Chap 3a. Propagation Characteristic

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- Radiation from Antenna
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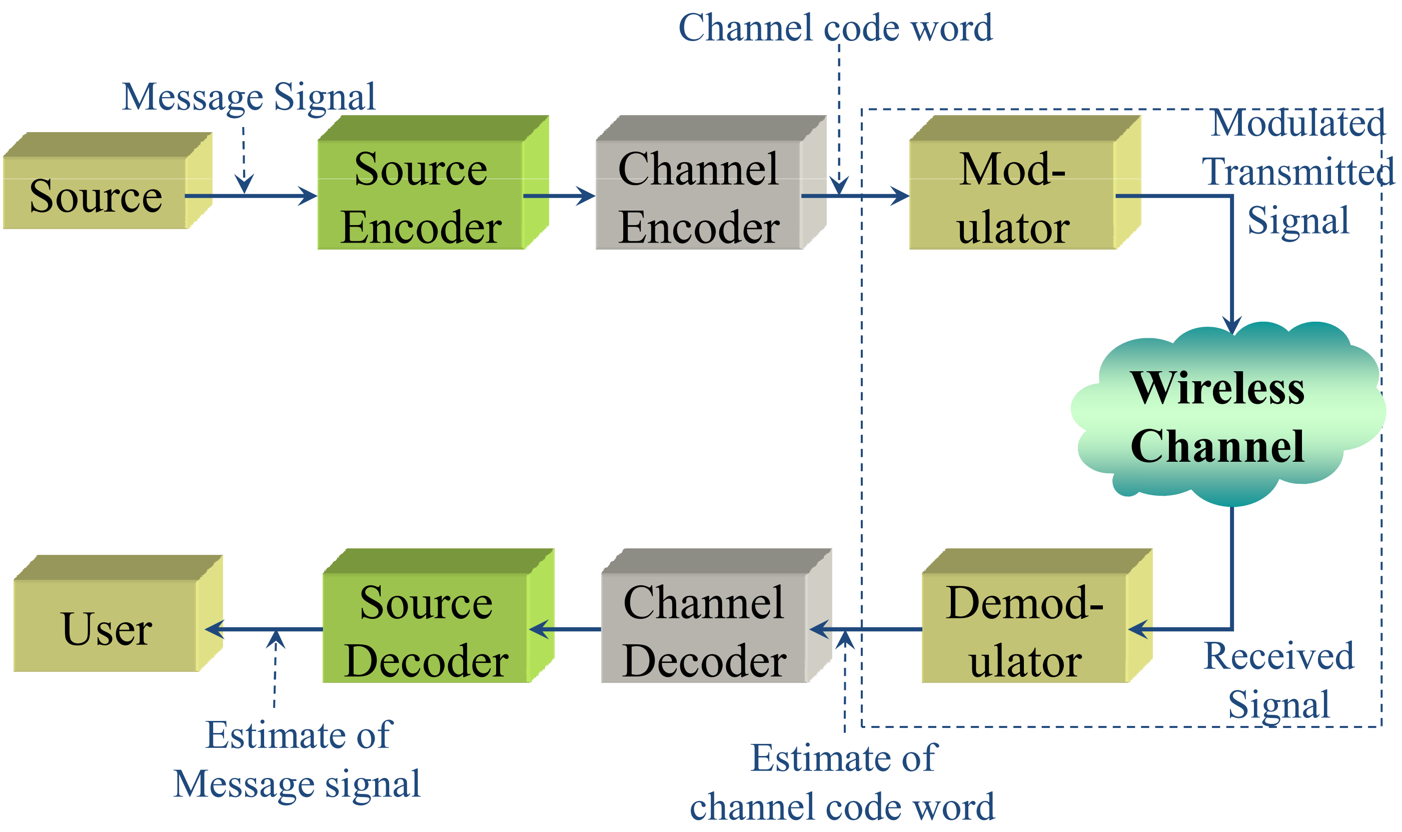
Wireless Communication System



Channel code word

Message Signal

Source

Source Encoder

Channel Encoder

Mod-ulator

Modulated Transmitted Signal

Wireless Channel

User

Source Decoder

Channel Decoder

Demod-ulator

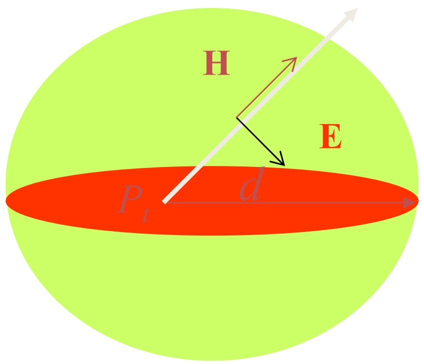
Received Signal

Estimate of Message signal

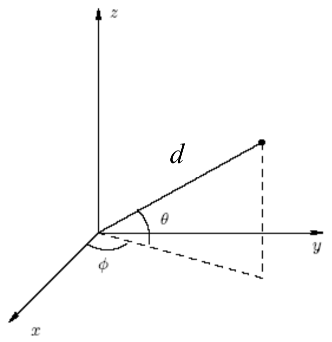
Estimate of channel code word

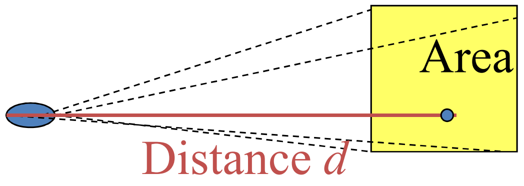
Antenna - Ideal

- Isotropics antenna: In free space radiates power equally in all direction. Not realizable physically



EM fields around a transmitting antenna , a polar coordinate





- *d*- distance directly away from the antenna.
- ϕ is the azimuth, or angle in the horizontal plane.
- θ is the zenith, or angle above the horizon.

Antenna - Real

- Not isotropic radiators, but always have directive effects (vertically and/or horizontally)
- A well defined radiation pattern measured around an antenna
- Patterns are visualised by drawing the set of constant-intensity surfaces

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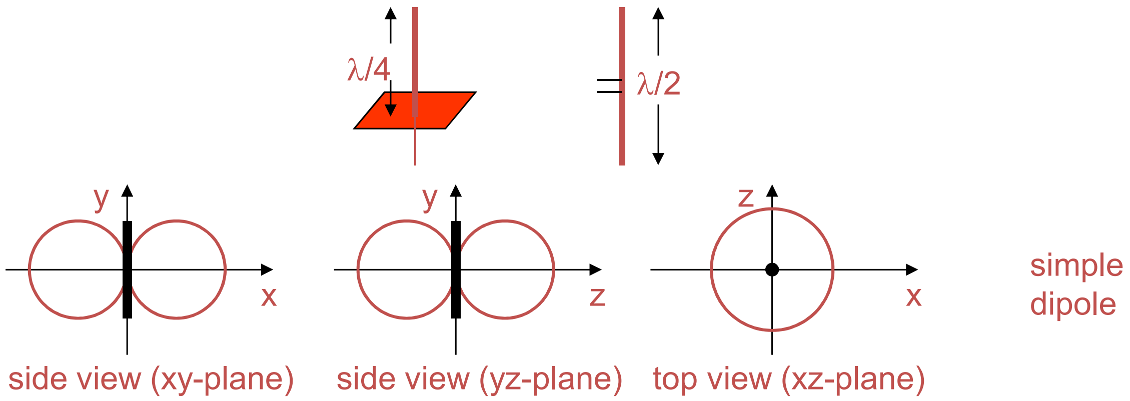
Antenna – Real - Simple Dipoles

- Not isotropic radiators, e.g., dipoles with lengths λ/4 on car roofs or λ/2 as Hertzian dipole

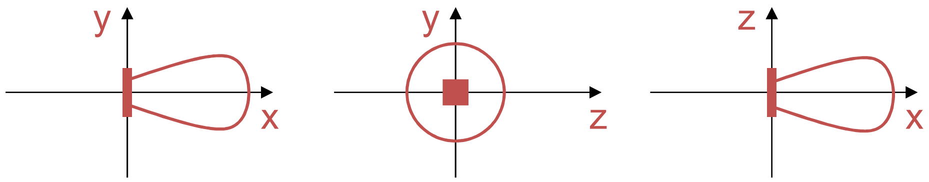


- Example: Radiation pattern of a simple Hertzian dipole

shape of antenna is proportional to the wavelength

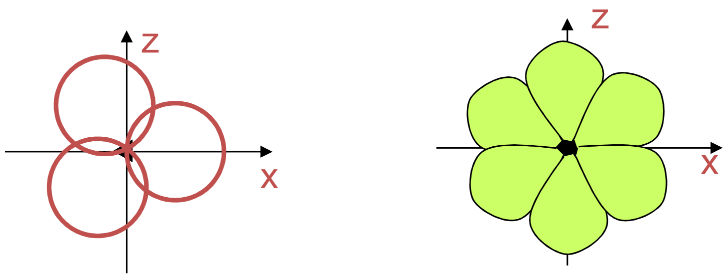
Antenna – Real - Sdirected and Sectorized

- Used for microwave or base stations for mobile phones (e.g., radio coverage of a valley)



side view (xy-plane) side view (yz-plane) top view (xz-plane)

Directed



top view, 3 sector top view, 6 sector

Sectorized

Antenna - Ideal - *contd.*

- The power density of an ideal loss-less antenna at a distance *d* away from the transmitting antenna:

$$P_a = \frac{P_t G_t}{4\pi d^2} \quad \text{W/m}^2$$

Note: the area is for a sphere.

- G_t is the transmitting antenna gain
- The product $P_t G_t$: **Equivalent Isotropic Radiation Power (EIRP)**

which is the power fed to a perfect isotropic antenna to get the same output power of the practical antenna in hand.

Antenna - Ideal - *contd.*

- The strength of the signal is often defined in terms of its Electric Field Intensity *E*, because it is easier to measure.

$P_a = E^2/R_m$ *where R_m is the impedance of the medium. For free space R_m = 377 Ohms.*

$$\boxed{E^2 = \frac{P_t R_m}{4\pi d^2} \quad and \quad E = \sqrt{\frac{P_t R_m}{4\pi d^2}}} \qquad \boxed{\text{V/m}}$$

Antenna - Ideal - *contd.*

- The receiving antenna is characterized by its effective aperture A_e, which describes how well an antenna can pick up power from an incoming electromagnetic wave
- The effective aperture A_e is related to the gain G_r as follows:

$$A_e = P_r / P_a \Rightarrow \qquad A_e = G_r\lambda^2/4\pi$$

which is the equivalent power absorbing area of the antenna.

G_r is the receiving antenna gain and $\lambda = c/f$

Signal Propagation
(Channel Models)

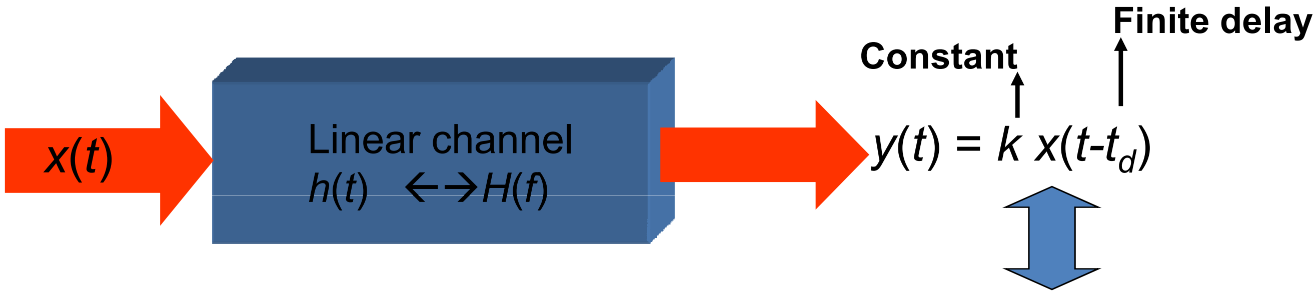
Channel Models

- High degree of variability (in time, space etc.)
- Large signal attenuation
- Non-stationary, unpredictable and random
  - Unlike wired channels it is highly dependent on the environment, time space etc.
- Modelling is done in a statistical fashion
- The location of the base station antenna has a significant effect on channel modelling
- Models are only an approximation of the actual signal propagation in the medium.
- Are used for:
  - performance analysis
  - simulations of mobile systems
  - measurements in a controlled environment, to guarantee repeatability and to avoid the expensive measurements in the field.

Channel Models - Classifications

- System Model - *Deterministic*
- Propagation Model- *Deterministic*
  - Predicts the received signal strength at a distance from the transmitter
  - Derived using a combination of theoretical and empirical method.
- Stochastic Model - *Rayleigh channel*
- Semi-empirical (Practical +Theoretical) Models

Channel Models - Linear



$$y(t) = k\,x(t-t_d)$$

$$\begin{aligned} H(f) &= F[y(t)] \\ &= ke^{-j\omega t_d} X(f) \\ &= H(f)X(f) \\ \text{where} \quad H(f) &= ke^{-j\omega t_d} \end{aligned}$$

- Therefore for a linear channel is:

$$\left|H(f)\right| = \left|k\right|, \arg H(f) = -2\pi f t_d$$

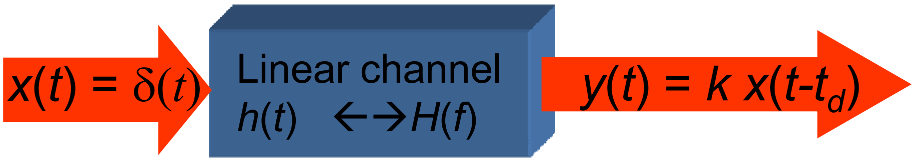
$$\underset{\substack{\uparrow \\ \text{Amplitude} \\ \text{distortion}}}{\left|H(f)\right| = \left|k\right|}, \quad \underset{\substack{\uparrow \\ \text{Phase} \\ \text{distortion}}}{\arg H(f) = -2\pi f t_d}$$

- The phase delay $t_d(f) = -\arg H(f)/2\pi f$

Describes the phase delayed experienced by each frequency component

Channel Models – Multipath Link

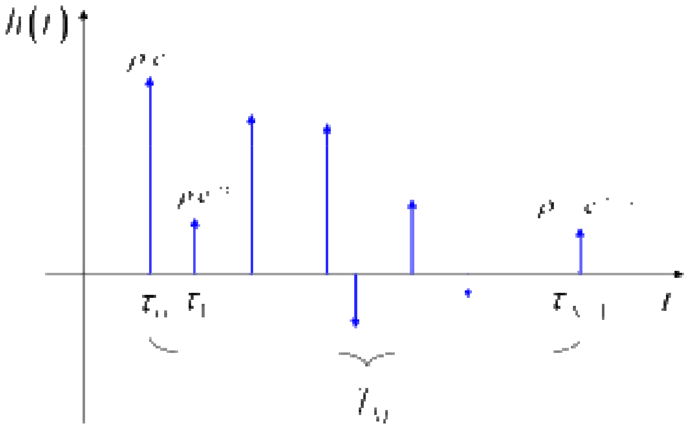
- The mathematical model of the multipath can be presented using the method of the impulse response used for studying linear systems.



$x(t) = \delta(t)$

Linear channel
$h(t) \leftrightarrow H(f)$

$y(t) = k\,x(t-t_d)$



Channel Models – Multipath Link

- Time variable multi-path channel impulse response

$$h_b(t,\tau) = \sum_{i=0}^{N-1} a_i(t,\tau)\exp[j(2\pi f_c \tau_i(t) + \phi_i(t,\tau))]\delta(\tau - \tau_i(t))$$

Where $a(t-\tau)$ = attenuated signal

- Time invariant multi-path channel impulse response
  - Each impulse response is the same or has the same statistics, then

$$h(\tau) = \sum_{i=0}^{N-1} a_i e^{-j\theta_i}\delta(\tau - \tau_i)$$

Where $a_i e^{(.)}$ = complex amplitude (i.e., magnitude and phase) of the generic received pulse.

τ = propagation delay generic i^{th} impulse

N = number signal arriving from N path

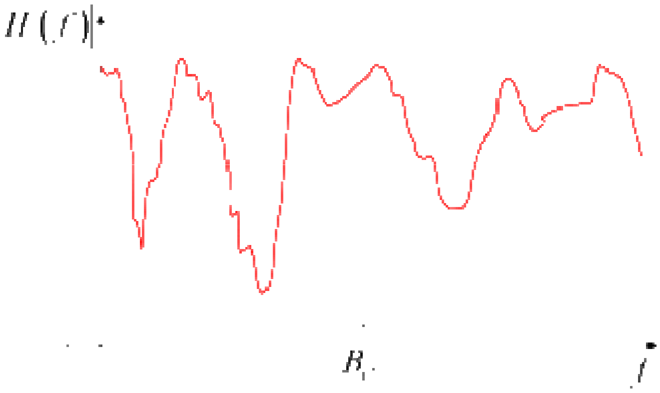
$\delta(.)$ = impulse signal

Channel Models – Multipath Link

- Channel transfer function

$$H(f) = \int_{-\infty}^{\infty} h(t) e^{-j2\pi ft} dt$$

$$= \sum_{i=0}^{N-1} a_i e^{-j\theta_i} e^{-i2\pi f\tau_i}$$



- Multipath Time
  - Mostly used to denote the severity of multipath conditions.
  - Defined as the time delay between the 1st and the last received impulses.

$$T_{MP} = \tau_{N-1} - \tau_0$$

- Coherence bandwidth - on average the distance between two notches

$$B_c \sim 1/T_{MP}$$

Propagation Path Loss

- The propagation path loss is

$$L_{PE} = L_a L_{lf} L_{sf}$$

where

L_a is average path loss (attenuation): (1-10 km),

L_{lf} - long term fading (shadowing): 100 m ignoring variations over few wavelengths,

L_{sf} - short term fading (multipath): over fraction of wavelength to few wavelength.

- Metrics (dBm, mW)

[P(dBm) = 10 * log[P(mW)]

Propagation Path Loss – Free Space

- Power received at the receiving antenna

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

Thus the free space propagation path **loss** is defined as:

$$L_f = -10\,\mathrm{Log}_{10} \frac{P_r}{P_t} = -10\,Log_{10} \left[\frac{G_t G_r \lambda^2}{(4\pi d)^2} \right]$$

- Isotropic antenna has **unity gain (*G* = 1)** for both transmitter and receiver.

Propagation - Free Space–*contd.*

The difference between two received signal powers in free space is:

$$\Delta P = 10\log_{10}\left(\frac{P_{r1}}{P_{r2}} \right) = 20\log_{10}\left(\frac{d1}{d2} \right) \quad \mathrm{dB}$$

If $d_2 = 2d_1$, the ΔP = -6 dB   i.e 6 dB/octave or 20 dB/decade

Propagation - Non-Line-of-Sight

- Generally the received power can be expressed as:

$$P_r \propto d^{-v}$$

- For line of sight *v* = 2, and the received power

$$P_r \propto d^{-2}$$

- For non-line of sight with no shadowing, received power at any distance *d* can be expressed as:

$$\boxed{P_r(d) = P_r(1m) - 20\log_{10}(d_{\mathrm{ref}}) - 20v\log_{10}\left(\frac{d}{d_{ref}}\right)}$$

100 m< d_{ref} < 1000 m

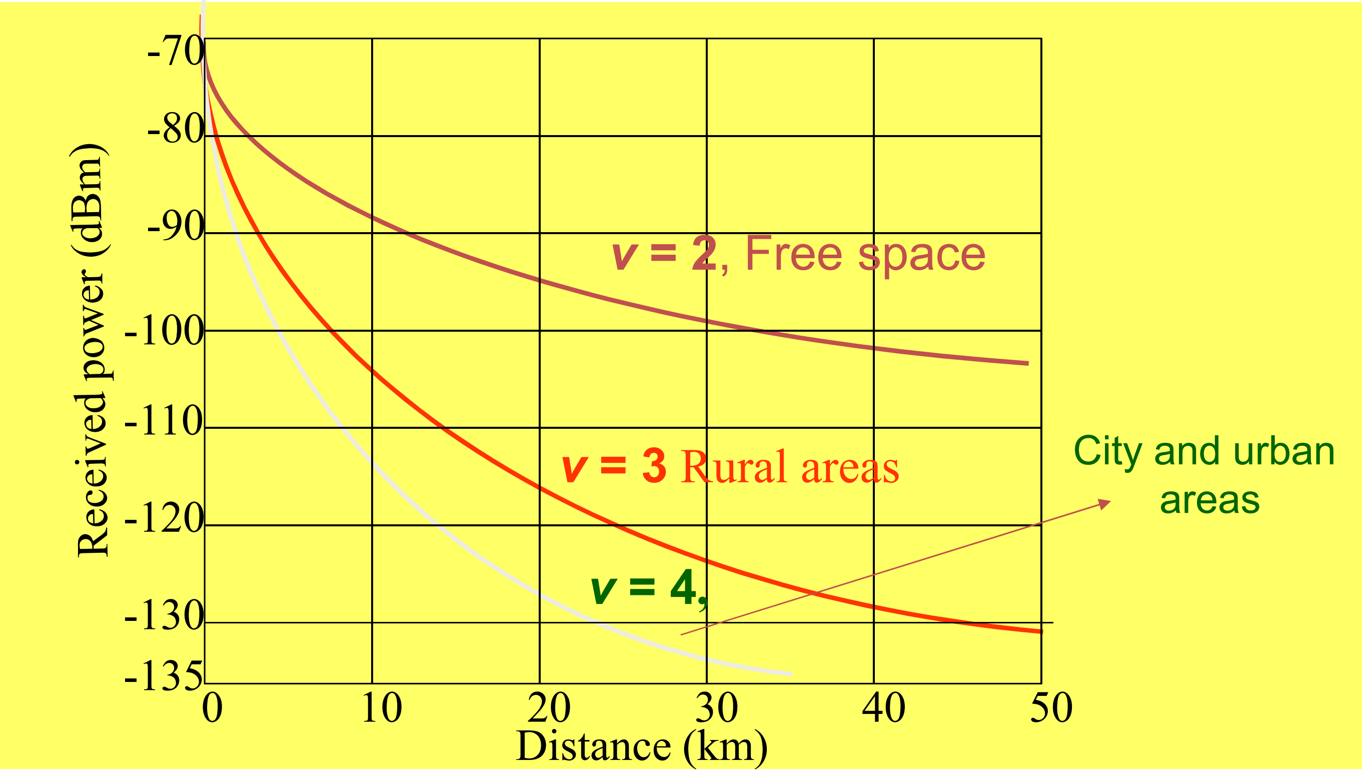
Propagation - Non-Line-of-Sight

- Log-normal Shadowing

$$\boxed{P_r(d) = P_r(1\ m) - 10\log_{10}(d_{\mathrm{ref}}) - 20v\log_{10}\left(\frac{d}{d_{ref}}\right) - X_\sigma}$$

Where X_σ: N(0,σ) Gaussian distributed random variable

Received Power for Different Value of Loss Parameter *v*



Propagation Model- Free Space

In terms of frequency *f* and the free space velocity of electromagnetic wave $c = 3 \times 10^8$ m/s it is:

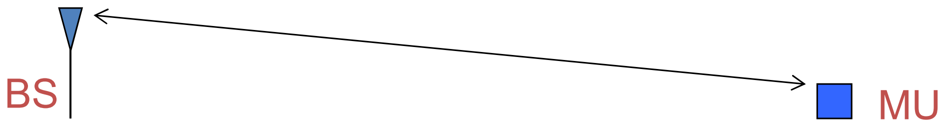
$$L_f = -20\log_{10}\left(\frac{c/f}{4\pi d}\right) \quad \text{dB}$$

Expressing frequency in MHz and distance *d* in km:

$$\begin{aligned} L_f &= -20\log_{10}(c/4\pi) + 20\log_{10}(f) + 20\log_{10}(d) \\ &= -20\ \log_{10}(0.3/4\pi) + 20\log_{10}(f) + 20\log_{10}(d) \quad \text{dB} \end{aligned}$$

$$L_f = 32.44 + 20\log_{10}(f) + 20\log_{10}(d) \qquad \text{dB}$$

Propagation Model- Free Space (non-ideal, path loss)



- Non-isotropic antenna gain ≠ unity, and there are additional losses ***L_{ad}***, thus the power received is:

$$P_r = G_t G_r \frac{P_t\lambda^2}{(4\pi d)^2}\cdot\frac{1}{L_{ad}}$$

$d > 0$ and $L \geq 0$

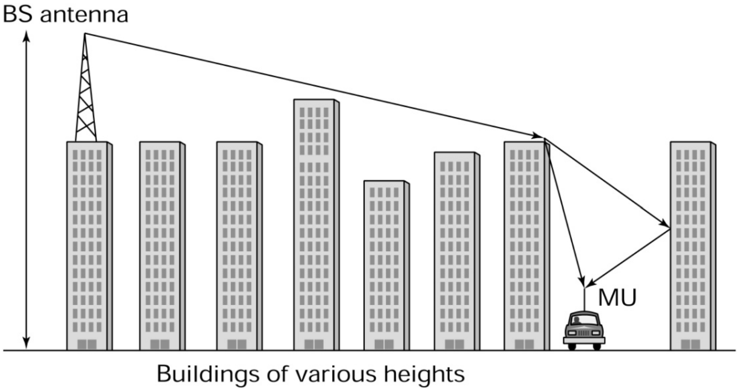
Thus for **Non-isotropic antenna** the path loss is:

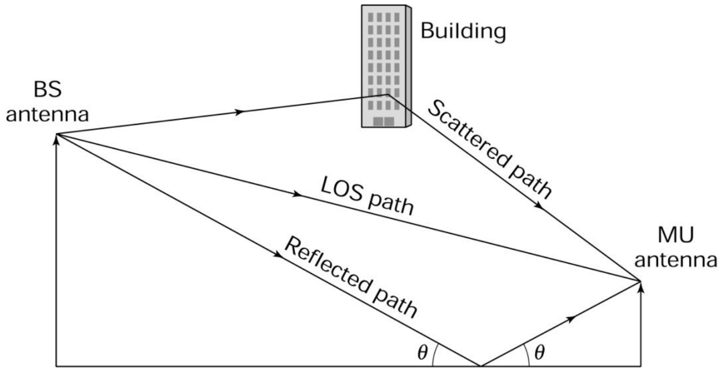
$$L_{f-ni} = -10\log_{10}(G_t) - 10\log_{10}(G_r) - 20\log_{10}(c/4\pi) + 20\log_{10}(f) + 20\log_{10}(d) + 10\log_{10}(L_{ad}) \quad \text{dB}$$

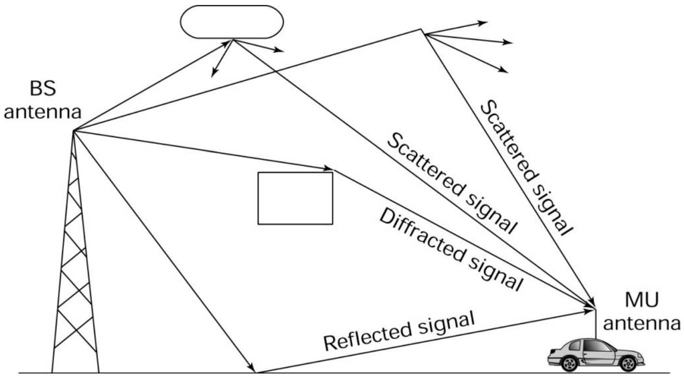
Note: Interference margin can also be added

Propagation Model - Mechanisms

- Reflection
- Diffraction
- Scattering



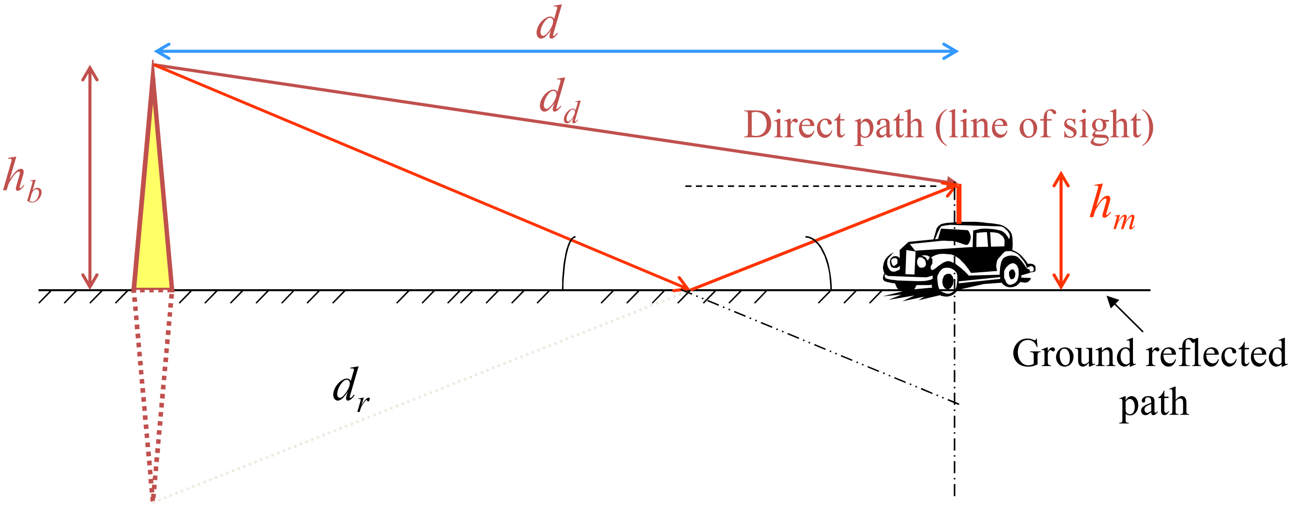




Source: P M Shankar

Channel Model- Plan Earth Path Loss - 2 Ray Reflection

- In mobile radio systems the height of both antennas (Tx. and Rx.) << *d* (distance of separation)



From the geometry $d_d = \sqrt{[d^2 + (h_b - h_m)^2]}$

Channel Model- Plan Earth Path Loss - *contd.*

Using the binomial expansion

Note d >> h_b or h_m.

$$d_d \cong d\left\{1 + 0.5\left(\frac{h_b - h_m}{d}\right)^2\right\}$$

Similarly

$$d_r \cong d\left\{1 + 0.5\left(\frac{h_b + h_m}{d}\right)^2\right\}$$

The path difference $\Delta d = d_r - d_d = 2(h_b h_m)/d$

The phase difference $\Delta\phi = \frac{2\pi}{\lambda} \times \frac{2h_b h_m}{d} = \frac{4\pi h_b h_m}{\lambda d}$

Channel Model- Plan Earth Path Loss– *contd.*

Total received power

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \times \left|1 + \rho e^{j\Delta\phi}\right|^2$$

Where ρ is the reflection coefficient.
For ρ = -1 (low angle of incident) and .

$$1 - e^{-j\Delta\phi} = 1 - \cos\Delta\phi + j\sin\Delta\phi$$

$$Hence \left|1 - e^{-j\Delta\phi}\right|^2 = (1 - \cos\Delta\phi)^2 + \sin^2\Delta\phi = 2(1 - \cos\Delta\phi)$$

$$= 4\sin^2(\Delta\phi / 2)$$

Channel Model- Plan Earth Path Loss– *contd.*

Therefore: $P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \times 4\sin^2\left(\frac{2\pi h_b h_m}{\lambda d}\right)$

Assuming that d >> h_m or h_b, then $\left(\frac{2\pi h_b h_m}{\lambda d}\right) << 1$

sin x = x for small x

Thus $P_r = P_t G_t G_r \left(\frac{h_b h_m}{d^2}\right)^2$ which is 4th power law

Channel Model- Plan Earth Path Loss– *contd.*

Propagation path loss (mean loss)

$$L_{PE} = -10\log\left(\frac{P_r}{P_t}\right) = 10\log\left[G_t G_r\left(\frac{h_b h_m}{d^2}\right)^2\right]$$

Compared with the free space = $P_r = 1/ d^2$

In a more general form (*no fading due to multipath*), path attenuation is

$$\begin{aligned} L_{PE} &= -10\log_{10} G_t - 10\log_{10} G_r - 20\log_{10} h_b \\ &\quad - 20\log_{10} h_m + 40\log_{10} d \qquad \text{dB} \end{aligned}$$

- L_{PE} increases by 40 dB each time d increases by 10

Channel Model- Plan Earth Path Loss– *contd.*

- Including impedance mismatch, misalignment of antennas, pointing and polarization, and absorption The power ration is:

$$\frac{P_r}{P_t} = G_t(\theta_t,\phi_t)G_r(\theta_r,\phi_r)\left(\frac{\lambda}{4\pi d}\right)^2\left(1+|\Gamma_t|^2\right)\left(1-|\Gamma_r|^2\right)\left|\overline{a_t}\cdot\overline{a_r}^*\right|^2 e^{-\alpha d}$$

where

$G_t(\theta_t,\phi_t)$ = gain of the transmit antenna in the direction (θ_t,ϕ_t) of receive antenna.

$G_r(\theta_r,\phi_r)$ = gain of the receive antenna in the direction (θ_r,ϕ_r) of transmit antenna.

Γ_t and Γ_r = reflection coefficients of the transmit and receive antennas

$\mathbf{a}_t$ and $\mathbf{a}_r$ = polarization vectors of the transmit and receive antennas

α is the absorption coefficient of the intervening medium.

LOS Channel Model - Problems

- Simple theoretical models do not take into account many practical factors:
  - Rough terrain
  - Buildings
  - Refection
  - Moving vehicle
  - Shadowing

Thus resulting in bad accuracy

Solution: Semi- empirical Model

Semi-empirical Model

Practical models are based on combination of measurement and theory. Correction factors are introduced to account for:

- Terrain profile
- Antenna heights
- Building profiles
- Road shape/orientation
- Lakes, etc.

- **Okumura model**
- **Hata model**

} Outdoor

- **Saleh model**
- **SIRCIM model**

} Indoor

Y. Okumura, et al, *Rev. Elec. Commun. Lab.*, 16(9), 1968.
M. Hata, *IEEE Trans. Veh. Technol.*, 29, pp. 317-325, 1980.

Okumura Model

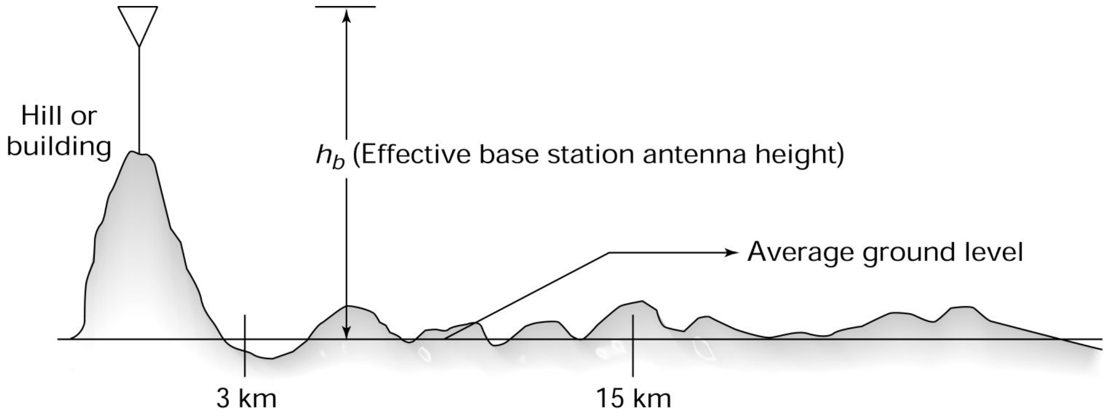
- Widely used empirical model (no analytical basis!) in macrocellular environment
- Predicts average (median) path loss
- “Accurate” within 10-14 dB in urban and suburban areas
- Frequency range: 150-1500 MHz
- Distance: > 1 km
- BS antenna height: > 30 m.
- MU antenna height: up to 3m.
- Correction factors are then added.

Hata Model

- Consolidate Okumura’s model in standard formulas for **macrocells** in urban, suburban and open rural areas.
- Empirically derived correction factors are incorporated into the standard formula to account for:
  - Terrain profile
  - Antenna heights
  - Building profiles
  - Street shape/orientation
  - Lakes
  - Etc.

Hata Model – *contd.*

- The loss is given in terms of effective heights.
- The starting point is an urban area. The BS antennae is mounted on tall buildings. The effective height is then estimated at 3 - 15 km from the base of the antennae.



Hata Model - Limits

- Frequency range: 150 - 1500 MHz
- Distance: 1 – 20 km
- BS antenna height: 30- 200 m
- MU antenna height: 1 – 10 m

Hata Model – Standard Formula for Average Path Loss for Urban Areas

$$\boxed{\begin{aligned} L_{pl-u} &= 69.55 + 26.16\log_{10}(f) + (44.9 - 6.55\log_{10} h_b)\log_{10} d \\ &\quad -13.82\log_{10} h_b - a(h_{mu}) \qquad \text{(dB)} \end{aligned}}$$

Correction Factors are:

- Large cities

$$a(h_{mu}) = 8.3[\log_{10}(1.5h_{mu})]^2 - 1.1 \quad (f \le 200\text{MHz}) \text{ dB}$$

$$a(h_{mu}) = 3.2[\log_{10}(11.75h_{mu})]^2 - 4.97 \quad (f \ge 400\text{MHz}) \text{ dB}$$

- Average and small cities

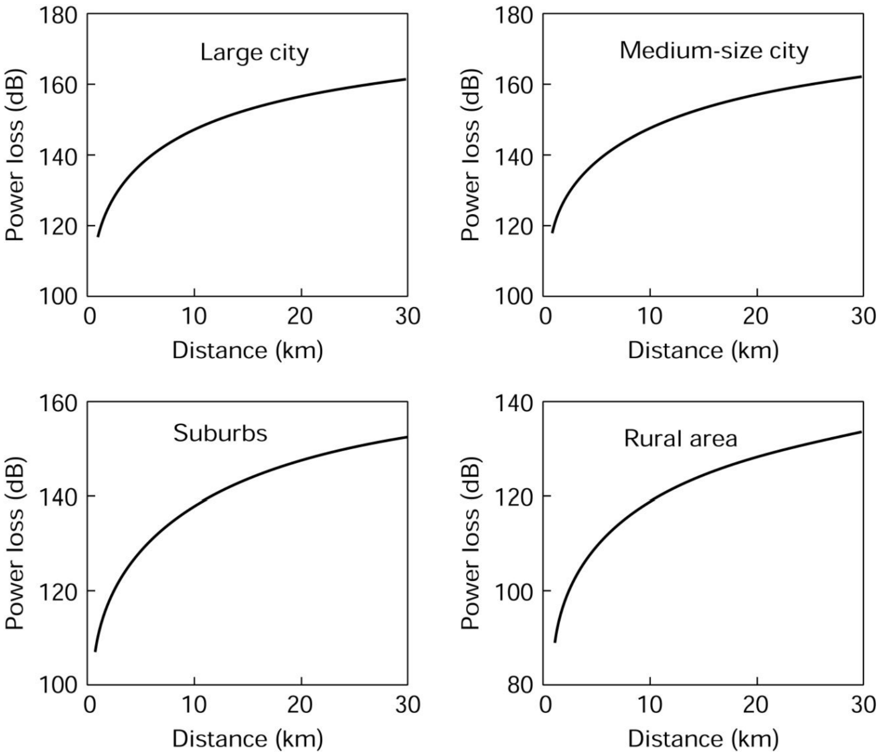
$$a(h_{mu}) = [1.1\log_{10}(f) - 0.7]h_{mu} - [1.56\log_{10}(f) - 0.8] \quad \text{dB}$$

Hata Model – Average Path Loss for Urban Areas *contd.*

Carrier frequency
- **900 MHz,**

BS antenna height
- **150 m,**

MU antenna height
- **1.5m.**



Hata Model – Average Path Loss for Suburban and Open Areas

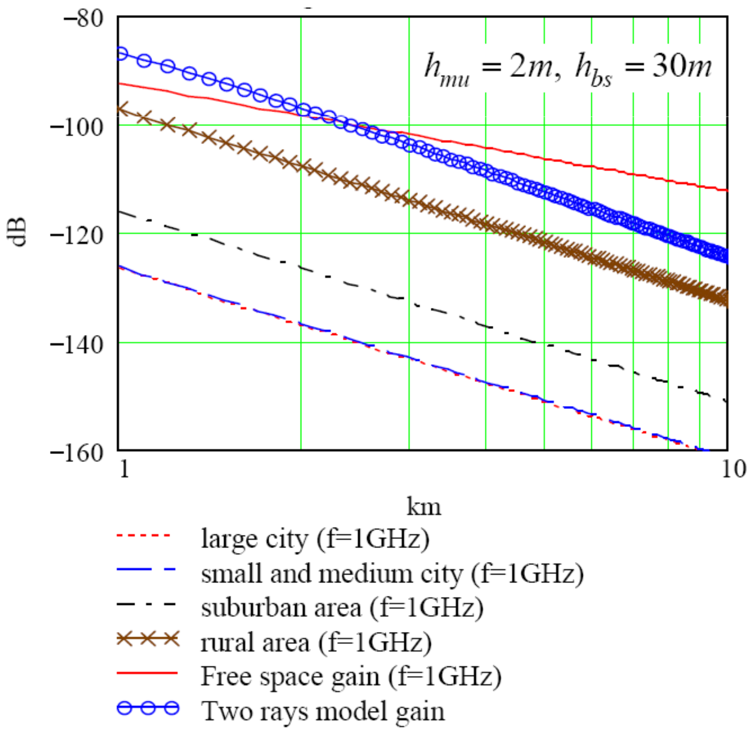
- Suburban Areas

$$L_{pl-su} = L_{pl-u} - 2\left[\mathrm{Log}_{10}\left(\frac{f}{28}\right)\right]^2 - 5.4$$

- Open Areas

$$L_{pl-o} = L_{pl-u} - 4.78(\mathrm{Log}_{10} f)^2 - 18.33\,\mathrm{Log}\, f - 40.94$$

Hata Model - Average Path Loss



S. Loyka, 2003,
Introduction to Mobile Communications

Improved Model

- Hata-Okumura model are not suitable for lower BS antenna heights (2 m), and hilly or moderate-to-heavy wooded terrain.
- To correct for these limitations the following model is used [1]:
- For a given close-in distance d_{ref}, the average path loss is:

$$L_{pl} = A + 10\, v \log10 (d / d_{ref}) + s \qquad \text{for } d > d_{ref}, \qquad \text{(dB)}$$

where

$A = 20 \log10(4 \pi d_{ref} / \lambda)$

v is the path-loss exponent = (a – b hb + c / hb)

hb is the height of the BS: between 10 m and 80 m

d_{ref} = 100m and

a, b, c are constants dependent on the terrain category

s is representing the shadowing effect

[1] V. Erceg et. al, *IEEE JSAC*, 17 (7), July 1999, pp. 1205-1211.

Improved Model

		Terrains	
Model parameter	**Type A**	**Type B**	**Type C**
a	4.6	4	3.6
b	0.0075	0.0065	0.005
c	12.6	17.1	20

The typical value of the standard deviation for **s** is between 8.2 And 10.6 dB, depending on the terrain/tree density type

- Terrain A: The maximum path loss category is hilly terrain with moderate-to-heavy tree densities .
- Terrain B: Intermediate path loss condition
- Terrain B: The minimum path loss category which is mostly flat terrain with light tree densities

Summary

- Attenuation is a result of reflection, scattering, diffraction and reflection of the signal by natural and human-made structures
- The received power is inversely proportional to $(\text{distance})^{v}$, where v is the loss parameter.
- Studied channel models and their limitations