EE 577: Wireless and Personal Communications

Large-Scale Signal Propagation Models

Propagation Models

- Basic Model is to determine the major path loss effects
- This can be refined to take into account the effects due to outdoor structures (buildings, trees, etc.)
- This can be refined for indoor use as well to take into account building wall composition, windows, etc.

Path Loss Model

- We use the basic average path loss as being a function of distance and environment
- $\langle PL(dB)\rangle = \langle PL(d_0)\rangle + 10\, n \log(d/d_0)$
- The coefficient *n* is:
  - 2 for straight path loss (free space)
  - Higher for other environments

Path Loss Model

Free space	$n = 2$
Urban area cellular radio (CR)	$n = 2.7 - 3.5$
Shadowed urban area CR	$n = 3 – 5$
In buildings: line-of-site	$n = 1.6 – 1.8$
Within buildings	$n = 4 - 6$

The exact value needs to be empirically determined for the application

Shadowing

- Buildings, trees, etc. will all shadow the signal from the transmitter to the receiver
- This is usually modeled by a log-normal probability distribution
- These parameters for the fit are usually locality-dependent

Log-Normal Shadowing

- The received power is then given by the following

$$P_r(d) = P_t(d) - \langle PL(d) \rangle + X_\sigma$$

- Here, X_σ is a random variable describing the amount of shadowing in the area.
- This is usually a **log-normal** random variable (dB value is normally distributed).
- This is best done by averaging over many paths in the area

Log-Normal Shadowing

- Note that the Gaussian statistics underlie everything

- Compute the probability that the received signal exceeds a given value γ by

$$\Pr[P_r(d) > \gamma] = Q[(\gamma - \langle P_r(d) \rangle)/\sigma]$$

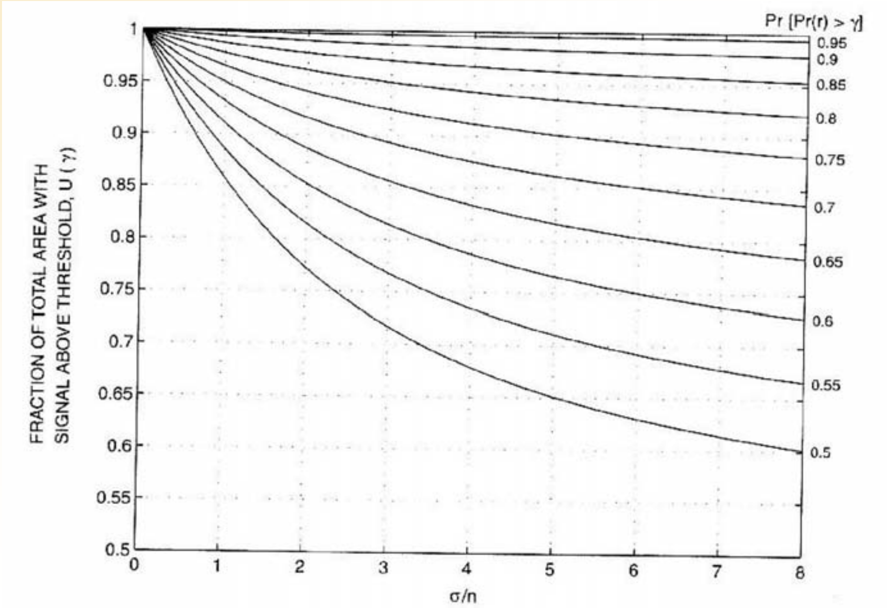
where σ is the standard deviation observed in the transmission path

Coverage Area

- This is also required to analyze the cell radius for proper power at the cell boundary
- Since the signal is random, we cannot tell for sure if the coverage will be acceptable (enough quality)
- We can only rate the coverage on a statistical basis
- **Coverage area:** the percentage of area with a signal level exceeding a threshold, γ

It is the useful coverage area

Coverage Area



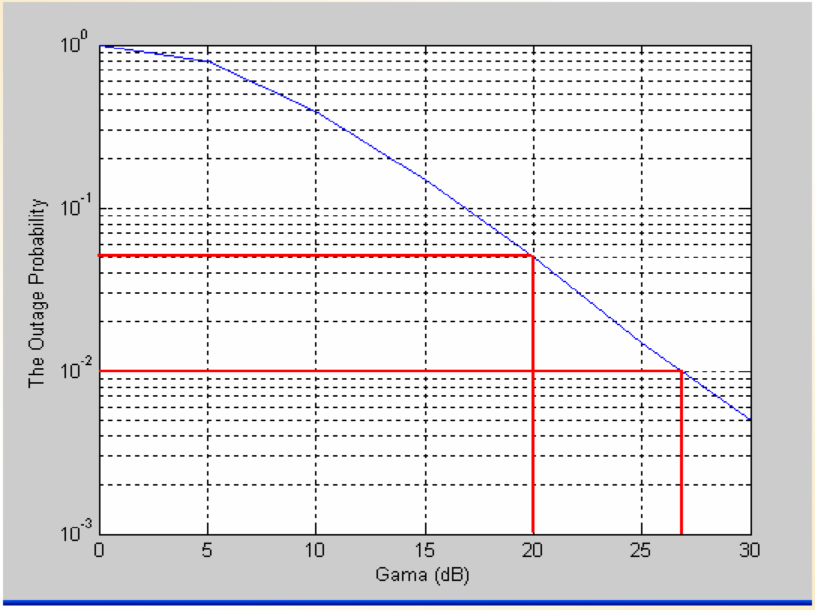
Outage Probability

- **It is the percentage of time the signal power falls below a minimum usable level**
- **It depends on the distribution of the signal power level**
- **It is the CDF of the signal distribution**

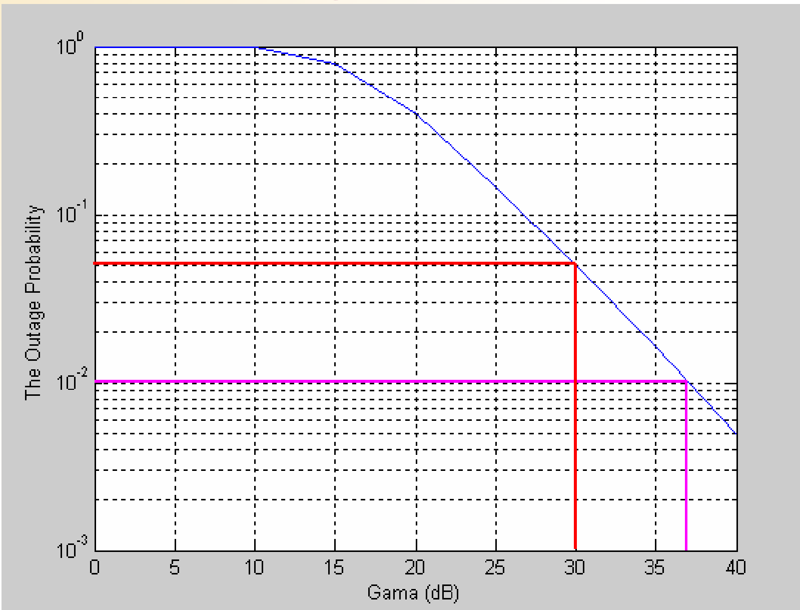
$$P_o = \Pr(\gamma < b)$$

- **As the threshold *b* decreases, the outage probability decreases => better performance**

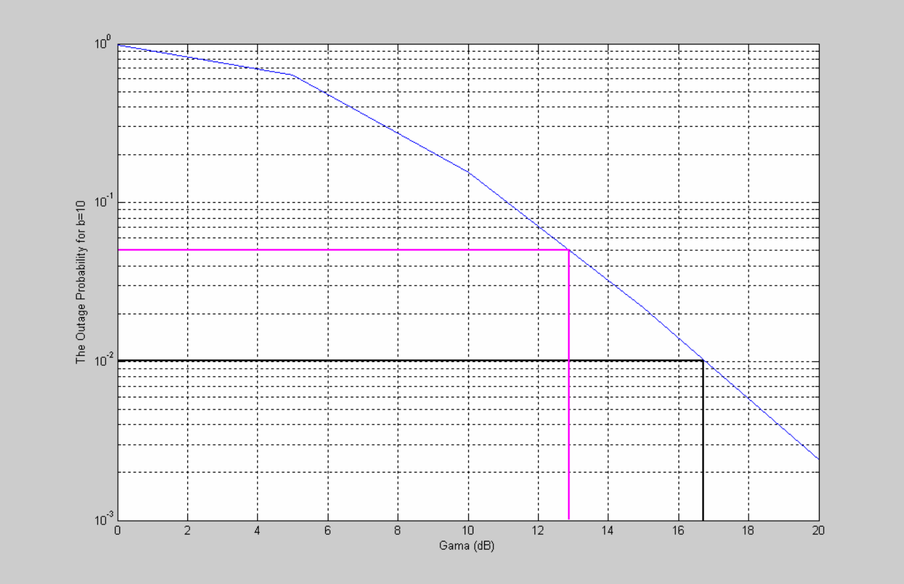
Rayleigh: *b* = 10 dB



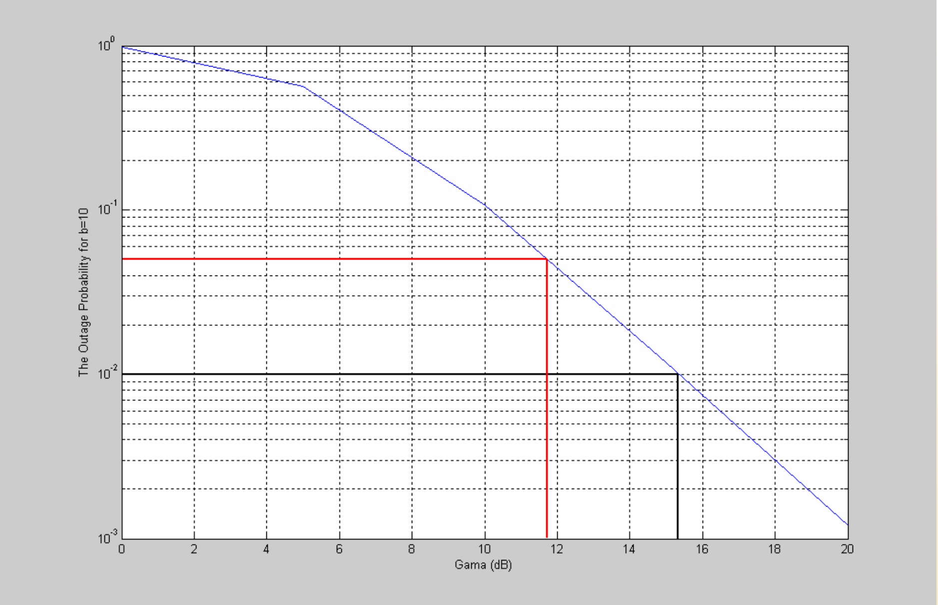
Rayleigh: *b* = 20 dB



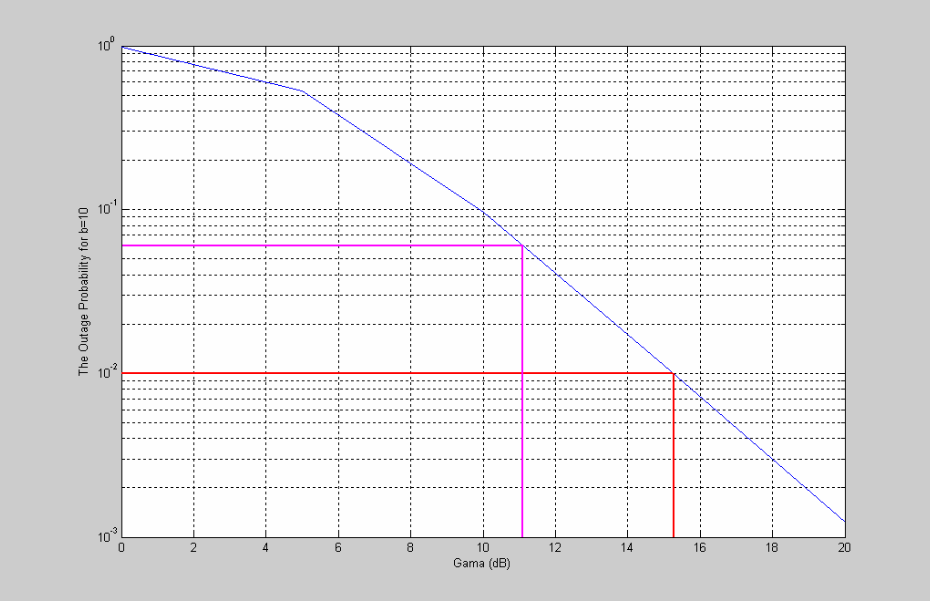
With 2-branch Selection Diversity: *b* = 10 dB



With 3-branch Selection Diversity: *b* = 10 dB



With 4-branch Selection Diversity: *b* = 10 dB

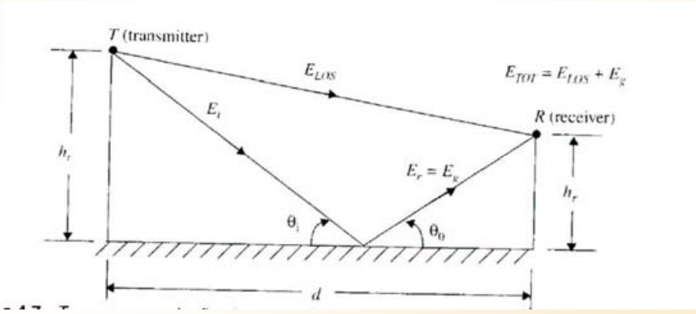


Reflection - Diffraction - Scattering

- **Reflection** occurs when a wave impinges upon a smooth surface of large size relative to λ (wavelength)
- **Diffraction** occurs when the path is blocked by an object with large dimensions relative to λ and sharp irregularities (edges)
- **Scattering** occurs when a wave impinges upon an object with dimensions on the order of λ or less

Two-Ray Ground Reflection

- Excess path: $\Delta = 2h_t\, h_r\, /d$
- It is the extra distance the reflected wave travels (compared to LOS)
- Phase difference: $\phi = 2\pi\Delta\, /\lambda$
- Time delay of reflected path: $t_d = \phi/2\pi f$



Fresnel Zones

- An electromagnetic wavefront is divided into:
  - Primary wave traveling through the LOS
  - Secondary waves traveling distances larger than that of the LOS by $n\lambda/2$
- Secondary waves define zones of concentric circles called **Fresnel Zones**
- The first Fresnel zone defines a propagation breakpoint, d_0
- If first Fresnel zone is captured, the propagation is approximately free space

Diffraction Loss

- Excess path (between LOS and a diffracted path):

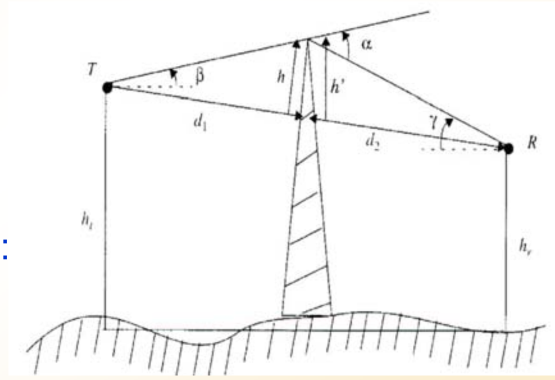
$$\Delta = \frac{h^2}{2}\frac{d_1+d_2}{d_1 d_2}$$

- Phase difference:

$$\varphi = \frac{2\pi\Delta}{\lambda} = \frac{\pi}{2}v^2$$

- Diffraction Parameter:

$$v = h\sqrt{\frac{2(d_1+d_2)}{\lambda d_1 d_2}}$$



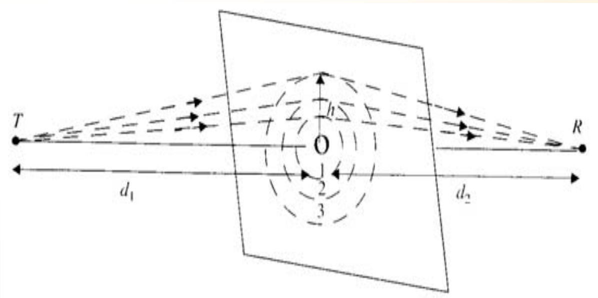
Diffraction Loss

- Received energy depends on received Fresnel zones.
- From excess path, find the received Fresnel Zones:

$$\Delta = n\lambda/2$$

- Find n => the n^{th} Fresnel Zones was not received
- The radii of Fresnel Zones around the diffraction:

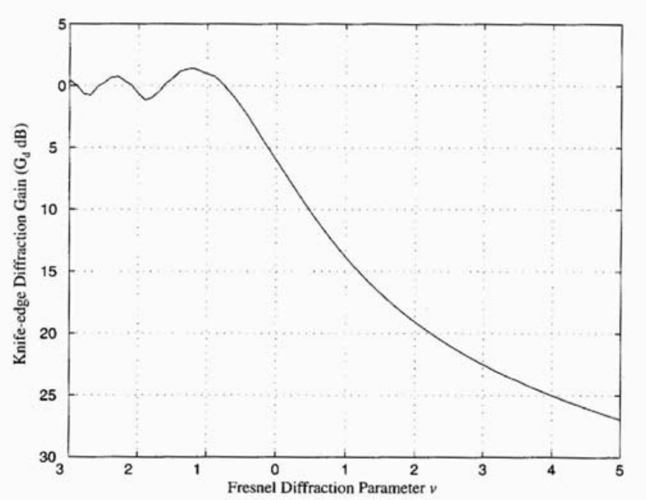
$$r_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}}$$



Diffraction Loss

- **Diffraction Loss:** G_d(dB) = 20 log $F(v)$

  where $F(v)$ is the Fresnel Integral



Diffraction Loss

Example 4.7: [Rappaport]:

- d_1 = 1 km, d_2 = 1 km, λ = 1/3 m
- Compute diffraction loss for:

  a) h = 25 m b) h = 0 m c) h = -25 m

Solution:

a) $v = 2.74$ => G_d = 21.7 dB

b) $v = 0$ => G_d = 6 dB

c) $v = -2.74$ => G_d = 0 dB

$\Delta = 0.625 = n\lambda/2$ => $n = 3.75$

=> The first 3 Fresnel zones are lost at the receiver

=> First zone captured is the 4^{th} one

Propagation Modeling

- Theoretically, propagation can be predicted using Fresnel zones
- **Rule-of-thumb:**

  Keep at least 55% of 1st Fresnel zone clear
- Fresnel zones are not useful for predicting indoor and microcell coverage
  - The distance between the transmitter and receiver is often less than the breakpoint (at which zones are formed)
  - Fresnel zones are not practical for distances beyond the breakpoint (short distances)

Statistical Propagation Models

- Based on statistical analysis of large amounts of measured 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

Statistical Propagation Models

- Easy to implement
- Very low confidence level if applied to spot predictions
- Very good confidence level for system- wide generalizations; i.e., budgeting and initial system design and planning
- **Examples:**
  - Log-distance model
  - Log-normal shadowing model

Outdoor Propagation Models

- Complex empirical models have been developed to characterize an environment with variable antenna heights, terrain, multipath, etc.
- These models predict the propagation loss:
  - Longley-Rice Model
  - Durkin’s Model
  - Okumura’s Model
  - Hata’s Model
  - PCS Extension to Hata’s Model (COST-231)

Longley-Rice Model

- An Outdoor Propagation Model
- Frequency Region: 40 MHz - 100 GHz
- Two-way reflection and knife-edge diffraction are used
- **Features:** accounts for free space propagation, scattering and terrain effects; some urban corrections
- **Limitations:** does not include good urban effects or blocking by buildings and foliage; no multipath effects

Durkin Model

- Computes signal levels at contours around Tx
- Uses 2-D arrays to provide a digital map
- Determines the path => uses diffraction techniques to find path loss
- **Features:** models multiple diffraction edges; imports standard terrain data; determines LOS or degree of obstruction
- **Limitations:** good to a “few dBs” in predictions (where valid); does not include good urban effects or blocking by buildings and foliage; no multipath effects

Okumura Model

- Frequency Region: 150 to 1920 MHz
- Can be extrapolated to 3000 MHz
- Models environments based totally on empirical measurements
- Used as a standard in Japan
- **Features:** Analytical performance curves can be obtained, many correction factors
- **Limitations:** Slow response to terrain changes, correct up to 10 dB

Okumura Equations

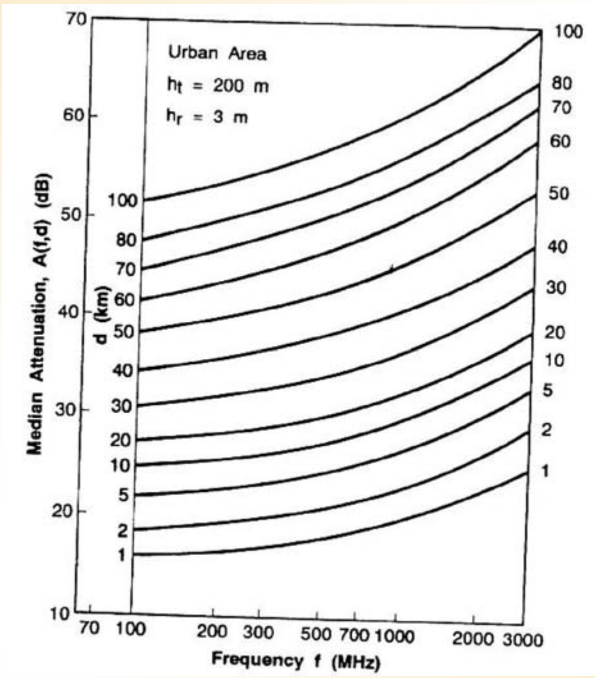
- Median propagation loss estimate:

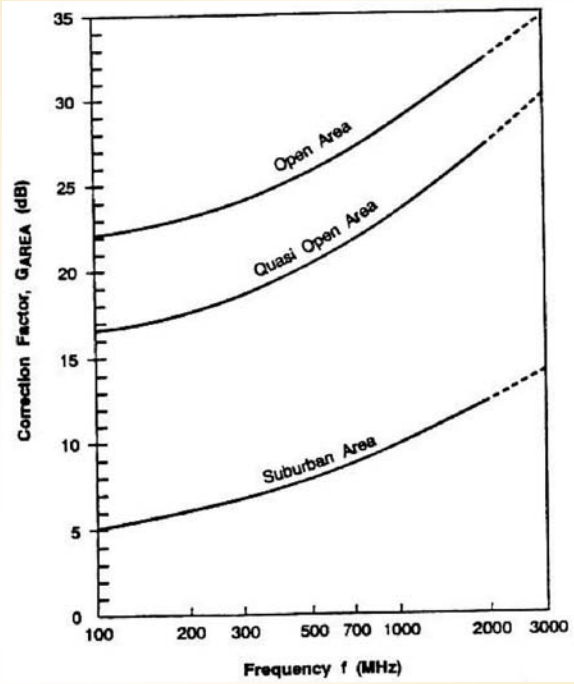
$$L_p(dB) = L_F + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

- d: Tx-Rx distance in km
- $L_F = 20 \log(\lambda / 4\pi d)$, free space loss
- $A_{mu}(f,d)$: median attenuation (from graph)
- G_{AREA}: city/rural correction factor (from graph)

Okumura Equations

- h_{te}: effective transmitter height (30 - 200 m)
- h_{re}: effective receiver height (1 m to 10 m)
- $G(h_{te})$: gain factor from Tx antenna
- $G(h_{re})$: gain factor from Rx antenna
- $G(h_{te}) = 20 \log(h_{te}/200)$, $1 \text{ km} < h_{te} < 10 \text{ m}$
- $G(h_{re}) = 10 \log(h_{re}/3)$, $h_{re} < 3 \text{ m}$
- $G(h_{re}) = 20 \log(h_{re}/3)$, $3 \text{ m} < h_{te} < 10 \text{ m}$





Example 4.10 [Rappaport]

- $d = 50$ km, $h_{te} = 100$ m, $h_{re} = 10$ m
  EIRP = 1 kW = 60 dBm, $f = 900$ MHz
- Find Rx power?

Solutions:

- $L_F = 125.5$ dB, $A_{mu}(f,d) = 43$ dB,
  $G(h_{te}) = -6$ dB, $G(h_{re}) = 10.46$ dB,
  $G_{AREA} = 9$ dB,
  $L_p = 125.5+43-(-6)-10.43-9 = 155.04$ dB
- Rx power = EIRP(dB) – 155.04 = -125.04 dB

Hata Model

- Frequency Region: 150 to 1500 MHz
- It is an empirical formulation to Okumura's model
- **Features:** based on urban areas and applies corrections for other effects
- **Limitations:** $d > 1$ km

Hata Equations

- Median path loss in dB in **urban areas**:

$$L_p(\text{urban}) = 69.55 + 26.16\log(f) - 13.82\log(h_{te})$$
$$-a(h_{re}) + (44.9 - 6.55\log(h_{te}))\log(d)$$

- Small-to-medium city correction (dB):
  $a(h_{re}) = (1.1 \log(f) - 0.7)\, h_{re} - (1.56 \log(f) - 0.8)$

Hata Equations

Large city correction:

$$a(h_{re}) = 8.29\ (\log 1.54 h_{re})^2 - 1.1 \text{ dB},$$
$$f < 300 \text{ MHz}$$

$$a(h_{re}) = 3.2\ (\log 11.75 h_{re})^2 - 4.97 \text{ dB},$$
$$f > 300 \text{ MHz}$$

Hata Equations

- **Suburban:**

$$L_p(\text{dB}) = L_p(\text{urban}) - 2\ [\log(f_C/28)]^2 - 5.4$$

- **Open, rural:**

$$L_p(\text{dB}) = L_p(\text{urban}) - 4.78\ [\log(f)]^2 - 18.33 \log(f) - 40.98$$

COST-231 Hata Model

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

- Extended to range: 1500 to 2000 MHz
- h_{te}: 30 m to 200 m
- h_{re}: 1 m to 10 m
- d: 1 km to 20 km
- C_M = 0 dB for medium cities and suburbs;
  = 3 dB for metropolitan centers

How to Use The Propagation Loss?

- A link budget tells us the maximum allowable path loss on each link, and which link is the limiting factor
- This maximum allowable path loss will set our maximum cell size
- Input the maximum allowable loss (from the link budget) in the propagation equations
- Calculate the cell radius, R

Typical Parameters

❑ Tx Power	(~ 30 - 45 dBm)
❑ Antenna Gain	(~ 18 dBd for BS)
❑ Diversity Gain	(~ 3 - 5 dB)
❑ Rx Sensitivity	(~ -105 dBm)
❑ Duplexer Loss	(~ 1 dB)
❑ Filter Loss	(~ 2 - 3 dB)
❑ Combiner Loss	(~ 3 dB)
❑ Feeder Loss	(~ 3 dB)
❑ Vehicle Penetration	(~ 6 dB)
❑ Body Loss	(~ 3 dB)
❑ Fade Margin	(~ 8 - 10 dB)

Indoor Propagation Models

- ❑ Propagation is influenced by: bldg. layout, material type, etc…
- ❑ Different from outdoor by:
  - ❑ Distance is smaller
  - ❑ Environments vary widely
- ❑ Reflections, diffraction and scattering dominate performance
- ❑ Log-Normal shadowing is also valid
- ❑ Measurements in same floor and within floors were taken => tabulated

Indoor Propagation Models

- **Parameters:**
  - FAF: floor attenuation factor
  - PAF: partition attenuation factor
  - Propagation index in same floor
  - Propagation index in multi-floor
- **Observations:**
  - Higher floors have less path loss (LOS)
  - Lower floors have higher path loss (no LOS)
  - Penetration loss increases with frequency
  - Lower floors are more urban environments

Indoor Propagation Models

- Different from outdoor in two aspects:
  - Much smaller distances
  - Greater variability in environment.
- Reflections, diffraction and scattering dominate performance.
- Log-Normal shadowing is also valid

Log-distance Path Loss Model

$$L(d) = L(d_0) + 10n\log(d/d_0) + X_\sigma; \quad \text{(dB)}$$

Shows up to 13 dB standard deviation difference from measured data.

Table 4.6 Path Loss Exponent and Standard Deviation Measured in Different Buildings [And94]

Building	Frequency (MHz)	n	σ (dB)
Retail Stores	914	2.2	8.7
Grocery Store	914	1.8	5.2
Office, hard partition	1500	3.0	7.0
Office, soft partition	900	2.4	9.6
Office, soft partition	1900	2.6	14.1
Factory LOS			
Textile/Chemical	1300	2.0	3.0
Textile/Chemical	4000	2.1	7.0
Paper/Cereals	1300	1.8	6.0
Metalworking	1300	1.6	5.8
Suburban Home			
Indoor Street	900	3.0	7.0
Factory OBS			
Textile/Chemical	4000	2.1	9.7
Metalworking	1300	3.3	6.8

Attenuation Factor Model

- Attenuation very much affected by:
  - Type of material
  - Floor difference between Tx and Rx.
- Measurements are made for partition losses in the same floor, and partition losses between floors.

$$\bar{L}(d) = \bar{L}(d_0) + 10n_{SF}\log(d/d_0) + FAF + \sum PAF; \quad \text{(dB)}$$

  - n_{SF} = same floor exponent
  - FAF = Floor Attenuation Factor
  - PAF = Partition Attenuation Factor.
- The model is applied using "*primary ray tracing*" technique
- Shows 4 dB standard deviation difference from measured data

Table 4.3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material

Material Type	Loss (dB)	Frequency	Reference
All metal	26	815 MHz	[Cox83b]
Aluminum siding	20.4	815 MHz	[Cox83b]
Foil insulation	3.9	815 MHz	[Cox83b]
Concrete block wall	13	1300 MHz	[Rap91c]
Loss from one floor	20-30	1300 MHz	[Rap91c]
Loss from one floor and one wall	40-50	1300 MHz	[Rap91c]
Fade observed when transmitter turned a right angle corner in a corridor	10-15	1300 MHz	[Rap91c]
Light textile inventory	3-5	1300 MHz	[Rap91c]
Chain-like fenced in area 20 ft high containing tools, inventory, and people	5-12	1300 MHz	[Rap91c]
Metal blanket — 12 sq ft	4-7	1300 MHz	[Rap91c]
Metallic hoppers which hold scrap metal for recycling — 10 sq ft	3-6	1300 MHz	[Rap91c]
Small metal pole — 6" diameter	3	1300 MHz	[Rap91c]
Metal pulley system used to hoist metal inventory — 4 sq ft	6	1300 MHz	[Rap91c]
Light machinery < 10 sq ft	1-4	1300 MHz	[Rap91c]
General machinery — 10 - 20 sq ft	5-10	1300 MHz	[Rap91c]
Heavy machinery > 20 sq ft	10-12	1300 MHz	[Rap91c]
Metal catwalk/stairs	5	1300 MHz	[Rap91c]
Light textile	3-5	1300 MHz	[Rap91c]
Heavy textile inventory	8-11	1300 MHz	[Rap91c]
Area where workers inspect metal finished products for defects	3-12	1300 MHz	[Rap91c]
Metallic inventory	4-7	1300 MHz	[Rap91c]
Large I-beam — 16 - 20"	8-10	1300 MHz	[Rap91c]
Metallic inventory racks — 8 sq ft	4-9	1300 MHz	[Rap91c]
Empty cardboard inventory boxes	3-6	1300 MHz	[Rap91c]
Concrete block wall	13-20	1300 MHz	[Rap91c]
Ceiling duct	1-8	1300 MHz	[Rap91c]
2.5 m storage rack with small metal parts (loosely packed)	4-6	1300 MHz	[Rap91c]
4 m metal box storage	10-12	1300 MHz	[Rap91c]

Table 4.3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material (Continued)

Material Type	Loss (dB)	Frequency	Reference
5 m storage rack with paper products (loosely packed)	2-4	1300 MHz	[Rap91c]
5 m storage rack with large paper products (tightly packed)	6	1300 MHz	[Rap91c]
5 m storage rack with large metal parts (tightly packed)	20	1300 MHz	[Rap91c]
Typical N/C machine	8-10	1300 MHz	[Rap91c]
Semi-automated assembly line	5-7	1300 MHz	[Rap91c]
0.6 m square reinforced concrete pillar	12-14	1300 MHz	[Rap91c]
Stainless steel piping for cook-cool process	15	1300 MHz	[Rap91c]
Concrete wall	8-15	1300 MHz	[Rap91c]
Concrete floor	10	1300 MHz	[Rap91c]
Commercial absorber	38	9.6 GHz	[Vio88]
Commercial absorber	51	28.8 GHz	[Vio88]
Commercial absorber	59	57.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	9.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	28.8 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	5	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	1	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	4	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	8	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	4	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	6	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	14	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	19	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	32	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	59	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	39	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	46	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	57	57.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	47	9.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	46	28.8 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	53	57.6 GHz	[Vio88]

Table 4.5 Average Floor Attenuation Factor in dB for One, Two, Three, and Four Floors in Two Office Buildings [Sei92b]

Building	FAF (dB)	σ (dB)	Number of locations
Office Building 1:			
Through One Floor	12.9	7.0	52
Through Two Floors	18.7	2.8	9
Through Three Floors	24.4	1.7	9
Through Four Floors	27.0	1.5	9
Office Building 2:			
Through One Floor	16.2	2.9	21
Through Two Floors	27.5	5.4	21
Through Three Floors	31.6	7.2	21

Other Forms of Attenuation Factor Model

- We have seen before

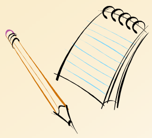
$$\bar{L}(d) = \bar{L}(d_0) + 10 n_{SF} \log(d/d_0) + FAF + \sum PAF; \quad \text{(dB)}$$

- The middle two terms could be substituted by one term for multi-floor propagation

$$\bar{L}(d) = \bar{L}(d_0) + 10 n_{MF} \log(d/d_0) + \sum PAF; \quad \text{(dB)}$$

Table 4.7 Path Loss Exponent and Standard Deviation for Various Types of Buildings [Sei92b]

	n	σ (dB)	Number of locations
All Buildings:			
All locations	3.14	16.3	634
Same Floor	2.76	12.9	501
Through One Floor	4.19	5.1	73
Through Two Floors	5.04	6.5	30
Through Three Floors	5.22	6.7	30
Grocery Store	1.81	5.2	89
Retail Store	2.18	8.7	137
Office Building 1:			
Entire Building	3.54	12.8	320
Same Floor	3.27	11.2	238
West Wing 5th Floor	2.68	8.1	104
Central Wing 5th Floor	4.01	4.3	118
West Wing 4th Floor	3.18	4.4	120
Office Building 2:			
Entire Building	4.33	13.3	100
Same Floor	3.25	5.2	37



Example 3

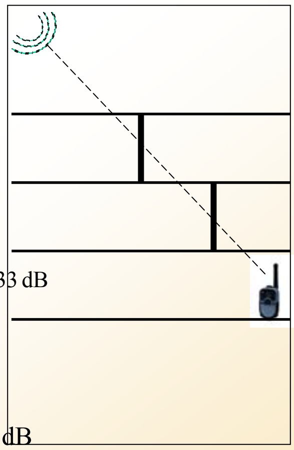
- Building type: Office Building 1
- *f* =1300 MHz; *d* =30 m;
- 3 floors; Two concrete partitions
- Solution

$$\overline{L}(d_0=1)=10\log\left(\frac{4\pi d_0}{\lambda}\right)^2=34.7\text{ dB}$$

1st estimation

$$\overline{L}(d)=\overline{L}(d_0)+10n_{SF}\log(d/d_0)+FAF+\sum PAF$$

$$\overline{L}(30)=34.7+10\times 3.27\times\log(30)+24.4+2\times 13=133\text{ dB}$$



2nd Estimation

$$\overline{L}(d)=\overline{L}(d_0)+10n_{MF}\log(d/d_0)+\sum PAF$$

$$\overline{L}(30)=34.7+10\times 5.22\times\log(10)+2\times 13=108\text{ dB}$$

Signal Penetration into Buildings

- Higher floors have less path loss (LOS)
- Lower floors have higher path loss (no LOS)
- Penetration loss decreases with increasing frequency (Higher frequencies penetrate better).
- Measurements behind windows are 6 dB stronger than behind walls (buildings with no windows).

Loss Pattern Through Floors