \frac{C}{I}\right] + 15\ \text{dB}, \quad \text{where } \frac{C}{I} > 13\ \text{dB}, \text{ and } \beta > 0.6$$

$\frac{S}{N}$ = BASEBAND SIGNAL-TO-NOISE RATIO

$\frac{C}{I}$ = RF CARRIER-TO-INTERFERENCE RATIO

- IN DIGITAL SYSTEMS WITH VOICE COMPRESSION, VOICE QUALITY IS USUALLY QUANTIFIED PSYCHOACOUSTICALLY VIA Mean Opinion Score (MOS) RATINGS ON A SCALE OF 1 TO 5.
- AN MOS SCORE OF 3 IS CONSIDERED MINIMALLY ACCEPTABLE

Bernardin, C.P. et al ,"Voice Quality Prediction in AMPS Cellular Systems using SAT," Wireless 94 Symposium, Calgary, July 12, 1994, pp 238-241.

Lesson 4 Complete