# Wireless Channel: Pathloss & Shadowing

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# Motivation

- The main bottleneck of wireless communication
  - →Communication based on EM Wave
- On the way to propagate between T-R, EM wave suffer
  - →Several large and small obstructions,
  - →terrain undulations
  - →relative motion between the transmitter and the receiver
  - →interference from other signals
  - →noise, and
  - →various other complicating factors together
- weaken, delay, and distort the transmitted signal in an unpredictable and time-varying fashion

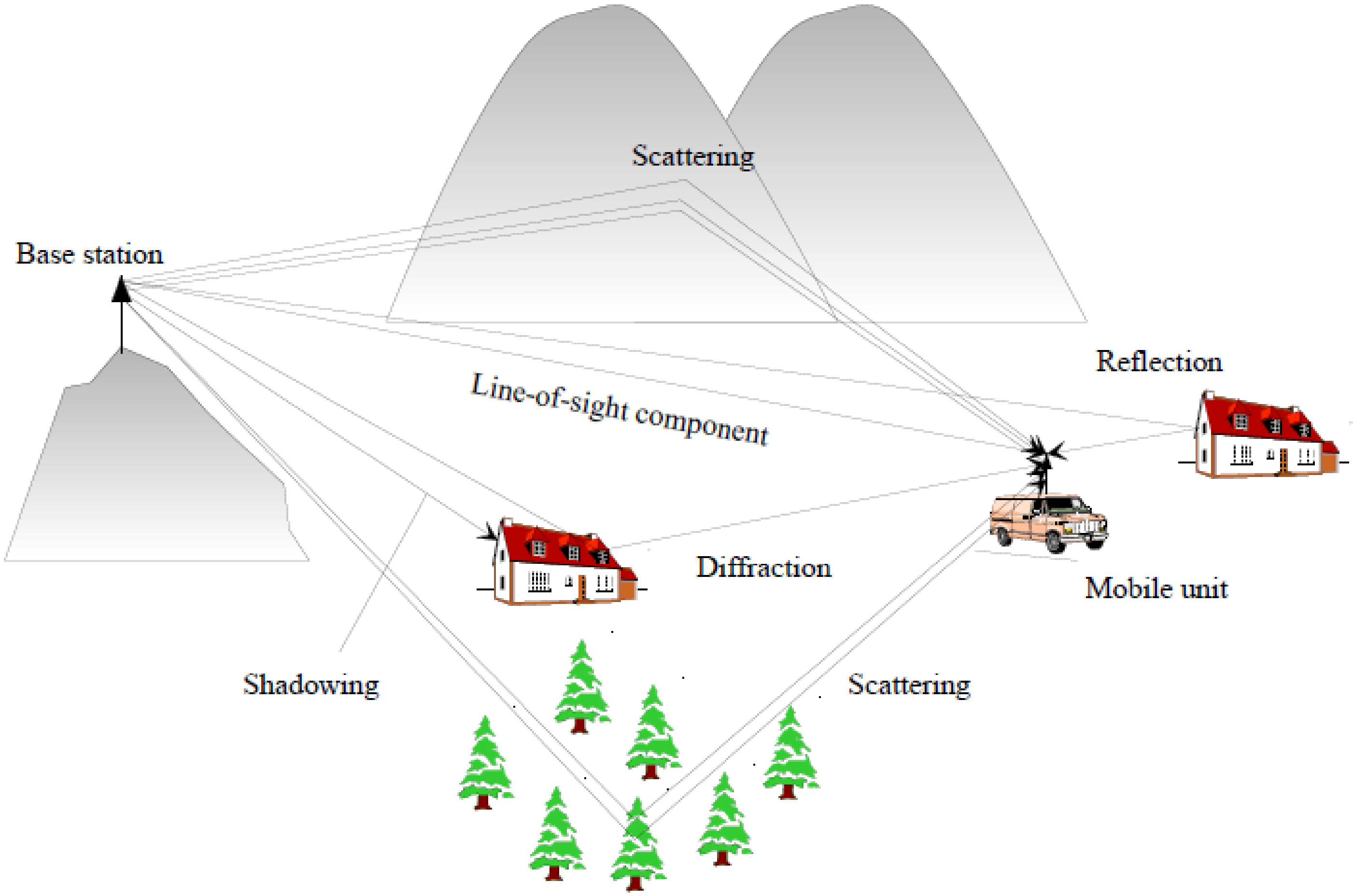
# Radio Propagation Mechanism

- Reflection
  - → Propagation wave impinges on an object which is large as compared to wavelength

    - e.g., the surface of the Earth, buildings, walls, etc.
- Diffraction
  - → Radio path between transmitter and receiver obstructed by surface with sharp irregular edges
  - → Waves bend around the obstacle, even when LOS (line of sight) does not exist
- Scattering
  - → Objects smaller than the wavelength of the propagation wave

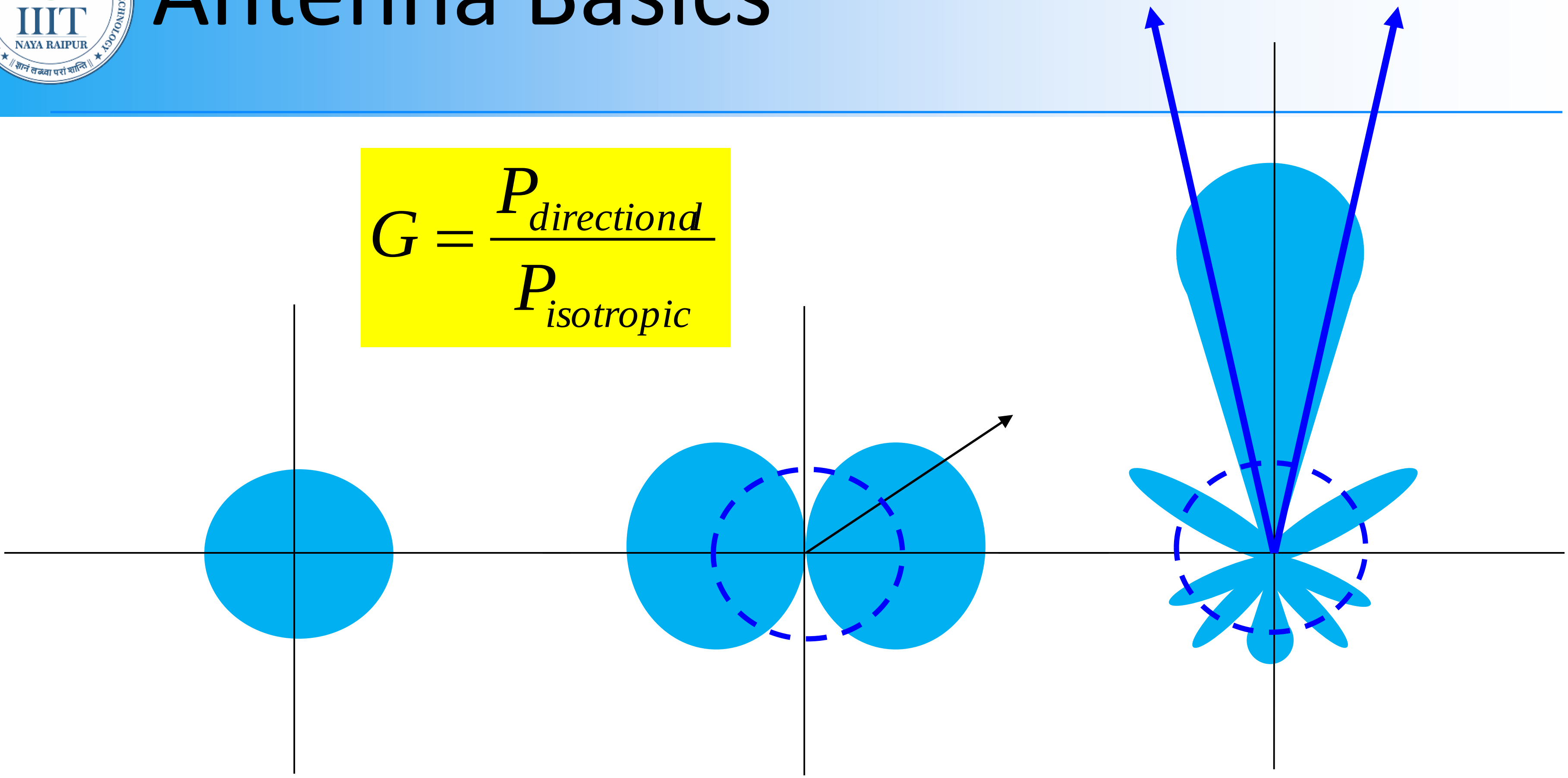
    - e.g. foliage, street signs, lamp posts

# Radio Propagation



# Antenna Basics

$$G = \frac{P_{directional}}{P_{isotropic}}$$



Isotropic

Dipole

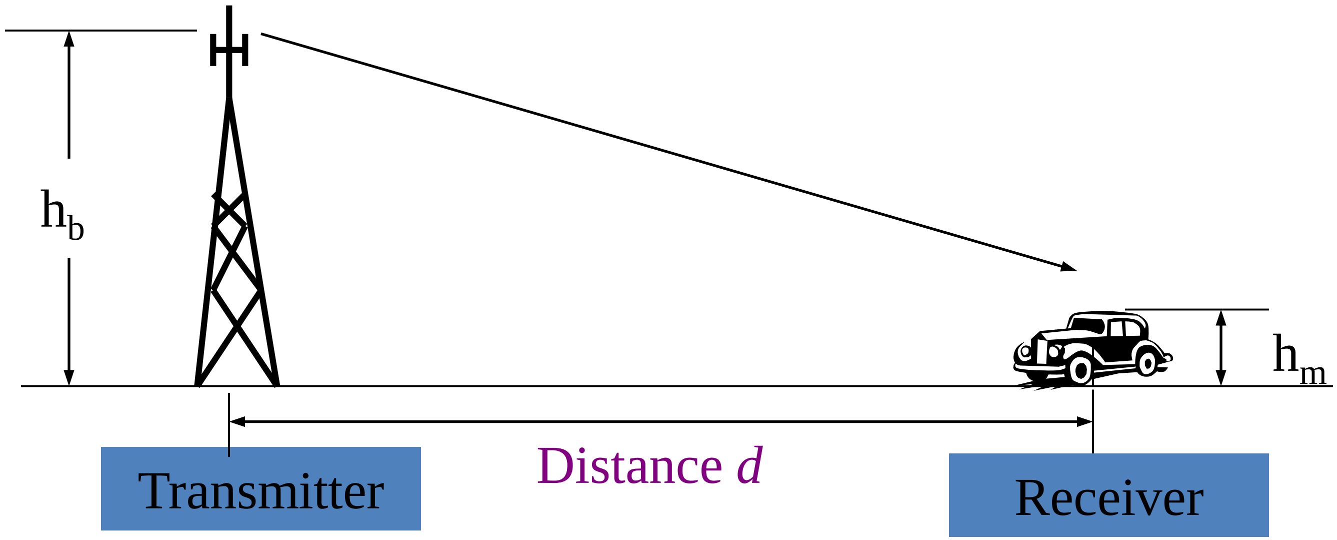
High gain directional

0 $dB_i$

2.2 $dB_i$

14 $dB_i$

# Free Space Propagation

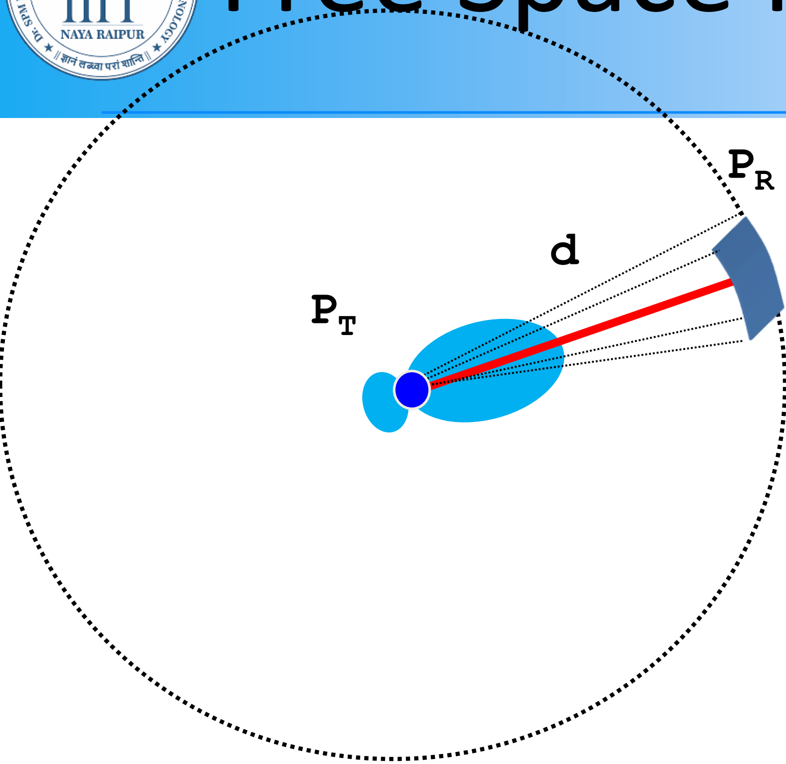



- Clear, unobstructed line-of-sight path → satellite and fixed microwave
- Assumes far-field (Fraunhofer region)

  → $d \gg D$ and $d \gg \lambda$, where

  - D is the largest linear dimension of antenna
  - $\lambda$ is the carrier wavelength

# Free Space Propagation Model




$$P_{Di} = \frac{P_T}{4\pi d^2} W / m^2$$

Isotropic power density

$$P_D = \frac{P_T G_T}{4\pi d^2}$$

Power density along the direction of maximum radiation

$$P_R = P_D A_{eff}$$

Power received by Antenna

$$P_R = \frac{P_T G_T}{4\pi d^2} A_{eff}$$

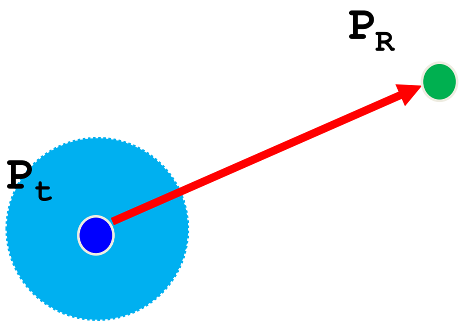
$$\frac{A_{eff}}{G} = \frac{\lambda^2}{4\pi}$$

Predict received signal strength when the transmitter and receiver have a clear line-of-sight path between them

$$P_R = P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2$$

Also known as Friis free space formula

# Path Loss




$$\frac{P_R}{P_T} = G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2$$

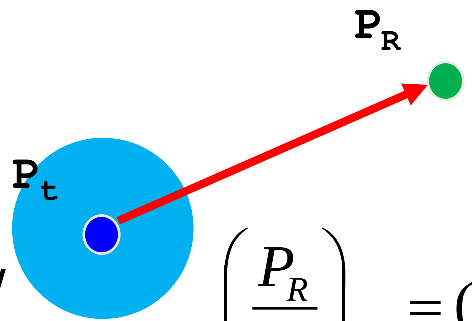
$$\frac{P_R}{P_T} = G_T G_R \frac{0.57 * 10^{-3}}{(df)^2}$$

*f* is in MHz
*d* is in Km

$$\left( \frac{P_R}{P_T} \right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20\log_{10} d + 20\log_{10} f)$$

Path Loss represents signal attenuation (measured on dB) between the effective transmitted power and the receive power (excluding antenna gains)

# Path Loss (Example)




50 W
= 47 dBm

Assume that antennas are isotropic. Calculate receive power (in dBm) at free space distance of 100m from the antenna. What is $P_R$ at 10Km?

$$\left(\frac{P_R}{P_T}\right)_{dB} = (G_T)_{dB} + (G_R)_{dB} - (32.5 + 20\log_{10} d + 20\log_{10} f)$$

$$\left(\frac{P_R}{P_T}\right)_{dB} = 0 + 0 - (32.5 + 20\log_{10} 0.1 + 20\log_{10} 900)$$

59

-20 (for d = 0.1)

20 (for d = 10)

$$\left(\frac{P_R}{P_T}\right)_{dB} = -71.5dB$$

$$\left(\frac{P_R}{P_T}\right)_{dB} = -111.5dB$$

$$(P_R)_{dBm} = 47 - 71.5 = -24.5dBm$$

$$(P_R)_{dBm} = 47 - 111.5 = -64.5dBm$$

# Typical Values

Example:

- Antenna with diameter = 2 m, frequency = 6 GHz, wavelength = 0.05 m

  $G$ = 39.4 dB

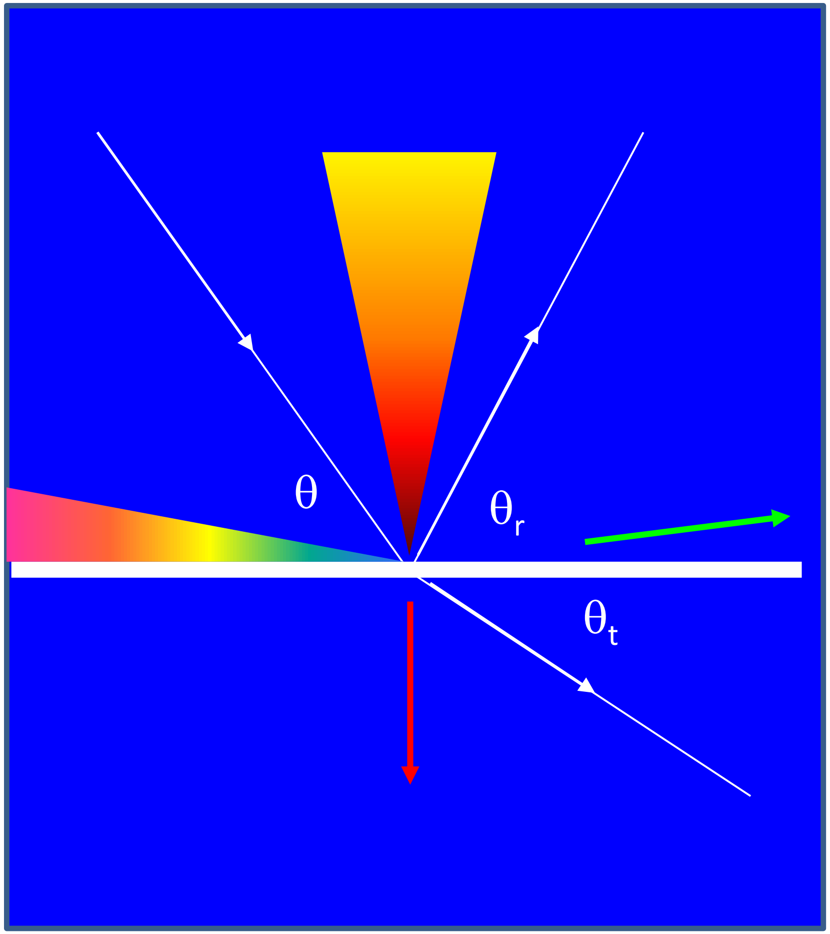
- Frequency = 14 GHz, same diameter, wavelength = 0.021 m

  $G$ = 46.9 dB

* Higher the frequency, higher the gain for the same size antenna

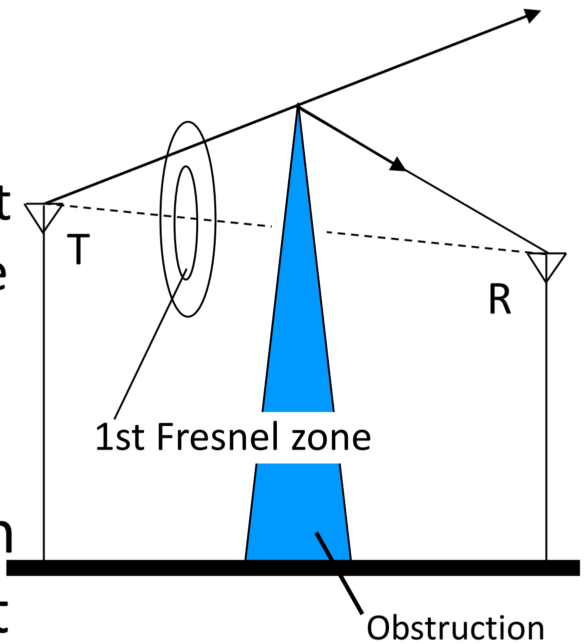
# Refraction

- Perfect conductors reflect with no attenuation
- Dielectrics reflect a fraction of incident energy
  - →"Grazing angles" reflect max*
  - →Steep angles transmit max*
- Reflection induces 180° phase shift



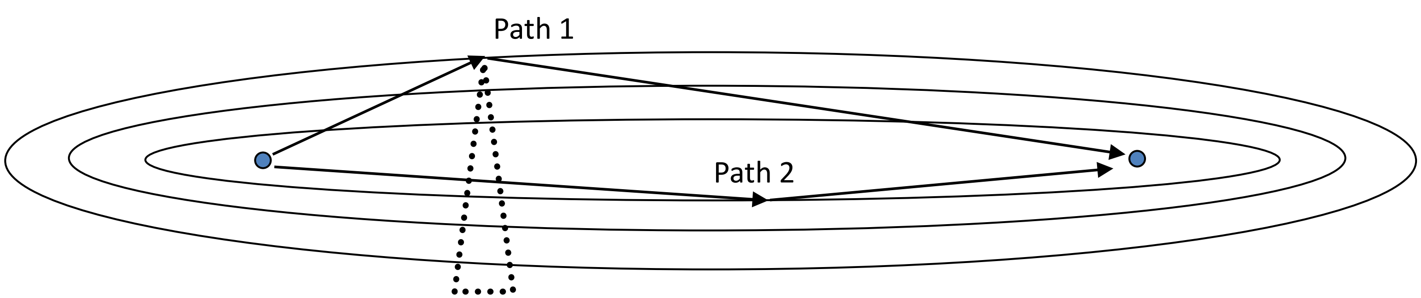
# Diffraction

- Diffraction occurs when waves hit the edge of an obstacle
  - → "Secondary" waves propagated into the shadowed region
    - Huygen's principle
  - → Excess path length results in a phase shift
  - → Fresnel zones relate phase shifts to the positions of obstacles
- Although EM field strength decays rapidly as Rx moves deeper into "shadowed" or obstructed (OBS) region
- The diffraction field often has sufficient strength to produce a useful signal



# Fresnel Zones

- Bounded by elliptical loci of constant delay
- The excess total path length traversed by a ray passing through each circle is $n\lambda/2$
- Alternate zones differ in phase by 180°
  - →Line of sight (LOS) corresponds to 1st zone
  - →If LOS is partially blocked, 2nd zone can destructively interfere (diffraction loss)




Fresnel zones are ellipses with the T&R at the foci; $L_1 = L_2+\lambda$

- The difference between the direct path and diffracted path, call *excess path length*

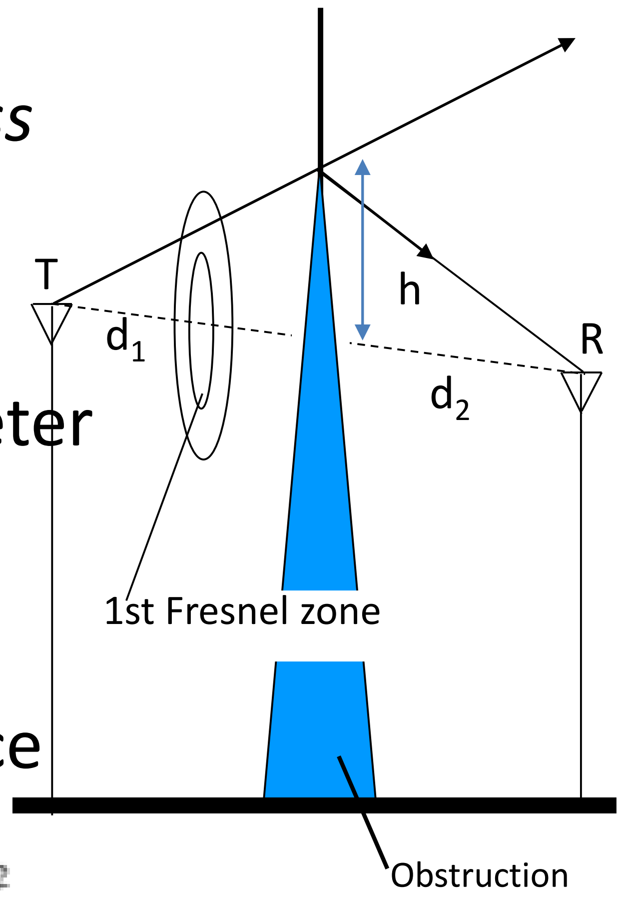
$$\Delta \approx \frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2}$$

- *Fresnel-Kirchoff* diffraction parameter

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

- The corresponding phase difference

$$\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda}\frac{h^2}{2}\frac{(d_1+d_2)}{d_1 d_2} \qquad \phi = \frac{\pi}{2}v^2$$



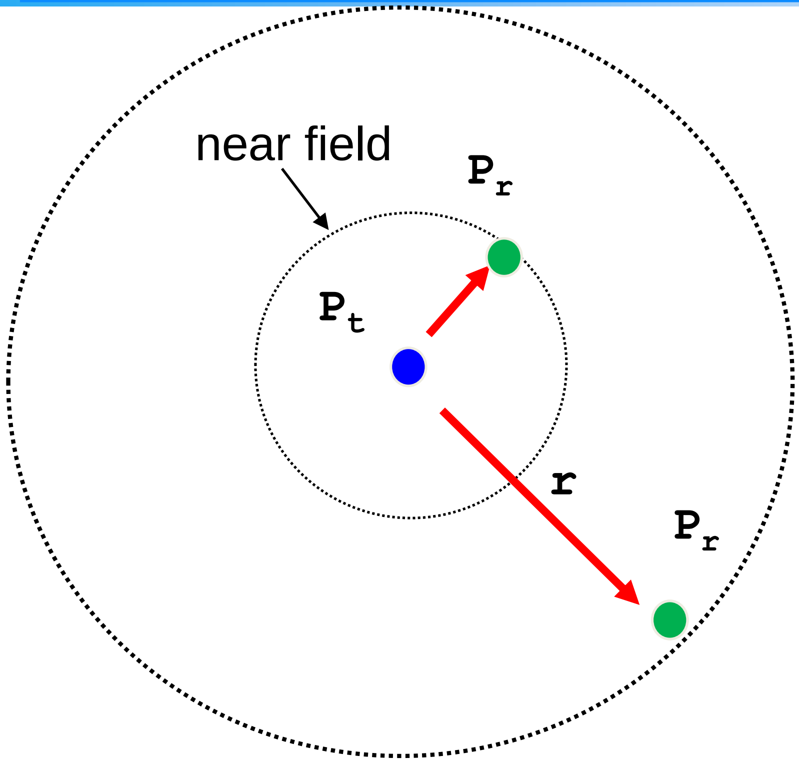
# Scattering

- Received signal strength is often stronger than that predicted by reflection/diffraction models alone
- The EM wave incident upon a rough or complex surface is **scattered** in **many** directions and provides more energy at a receiver
  - → energy that would have been absorbed is instead reflected to the Rx.
- Scattering is caused by trees, lamp posts, towers, etc.
- flat surface → EM reflection (one direction)
- rough surface → EM scattering (many directions)

# Cause and Effect

- ➢ Distance-dependent decay of signal power
  - →Pathloss
- ➢ Blockage due to large obstructions
  - →Shadowing
- ➢ Large variations in received signal envelope
  - →Multipatha fading
- ➢ Intersymbol interference due to time dispersion
  - →Delay spread
- ➢ Frequency dispersion due to motion
  - →Doppler spread

# Radio propagation: path loss




path loss in 2.4 Ghz band

$r \leq 8m$ → near field $\propto r^2$

$r > 8m$ → far field $\propto r^{3.3}$

path loss $= 10 \log (4\pi r^2/\lambda)$ $\quad r \leq 8m$

$= 58.3 + 10 \log (r^{3.3}/8)$ $\quad r > 8m$

# Link Budget

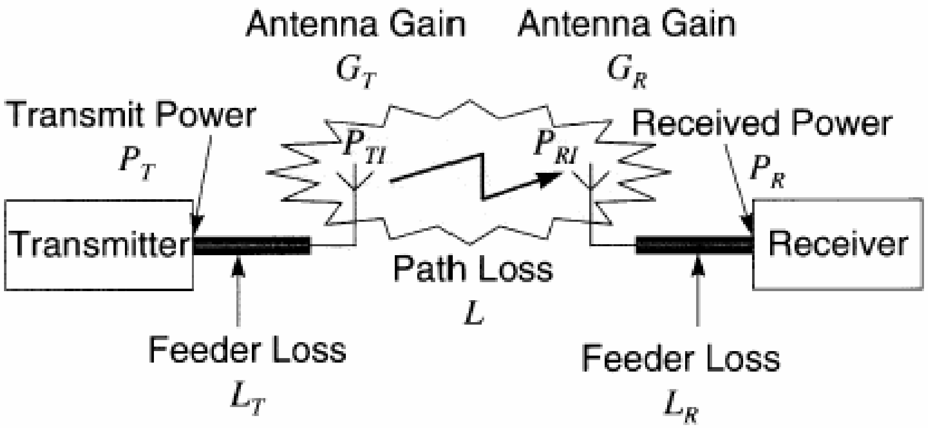
- A **link budget** is the accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a communication system

Received Power (dBm) = Transmitted Power (dBm) + Gains (dB) − Losses (dB)

$$P_R = P_T + G_T - L_T - L + G_R - L_R$$

What is dBm and dB ?

For proper link budget, we consider various models



# Pathloss Models

Three kinds of Models → Empirical Models

→ Semi-deterministic Models

→ Deterministic Models

- Empirical models
  - → based on measurement data, simple (few parameters), use statistical properties, not very accurate
- Semi-deterministic models
  - → based on empirical models + deterministic aspects
- Deterministic models
  - → site-specific, require enormous number of geometry information about the cite, very important computational effort, accurate

# Pathloss Models

- Each model is define for a specific environment

| Cell type | Typical cell radius | Location | Typical base station antenna installation height |
|---|---|---|---|
| Large macro cell | 1 km to 30 km | outdoor | Above medium roof-top level, all surrounding buildings are below antenna height |
| Small macro cell | 0.5 km to 3 km | outdoor | Above medium roof-top level, heights of some surrounding buildings are above antenna height |
| Micro cell | up to 1 km | outdoor | Below medium roof top level |
| Pico cell | up to 500 m | indoor/ outdoor | Below roof-top level |

# Okumura-Hata Model

- Most popular empirical model for macrocell
- Based on measurements made in and around Tokyo in 1968
  - → between 150 MHz and 1500 MHz
- Predictions from series of graphs approximate in a set of formulae (Hata)
- Output parameter : mean path loss (median path loss) $L_{dB}$
- Validity range of the model :
  - → Frequency $f$ between 150 MHz and 1500 Mhz
  - → TX height $h_b$ between 30 and 200 m
  - → RX height $h_m$ between 1 and 10 m
  - → TX - RX distance r between 1 and 10 km

# Okumura-Hata Model

- Three types of prediction area :
  - →Open area : open space, no tall trees or building in path
  - →Suburban area : Village Highway scattered with trees and house
    - Some obstacles near the mobile but not very congested
  - →Urban area : Built up city or large town with large building and houses
    - Village with close houses and tall

# Okumura-Hata Model

- Okumura takes urban areas as a reference and applies correction factors
  - → Urban areas : LdB = A + B log10 R – E
  - → Suburban areas : LdB = A + B log10 R – C
  - → Open areas : LdB = A + B log10 R – D
- Okumura-Hata model for medium to small cities has been extended to cover 1500 MHz to 2000 MHz (1999)
- $L_{dB} = F + B \log_{10} R - E + G$
- $F = 46.3 + 33.9 \log_{10} f_c - 13.82 \log_{10} h_b$
- *E* designed for medium to small cities
- G =
  - → 0 dB medium sized cities and suburban areas
  - → 3 dB metropolitan areas

$A = 69.55 + 26.16 \log 10\, f_c - 13.82 \log 10\, h_b$

$B = 44.9 - 6.55 \log 10\, h_b$

$C = 2\, ( \log 10\, (f_c / 28\, ))^2 + 5.4$

$D = 4.78\, ( \log 10\, f_c\, )^2 + 18.33 \log 10\, f_c + 40.94$

$E = 3.2\, ( \log 10\, ( 11.7554\, h_m\, ))^2 - 4.97$ for large cities, $f_c \geq 300\text{MHz}$

$E = 8.29\, ( \log 10\, ( 1.54\, h_m\, ))^2 - 1.1$ for large cities, $f_c < 300\text{MHz}$

$E = ( 1.1 \log 10\, f_c - 0.7\, )\, h_m - ( 1.56 \log 10\, f_c - 0.8\, )$ for medium to small cities

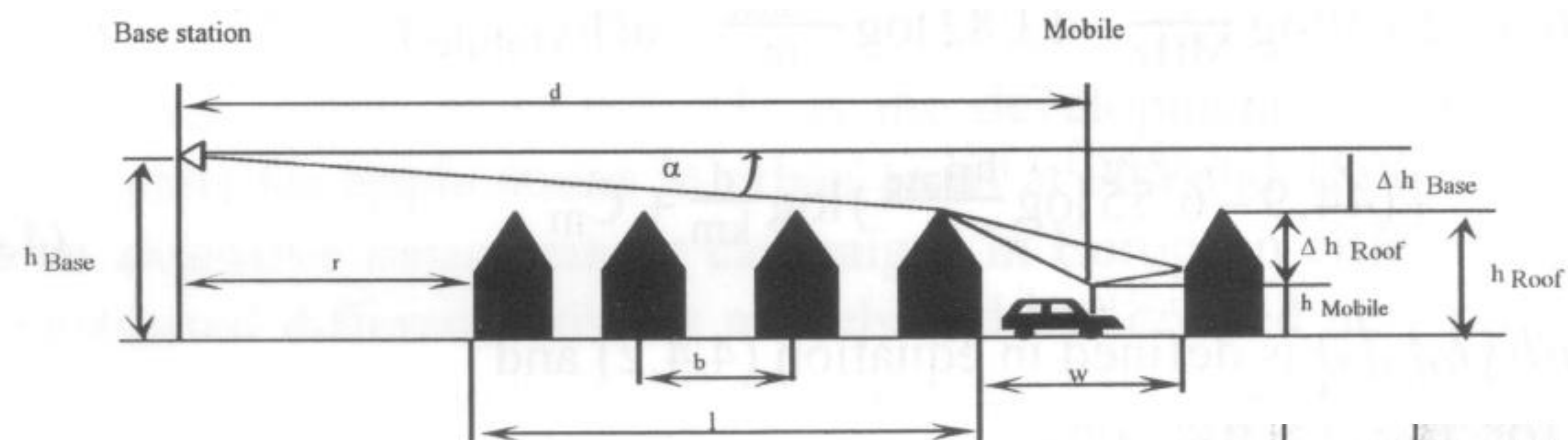
# Okumura-Hata Model: Accuracy

- Extensive measurement in Lithuania at 160, 450, 900 and 1800MHz
  - → Standard deviation of the error = 5 to 7 dB in urban and suburban environment
  - → Best precision at 900 MHz in urban environment
  - → In rural environment : standard deviation increases up to 15 dB and more
- Measurements in Brazil at 800 / 900 MHz
  - → mean absolute error = 4.42 dB in urban environment
  - → standard deviation of the error = 2.63 dB
- Facts
  - → path loss prediction could be more accurate
  - → but models are not complex and fast calculations are possible
  - → precision greatly depends on the city structure

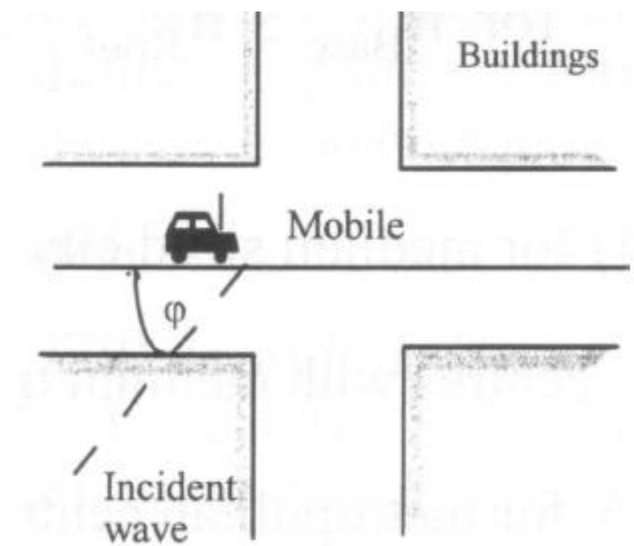
# COST 231-Walfisch-Ikegami

- Cost 231-WI takes the characteristics of the city structure into account
  - →Heights of buildings $h_{Roof}$
  - →Widths of roads $w$
  - →Building separation $b$
  - →Road orientation with respect to the direct radio path $\Phi$
- Increases accuracy of the propagation estimation
- More complex
- Allows estimation from 20 m (instead of 1 km for Okumura-Hata model )
- Output parameter : mean path loss

# COST 231




- Restrictions :
  - → Frequency $f$ between 800 MHz and 2000 MHz
  - → TX height $h_{Base}$ between 4 and 50 m
  - → RX height $h_{Mobile}$ between 1 and 3 m
  - → TX - RX distance $d$ between 0.02 and 5 km



# COST 231

- Two cases : LOS and NLOS
- LOS
  - → $L_{LOS}$ [dB] = 42.6 + 26 $\log_{10} d$[km] + 20 $\log_{10} f$ [MHz]
- NLOS
  - → $L_{NLOS}$ [dB] = $L_{FS} + L_{rts}\,(w_r, f, \Delta h_{Mobile}, \Phi) + L_{MSD}\,(\Delta h_{Base}, h_{Base}, d, f, b_S)$
- $L_{FS}$ = free space path loss =
  - → 32.4 + 20 $\log_{10} d$[km] + 20 $\log_{10} f$ [MHz]
- $L_{rts}$= roof-to-street loss
- $L_{MSD}$= multi-diffraction loss

# COST 231

- $L_{rts}$= -8.8 + 10 $\log_{10}$ ( $f$ [MHz] ) + 20log10 ($\Delta h_{Mobile}$[m] ) – 10 $\log_{10}$ ( $w$ [m] )+ $L_{ORI}$
- $L_{ORI}$ = street orientation function
  - →-10 + 0.35 $\Phi$     $0 < \Phi < 35°$
  - →2.5 + 0.075 ($\Phi$ – 35 )     $35° < \Phi <= 55°$
  - →4.0 – 0.114 ($\Phi$ –55 )     $55° < \Phi < =90°$

$$L_{MSD} = L_{bsh} + k_a + k_d \log_{10}(d\,[\mathrm{km}]) + k_f \log_{10}(f\,[\mathrm{MHz}]) - 9\log_{10}(b)$$

$$L_{bsh} = \begin{cases} -18\log_{10}(1+\Delta h_{Base}) & h_{Base} > h_{Roof} \\ 0 & h_{Base} \le h_{Roof} \end{cases}$$

# COST 231

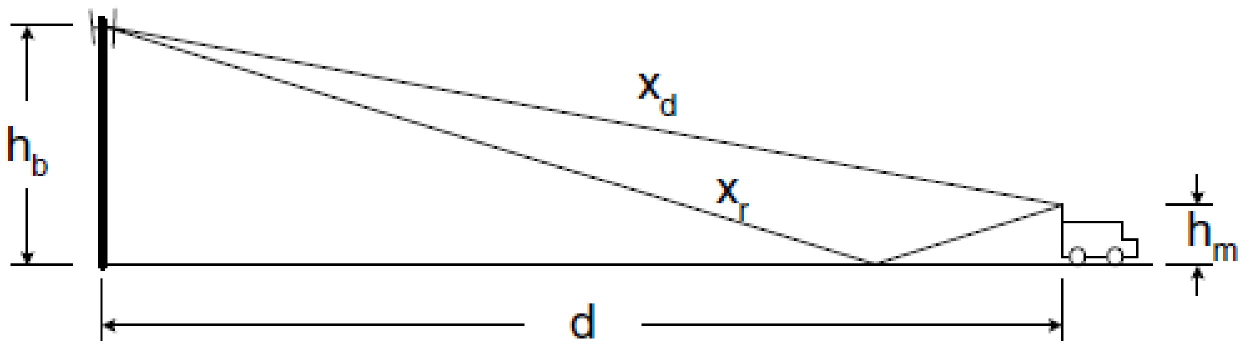
$$k_d = \begin{cases} 18 & h_{Base} > h_{Roof} \\ 18 - 15\Delta h_{Base} / h_{Roof} & h_{Base} \le h_{Roof} \end{cases}$$

$$k_a = \begin{cases} 54 & h_{Base} > h_{Roof} \\ 54 - 0.8\Delta h_{Base} & d \ge 0.5\,\text{km}, h_{Base} \le h_{Roof} \\ 54 - 0.8\Delta h_{Base} d\,[\text{km}] / 0.5 & d < 0.5\,\text{km}, h_{Base} \le h_{Roof} \end{cases}$$

$$k_f = -4 + \begin{cases} 0.7\left(f / 925 - 1\right) & \text{medium sized city} \\ 1.5\left(f / 925 - 1\right) & \text{metropoliton center} \end{cases}$$

# Two Ray Model

- Good for systems that use tall towers (over 50 m tall)
- Good for line-of-sight microcell systems in urban environments



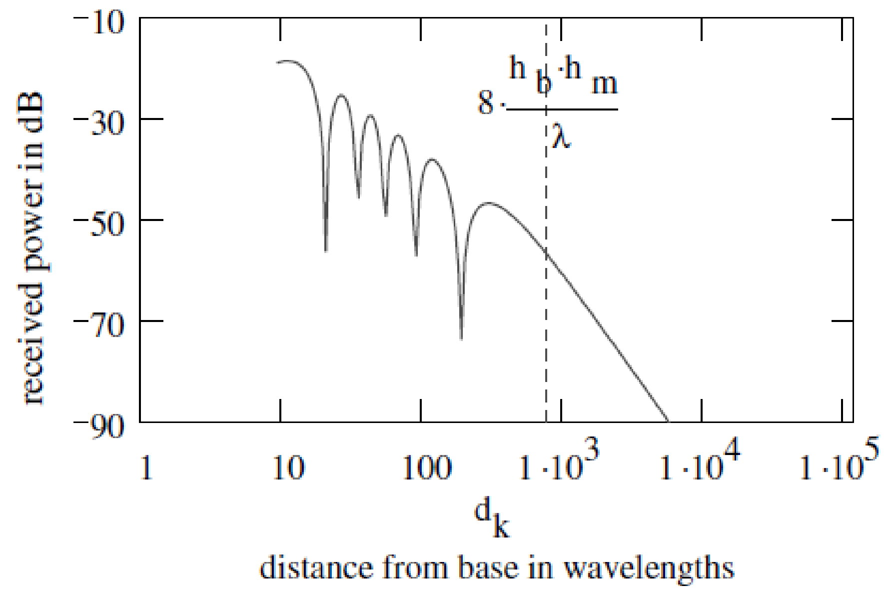
# Two Ray Model

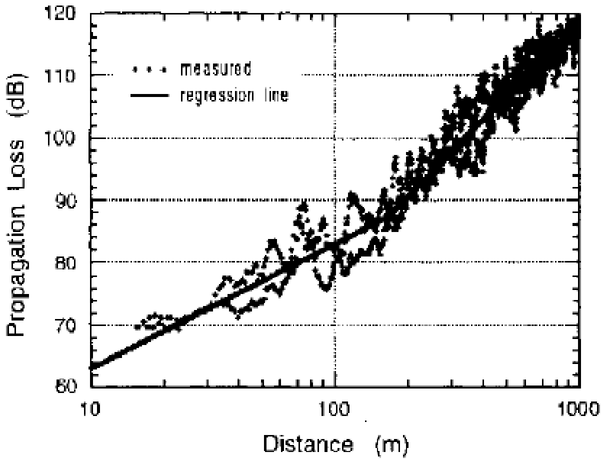
- Two rays will interfere at mobile station
- Interference depends on phase difference, which is a function of path difference
- Maximum path length is $2h_m$
  - →When mobile is right beside the base antenna ($d$=0)
- When mobile moves away from base, path difference decreases, approach to zero for very large distance
  - →Thus there are several oscillation, for alternatively cancel or reinforce
  - →After the path length difference has decreased to $\lambda/4$,
    - Phase difference upto $\pi/2$, follow inverse-square law
  - → the outer region, phase difference less than $\pi/2$
    - Follow inverse fourth power law

# Two Ray Model

- Near the base, strong ripple
  - →Maxima drops according to inverse square law
- After last maxima, the signal drop as inverse fourth power law
- In case of macrocell,
  - →The boundary at 150 m

$h_b$=30. $h_m$=3 m



# Generalized path loss

$$P_r \propto \frac{P_t}{d^n}$$

- $n$ is order of exponent
- The value of $n$ depends on the environment

| Environment | Value of exponent |
|---|---|
| Free space | 2 |
| Urban | 2.7 to 3.5 |
| Shadowed urban | 3-5 |
| Indoor LOS | 1.6-1.8 |
| Indoor Non LOS | 4-6 |

# Range versus Bandwidth

- much of the globally available bandwidth is at carrier frequencies of several GHz. Lower carrier frequencies are generally considered more desirable, and frequencies below 1GHz are often referred to as “beachfront” spectrum.
- Two reason
- First, high-frequency RF electronics have traditionally been more difficult to design and manufacture and hence more expensive
- Second, the pathloss increases as $f_c^{\,2}$.
  - → A signal at 3.5GHz will be received with about 20 times less power than at 800MHz, a popular cellular frequency.
- In fact, measurement campaigns have consistently shown that the effective pathloss exponent α also increases at higher frequencies, owing increased absorption and attenuation of high-frequency signals
- there is a **direct conflict between range and bandwidth**
- bandwidth at higher carrier frequencies is more plentiful and less expensive but, as we have noted, does not support large transmission ranges
- three generally desirable characteristics: high data rate, high range, low cost

# Large PathLoss and Increased Capacity

- Since many users are attempting to simultaneously access the network, both the uplink and the downlink generally become interference limited, which means that increasing the transmit power of all users at once will not increase the overall network throughput.
- Instead, a lower interference level is preferable. In a cellular system with base stations, most of the interfering transmitters are farther away than the desired transmitter.
- Thus, their interference power will be attenuated more severely by a large path loss exponent than the desired signal

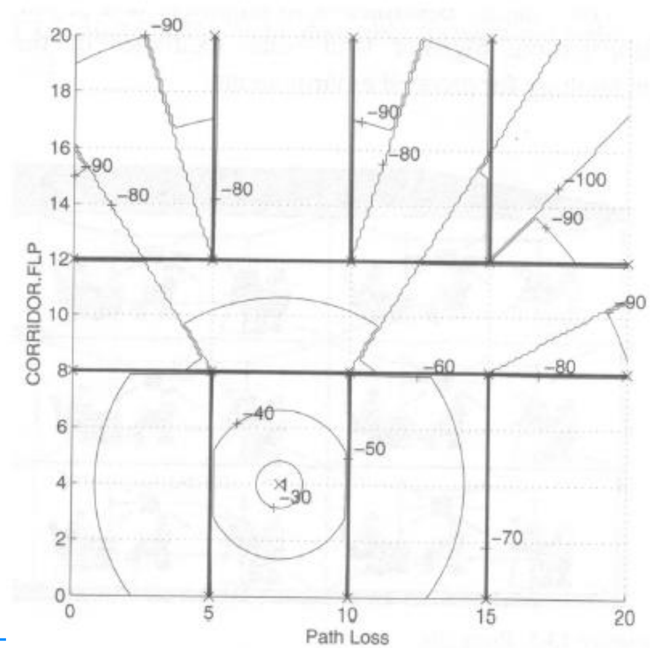
# Example

- Consider a user in the downlink of a cellular system, where the desired base station is at a distance of 500 meters, and numerous nearby interfering base stations are transmitting at the same power level. If three interfering base stations are at a distance of 1 km, three at a distance of 2 km, and ten at a distance of 4 km, use the empirical pathloss formula to find the signal-to-interference ratio (SIR)—the noise is neglected—when $\alpha=3$ and when $\alpha=5$

# Propagation within buildings

- Wall and floor factor models
- Characterize indoor path loss by :
  - → a fixed exponent of 2 (as in free space) + additional loss factors relating to number of floors $n_f$ and walls $n_w$ intersected by the straight-line distance $r$ between terminals

$$L = L_1 + 20\log_{10} r + n_f a_f + n_w a_w$$




- $a_f$ = attenuation factor per floor
- $a_w$ = attenuation factor per wall
- $L_1$ = reference path loss at $r$ =1 m

# ITU-R models

- only floor loss is accounted explicitly
- loss between points on same floor included implicitly by changing path loss exponent

$$L_T = 20\log_{10} f_c[\mathrm{MHz}] + 10n\log_{10} r[\mathrm{m}] + L_f(n_w) - 28$$

# ITU-R models

| Frequency [GHz] | Environment | | |
|---|---|---|---|
| | Residential | Office | Commercial |
| 0.9 | – | 3.3 | 2.0 |
| 1.2–1.3 | – | 3.2 | 2.2 |
| 1.8–2.0 | 2.8 | 3.0 | 2.2 |
| 4.0 | – | 2.8 | 2.2 |
| 60.0 | – | 2.2 | 1.7 |

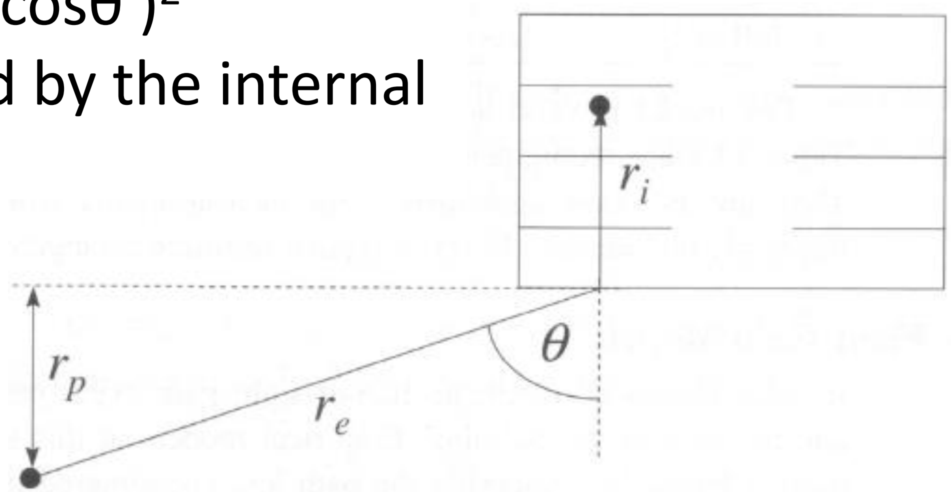
[a] The 60 GHz figures apply only within a single room for distances less than around 100 m, since no wall transmission loss or gaseous absorption is included.

| Frequency [GHz] | Environment | | |
|---|---|---|---|
| | Residential | Office | Commercial |
| 0.9 | – | 9 (1 floor)<br>19 (2 floors)<br>24 (3 floors) | – |
| 1.8–2.0 | $4\, n_f$ | $15 + 4\,(n_f - 1)$ | $6 + 3\,(n_f - 1)$ |

[a] Note that the penetration loss may be overestimated for large numbers of floors, for reasons described in Section 13.4.1. Values for other frequencies are not given.

# COST231 line-of-sight model

- Total path loss : $L_T = L_F + L_e + L_g\,(1\text{-}\cos\theta\,)^2 + \max(L_1\,,\,L_2)$
- $L_F$ = free space loss for total path length $(r_i + r_e)$
- $L_e$ = path loss through external wall at normal incidence ($\theta$ = 0°)
- $L_g$ = additional external wall loss incurred at grazing incidence ($\theta$ = 90°)
- $L_1 = n_w L_i$ and $L_2 = \alpha\,(r_i - 2)(1\text{-}\cos\theta\,)^2$
- $n_w$ = number of wall crossed by the internal path ri
- $L_i$ = loss per internal wall
- $\alpha$= specific attenuation which applies for unobstructed internal path



# COST231 line-of-sight model

| Parameter | Material | Approximate value |
|---|---|---|
| $L_e$ or $L_i$ [dB m$^{-1}$] | Wooden walls | 4 |
| | Concrete with non-metallised windows | 7 |
| | Concrete without windows | 10–20 |
| $L_g$ [dB] | Unspecified | 20 |
| $\alpha$ [dB m$^{-1}$] | Unspecified | 0.6 |

# Shadowing

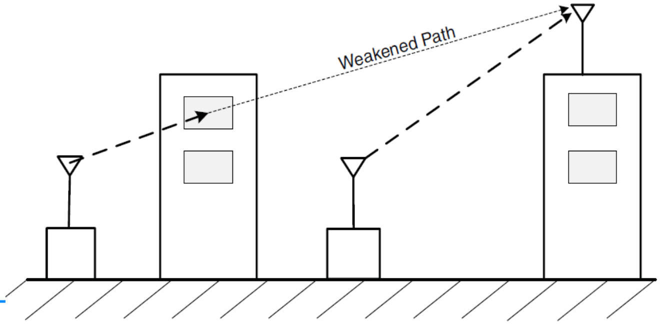
- Shadowing occurs when objects block LOS between transmitter and receiver
- A simple statistical model can account for unpredictable "shadowing"
  - → Add a 0-mean Gaussian RV to Log-Distance PL

    $$X_\sigma = 10^{x/10}, \quad \text{where } x \sim N\left(0, \sigma_s^2\right)$$

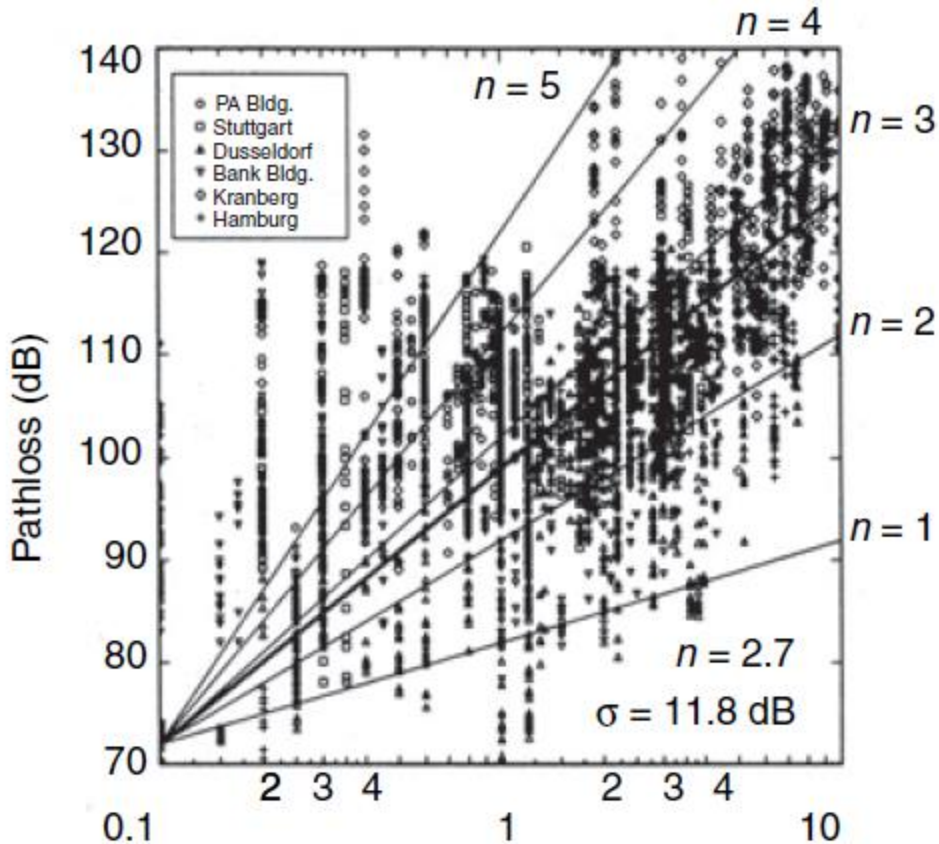
  - → Markov model can be used for spatial correlation
- PL($d$)[dB] = PL($d_0$) +10$n$log($d/d_0$)+ $X_\sigma$
  - → where $X_\sigma$ is a zero-mean Gaussian RV (dB)
  - → $\sigma$ and $n$ computed from measured data, based on linear regression
- Shadowing value $X_\sigma$ is typically modelled as a lognormal random variable
- The typical value of variance $\sigma_s$ is 6-12 dB

# Shadowing

- Shadowing is an important effect in wireless networks because it causes the received SINR to vary dramatically over long time scales
- shadowing can sometimes be beneficial
  - →if an object is blocking interference—it is generally detrimental to system performance because it requires a several-dB margin to be built into the system



# Shadowing



PA Bldg.
Stuttgart
Dusseldorf
Bank Bldg.
Kranberg
Hamburg
n = 5
n = 4
n = 3
n = 2
n = 1
n = 2.7
σ = 11.8 dB
Pathloss (dB)
140
130
120
110
100
90
80
70
2
3
4
2
3
4
0.1
1
10

# Why is the shadowing lognormal?

- a transmission experiences N random attenuations $\beta_i$ , $i = 1, 2,\ldots,N$ between the transmitter and receiver, the received power can be modeled as

$$P_r = P_t \prod_{i=1}^{N} \beta_i$$

- In dB

$$P_r(dB) = P_t(dB) + 10 \sum_{i=1}^{N} \log_{10} \beta_i$$

- Then, using the Central Limit Theorem,
  - →it can be argued that the sum term will become Gaussian as N becomes large—and often the CLT is accurate for fairly small N—and
- since the expression is in dB, the shadowing is hence lognormal.

# What does “dB” mean?

- dB stands for deciBel or 1/10 of a Bel
- The Bel is a dimensionless unit for expressing ratios and gains on a log scale

$$\left[\frac{\mathrm{P}_2}{\mathrm{P}_1}\right]_{\mathrm{dB}} = 10\log_{10}\left(\frac{P_2}{P_1}\right) = 10(\log(P_2) - \log(P_1))$$

- Gains add rather than multiply
- Easier to handle large dynamic ranges

# What does "dB" mean?

- Ex: Attenuation from transmitter to receiver.
  - → $P_T$=100, $P_R$=10
  - → attenuation is ratio of $P_T$ to $P_R$
  - → $[P_T/P_R]_{dB} = 10 \log(P_T/P_R) = 10 \log(10) = 10$ dB
- Useful numbers:
  - → $[1/2]_{dB} \approx -3$ dB
  - → $[1/1000]_{dB} = -30$ dB

# What does "dB" mean?

- dB can express *ratios*, but what about absolute quantities?
- Similar units reference an absolute quantity against a defined reference.
  - → $[n \text{ mW}]_{\text{dBm}} = [n/\text{mW}]_{\text{dB}}$
  - → $[n \text{ W}]_{\text{dBW}} = [n/\text{W}]_{\text{dB}}$
- Ex: $[1 \text{ mW}]_{\text{dBW}} = -30 \text{ dBW}$