Mobile Communications

Part VII- Propagation Characteristics

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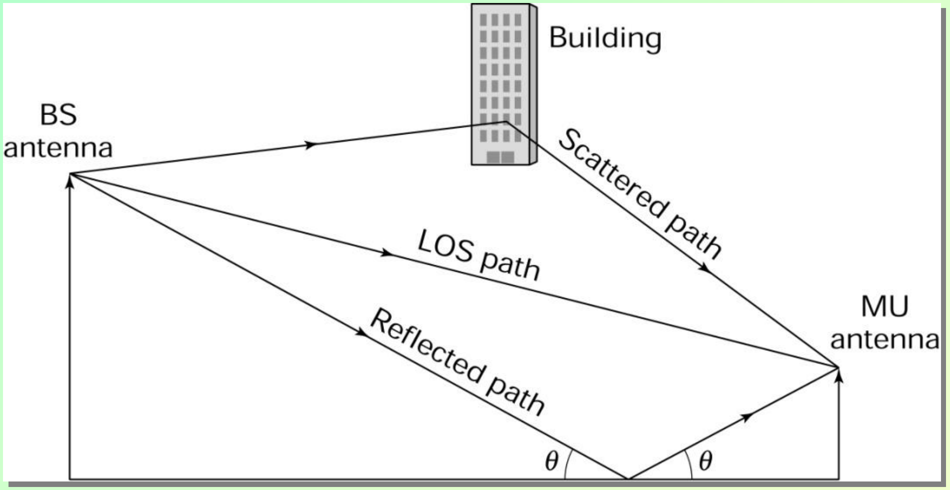
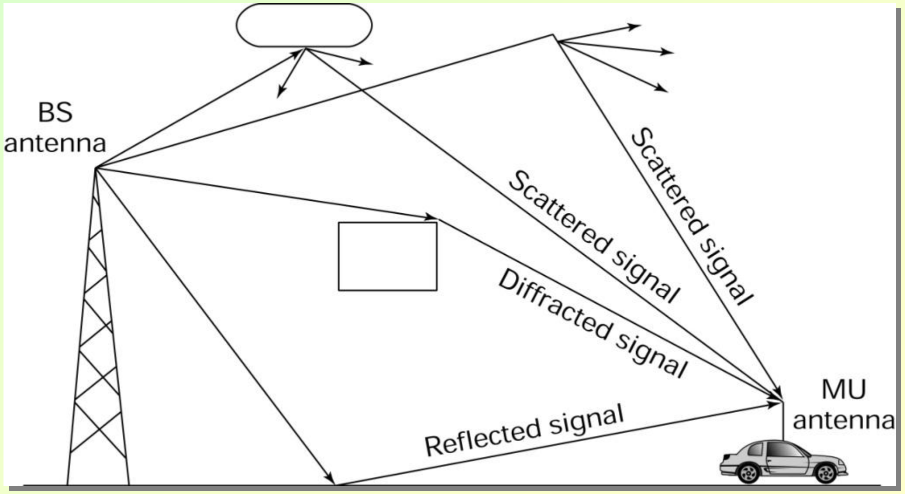
Contents

- Propagation path loss
  - LOS
  - NLOS
- Free space path loss model
- Plan earth path loss model
- Semi empirical models

Propagation Model - Mechanisms

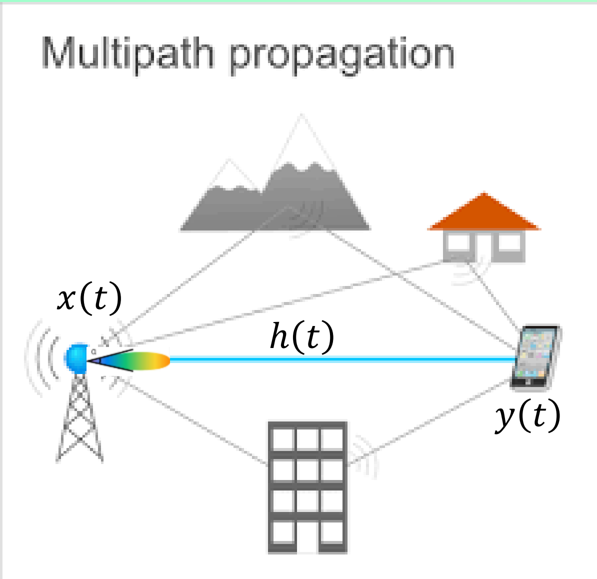
- LOS
- Reflection
- Diffraction
- Scattering





Source: P M Shankar

Propagation – Ray Tracing Path



- The received pass-band signal with no noise and interference:

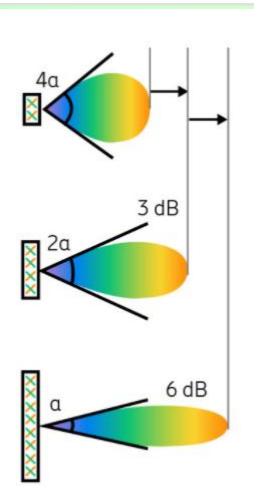
$$y(t) = x(t) * h(t) + n(t) + i(t)$$

$$y(t) = \mathrm{Re}\{(g(t) * h(t))e^{-j2\pi f_c(t)}\} + n(t) + i(t)$$

For a single path

$$y(t) = \mathrm{Re}\left\{\frac{\lambda\sqrt{G_{an}}e^{-\frac{j2\pi d}{\lambda}}}{4\pi d} g(t)e^{j2\pi f_c t}\right\}$$

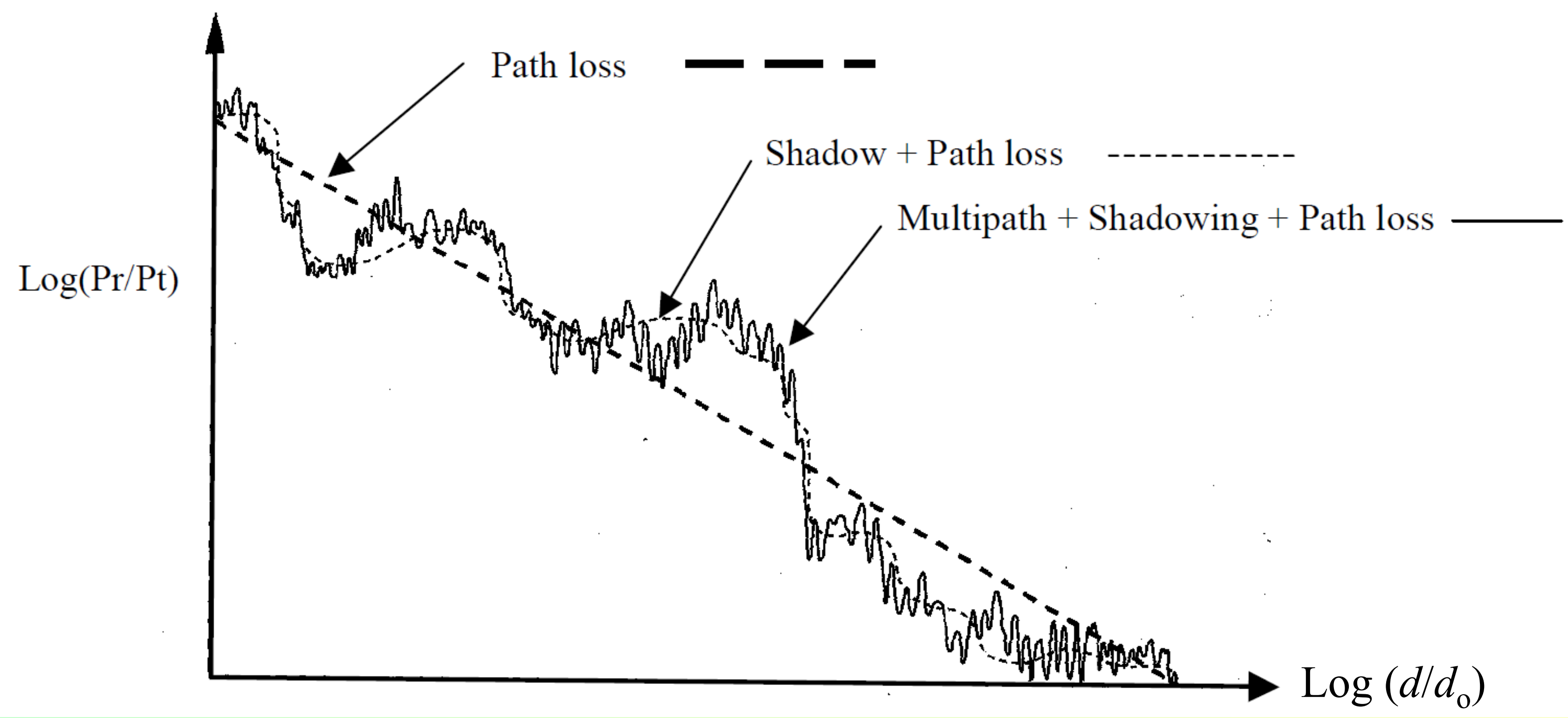
Rotation; Channel; Information; Carrier signal



Antenna gain patterns

- Note:
  - Distance-dependent rotation
  - Distance-dependent power decay, i.e., $1/d$
  - Wavelength, and Tx and Rx antenna gains G_{an}

Propagation Model- Path loss +



P_r [dBm] = P_t [dBm] + path loss [dB] + shadowing [dB] + multipath [dB]

Models:	Deterministic	Random, Log-normal	Random

[Goldsmith2005]

Propagation Path Loss

- The propagation path loss $L_{PE} = L_a L_{lf} L_{sf}$

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 Model

- Generally the received power can be expressed as:

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

$$P_r = P_t \left(\frac{d_{ref}}{d}\right)^v$$

$$P_r[dBm] = P_t[dBm] + K\ [dB] - 10\ v\log_{10}\left(\frac{d}{d_{ref}}\right)$$

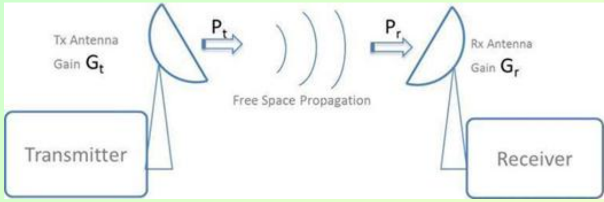
Environment	*v*
Urban marocells	3.7-6.5
Urban microcells	2.7-3.5
Office (one floor)	1.6-3.5
Office (multiple floors)	2-6
Store	1.8-2.2
Factory	1.6-3.3
Home	3

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

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

Propagation Path Loss – Free Space

- Power received at the receiving antenna *at far field only*



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

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

- If the $P_r = P_{r\text{-}min}$ (i.e., the minimum signal required for the system), then the maximum range is:

$$d_{max} = \left[\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 P_{r-min}} \right]^{0.5}$$

Propagation Path Loss – Free Space

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

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

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

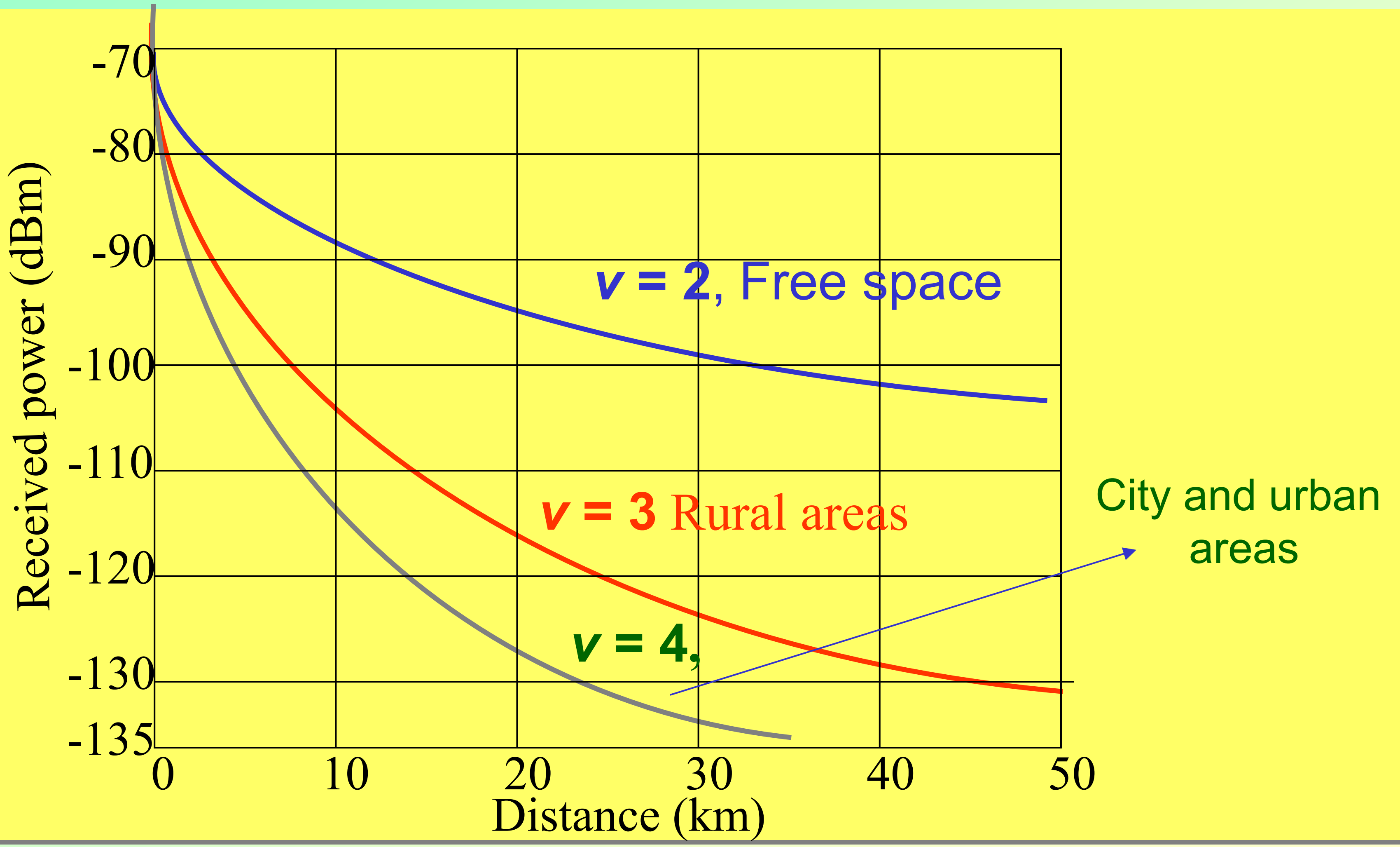
- Shadowing - Log-normal

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

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

https://www.youtube.com/watch?v=sWKLaQ-6ffQ&list=PLHGIkY491Cy1ll7CopaAO_mt_lo_A2L2A&index=2

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 x 10^8 m/s, the path loss is:

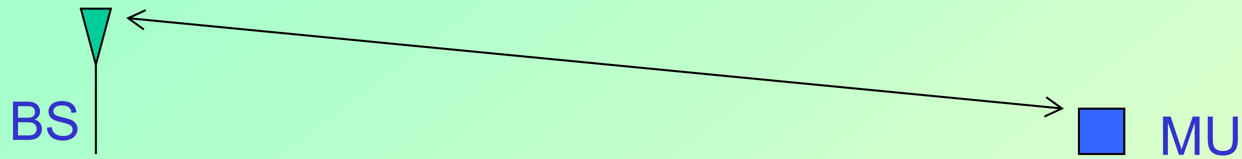
$$L_f = -20\log_{10}\left(\frac{c/f}{4\pi d}\right) \quad \text{dB}$$

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

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

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

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



- Non-isotropic antenna gain ≠ unity
- Additional losses L_{ad} (shadowing, cable loss)

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 $L \geq 0$

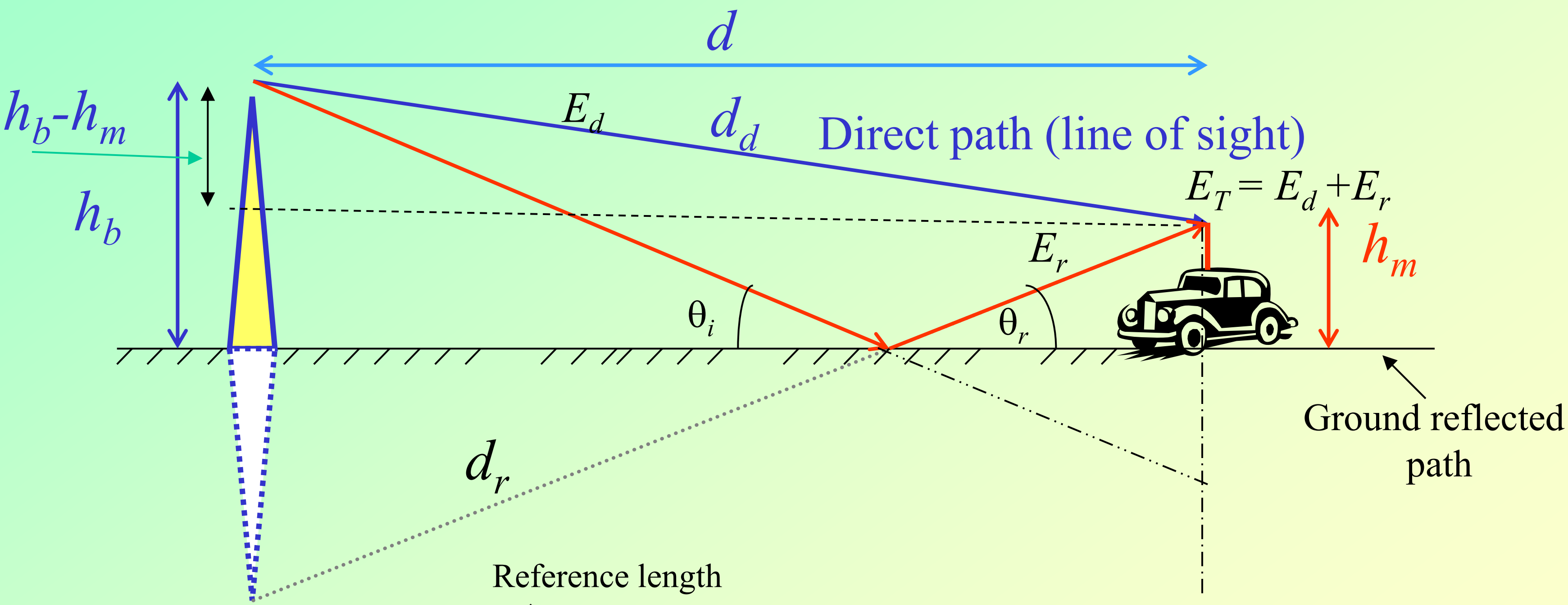
Thus for **Non-isotropic antenna** the path loss is:

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

Note: Interference margin can also be added

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)



$$E_{d_d}(d,t) = \frac{E_o d_o}{d_d} cos\left(w_c(t - \frac{d_d}{c})\right) \qquad E_{d_r}(d,t) = \rho \frac{E_o d_o}{d_r} cos\left(w_c(t - \frac{d_r}{c})\right)$$

ρ → Reflection coefficient.

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

$$E_T = E_d + E_r \Rightarrow \qquad E_T(d,t) = \frac{E_o d_o}{d_d} cos\left(w_c\left(t - \frac{d_d}{c}\right)\right) + \rho \frac{E_o d_o}{d_r} cos\left(w_c\left(t - \frac{d_r}{c}\right)\right)$$

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

Using the binomial expansion

Note Ideally $d >> h_b + h_m$.

Practically $d = 10\ (h_b + h_m)$

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

Similarly

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

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

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

The phase difference

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

The time delay

$$\tau_d = \frac{\Delta d}{c} = \frac{\Delta\phi}{2\pi f_c}$$

Relative permittivity

Reflection coefficient.

$$\rho = \frac{\sin\theta_i - \sqrt{\varepsilon_r - cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - cos^2\theta_i}}$$

- At low angle of incident, i.e., long distance between Tx and Rx), ρ = -1.
- For $d >> h_b$ or h_m.
- and at $t = d_r/c$

$$E_T(d, \frac{d_r}{c}) = \frac{E_o d_o}{d_d} cos\left(w_c(\frac{d_r - d_d}{c})\right) - \frac{E_o d_o}{d_r} cos(0)$$

$$E_T(d, \frac{d_r}{c}) = \frac{E_o d_o}{d_d} cos\Delta\phi - \frac{E_o d_o}{d_r} = \frac{E_o d_o}{d}[cos\Delta\phi - 1]$$

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

Thus

$$|E_T(d)| = \sqrt{\left(\frac{E_o d_o}{d}\right)^2 (cos\Delta\phi - 1)^2 + \left(\frac{E_o d_o}{d}\right)^2 sin^2\Delta\phi}$$

$$|E_T(d)| = \frac{E_o d_o}{d}\sqrt{2 - 2cos\Delta\phi}$$

$$|E_T(d)| = 2\frac{E_o d_o}{d} sin\left(\frac{\Delta\phi}{2}\right)$$

Note. The delay in *E* in an oscillating mode with the increasing distance

Now the aim is to eliminate sin(.).

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

We have $$|E_T(d)| = 2\frac{E_o d_o}{d} sin\left(\frac{\Delta\phi}{2}\right)$$

For small angle (in this case $\frac{\Delta\phi}{2} < 0.3$, we have sin(x) ~= x, thus

The phase difference $$\frac{\Delta\phi}{2} = \frac{2\pi h_b h_m}{\lambda d} < 0.3$$

$$E_T(d) \approx \frac{4\pi E_o d_o h_b h_m}{\lambda d^2} \qquad V/m$$

Total received power $$P_r = \frac{E^2}{120\pi} A_e$$

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.*

Alternatively, we could drive the equation for the received power as

Total received power

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

For ρ = -1 (low angle of incident, long distance between Tx and Rx):

$$1 - e^{-j\Delta\phi} = 1 - [1 - j\,\Delta\phi]$$

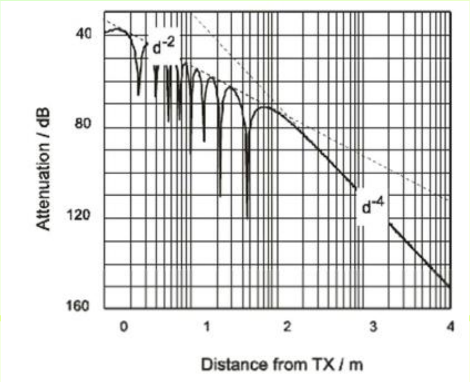
$$Hence \left|1 - (1 - e^{-j\Delta\phi})\right|^2 = (\Delta\phi)^2$$

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

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

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 = $\boldsymbol{P_r = 1/d^2}$

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

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

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

Propagation - Path Loss Model

- Generally the received power can be expressed as:

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

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

$$P_r(d) = 10\log P_r(d_{ref}) + 10v\log\left({}^{d}/_{d_{ref}}\right)$$

1-10 m indoor < d_{ref} < 10-100 m outdoor

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

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

$G_r(\theta_r,\varphi_r)$ = 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

Sem-iempirical 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

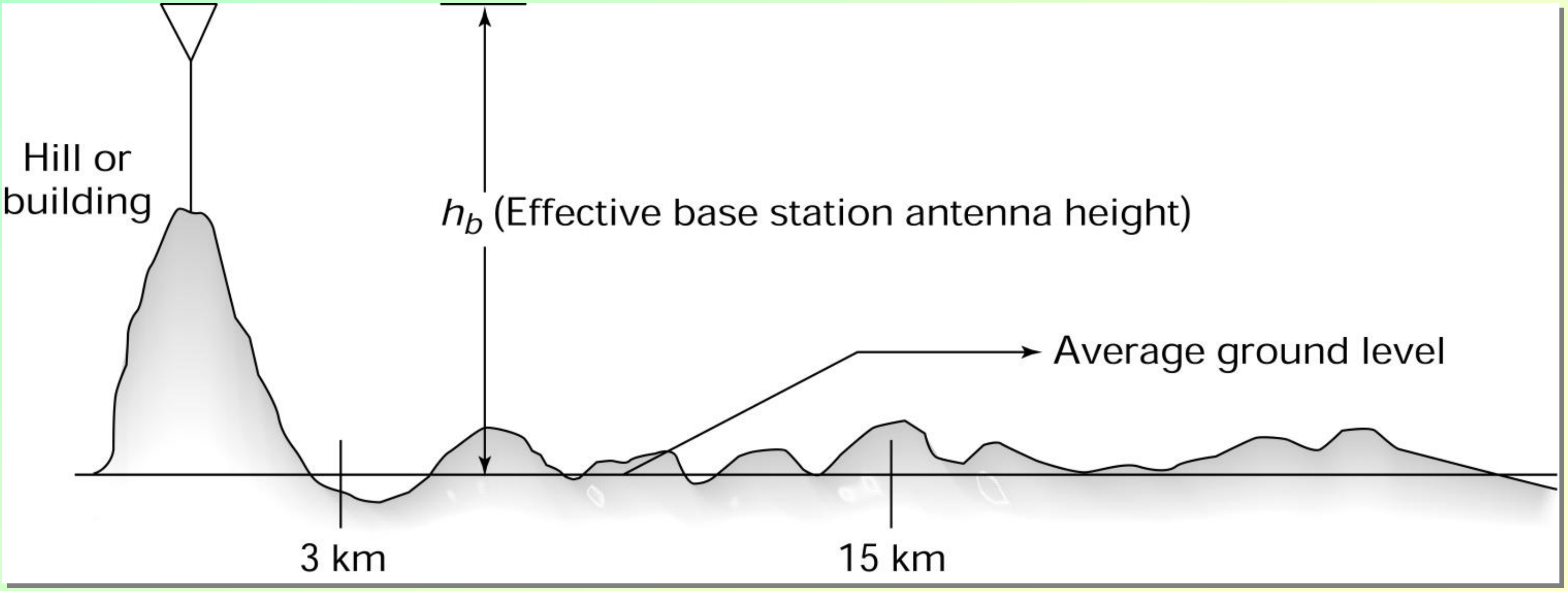
- Widely used empirical model (no analytical basis!) in macrocellular environment
- Predicts average (median) path loss
- “Accurate” within 10-14 dB in urban and suburban areas
- Frequency range: 150-1500 MHz
- Distance: > 1 km
- BS antenna height: > 30 m.
- MU antenna height: up to 3m.
- Correction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

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

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

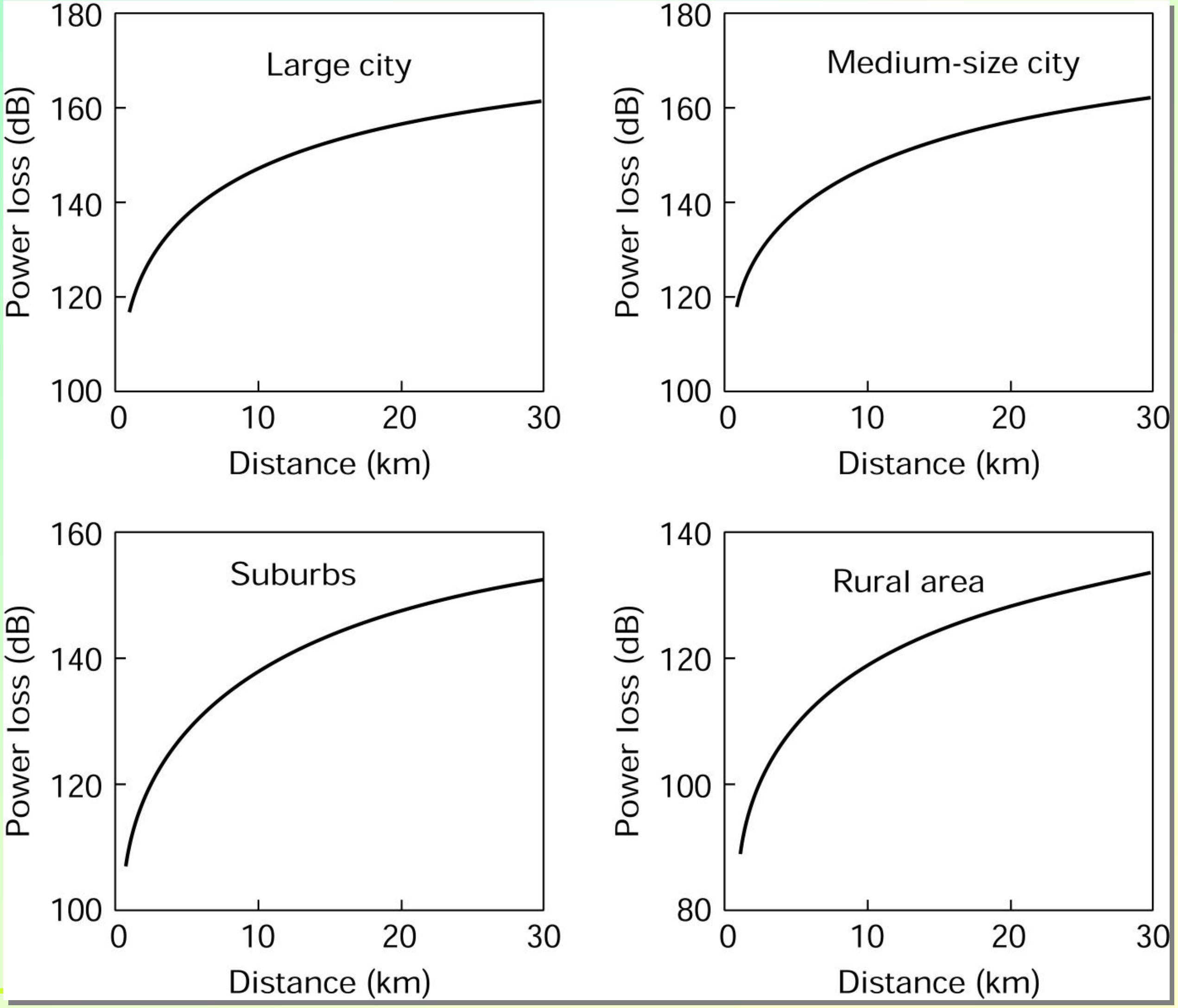
$$a(h_{mu}) = [1.1\log_{10}(f) - 0.7]h_{mu} - [1.56\log_{10}(f) - 0.8] \quad \text{dB}$$

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

Carrier frequency
- **900 MHz,**

BS antenna height
- **150 m,**

MU antenna height
- **1.5m.**



P M Shankar

Hata Model – Average Path Loss for Suburban and Open Areas

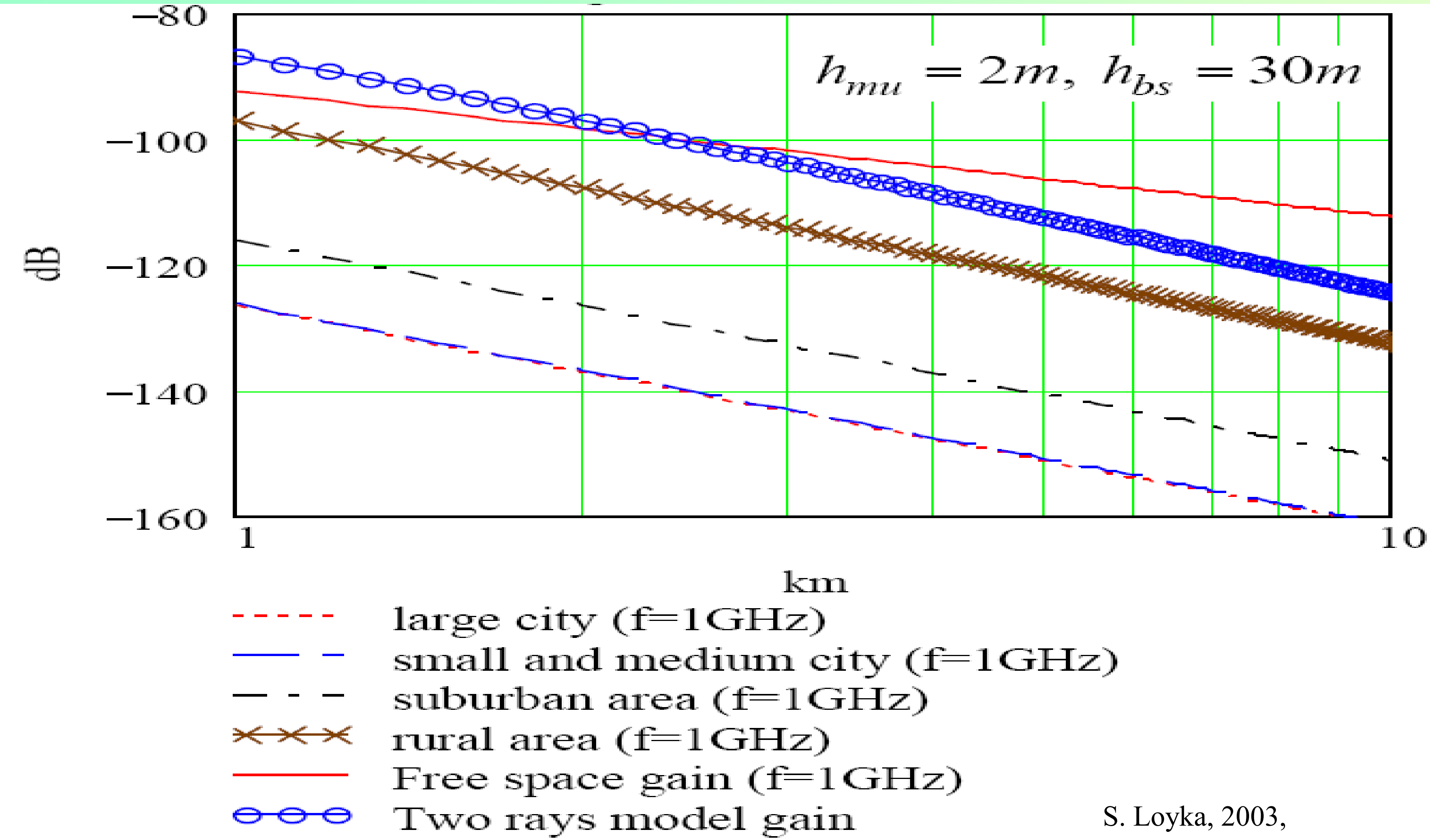
- Suburban Areas

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

- 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:

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

where

$A = 20 \log 10(4\pi\, d_{ref} / \lambda)$

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} = 100 m

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

Losses

Summary of penetration losses through various common building materials at 28 GHz. Both of the horn antennas have 24.5 dBi gains with 10
half power beamwidth [28].

Environment	Location	Material	Thickness (cm)	Received Power - Free Space (dBm)	Received Power - Material (dBm)	Penetration Loss (dB)
Outdoor	ORH	Tinted Glass	3.8	-34.9	-75.0	40.1
	WWH	Brick	185.4	-34.7	-63.1	28.3
Indoor	MTC	Clear Glass	<1.3	-35.0	-38.9	3.9
	WWH	Tinted Glass	<1.3	-34.7	-59.2	24.5
		Clear Glass	<1.3	-34.7	-38.3	3.6
		Wall	38.1	-34.0	-40.9	6.8

Penetration losses for multiple indoor obstructions in an office environment at 28 GHz. Weak signals are denoted by locations where the SNR
was high enough to distinguish signal from noise but not enough for the signal to be acquired, i.e. penetration losses were between 64 dB to 74 dB relative to a 5 m free space test. No signal detected denotes an outage, where penetration loss is greater than 74 dB relative to a 5 m free space test [28].

RX ID	TX-RX Separation (m)	# of Partitions				Transmitted Power (dBm)	Power Received – Free Space (dBm)	Received Power – Test Material (dBm)	Penetration Loss (dB)
		Wall	Door	Cubicles	Elevator				
1	4.7	2	0	0	0	-8.6	-34.4	-58.8	24.4
2	7.8	3	0	0	0	-8.6	-38.7	-79.8	41.1
3	11.4	3	1	0	0	11.6	-21.9	-67.0	45.1
5	25.6	4	0	2	0	21.4	-19.0	-64.1	45.1
4	30.1	3	2	0	0	21.4	-30.4	Weak Signal Detected	
6	30.7	4	0	2	0	21.4	-30.5	Weak Signal Detected	
7	32.2	5	2	2	0	21.4	-30.9	Weak Signal Detected	
8	35.8	5	0	2	1	21.4	-31.9	No Signal Detected	

Reflection Coefficients

- Comparison of reflection coefficients for various common building materials at 28 GHz. Both of the horn antennas have 24.5 dBi gains with 10 half power beam-width.

Environment	Location	Material	Angle (°)	Reflection Coefficient ($\|\Gamma_{\|\|}\|$)
Outdoor	ORH	Tinted Glass	10	0.896
		Concrete	10	0.815
			45	0.623
Indoor	MTC	Clear Glass	10	0.740
		Drywall	10	0.704
			45	0.628

Summary

- Propagation path loss
- Free space path loss model
- Plan earth path loss model
- Semi empirical models

- **Next lecture: Multi-path Propagation- Fading**