Radio Transmission

(Large-Scale Fading)

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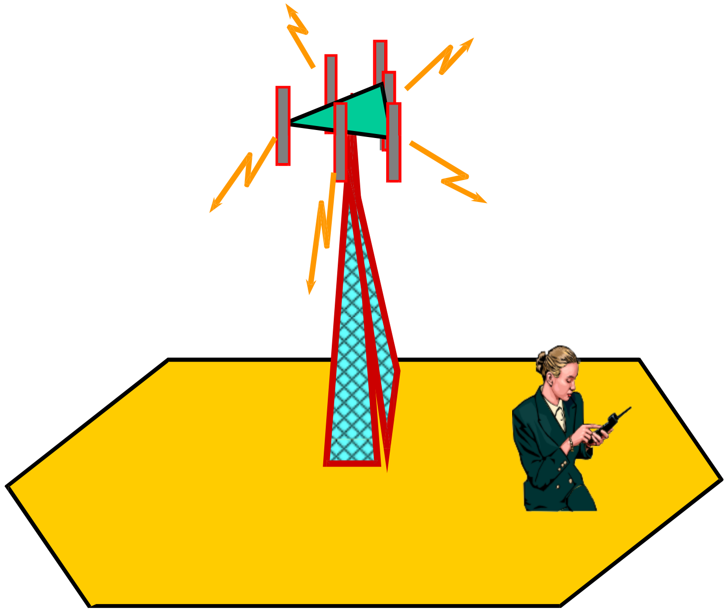


Radio Wave Propagation

- Mechanisms very diverse
  - reflection, diffraction and scattering
- In urban areas where there is no direct LOS, high rise buildings cause severe diffraction loss
- Waves travel along different paths of varying lengths
  - interaction causes multi-path fading
- Strength decreases as the distance between the transmitter and receiver increases

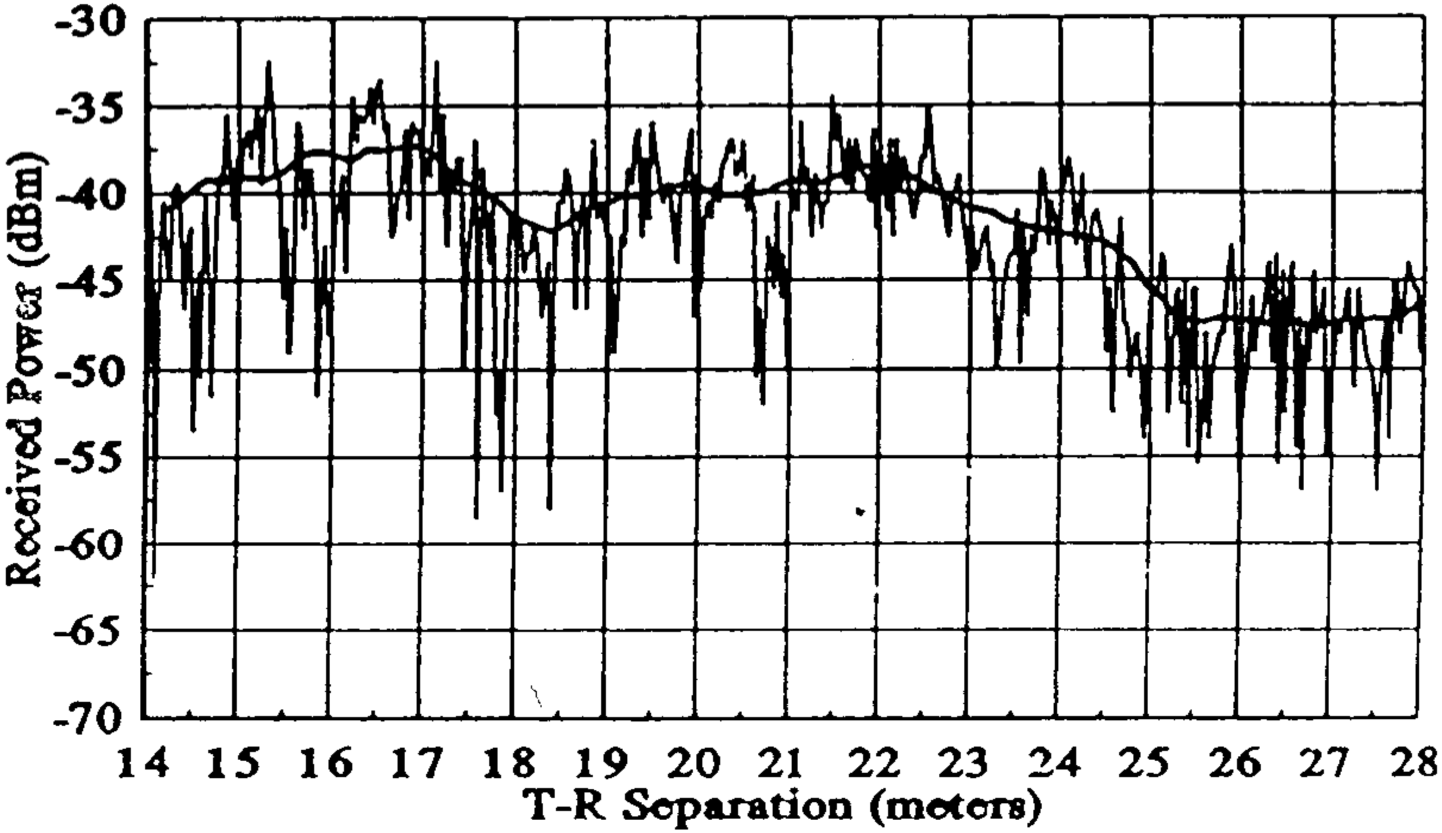
Propagation Models

- Have traditionally focused on predicting the average received signal strength in close spatial proximity to a particular location
- Models that predict mean signal strength for an arbitrary transmitter receiver (T-R) separation
  – Useful for estimating the radio coverage area of a transmitter - *large-scale* models

Propagation Models 2

- *Large scale* models have T-Rs of several hundred or thousands of meters
- Models that can characterize the rapid fluctuations of received signal strength over short distances (few wavelengths) or short duration (second) are called *small-scale* or *fading* models

Typical Look



Free Space Propagation Model

- Predicts received signal strength when Transmitter (T) and Receiver (R) have direct Line of Sight (LOS)
- Satellite & Microwave LOS radio links
- As with most large scale models, the free space model predicts that the received power decays as a function of T-R separation raised to some power (power law function)

Isotropic Antenna

$$G = 1$$

$$\boxed{G = \frac{4}{\lambda^{2}} A_{ea}}$$

$$\boxed{A_{ea} = \frac{{}^{2}}{4\pi}}$$

Free Space Equation

– For a T-R distance of *d*

$$W_{\mathrm{rav}} = P_r \cdot A_{ea}$$

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

– P_t - transmitted power,

– $P_r(d)$ - received power (change of notation !! $P_r(d) \equiv W_{\mathrm{rav}}$),

Isotropic receiver and transmitter antenna used

Friis Free Space Equation

– For a T-R distance of *d*

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

– P_t - transmitted power,

– $P_r(d)$ - received power,

– G_t & G_r - transmitter & receiver antenna gains, L - system loss factor not related to propagation (L >= 1), λ - wavelength in meters

Antenna Gain

- The gain of an antenna is related to its effective aperture, A_e, by:

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

- A_e is related the physical size of the antenna, and λ is related to the carrier frequency by:

$$\lambda = \frac{c}{f} = \frac{2\pi c}{\omega_c}$$

f - the carrier frequency in Hz,
ω_c - carrier frequency in radians/sec,
c - speed of light in m/sec

EXAMPLE

$$f = 1\,GHz \rightarrow \qquad \lambda = \frac{3 \cdot 10^8\ m/s}{10^9\ 1/s} = 0.3\ m = 30\ cm$$

Units

- P_t and P_r must be in the same units [W, mW]
- G_t & G_r are dimensionless
- L is due to transmission line attenuation, filter & antenna losses
- Friis shows that the received power falls off as the square of d - 20 dB/decade

EIRP

- Isotropic radiator is an ideal antenna which radiates power with unit gain uniformly in all directions - reference antenna gain in wireless systems
- *Effective Isotropic Radiated Power* (EIRP) is defined as

$$\mathrm{EIRP} = P_t G_t$$

- Represents the maximum radiated power available from the transmitter in the direction of antenna gain as compared to an isotropic radiator

ERP

- In practice, *effective radiated power* (ERP) is used instead to denote the max radiated power as compared to an half-wave-dipole antenna
- Dipole antenna gain = 1.64, ERP will be 2.15dB smaller than the EIRP for the same transmission system
- *dBi* - dB gain wrt to an isotropic source
- *dBd* - dB gain wrt to a half wave dipole

Path Loss

- Path Loss represents signal attenuation as a positive quantity measured in dB

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

If antenna gains G_r are G_r equal to 1

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

Far Field

- Friis model is onlyvalid for received powers, P_r at distances *d,* which are in the *far field* or ***Fraunhofer*** region.
- Far field of a transmitting antenna is defined as the region beyond the far field distance d_f, which is related to the largest linear dimension of the antenna aperture and/or carrier wavelength.

Fraunhofer Distance

- Fraunhofer distance is given by

$$d_f = \frac{2D_l^2}{\quad}$$

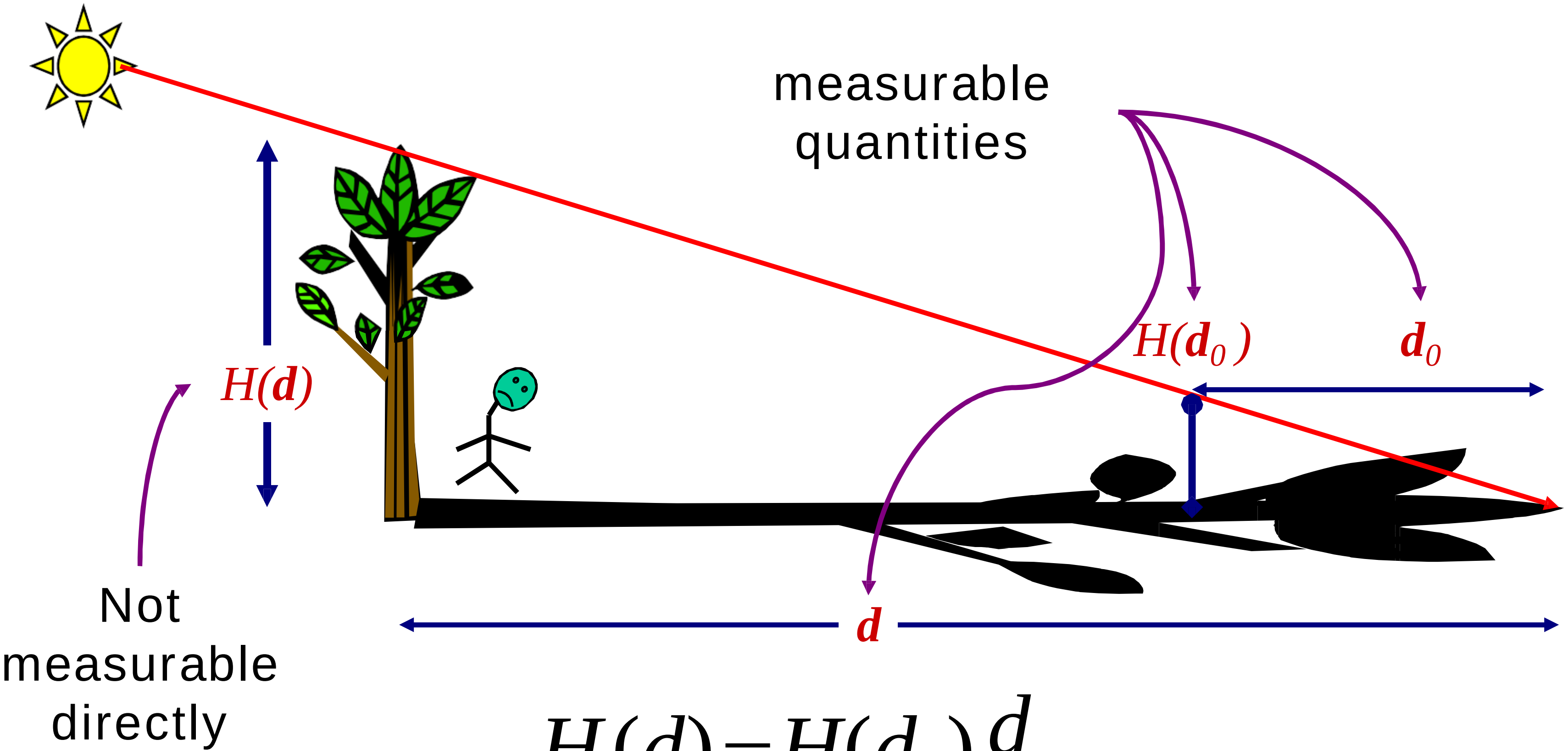
- D_l is the largest physical liner dimension of the antenna
- To be in the far-field region, d_f must satisfy
- $d_f >> D_l$ and $d_f >> \lambda$

Distance d = 0

- The received power equation does not hold for $d = 0$.
- Large scale models use a close-in distance d_0 - *received power reference point*
- The received power at any distance $d > d_0$ may be related to $P_r(d_0)$ at d_0
- $P_r(d_0)$ may be predicted or determined through empirical measurements

Proportions

Calculating height of an inaccessible point



$$H(d) = H(d_0)\frac{d}{d_0}$$

Received power $P_r(d)$

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

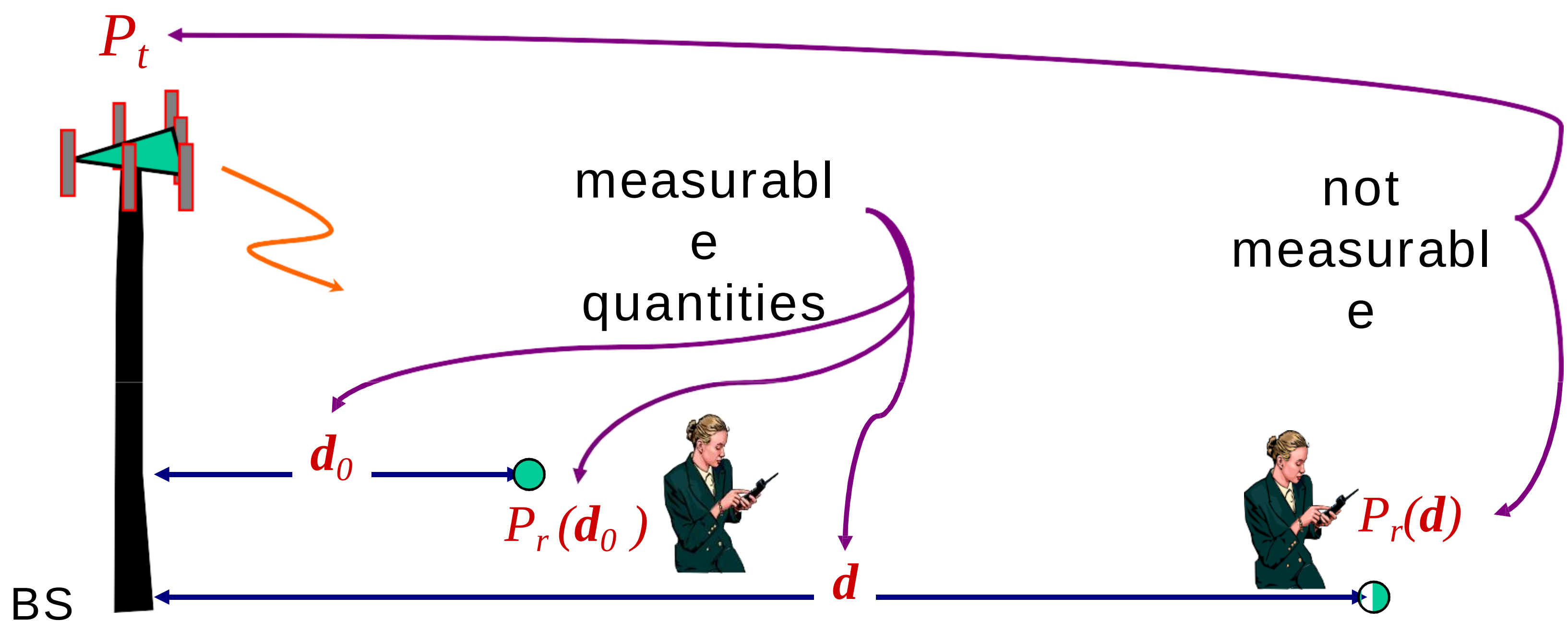
$$P_r(d) = con \cdot \frac{P_t}{d^2} \qquad P_r(d_0) = con \cdot \frac{P_t}{d_0^2} \quad \Rightarrow \quad con = P_r(d_0) \cdot \frac{d_0^2}{P_t}$$

- d_0 must be chosen to be in the far-field region

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

$$P_r(d)\,[dBm] = 10\log\left[\frac{P_r(d_0)}{0.001\,\mathrm{W}}\right] + 20\log\left(\frac{d_0}{d}\right); \qquad d \geq d_0 \geq d_f.$$

Received power $P_r(d)$

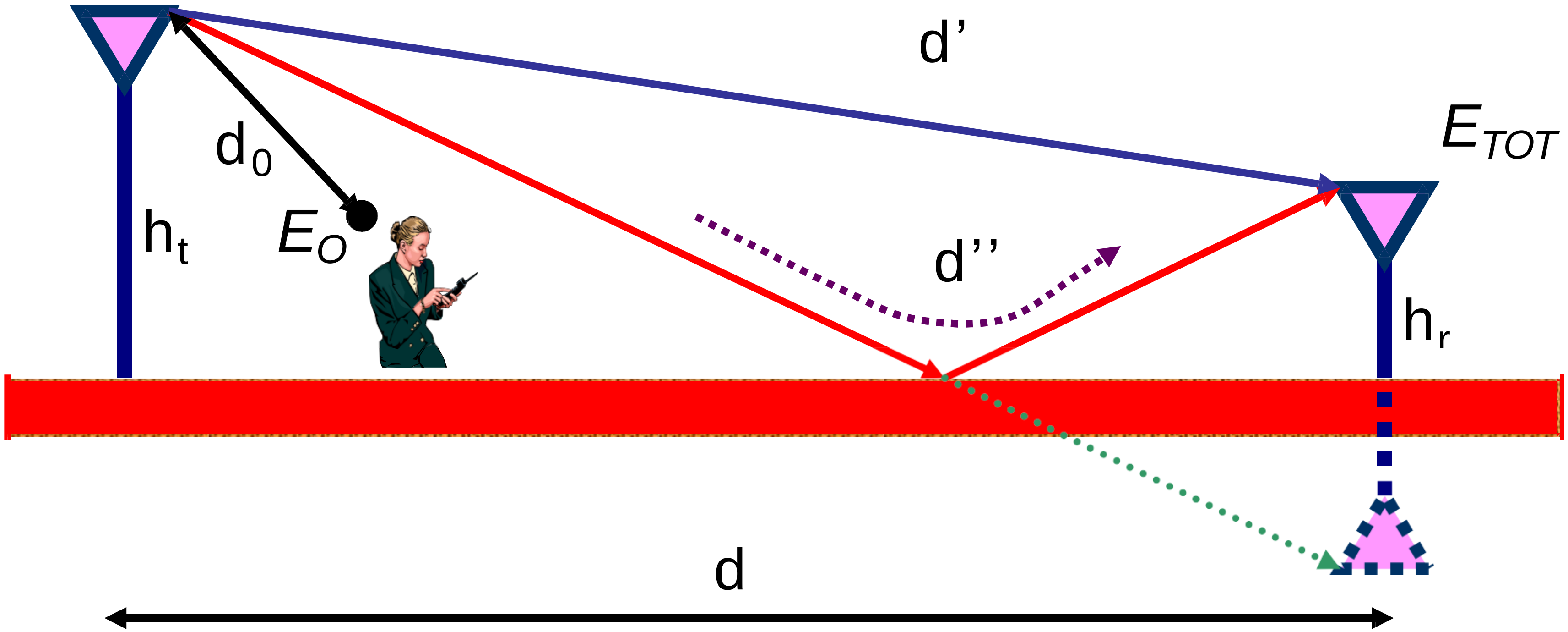


$$P_r(d)=P_r(d_0)\left(\frac{d_0}{d}\right)^2 \qquad d \geq d_0 \geq d_f$$

Ground Reflection (2-ray) Model

- In a mobile radio channel, a single direct path between the base station and a mobile is exception rather then rule
- Two ray ground reflection model is reasonably accurate for predicting the large scale signal strength over distances of several kilometers for mobile radio systems

Two Ray Model



$$E_{TOT}(d,t) = \frac{E_0 d_0}{d'} \cos\left(\omega_C\left(t \quad \frac{d}{c}\right)\right) - \frac{E_0 d_0}{d''} \cos\left(\omega_C\left(t - \frac{d''}{c}\right)\right)$$

Two Ray Model

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

$$E_\theta(d) = \frac{E_0 d_0}{d} \qquad (d > d_0 > d_f)$$

d_0 – reference distance

$$E_\theta(d,t) = \frac{E_0 d_0}{d}\cos\left(\omega_C\left(t - \frac{d}{c}\right)\right) \qquad (d > d_0)$$

$$E_{TOT}(d,t) = E_{LOS}(d',t) - E_{REF}(d'',t)$$

$$E_{TOT}(d,t) = \frac{E_0 d_0}{d'}\cos\left(\omega_C\left(t - \frac{d'}{c}\right)\right) - \frac{E_0 d_0}{d''}\cos\left(\omega_C\left(t - \frac{d''}{c}\right)\right)$$

Two Ray Model Approximations

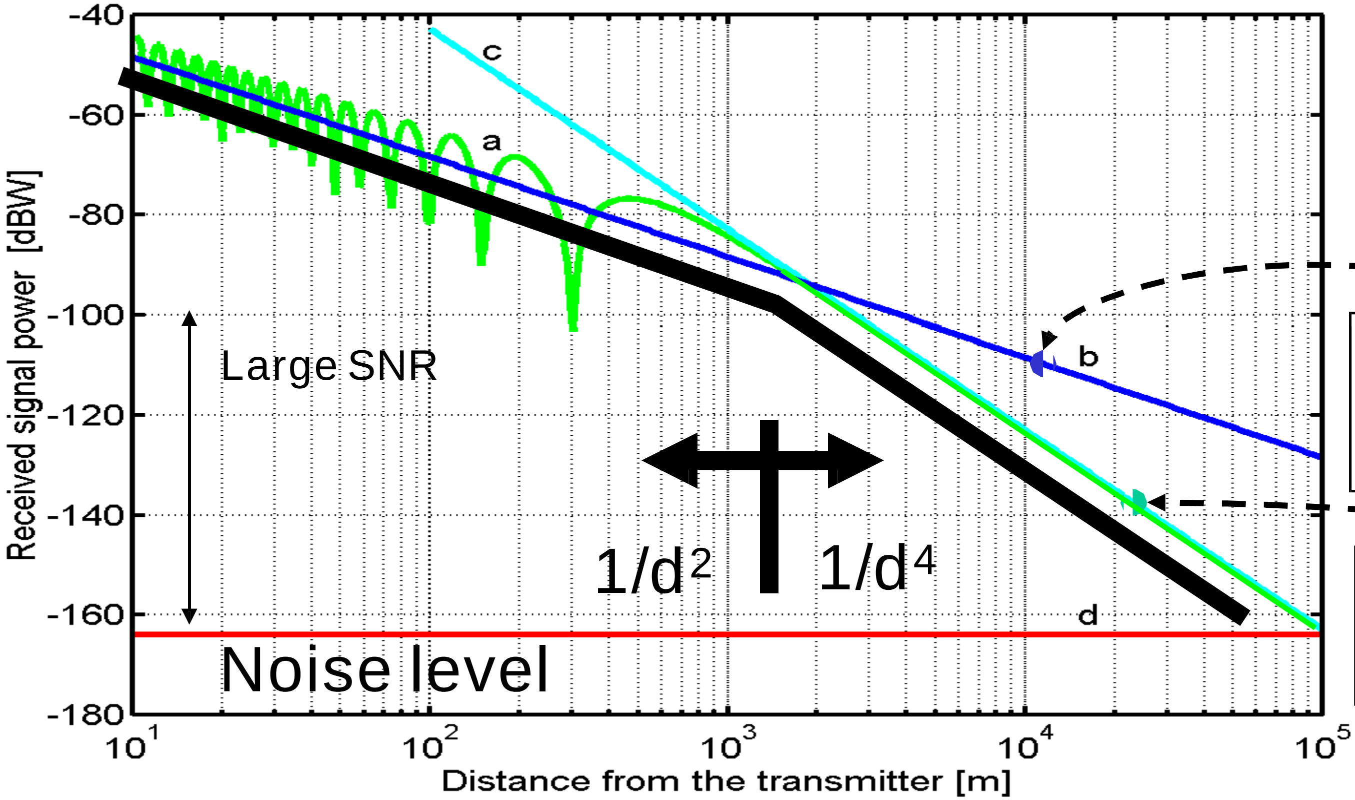
$$\boxed{d' = \sqrt{(h_t - h_r)^2 + d^2}\,;\; d'' = \sqrt{(h_t + h_r)^2 + d^2}\,;}$$

$$d \gg h_t + h_r; \quad \Rightarrow d'' - d' \approx \frac{2h_t h_r}{d}; \quad \Rightarrow \left|\frac{E_0 d_0}{d}\right| \approx \left|\frac{E_0 d_0}{d'}\right| \approx \left|\frac{E_0 d_0}{d''}\right|$$

$$\boxed{E_{TOT}(d) = 2\frac{E_0 d_0}{d}\sin\left(\frac{2\pi h_t h_r}{\lambda d}\right)} \qquad \text{for } \frac{2\pi h_t h_r}{\lambda d} < 0.3\,\text{rad}$$

$$E_{TOT}(d) = \frac{4\pi E_0 d_0 h_t h_r}{\lambda d^2} \qquad \boxed{P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}}$$

Two Ray Model Path Loss

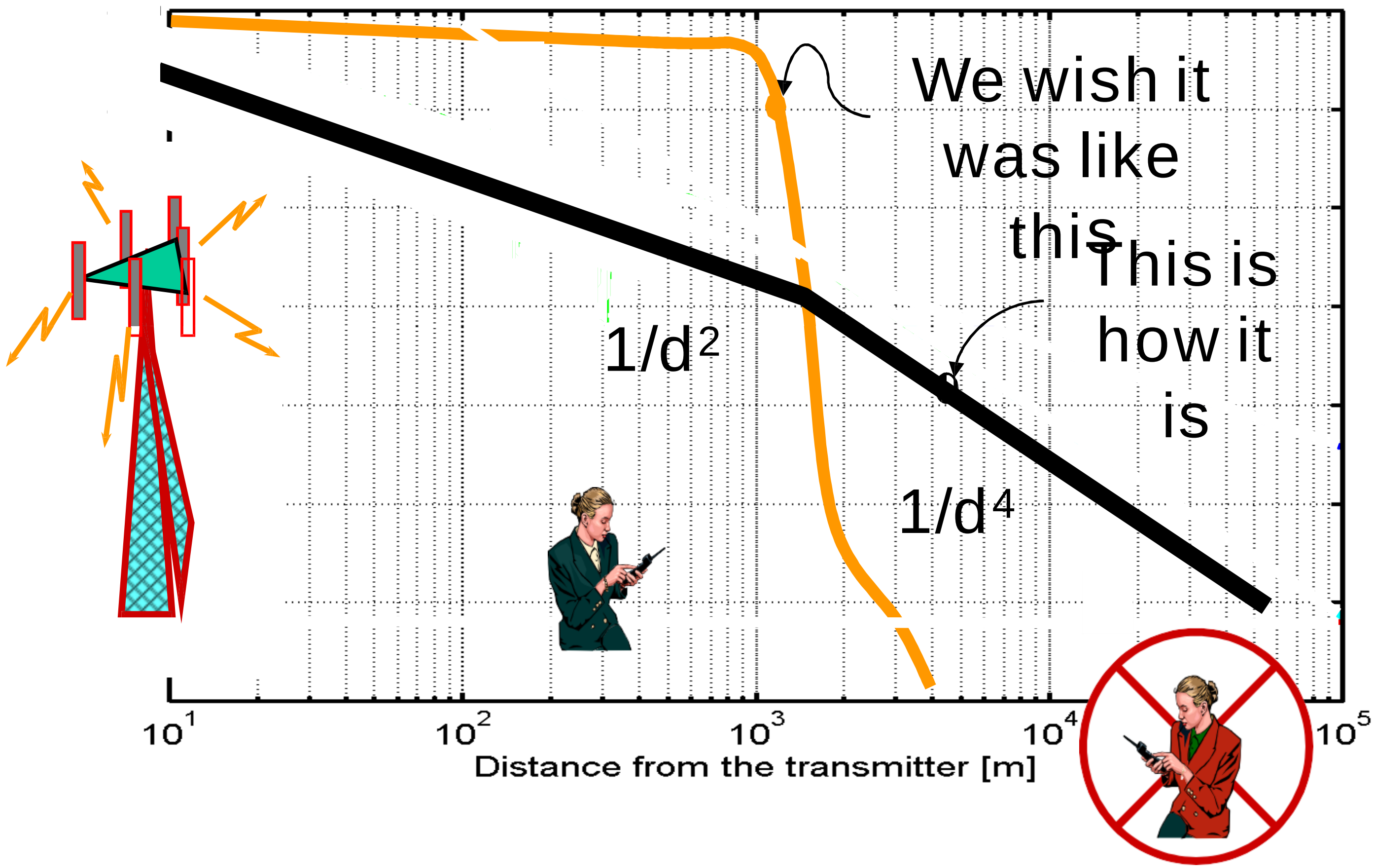



```
Pt=1;transmitted power[W]
Gt=1;trans antenna gain
Gr=1;receiver antenna gain
0.15 [m] wavelength
1990 mHz carrier frequency
ht=15;
hr=1.5;
```

$$P_r(d) = con \cdot \frac{P_t}{d^2}$$

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

Two Ray Model -The Model of ‘Distance Filtering’

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0.15 [m] wavelength
1990 mHz carrier frequency
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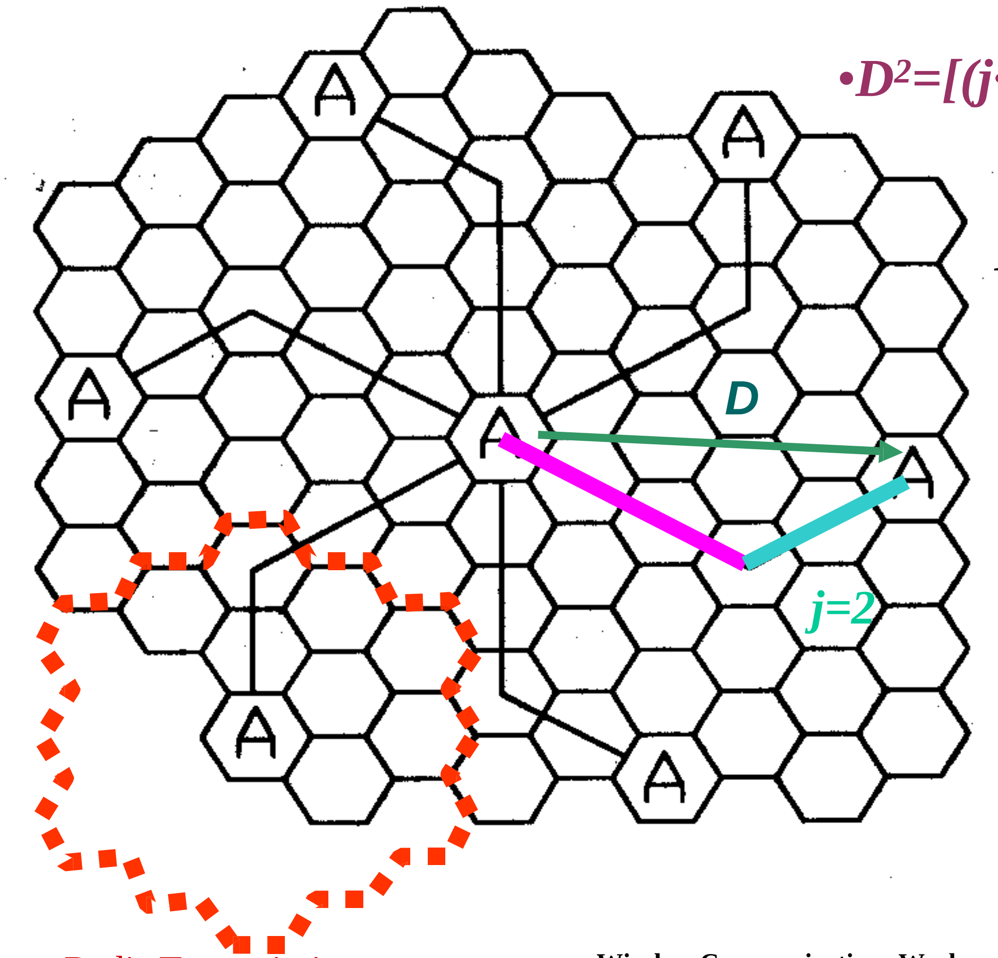
Distance between interfering cells



- $D^2=[(j\cdot R)^2+(i\cdot R)^2-(i\cdot R)(j\cdot R)\cos(120^O)]$

$$D=\sqrt{3}R\sqrt{j^2+i^2+j\cdot i}=R\sqrt{3N}$$

$$D = R\sqrt{3N}$$

R – cell radius

N- cluster size

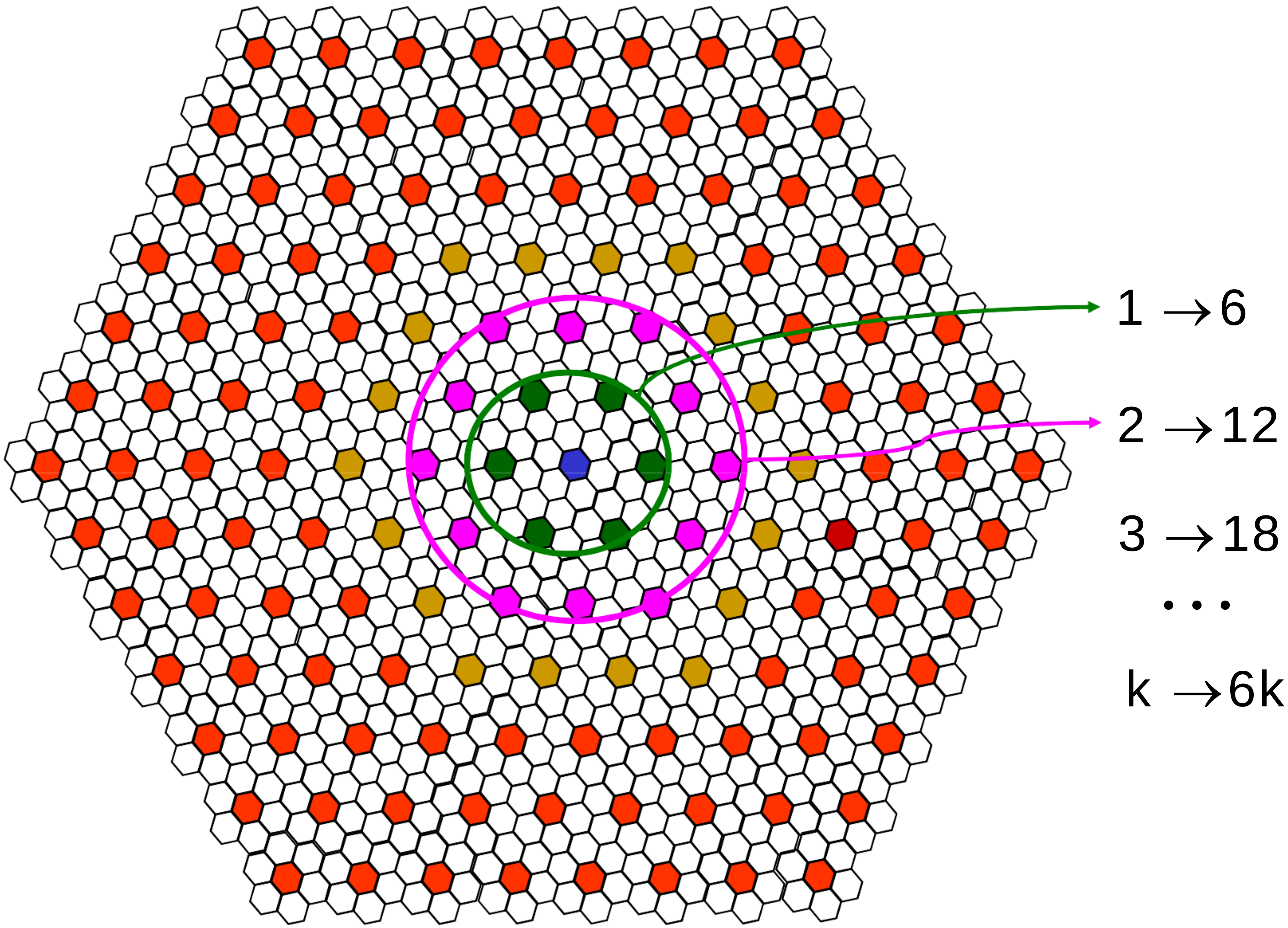
D – distance between interfering cells

Simpler SIR

– Considering only the first layer of interfering cells & if all these BS are equidistant

$$\frac{S}{I} = \frac{(D/R)^n}{i_0} = \frac{(\sqrt{3N})^n}{i_0}$$

– i_0 - number of neighboring/interfering co-channel cells


1 → 6
2 → 12
3 → 18
• • •
k → 6k

Interference Limitation

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{i=1}^{i_0} (D_i)^{-n}}$$

$$D_K < kR\sqrt{3N}$$

$$\frac{S}{I} = \frac{R^{-n}}{\sum_{k=0}^{K} 6 \cdot k(kR\sqrt{3N})^{-n}}$$

$$\frac{S}{I} = \frac{(\sqrt{3N})^{n}}{6 \cdot \sum_{k=0}^{K} k^{1-n}}$$

k – circle of interfering cels

Interference Limitation

$$\frac{S}{I} = \frac{(\sqrt{3N})^n}{6 \cdot \sum_{k=0}^{K} k^{1-n}}$$

– Considering *K* layers of interfering cells

– For *N* fixed, *n=2* and the number of layers $K \rightarrow \infty$; $S/I \rightarrow 0$

$$I = \lim_{K \rightarrow \infty} O\left(\sum_{k=0}^{K} \frac{1}{k}\right) = \infty$$

Log-distance Path Loss Model

- Average received power decreases as the n-th power of the relative distance between the transmitter and the receiver
- The average large scale path loss for an arbitrary T-R separation is expressed as function of distance using a path-loss exponent

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

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

Log-distance Path Loss Model

- n - the rate at which the path loss increases
  - For free space n=2
- d_0 – close-in reference distance
- The value of n depends on the specific propagation environment

Example

Environment	***Path Loss Exponent, n***
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
Inbuilding LOS	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Log-normal Shadowing 1

- The log distance Model does not consider the effects of environmental clutter
  - Large discrepancies
- It has been shown that path loss at a particular location is random, and distributed *log-normally*

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

Log-normal Shadowing 2

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

- X_σ - zero mean Gaussian distributed random variable (dB) with standard deviation σ (dB)
- d_0, n and σ statistically describe the path loss model for an arbitrary location

Log-normal Shadowing 3

- *n* and σ are in practice computed from measured data using linear regression (fitting)
- $PL(d_0)$ is based either on close-in measurements or on a free space assumption from transmitter to d_0
- A number of practical models exist for predicting path loss in "real" propagation conditions

A Cell Design Problem

A GSM-1800 operator provides cellular coverage in Karachi (Area: 2500 km^2) with 49 microcells of similar hexagonal geometry. If a mobile unit is considered to be located at the edge of a cell, find the Signal to Noise Ratio (SNR) that is ensured for 90% of the time at the mobile unit.

Assume the following: The close-in reference distance $d_0 = 1$ km. Transmitter power $P_t = 10$W, the receiver and the transmitter antenna gains are G_t=3 dB and G_r=0 dB, respectively. The propagation beyond the close-in distance occurs with a path loss exponent n=4 and follows a log-normal distribution with standard deviation σ=6.5dB. Normal temperature in Karachi is 27^{O} C and the noise figure of the mobile unit is 10dB.

Okumura Model 1

- Okumura 1963;
- Okumura-Hata; ITU-R recommendation P.529-2; pages 5-7, 1995.
- Applicable for frequencies in the range 150 MHz to 1920 MHz
- Distances of 1 km to 100 km
- Effective antenna heights from 30m to 1000m (hills!!)

Okumura Model 2

- Set of curves giving the median attenuation G
  - relative to free space – A_{mu} (Graph)
  - in an urban area over quasi-smooth terrain
  - mobile antenna height of 3m
- Developed form extensive measurements
- Path loss is calculated by determining A_{mu} from the curves and adding correction factors
  - Type of terrain

Okumura Model 3

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

- L_{50} - 50th percentile value of the propagation path loss (median "average" not mean-square average)
- L_F Free space propagation loss (Formula)
- A_{mu}- Median attenuation relative to free space (G)
- $G(h_{he})$ - Base station antenna height gain factor (F)
- $G(h_{re})$ - Mobile antenna height gain factor (F)
- G_{AREA} - Gain due to the type of environment (G)

Free Space Propagation Loss

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

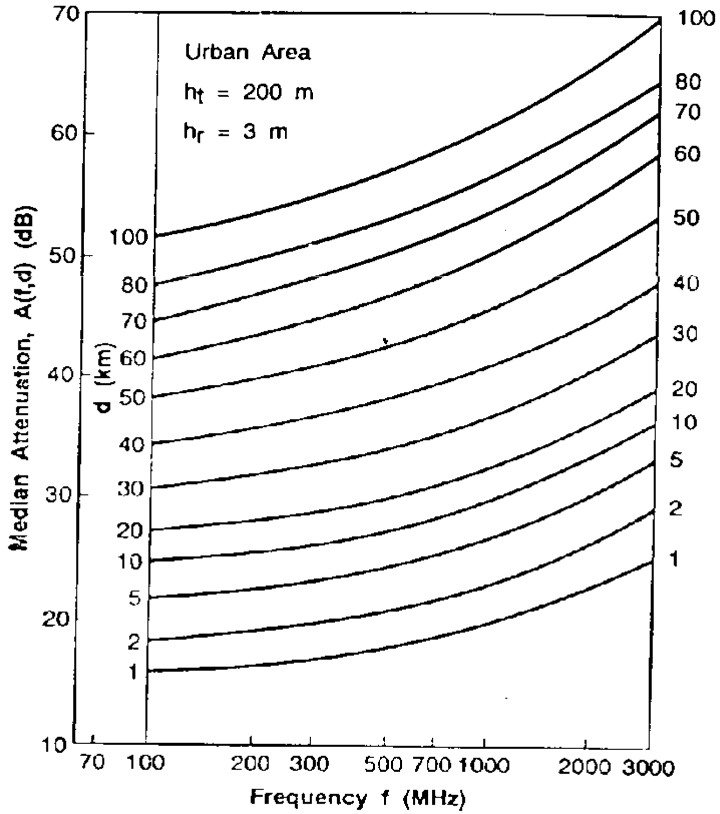
- The free space propagation loss is given by formula:

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

A_{mu}

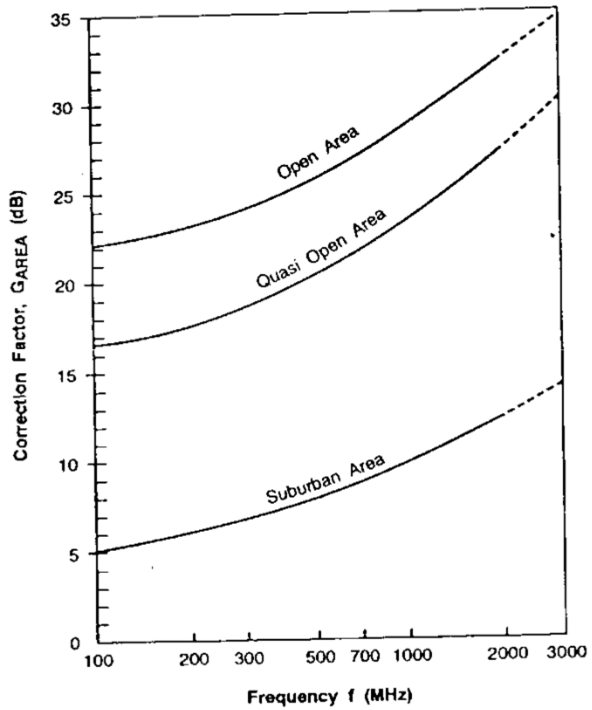
$$L_{50}(dB) = L_F + A_{mu}(f,d) - G(h_{te}) - G(h_{re}) - G_{AREA}$$

Median attenuation with respect to free space loss



G_{AREA}

Gain due to the type of environment



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

Antenna gain factors $G(h_{he}),G(h_{re})$

Okumura found that for heights less than 3 m

- $G(h_{he})$ -varies at a rate of 20 dB/decade
- $G(h_{re})$ - varies 10dB/decade

$$G(h_{te}) = 20\log\left(\frac{h_{te}}{200}\right) \qquad 1000m > h_{re} > 10m$$

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

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

Other Corrections

- Can be applied to Okumura's model
  - Terrain undulation height
  - Isolated ridge height
  - Average slope of terrain and
  - Mixed land-sea parameters
- All available as Okumura curves (Oku68)

Okumura Model Summary

- Okumura's model is wholly based on measured data (empirical)
- Extrapolations can be made to obtain values outside the measurement range
- Simplest and the best in terms of accuracy (the best tradeoffin terms of simplicity-accuracy)
- Major disadvantage – decreased accuracy in situations of rapid changes in terrain

Hata Propagation Model

- An empirical formulation of graph path loss data provided by Okumura
- Curves from Okumura model replaced by formulas
- Valid from 150 to 1500 MHz
- Presents an urban area propagation loss as a standard formula
  - correction equations for application to other situations

Urban Path Loss Equation

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

- fc - Frequecny in MHz from 150-1500MHz
- h_{he} -BS antenna heing in meters from 30-200 m
- h_{re} - MS antenna height in meters from 1-10 m
- d - T-R separation distance in km
- $a(h_{re})$ - correction factor for effective MS antenna height (size of the coverage area)

Mobile antenna correction factor $a(h_{re})$

– Small to medium size city

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

– Large city

$$a(h_{re}) = 8.29(\log 1.54 h_{re})^2 - 1.1\, dB \qquad for \quad f_c \le 300MHz$$

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

Suburban and Rural Path Loss Equation

– Suburban area

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

– Open rural area

$$L_{50}(dB) = L_{50}(urban) - 4.78(\log f_c)^2 - 18.33\log f_c - 40.98$$

Hata-model Summary

- Simple and sufficiently accurate
- Presents significant practical value
- Compares very favorably with Okumura's model for d > 1 km (in fact it has been derived from Okumura model)
- Suitable for large cell mobile systems planning
- Extensions and corrections for smaller cells are available