# Radio Channel Principles

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# Brief Intro of myself

- Prof. Christos Masouros
- Professor in the **Information and Communications Engineering** Group
- Interests / Projects :
  - Algorithm design for Wireless Communications
  - 5G and Beyond Communications (MIMO, OFDM, LTE)
  - Multiple Antenna systems, Interference cancellation
  - Energy Efficient wireless transmission
  - HetNets, Large-Scale (Massive) MIMO, mmWave, Comms-Radar

## Radio Channel Principles

- Large Scale Propagation – Antenna Directivity, Path Loss, Fading
- Small Scale Propagation – Multipath, Freq. Selectivity, Doppler
- Calculation of link budget – Path Loss $\longrightarrow$ Receive SNR

## RF System Design

- RF components
- Baseband processing and Channel Estimation
- SNR $\longrightarrow$ Link Performance (Probability of error)
- Modulation tradeoffs – Spectral/Power Efficiency
- MIMO, Satellite Comms

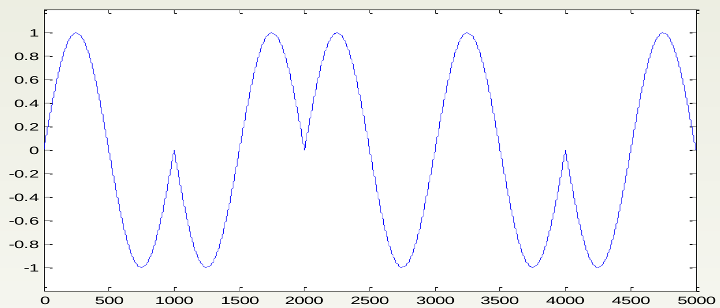
# This Video : Large Scale Propagation

- Antenna gain
- Free space path loss
- Plain earth propagation

# The radio channel

- The propagation channel is the cause of many of the problems and limitations of radio systems – the main challenge

Transmitted

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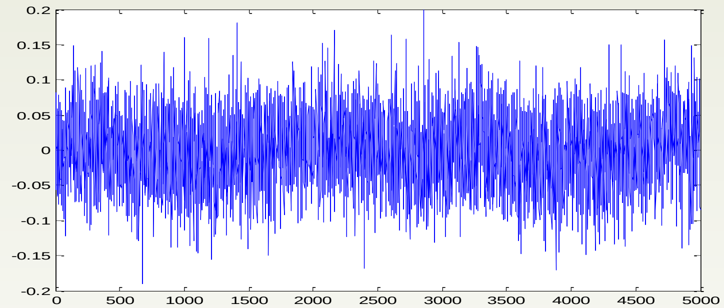
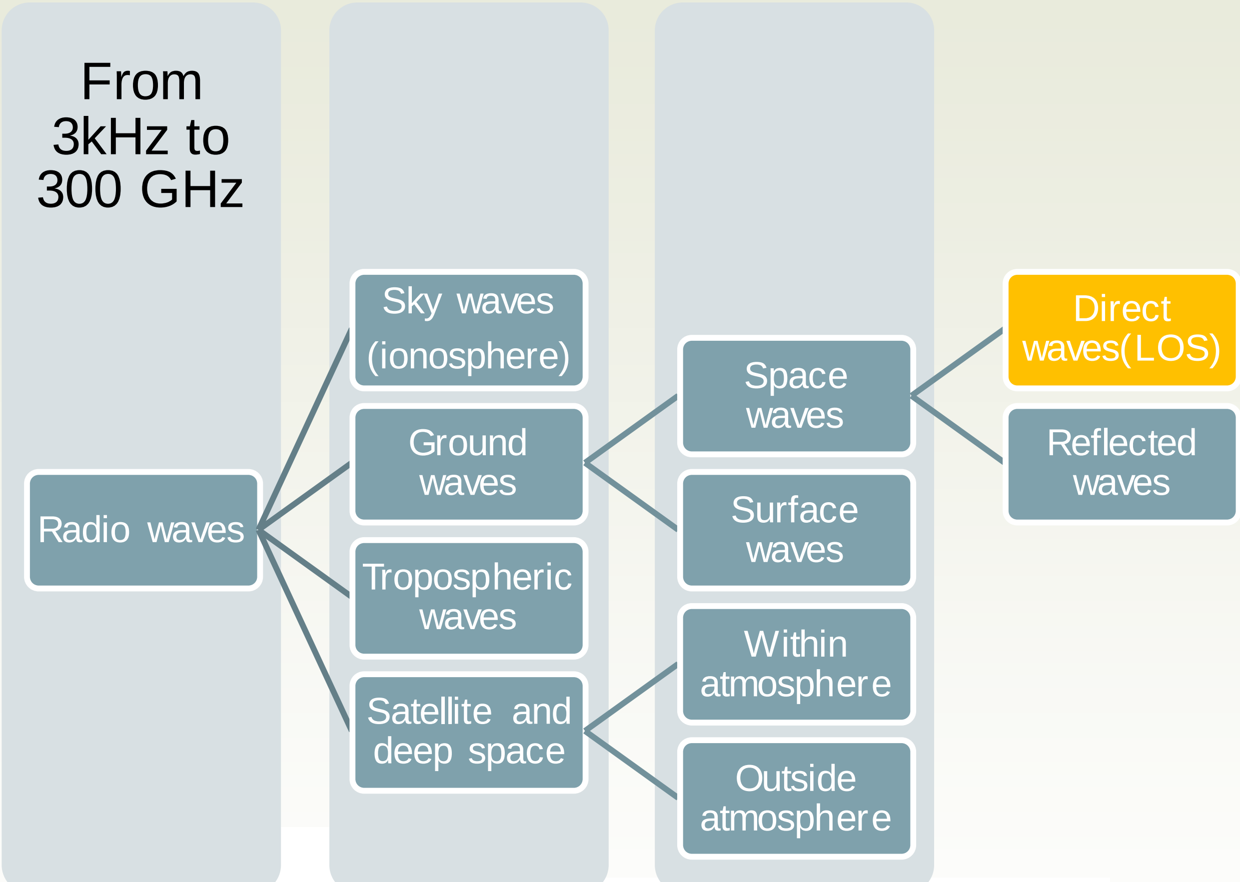
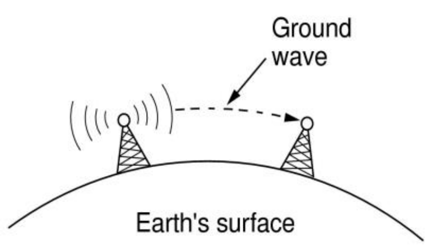


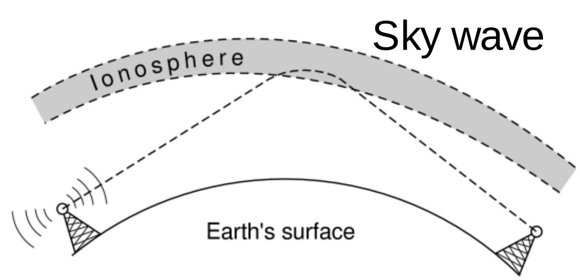

- Understanding of the channel's properties is therefore key to the understanding of radio systems
- Key in designing the transceivers to combat the channel effects
- A line of sight (LOS) path between transmitter and receiver is the normal basis for radio transmission systems
- Many practical scenarios involve non-line of sight (NLOS) transmission.

# Radio propagation modes and frequencies




- ELF <3kHz
- VLF 3-30 kHz
- LF 30-300 kHz
- MF 300kHz-3 MHz
- HF 3-30 MHz
- VHF 30-300 MHz
- UHF 300MHz-3GHz
- SHF 3-30 GHz
- EHF 30-300GHz (mm-waves)
- THz range >300 GHz



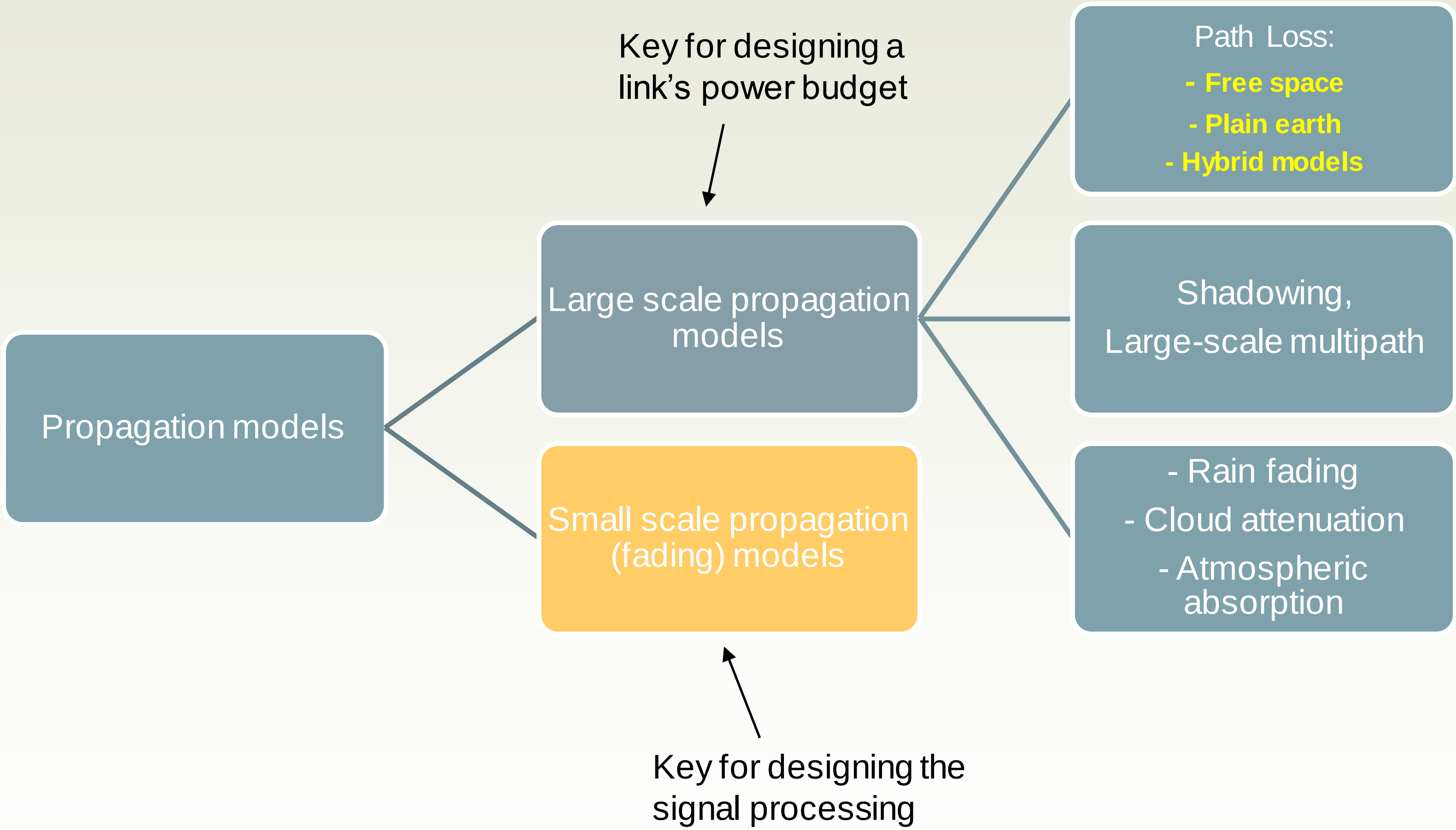




Wavelength = c/f; (1 GHz is ~30cm)

LTE bands within 700 MHz - 3.8 GHz

WiFi, BlueTooth: 2.4 GHz (5 GHz)

# Fading


Key for designing a link's power budget
Path Loss:
- Free space
- Plain earth
- Hybrid models
Large scale propagation models
Shadowing,
Large-scale multipath
Propagation models
Small scale propagation (fading) models
- Rain fading
- Cloud attenuation
- Atmospheric absorption
Key for designing the signal processing

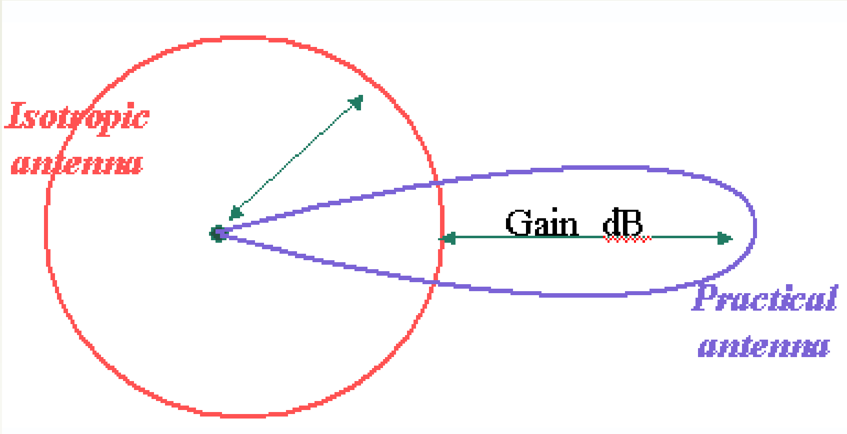
# LARGE SCALE PROPAGATION: ANTENNA GAIN – PATH LOSS

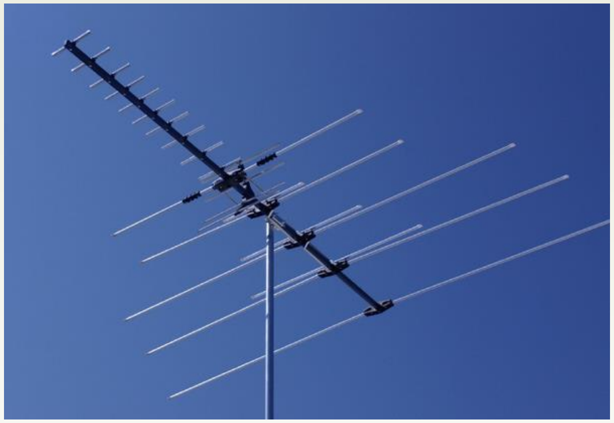
# Antenna Directivity

Transmit Directivity

Receive Directivity

- Directional antennas mean that the power radiated is concentrated in the direction of the receiver



- The extent to which the antenna 'directs' the power is referred to as the antenna gain G
- The effective isotropic radiated power is then:

$$\text{EIRP} = P_T \times G \times \eta$$

$\eta$ : antenna ohmic efficiency

Directivity + Beam-forming: Key role in **5G – massive MIMO**

# Antenna radiation pattern

## Directivity → Gain

Power flux density ($P_D$) W/m$^2$

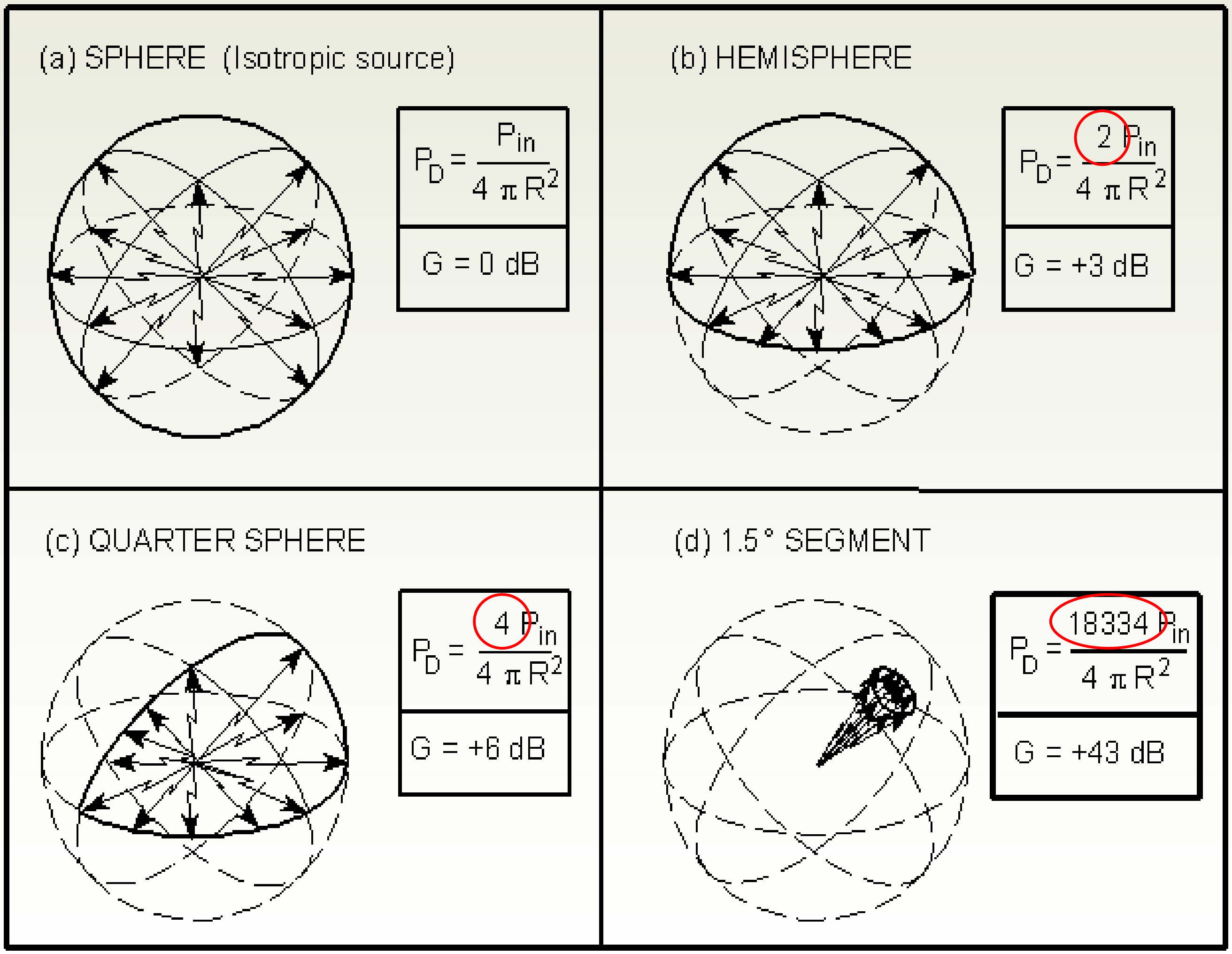
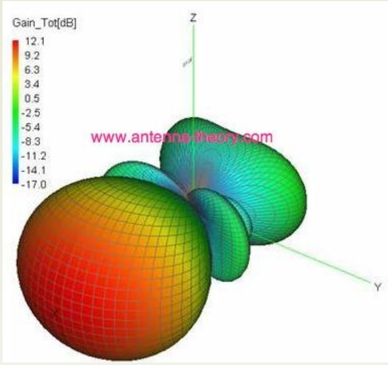
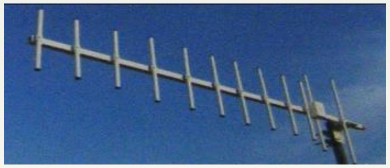


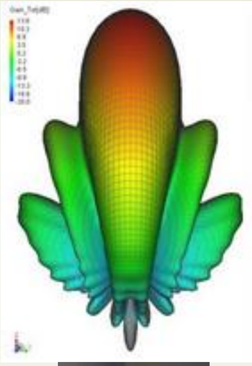

**Figure 2.** Antenna Gain

Yagi-Uda

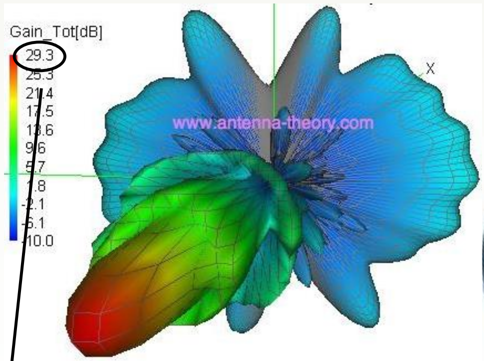


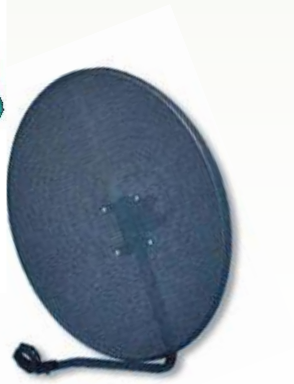



Horn antenna



Satellite dish



~30dB -> x1000 power!

## This Video : Large Scale Propagation

- Free space path loss
- Plain earth propagation

# Path loss (in Free Space)

- Normally is the major source of loss (also called Free space loss or LOS)
- Due to the spatial separation between the TX and the RX
- In LOS case loss varies as (frequency)$^2$ & (distance)$^2$

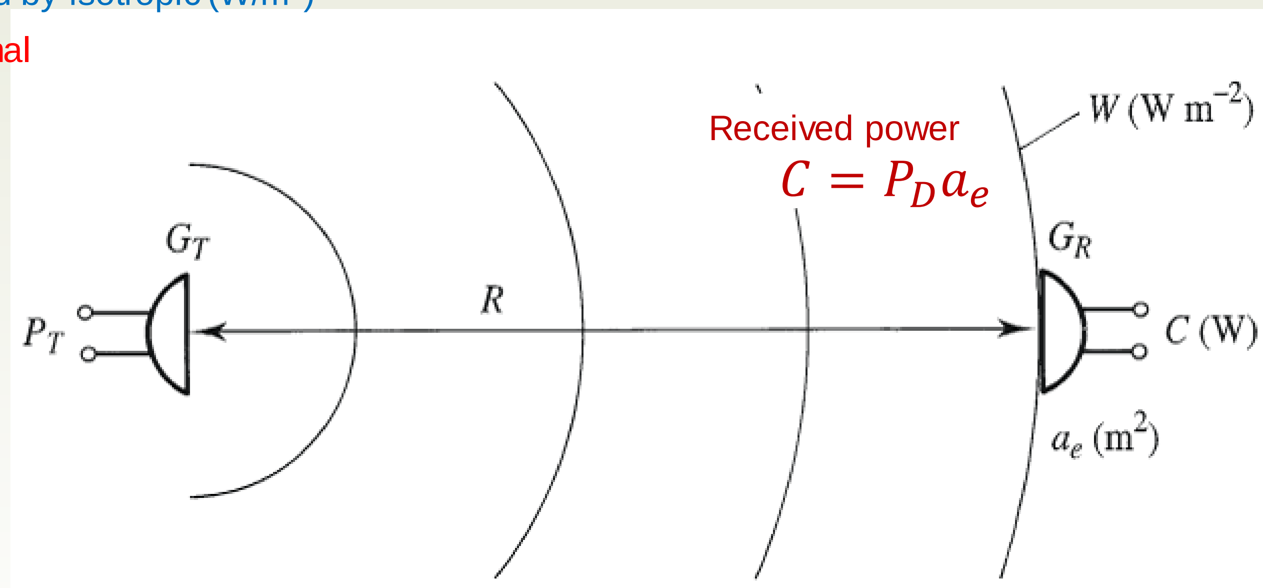
Power density: Radiated by isotropic (W/m$^2$)

Radiated by directional

$$C = \frac{P_T}{4\pi R^2} G_T a_e$$

$$= \frac{P_T}{4\pi R^2} G_T \frac{\lambda^2}{4\pi} G_R$$

$$= P_T G_T \boxed{\left(\frac{\lambda}{4\pi R}\right)^2} G_R \quad [\mathrm{W}]$$




$a_e$= Antenna effective area
G= Antenna gain
λ= wavelength

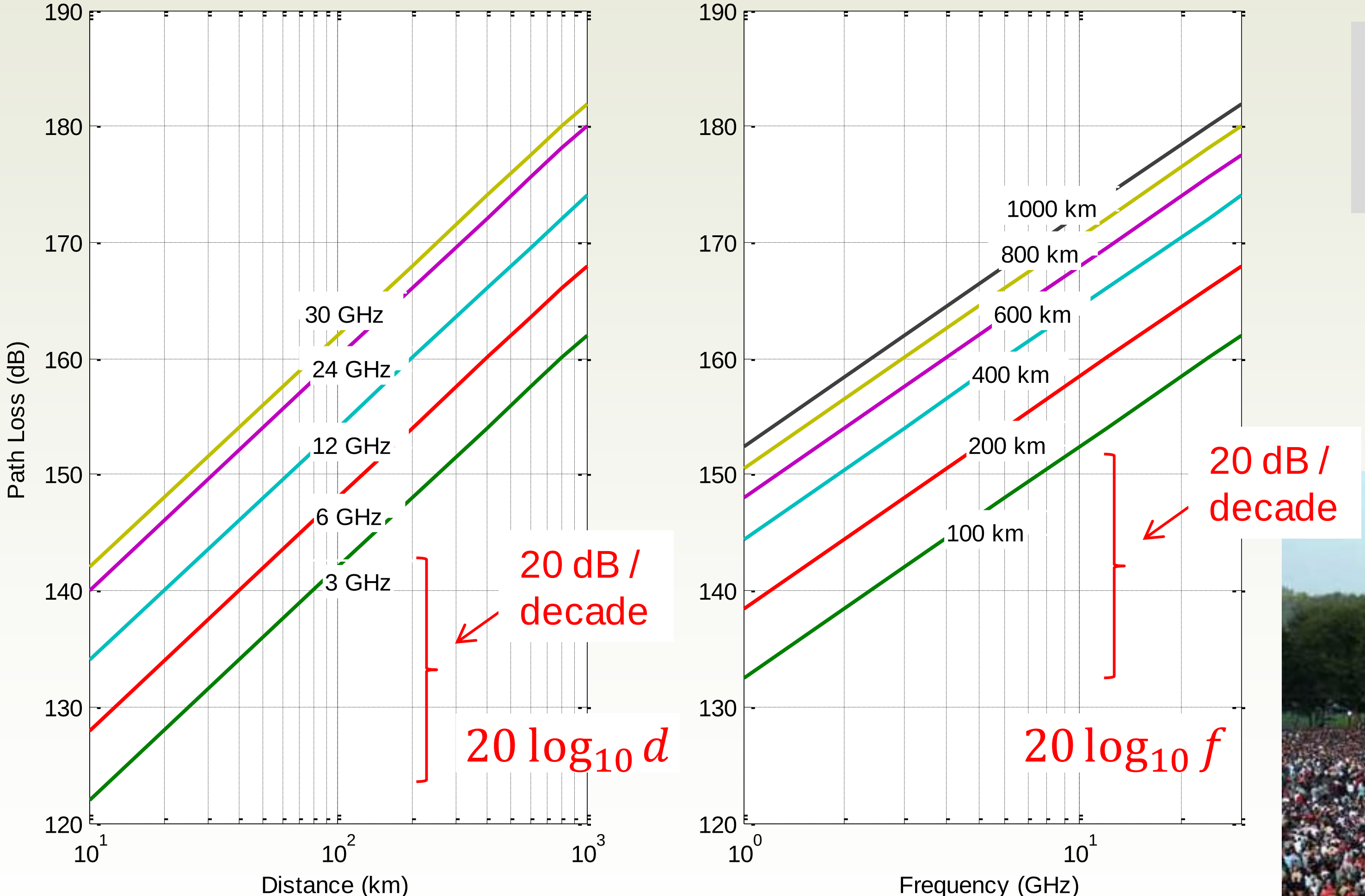
**Path Loss:**

$$L = \left(\frac{4 \cdot \pi \cdot d}{\lambda}\right)^2 = \left(\frac{4 \cdot \pi \cdot d \cdot f}{c}\right)^2$$

Assumptions:
- single path
- in vacuum

$$L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} d_{km} + 32.44$$

# Path loss as a function of d and f



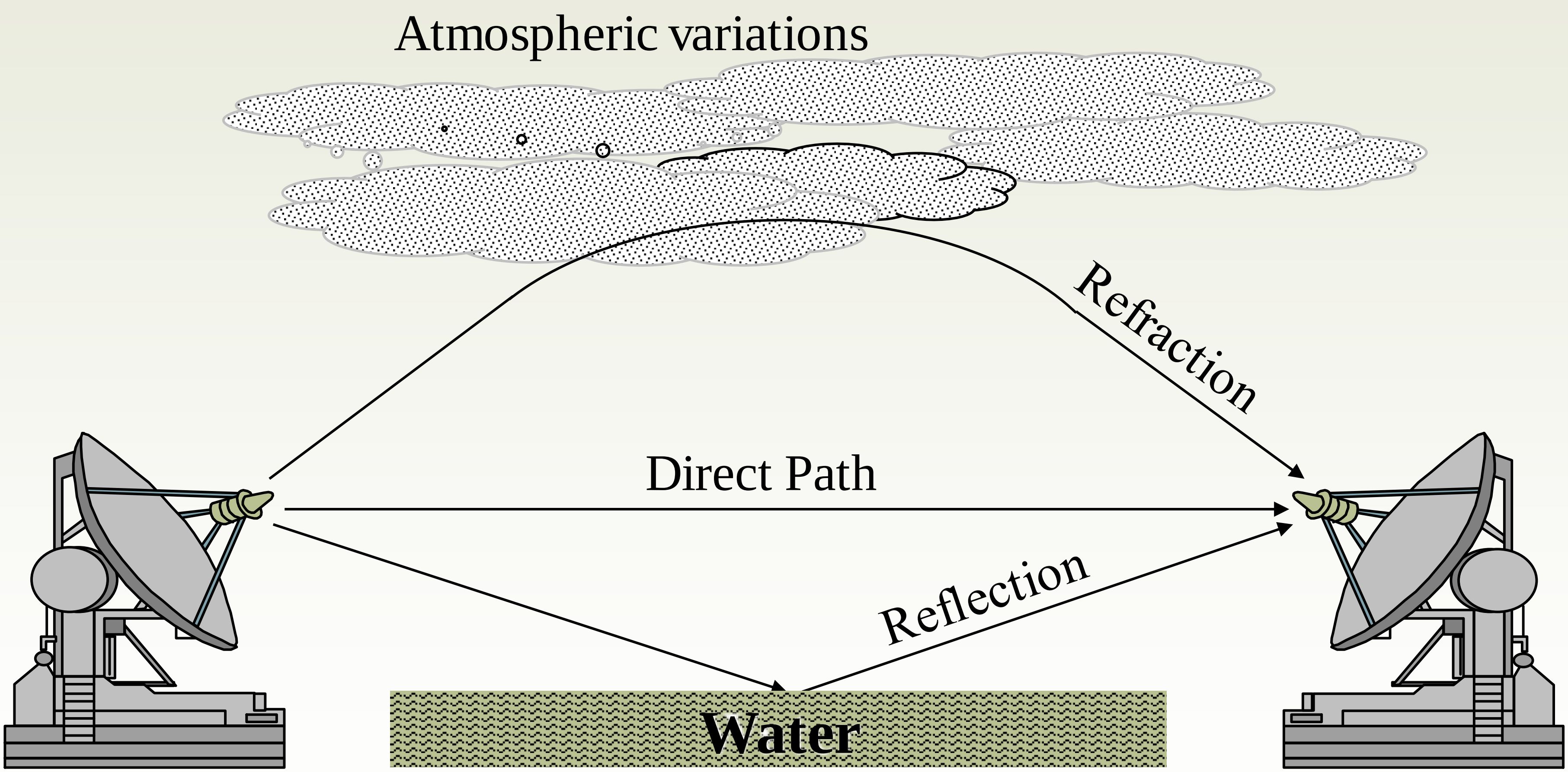

$$L = \left( \frac{4 \cdot \pi \cdot d \cdot f}{c} \right)^2$$

The 'concert effect'

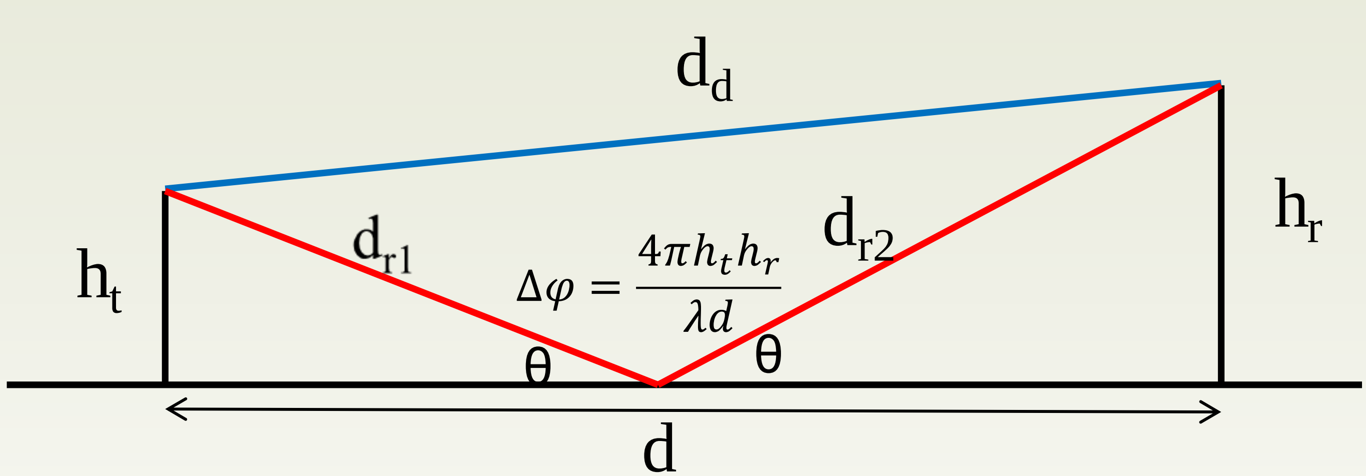
Ref. JPL report 2005;

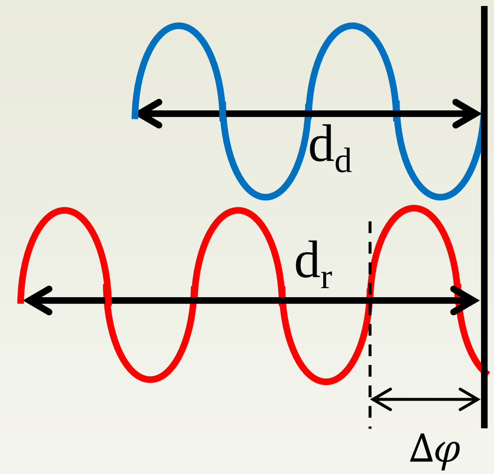
Estimation of Microwave Power Margin Losses Due to Earth's Atmosphere and Weather in the Frequency Range of 3–30 GHz

# Multi-path fading (large-scale)



# Multi-path induced fading, frequency and height dependence




- When θ is small, the earth acts as a reflector
- The reflected signal is 180° out of phase with the incident

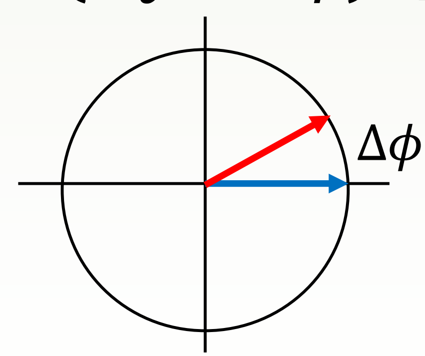
$$d_d = [d^2 + (h_r - h_t)^2]^{0.5}$$

$$d_r = d_{r1} + d_{r2} = [d^2 + (h_t + h_r)^2]^{0.5}$$

For $d \gg h_t, h_r$:
$$\Delta d = d_r - d_d = \frac{2h_t h_r}{d}$$

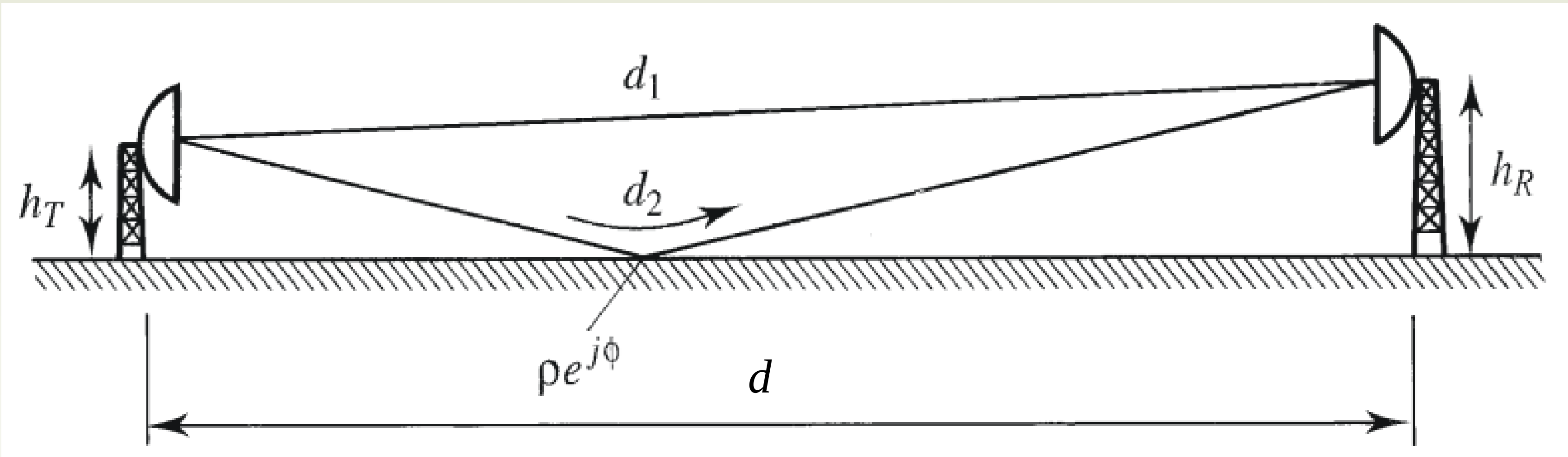
$$\Delta\varphi = \frac{2\pi}{\lambda} \times \Delta d = \frac{4\pi h_t h_r}{\lambda d}$$

Assumptions:
- two paths
- in vacuum

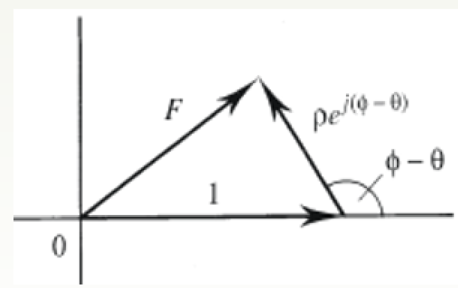



$$\Delta\varphi_{tot} = \Delta\varphi + 180$$

# Two ray fading (Plane Earth Propagation)




$$P_r^{total} = P_r^d + P_r^r = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \times F$$




Received free-space field strength modified by factor *F*:

$$F = \left|1 + \rho e^{j\varphi}\right|^2 = \left|\underbrace{4\sin^2\left(\frac{2\pi h_T h_R}{\lambda d}\right)}\right| \cong \underbrace{\left(\frac{4\pi h_T h_R}{\lambda d}\right)^2}$$

for small argument

$$P_r = P_T G_T G_R \frac{h_t^2 h_r^2}{d^4}$$

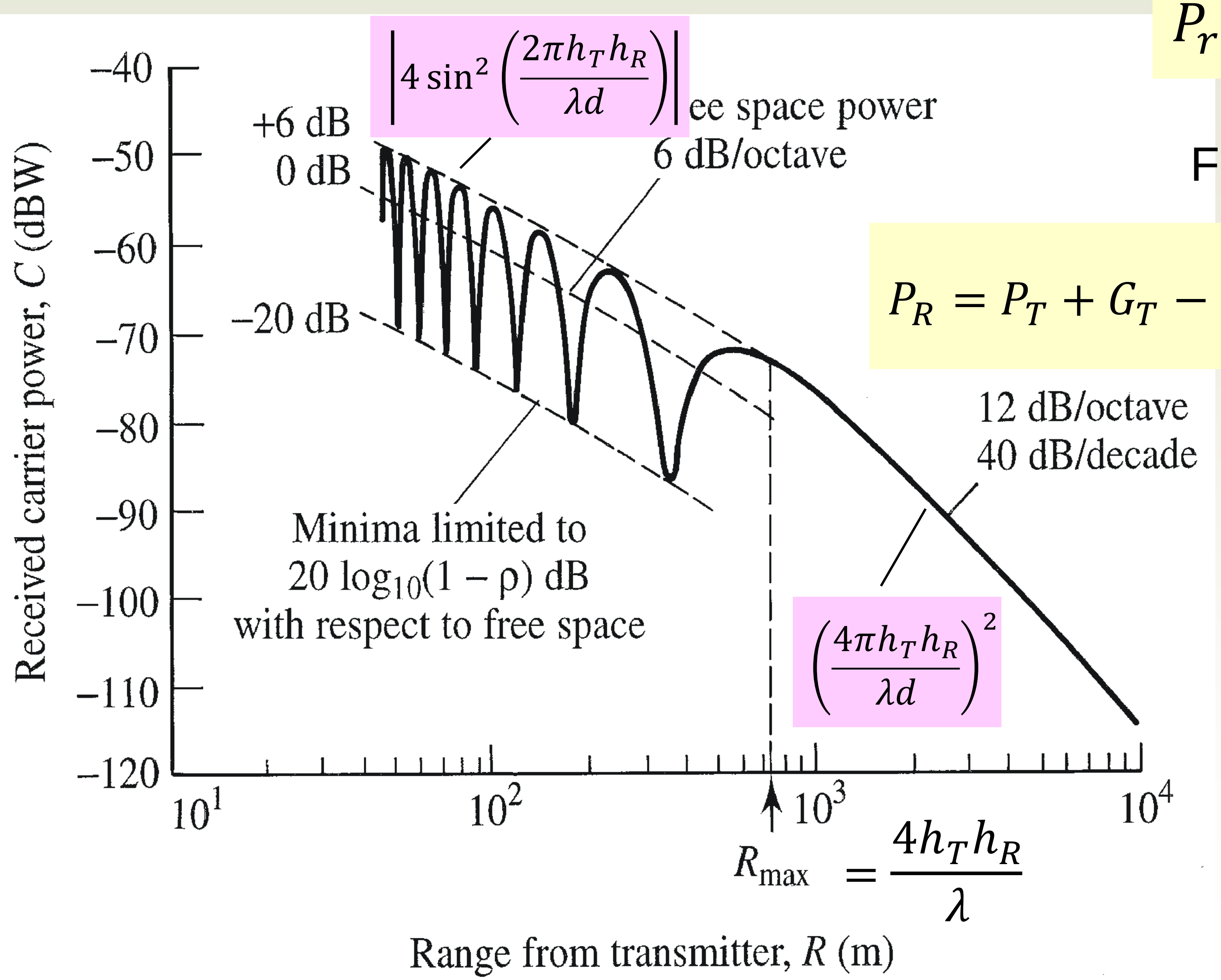
$\rho$ is the reflection coefficient, for earth~1

$\sin^2(1/x)$ behaviour for short

$(1/x)^2$ behaviour for long range

When d>> $h_t$ and $h_r$

# Plane-Earth propagation




$$P_r = P_T G_T G_R \frac{h_t^2 h_r^2}{d^4}$$

For $R > R_{\max}$:

$$P_R = P_T + G_T \underbrace{- 20\log_{10}\left(\frac{R^2}{h_T h_R}\right)}_{L_{PEPL}} + G_R$$

- No longer a function of frequency!!
- $L \propto d^4$

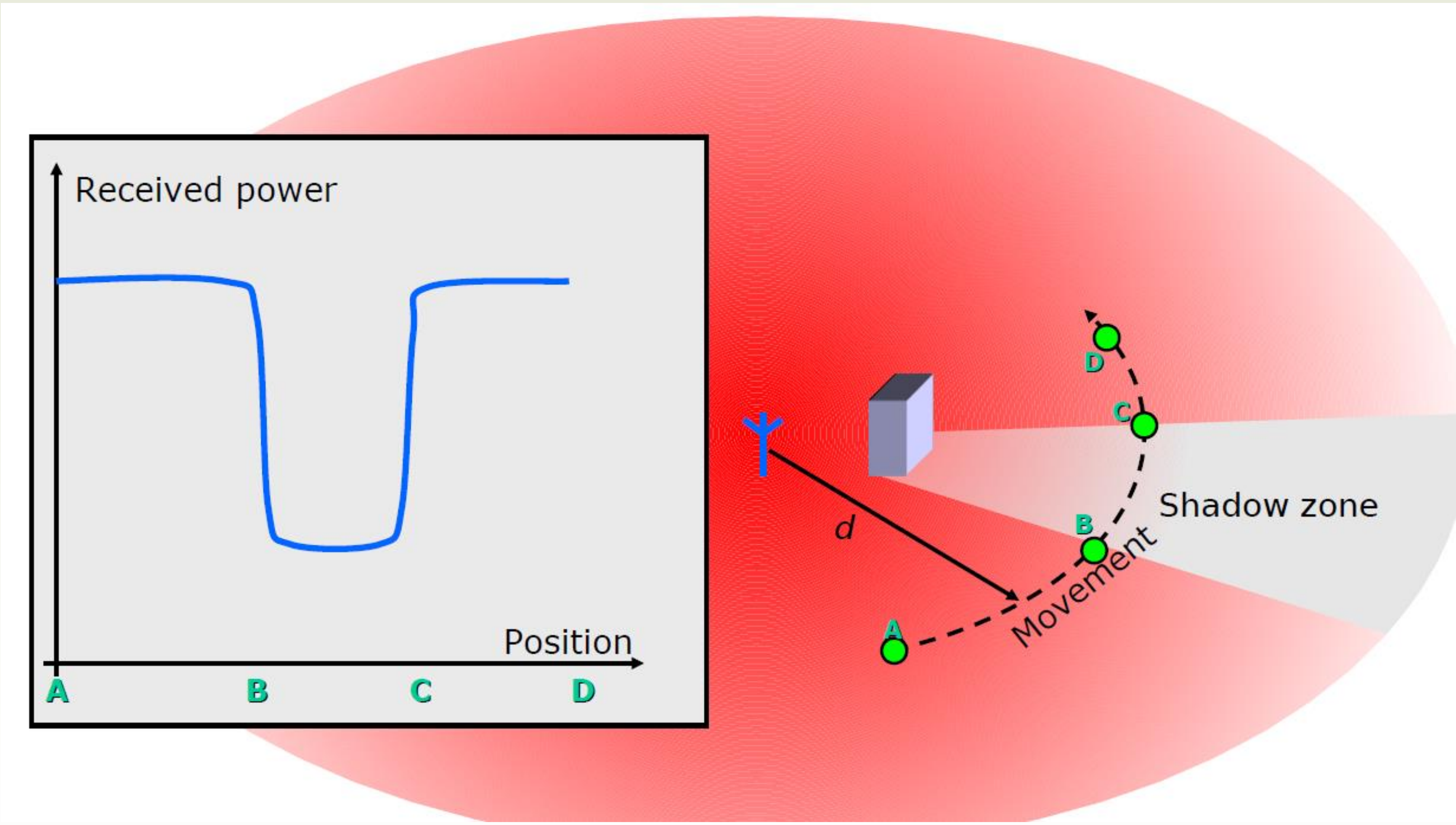
Assumptions:
- two paths
- in vacuum

[Note the path loss is *subtracted*]

# This Video : Large Scale Propagation

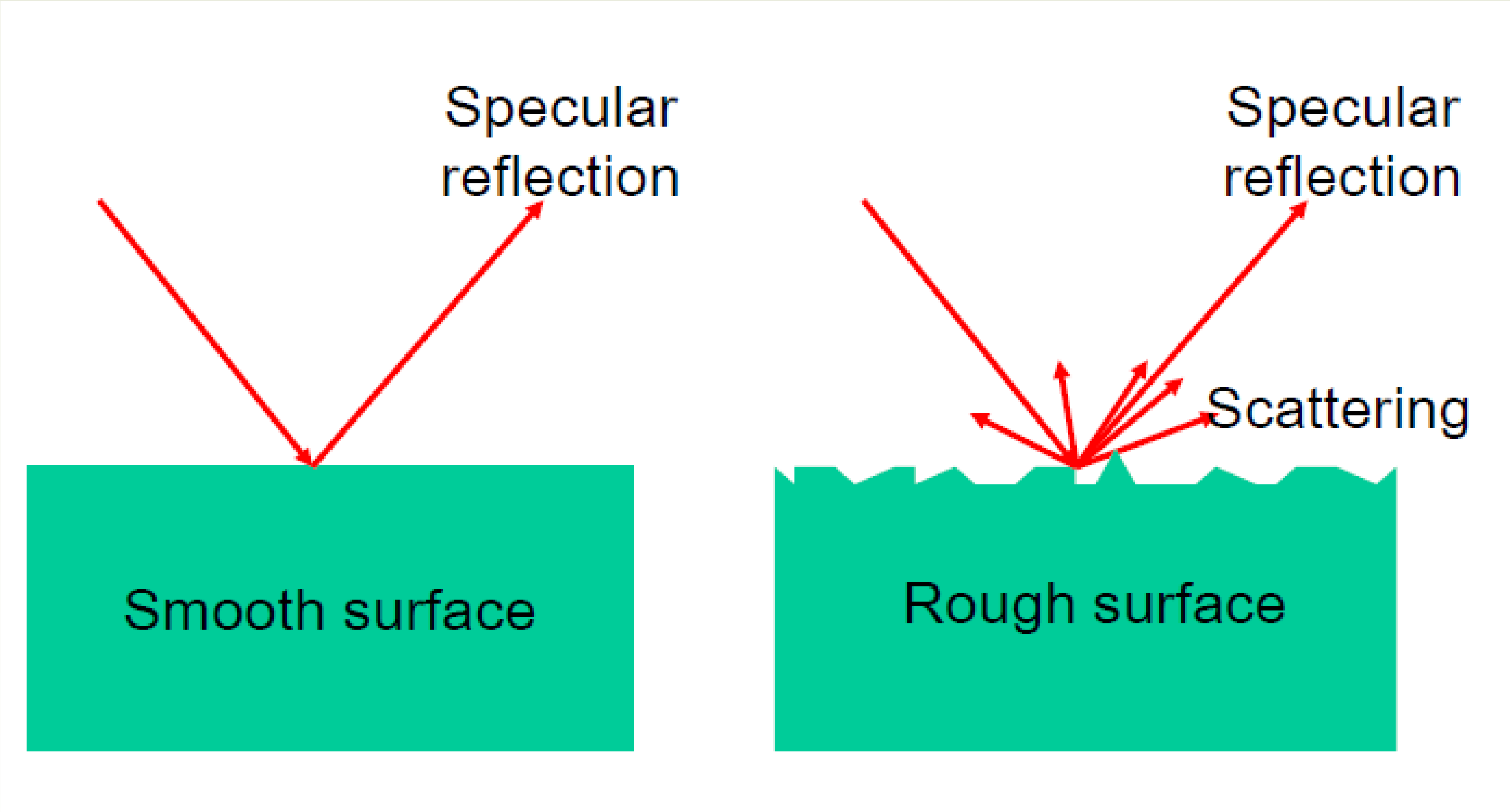
- Shadowing and geometrical effects
- Atmospheric effects
- Advanced propagation models

# Shadowing



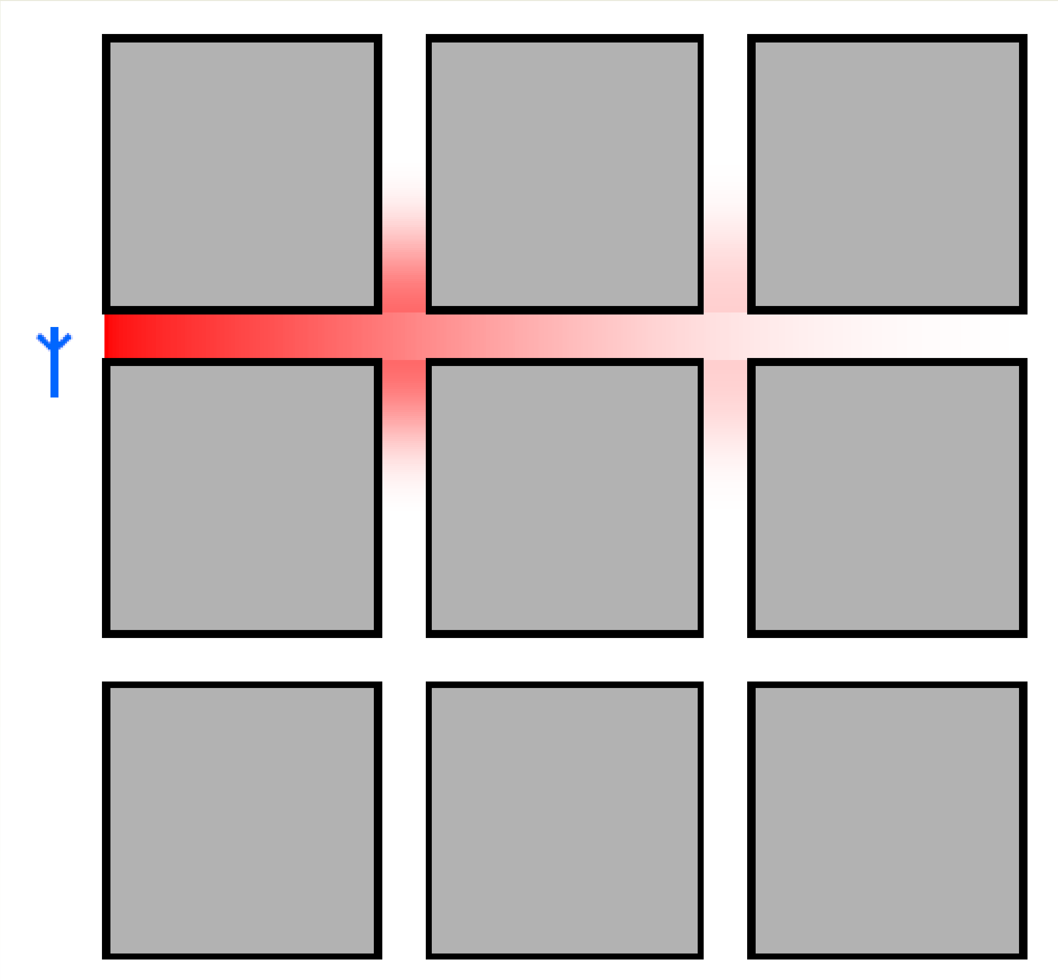

Not accounted for, in the previous models!

# Scattering




These are parameters that can complicate the propagation.
More detailed and advanced propagation models exist.

# Waveguiding



Waveguiding effects often result in lower propagation exponents:

lower path loss, better propagation along certain street corridors

A ‘focusing’ effect due to the street corridors

These are effects that can complicate the propagation.
More detailed and advanced propagation models exist.

FSPL: $L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} d_{km} + 32.44$

# Path loss - obstructed path

$L \propto d^{\alpha}$

- Over a non-LOS path the path-loss exponent ($\alpha$) becomes greater than 2 (e.g. cellular radio systems)
- Can now write the path loss expression as

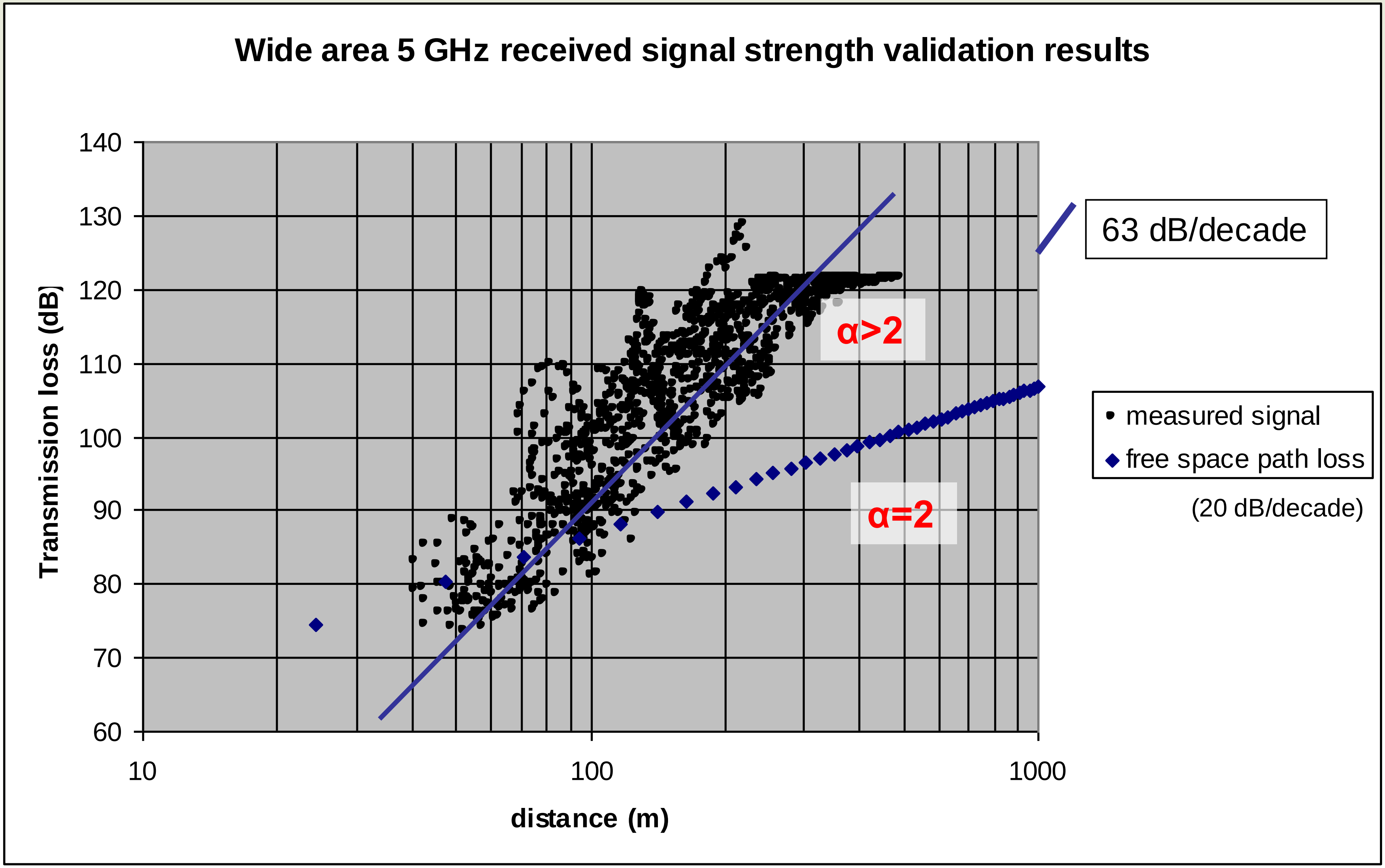
$$L_{dB} = 20\log_{10} f_{MHz} + 10\alpha\log_{10} d_{km} + 32.44$$

- Typical values for the loss exponent $\alpha$ are 3 to 5 in outdoor environments

| | |
|---|---|
| • Free-space | 2 $(L \propto d^{2})$ |
| • Plane Earth (ideal reflection) | 4 $(L \propto d^{4})$ |
| • Urban macro-cells | 2.7 – 3.5 |
| • Urban macro-cells, shadowed | 3 – 5 |
| • Indoor, LOS | 1.6 – 1.8 |
| • Indoor, NLOS (Obstructed path) | 4 – 6 |
| • Indoor (factory, NLOS) | 2 - 3 |

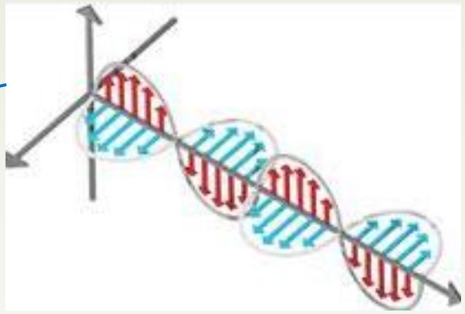
# Example

$$L_{dB} = 20\log_{10} f_{MHz} + 10\alpha \log_{10} d_{km} + 32.44$$



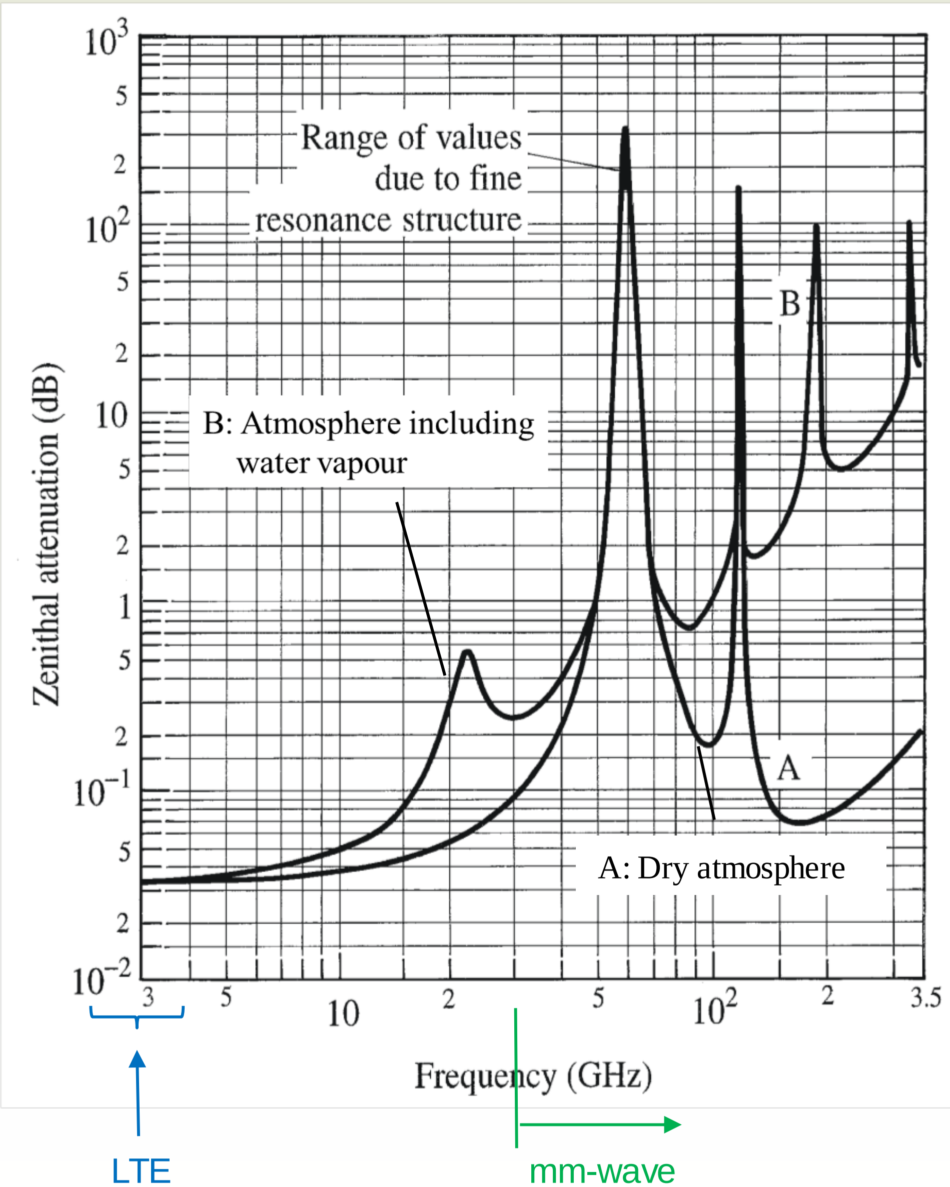
# Atmospheric effects

- Mechanisms affecting noise and interference
  - Rain emission (thermal noise)
  - Precipitation scatter (interference)
  - Cross-polarisation (crosstalk)



- Mechanisms affecting signal level
  1. Background atmospheric absorption
  2. Rain fading
  3. Cloud attenuation
  4. Scintillation

# 1. Effects of gaseous absorption



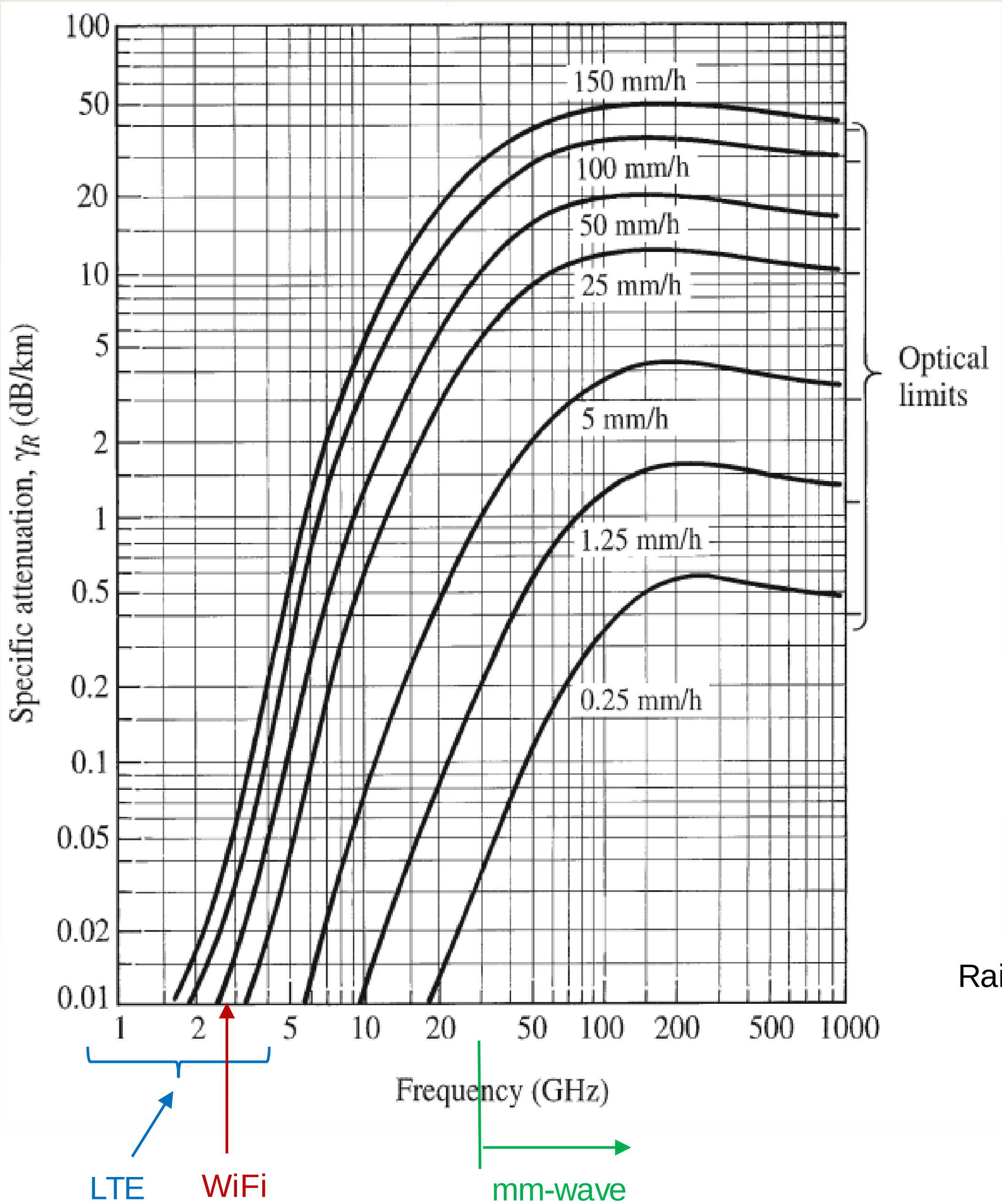

Reference atmosphere surface parameters:

| | |
|---|---|
| temperature | 15°C |
| pressure | 1013 mBars |
| water vapour | 7.5 g/m³ |

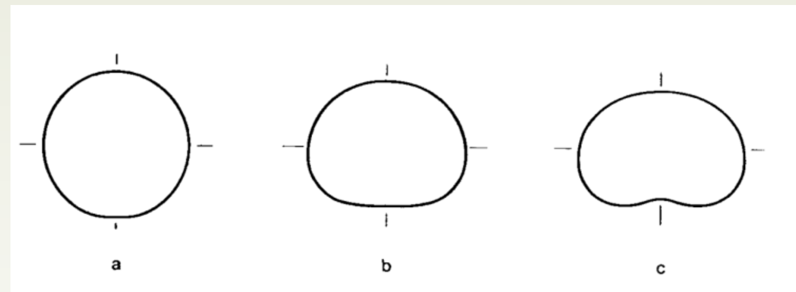
- Peak of water vapour absorption ~ 22 GHz
- Peak of oxygen absorption ~ 60 GHz

# 2. Specific attenuation due to rain

[After ITU-R, 1996]




Spherical raindrops assumed (therefore no polarisation dependence)

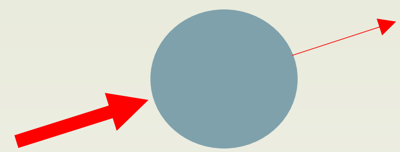



| | | | |
|---|---|---|---|
| Drop size (Major axis) | 1mm | 4mm | 6mm |
| Drop shape (a/b) | 0.9 | 0.8 | 0.7 |

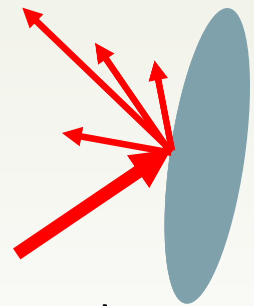
Rain intensity (mm/h)

# 3. Cloud attenuation

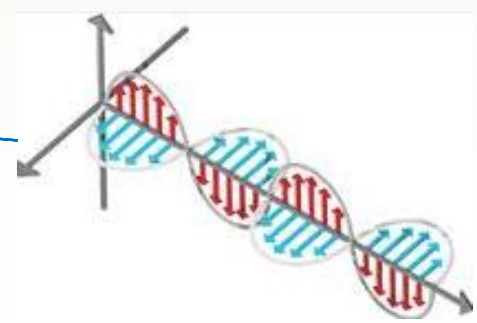
- Liquid clouds



  - small, spherical, water droplets (0 – 10 μm radius)
  - Significant attenuation above 20 GHz
  - Attenuation proportional to total water content (g/$m^3$)
  - No cross polarisation



- Ice clouds
  - small needles and plates (sub-millimetre in size)
  - Attenuation (dominated by scattering rather than absorption) negligible below 100 GHz
  - Severe cross polarisation



# 3. Liquid cloud specific attenuation

| Frequency (GHz) | Attenuation (dB/km) |
|---|---|
| 5.0 | 0.023 |
| 10.7 | 0.106 |
| 15.4 | 0.217 |
| 23.8 | 0.507 |
| 31.4 | 0.859 |
| 90.0 | 4.74 |

- Clouds occur in many types
- Thicknesses from 100 m to several km
- Attenuation modest but may be present for large fractions of time - significant for low availability systems

[Extracted from Table 7.1, Brussaard, G & Watson, P A: Atmospheric modelling and millimetre wave propagation, Chapman Hall, 1995] (0°C, 1 g/m$^3$)

# 4. Scintillation

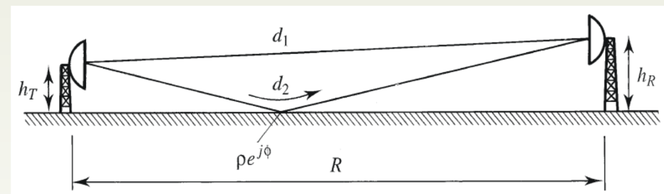
- Rapid fluctuation of signal amplitude and phase due to spatial and temporal variations in refractive index of atmosphere (thickness/density of atmosphere, vapour content, temperature)
- Fluctuation time scale - seconds to minutes
- Fluctuation amplitude - up to several decibels
- May result in signal enhancement as well as fades
- Most severe for low elevation-angle systems

# Channel and propagation models

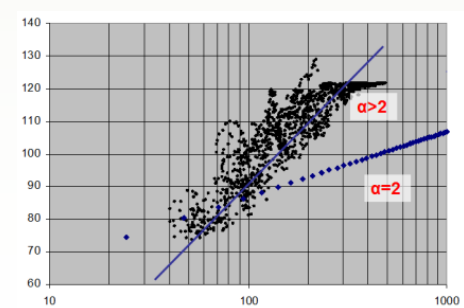
- Channel model describes *what* happens
  - gives channel output for a particular input
  - black box
  - requires appropriate parameter (e.g. loss, fading, dispersion statistics)

$$L_{dB} = 20\log_{10} f_{MHz} + 10\alpha \log_{10} d_{km} + 32.44$$

- Propagation model describes *how* it happens
  - how signal gets from transmitter to receiver
  - how energy is redistributed in time and frequency
  - how the resulting fields 'satisfy' Maxwell's equations
  - can be used to obtain the parameters needed by channel models

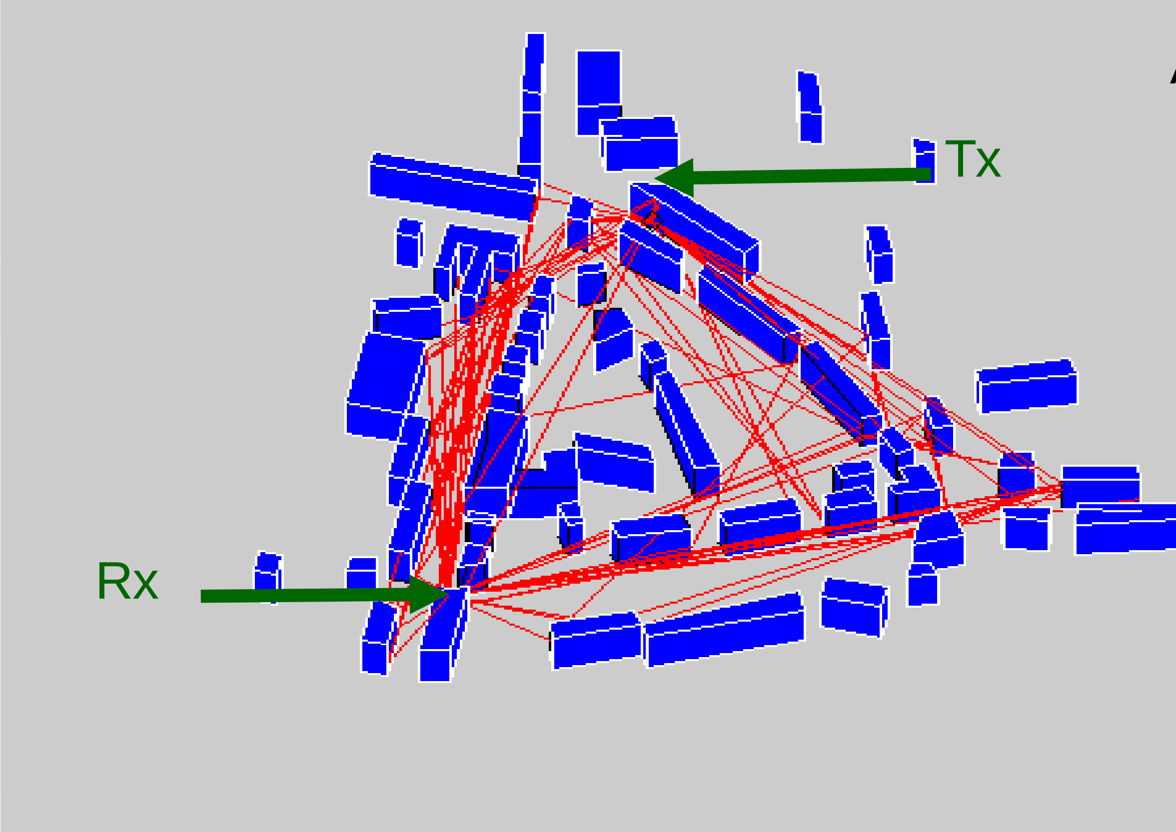



- Measurement based (semi-empirical) models
  - Based on simple physical model (e.g. free-space path loss) plus a correction factor derived from measurements
  - Valid for specific channels and ranges of variables (antenna heights, frequencies etc.)
  - Sensitive to changes in environment but probably less so than purely empirical model



# Example propagation model

- Geometric optics (Snell's laws (relfection) + Geometrical Theory of Diffraction, Uniform TD)
- Finds approximate solution of Maxwell's equations
- Most useful physical model at frequencies used for mobile communications
- Can predict (i) path loss, (ii) fading




A geometrical model :

Ray tracing

+ FSPL expressions

+ reflection coefficients

+ phase shifts

+…

# Enhanced propagation models (Mobile systems)

- Hata-Okumura model
- takes basic model described above and adds correction factors to accommodate effects such as antenna height, terrain, streets etc
  - based on extensive measurements in *urban* environments
  - corrections presented graphically
  - Hata enhanced the model by establishing empirical relationships to describe Okumura's graphical data
- Often taken as empirical 'reference' model
- Adopted with slight variations by ITU-R standard

$$L_{Ur,dB} = 69.55 + 26.16\log f_{MHz} - 13.82\log h_{TX} - a(h_{RX})$$
$$+(44.9 - 6.55\log h_{TX})\log d_{km}$$

Gives median path loss ($L_{ur}$) as a function of
- frequency in MHz ($f_{MHz}$)
- height of the base station in m ($h_{TX}$)
- height of the mobile station in m ($h_{RX}$)
- range in km ($d_{km}$)

Range of validity
$150 < f_{MHz} < 1500$ (MHz)
$30 < h_{TX} < 200$ (m)
$1 < h_{RX} < 10$ (m)
$1 < d < 20$ (km)

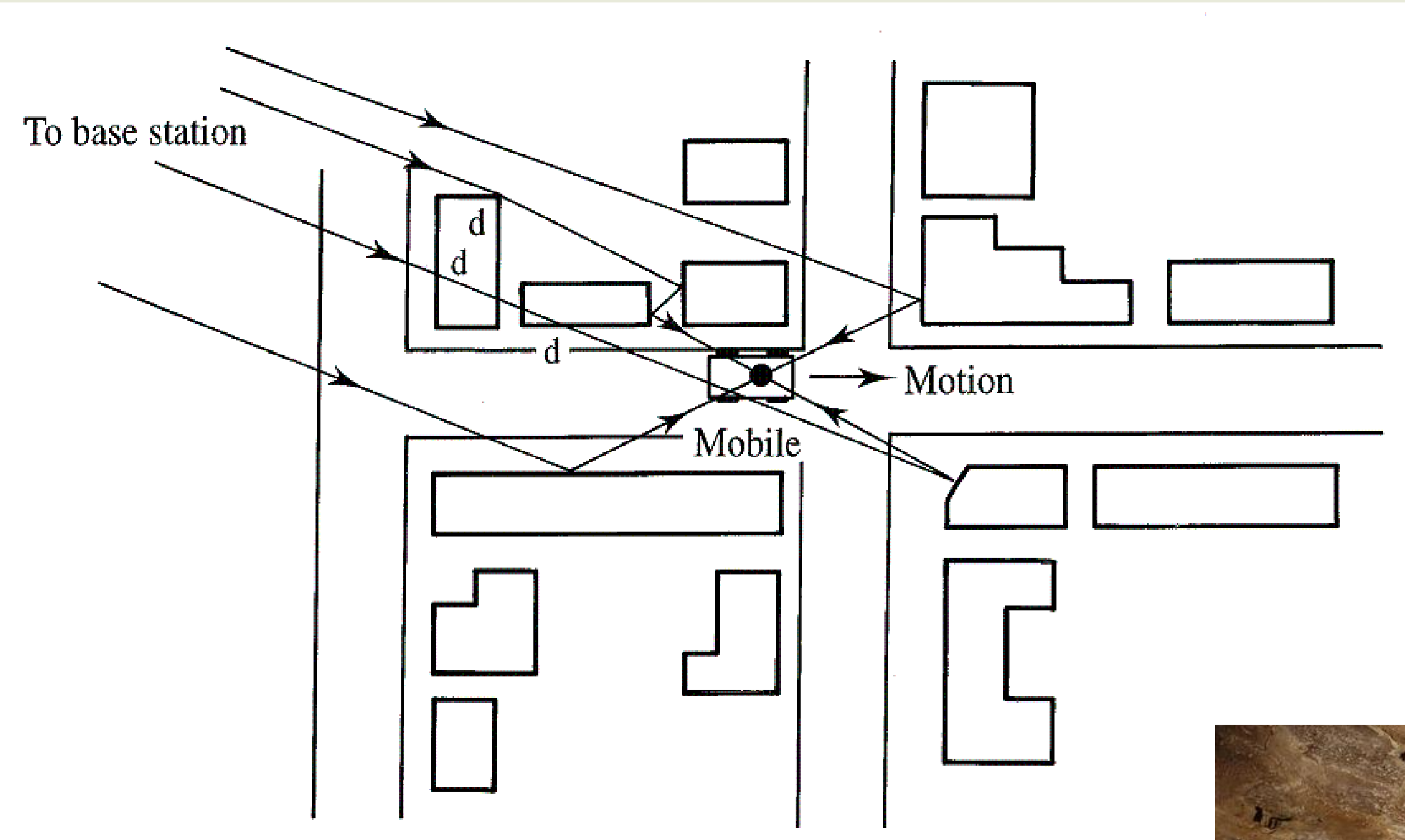
# This Video : Small Scale Propagation

- Multipath
- Channel response
- Frequency Selectivity

# Fading

- Propagation models
  - Large scale propagation models (path loss, rain attenuation etc.)
  - Small scale propagation (fading) models
    - Multi-path induced fading is an issue for small movements/deviations **Rayleigh distribution**
    - Shadowing based fading is an issue over a wider area **log-normal distribution**
    - Indoor multipath has strong line of sight component and follows a **Rician distribution**

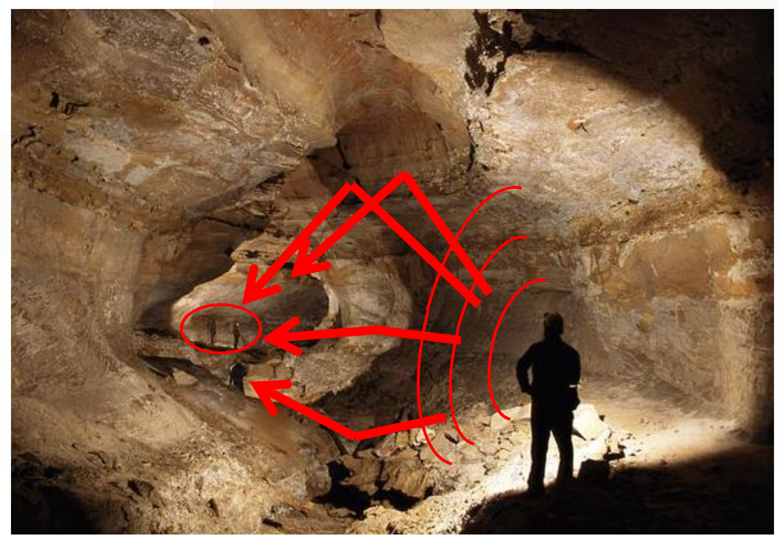
# Urban multipath propagation




d: denotes diffraction

Excess delays up to say 10 μs for flat rural areas

Effect of shouting inside a cave

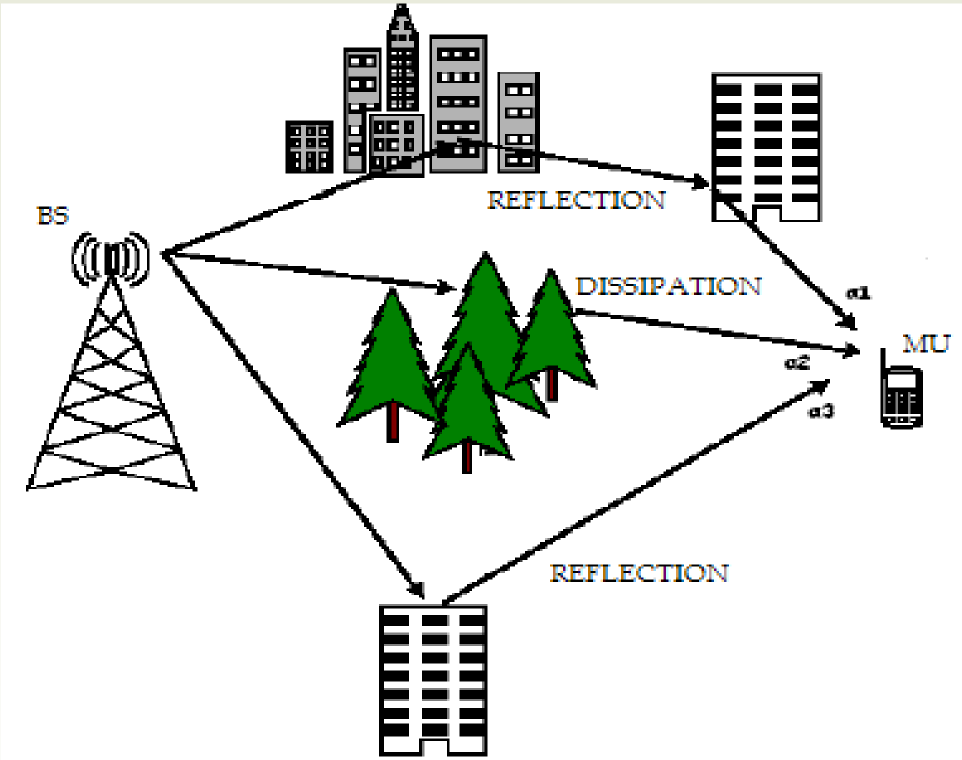


# Fading effects of multipath propagation

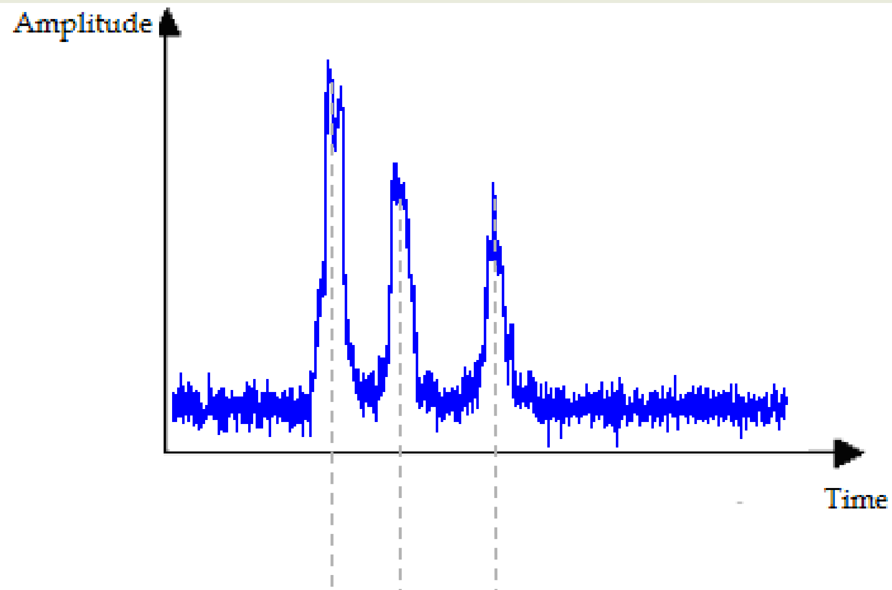
- Spatial fading (~ position)
  - Constructive and destructive interference between signals arising from multiple paths
  - Small-scale or fast fading
- Temporal fading (~ movement)
  - Mobile terminal’s motion through spatially varying field
  - Also movement of scatterers
- Frequency selective fading (~carrier)
  - Some frequencies will be faded more than others if signals are broadband

# The Multipath Channel

Typical urban multipath channel




Channel impulse response




Hi! my name is Chris

Hi! my name is Chris

\+ Hi! my name is Chris

---

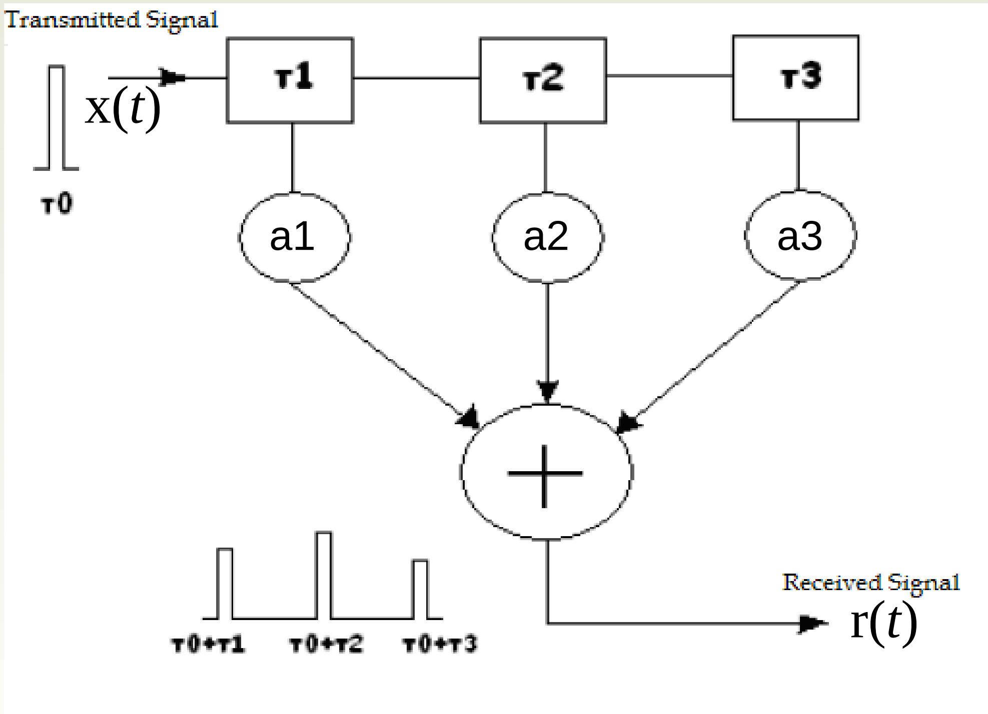
Hi! my name is Chris Hi! my name is Chris Hi! my name is Chris

ISI

Inter-Symbol Interference (ISI) because each symbol leaves its “echo” in the following symbols

# Multipath Channel Mathematical Model

Channel model – tap delay line

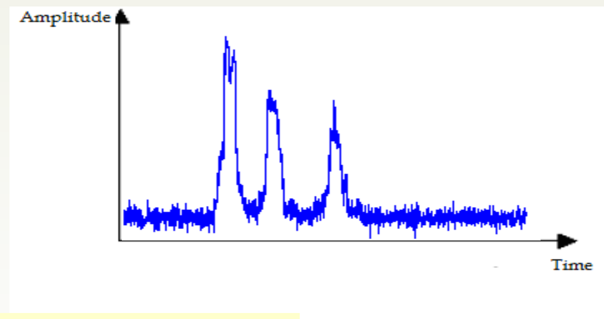



$x(t)$: transmitted

$\tau_i$ : delay of path $i$

$a_p$: coefficient of channel path $p$

$r(t)$: received



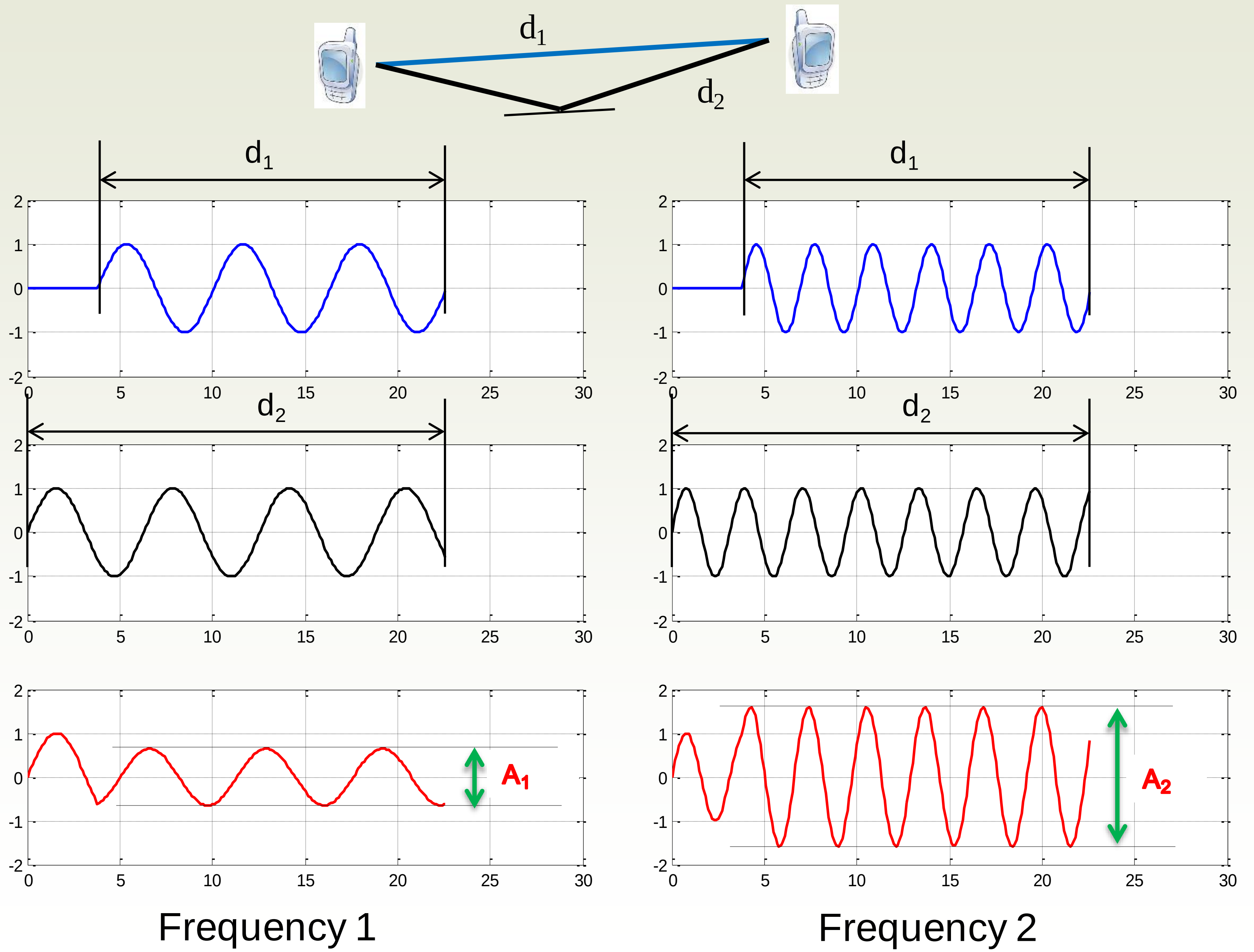

$$h(t) = \alpha_1\delta(t-\tau_1) + \alpha_2\delta(t-\tau_2) + \alpha_3\delta(t-\tau_3)$$

$$\boxed{r(t) = a_1x(t-\tau_1) + a_2x(t-\tau_2) + a_3x(t-\tau_3)} = h(t) \otimes x(t)$$

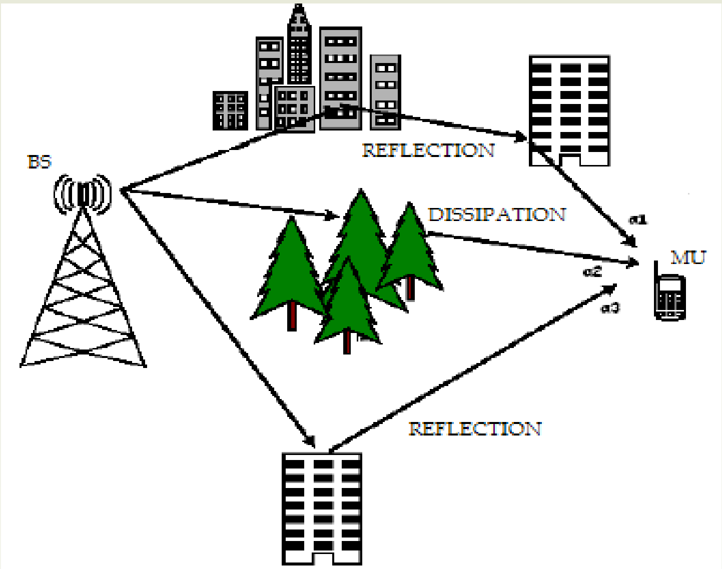
Desired

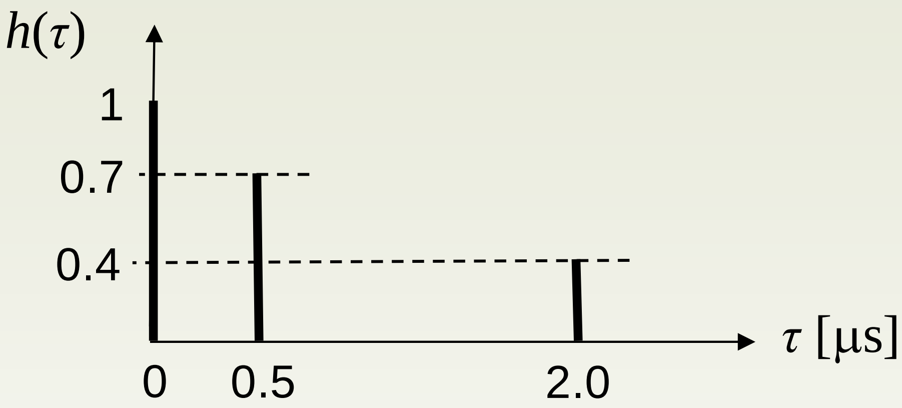
ISI

# Where does the frequency selectivity come from??



# Where does the frequency selectivity come from??



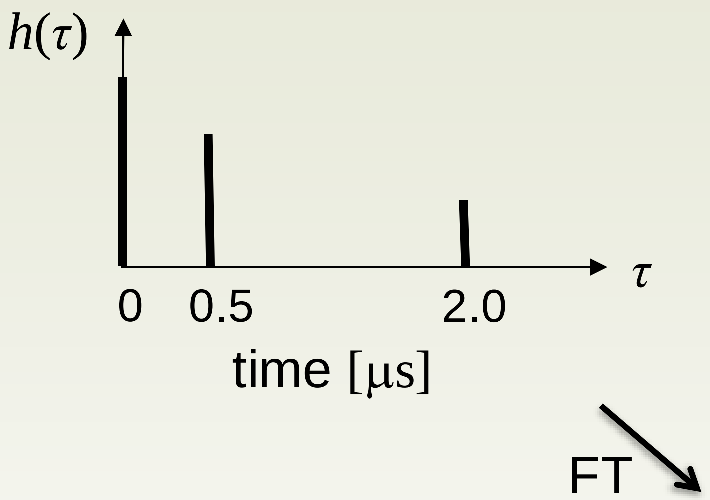

- Three ray channel with impulse response:

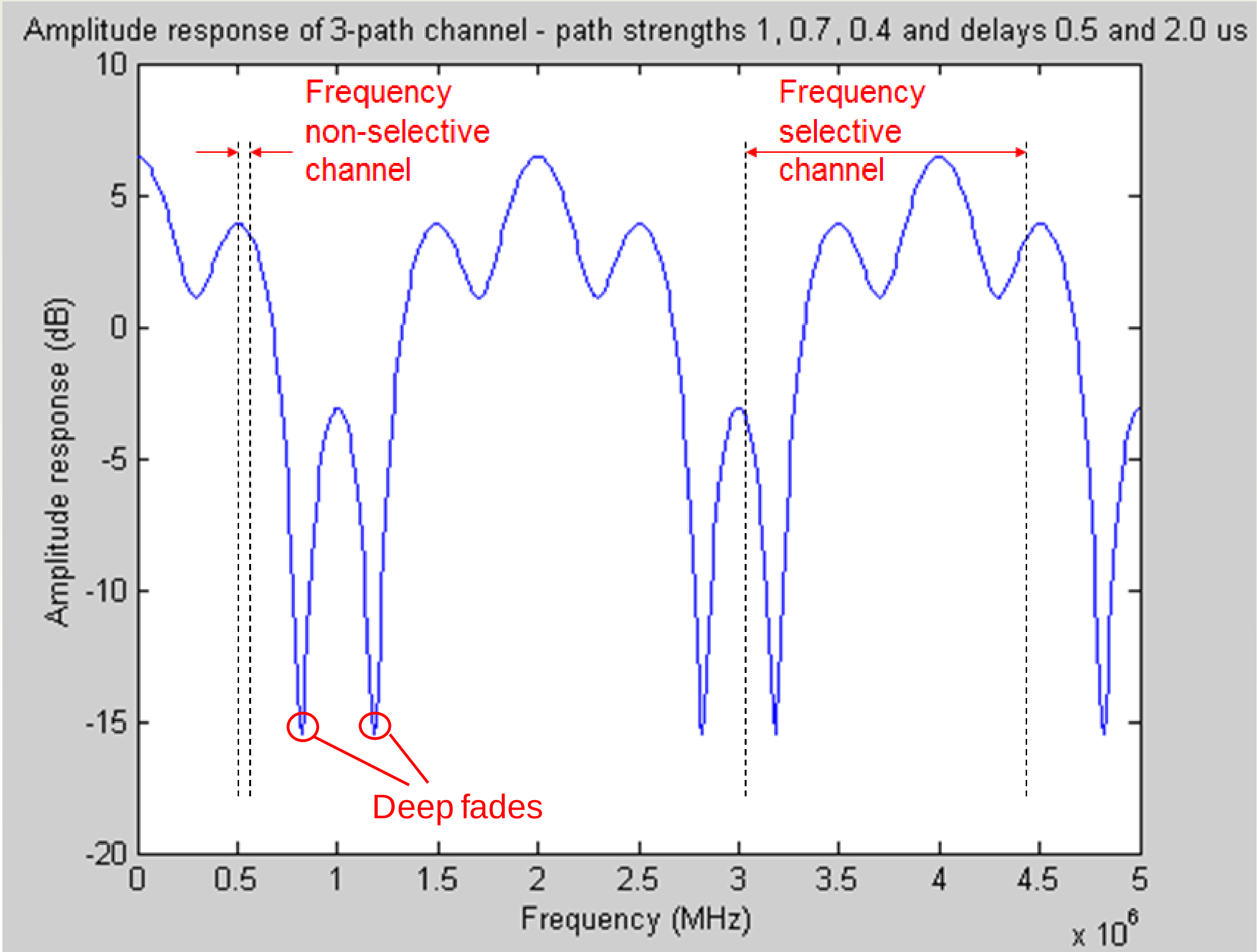
$$h(\tau) = 1\delta(\tau) + 0.7\delta(\tau - 0.5 \times 10^{-6}) + 0.4\delta(\tau - 2.0 \times 10^{-6})$$

- Has the frequency response:

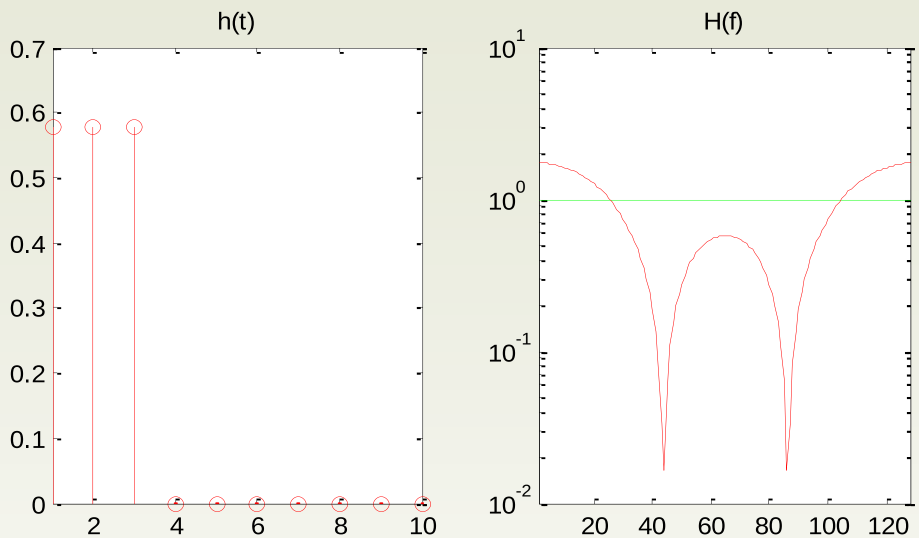
$$H(f) = 1 + 0.7e^{-j2\pi 0.5\times 10^{-6} f} + 0.4e^{-j2\pi 2.0\times 10^{-6} f}$$

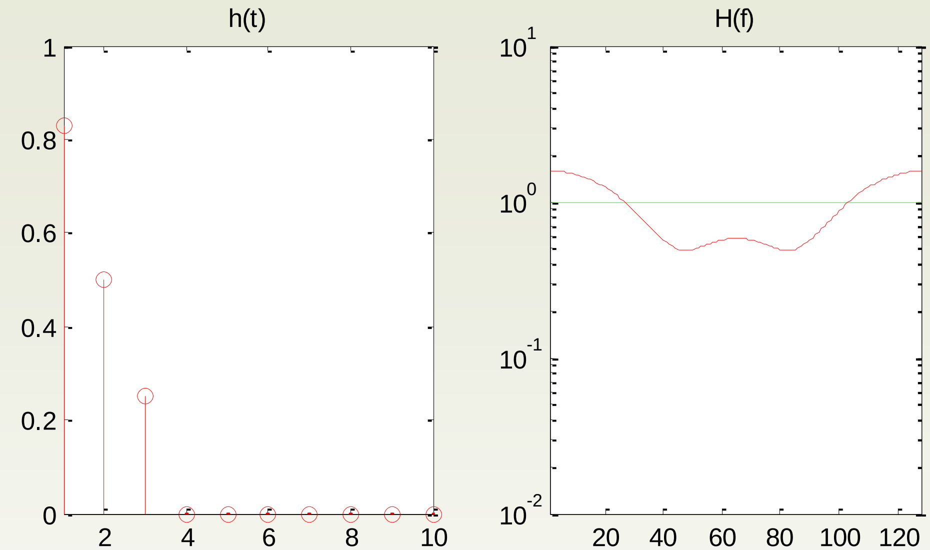
# Three-path example

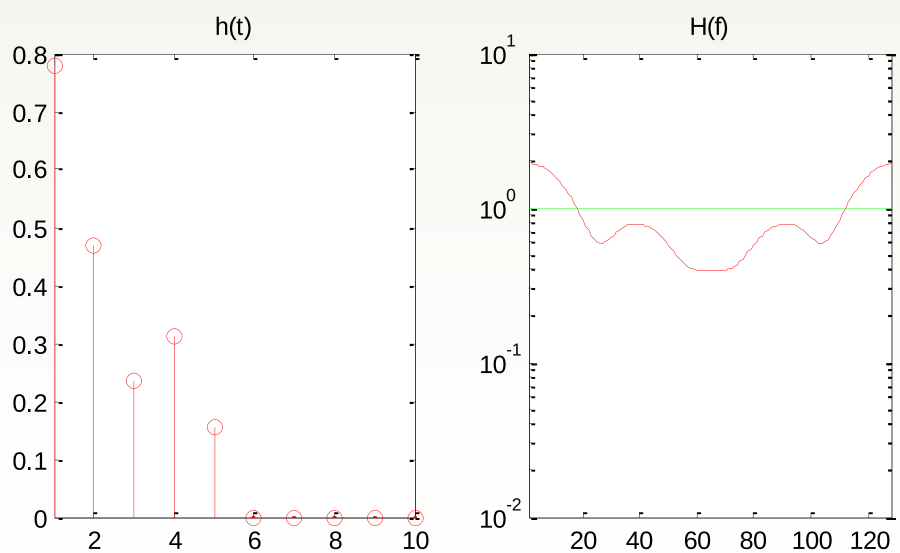


# More multi-path examples (channel power = 1 for all)



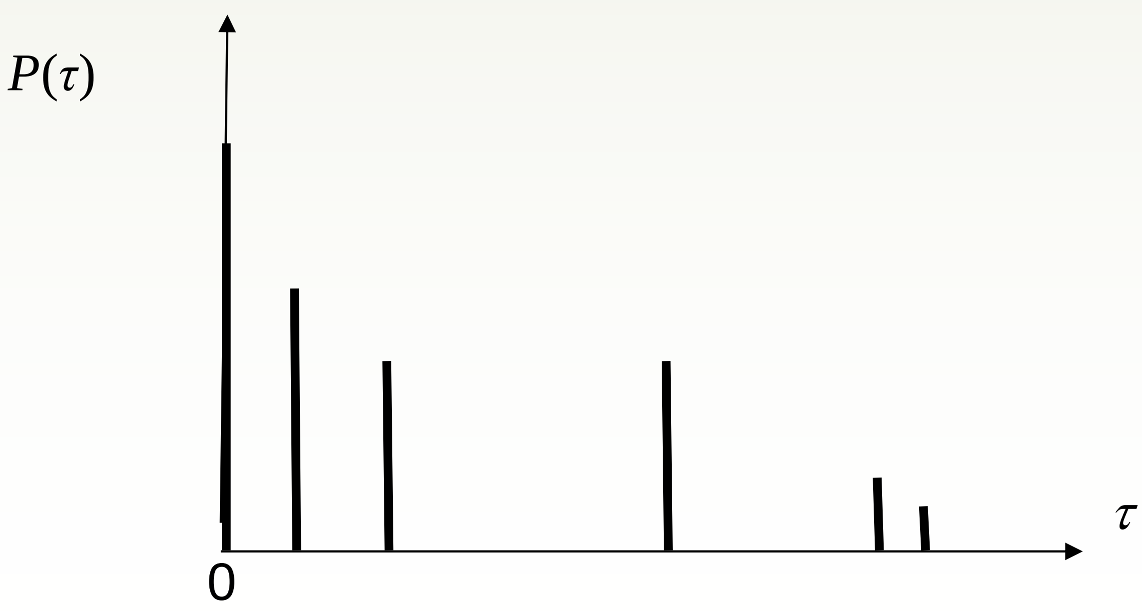

⇧ #paths → ⇧ variation

More equally distributed path power → deeper fades

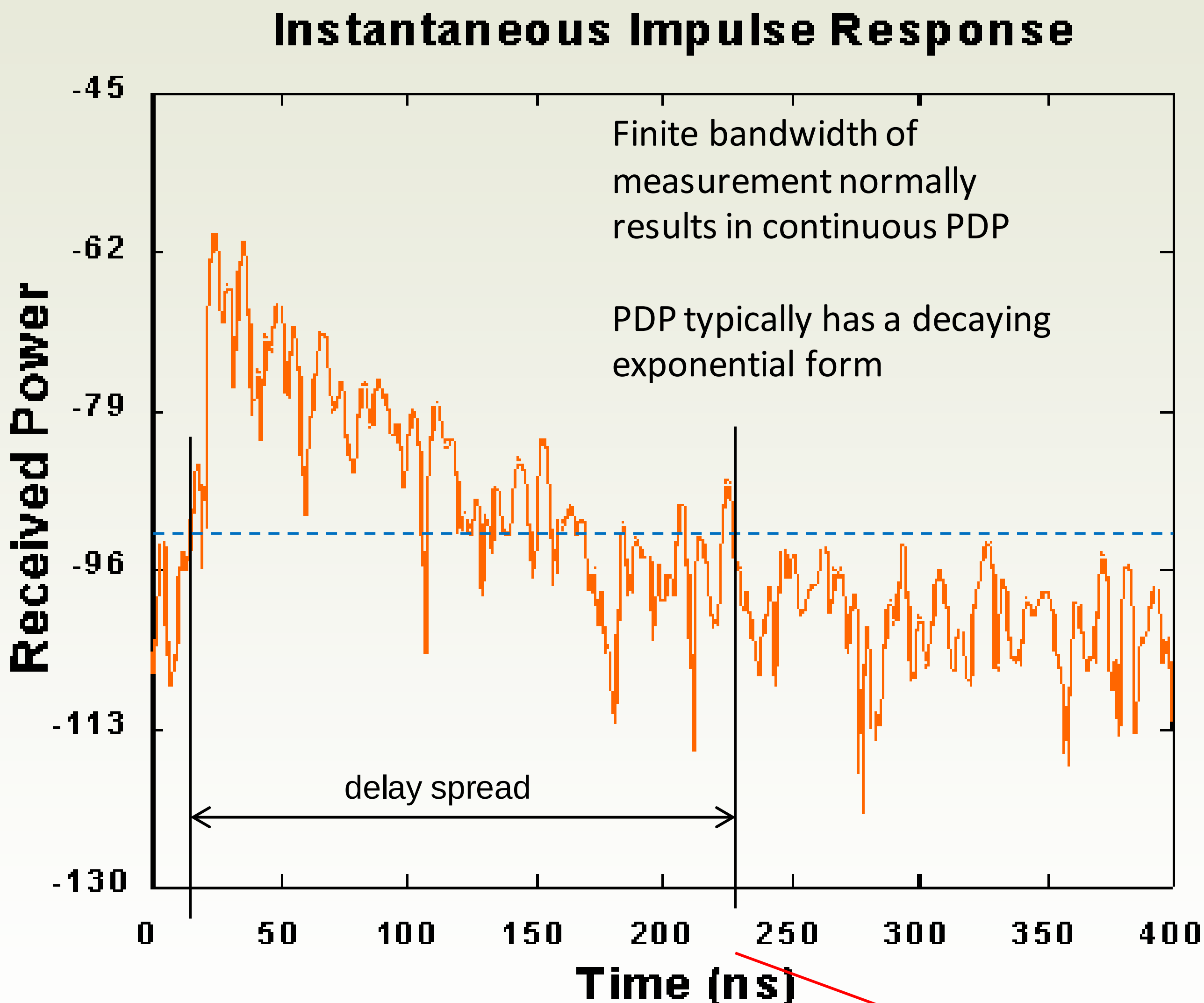
## Power delay profile (PDP)

- Power received via the path with excess time delay $\tau_i$ is the value (height) of the discrete PDP component at $t_i$

$$P(\tau) \propto |h(\tau)|^2$$



# Example indoor PDP measurement




~0.23μs – is this important?

## Typical RMS delay spreads

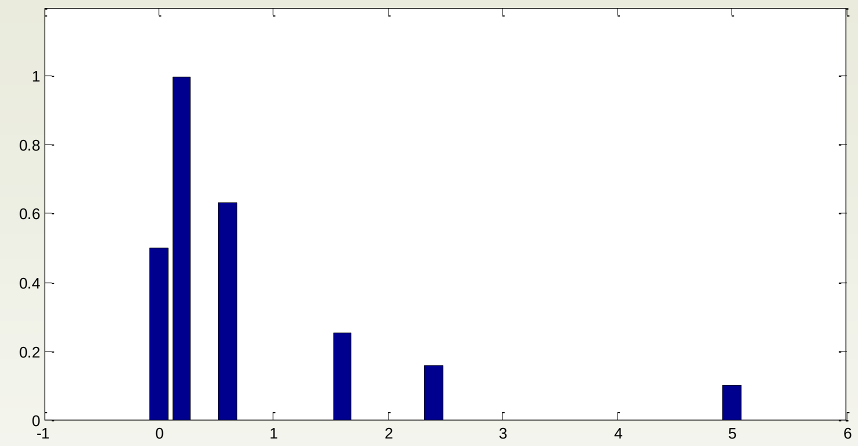
| Environment | RMS delay spread (μs) |
|---|---|
| Indoor cell | 0.01 – 0.05 |
| Satellite mobile | 0.04 – 0.05 |
| Open area (rural) | < 0.2 |
| Suburban macrocell | < 1 |
| Urban macrocell | 1 – 3 |
| Hilly macrocell | 3 – 10 |

Delay spread (echoing time) ≠ propagation delay (time it takes for signal to travel)

# 6-tap outdoor urban model (COST 207) for 900 MHz

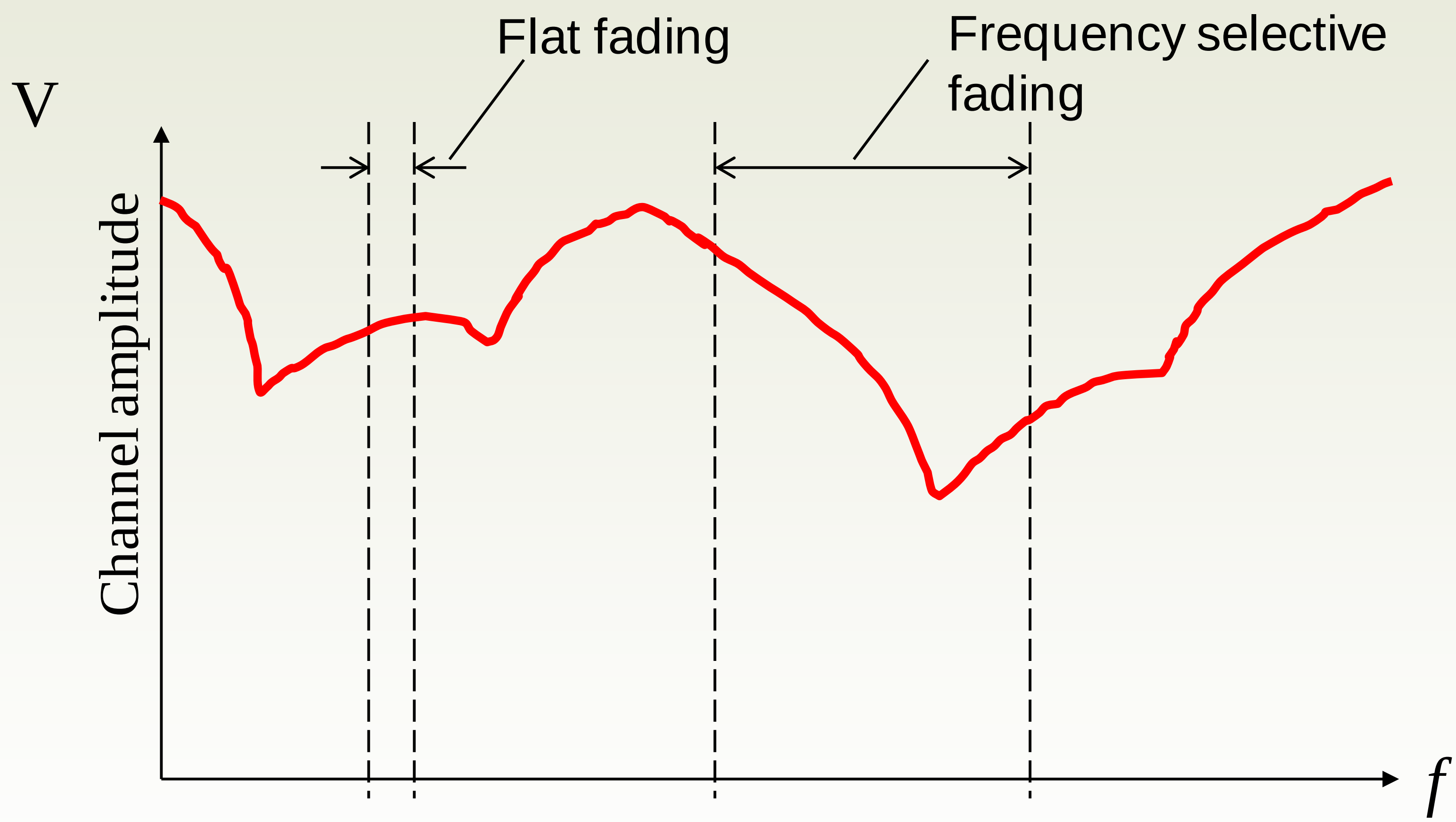
from COST 207 Management Committee: *Digital land mobile radio communications*, Final Report of COST Action 207, Office for Official Publications of the European Communities, 1989.

| Tap no. | Delay ($\mu$s) | Average power level (dB) |
|---|---|---|
| 1 | 0 | -3 |
| 2 | 0.2 | 0 |
| 3 | 0.6 | -2 |
| 4 | 1.6 | -6 |
| 5 | 2.4 | -8 |
| 6 | 5.0 | -10 |




1. Short (direct) path assumed shadowed, therefore 2nd path is strongest
2. Uneven spacing of taps (can be realised in equal spacing implementation) by setting intermediate tap weights to zero
3. A more sophisticated version of this model uses 12 taps

# Frequency selective fading

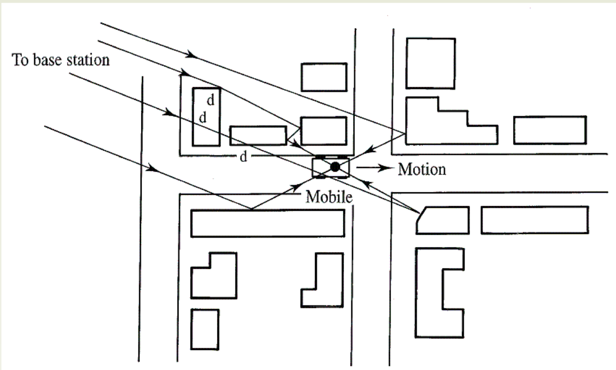


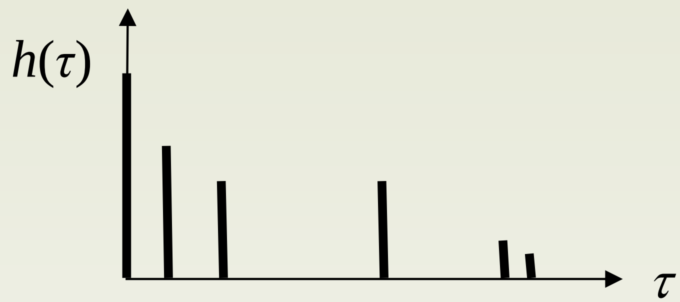

Frequency selective: When the amplitude of the channel response varies significantly ( > 3dB ) within the signal bandwidth

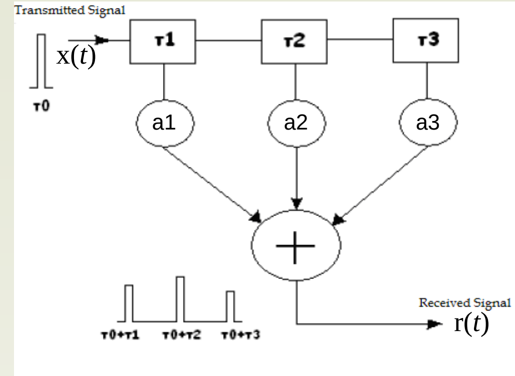
# This Video : Small Scale Propagation

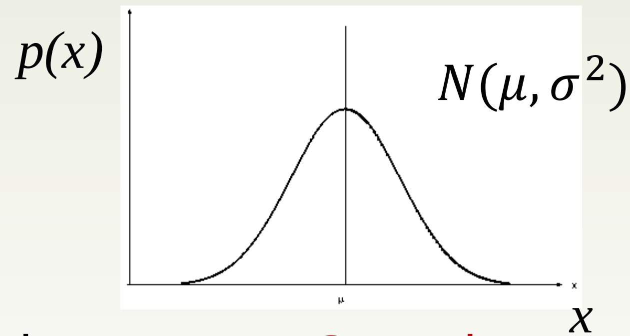
- Rayleigh-Rice distribution
- Doppler effect

# Rayleigh fading model – rich multipath



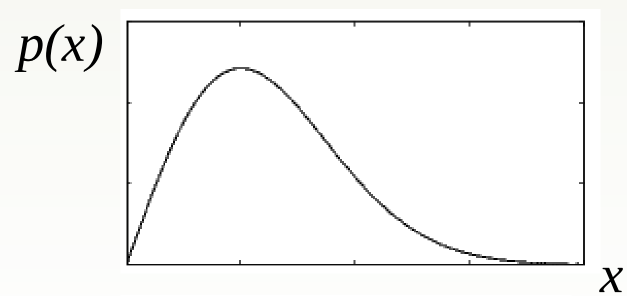




Gain of each arriving path: $\tilde{a}_k = a_k e^{j\theta_k} = a_k^I + j a_k^Q$

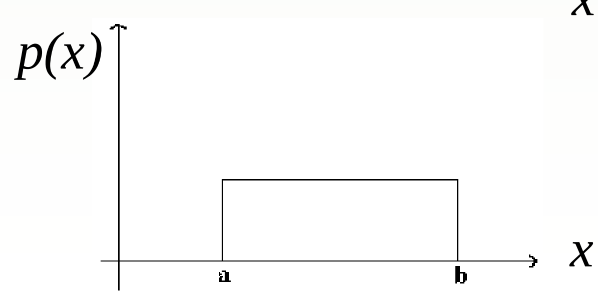
- I and Q components are statistically independent and zero-mean Gaussian distributed
- Then, amplitude is Rayleigh distributed

$$a_k = \sqrt{{a_k^I}^2 + {a_k^Q}^2}$$




- Phase is uniformly distributed

$$\theta_k = \tan^{-1}\left(\frac{a_k^Q}{a_k^I}\right)$$



# Ricean channel – strong LOS

- One path dominates
- Pdf of signal envelope is Ricean
- Rayleigh channel + one stronger (often LOS) signal
- Rice-factor, *k*, is defined by:

$$k = \frac{\text{Power of constant (LOS) component}}{\text{Power of random (Rayleigh) component}} = \frac{s^2}{2\sigma^2}$$

where *s* is amplitude of the constant component and $\sigma$ is RMS amplitude of *either* inphase *or* quadrature part of the random component

- Comes from I and Q components that are statistically independent and Gaussian with **non-zero** means

$$\widetilde{a}_k = a_k e^{j\theta_k} = a_k^I + j a_k^Q$$

# DOPPLER EFFECT

# Doppler shift from obliquely incident ray

Observed frequency can be thought of as the rate at which a mobile terminal crosses the arriving wavefronts

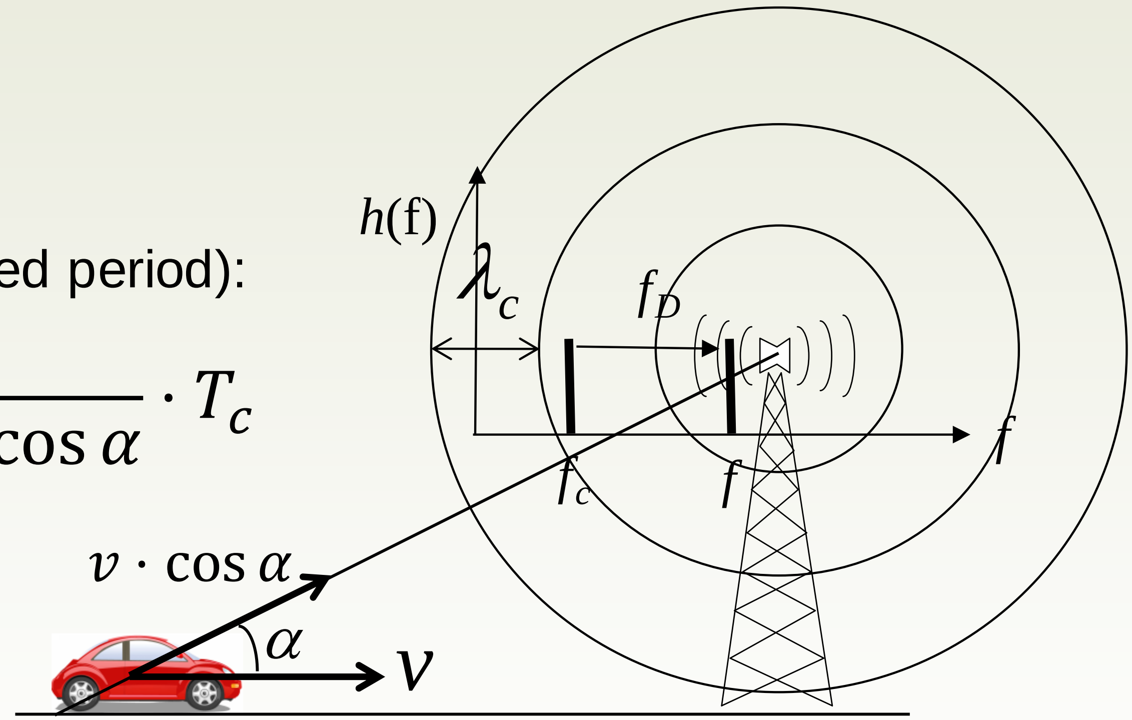
Carrier period: $T_c = \frac{\lambda_c}{c}$

Time between wavefronts (observed period):

$$t = \frac{\lambda_c}{c + v \cdot \cos\alpha} = \frac{c}{c + v \cdot \cos\alpha} \cdot T_c$$

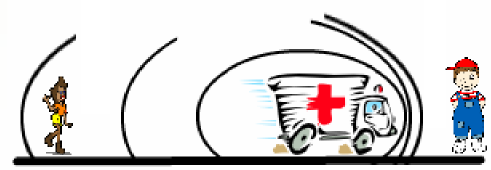
Observed frequency:

$$f = f_c \cdot \frac{c + v \cdot \cos\alpha}{c}$$

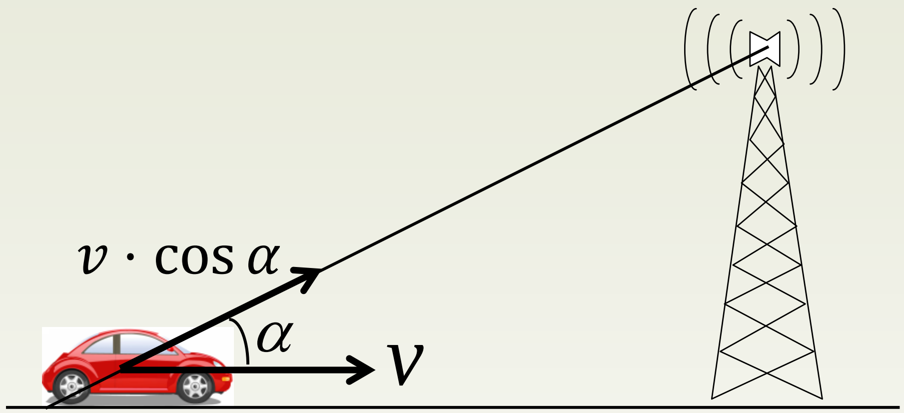


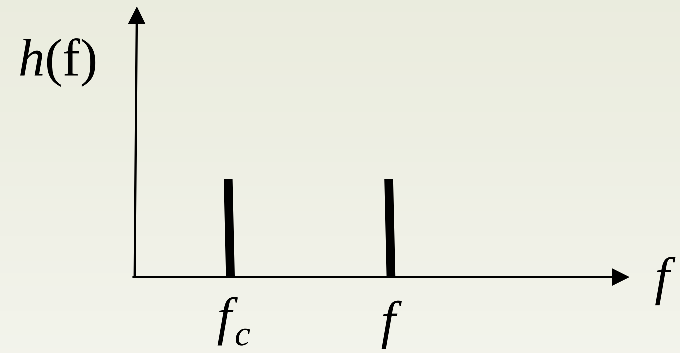

Doppler shift (frequency shift):

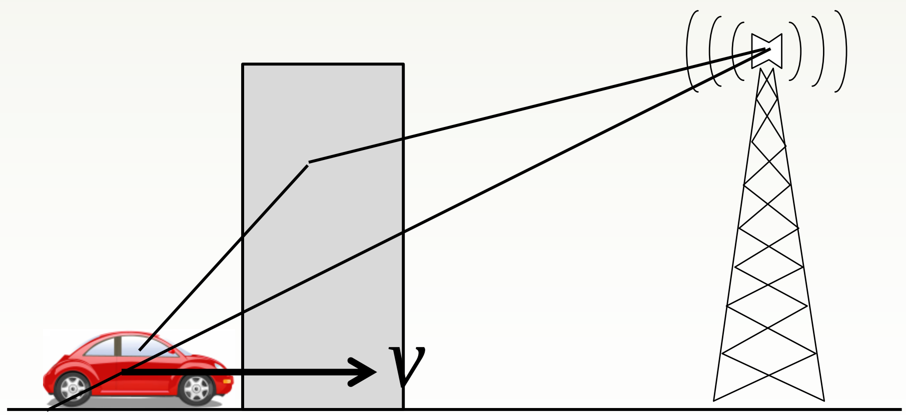
$$f_D = \Delta f = f - f_c = f_c \cdot \frac{v}{c} \cos\alpha$$

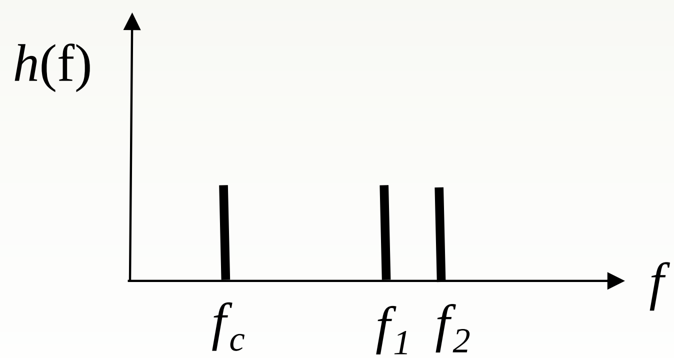


# Doppler shift from obliquely incident ray



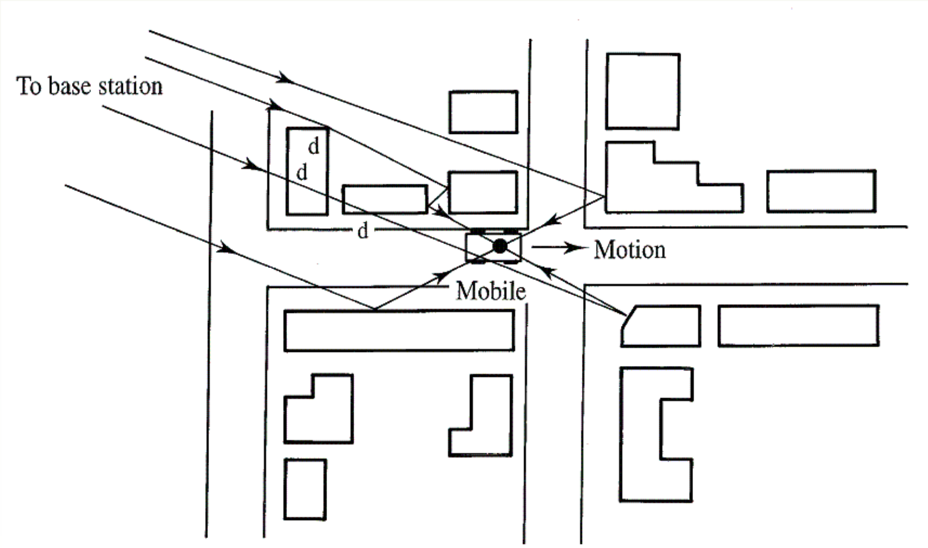



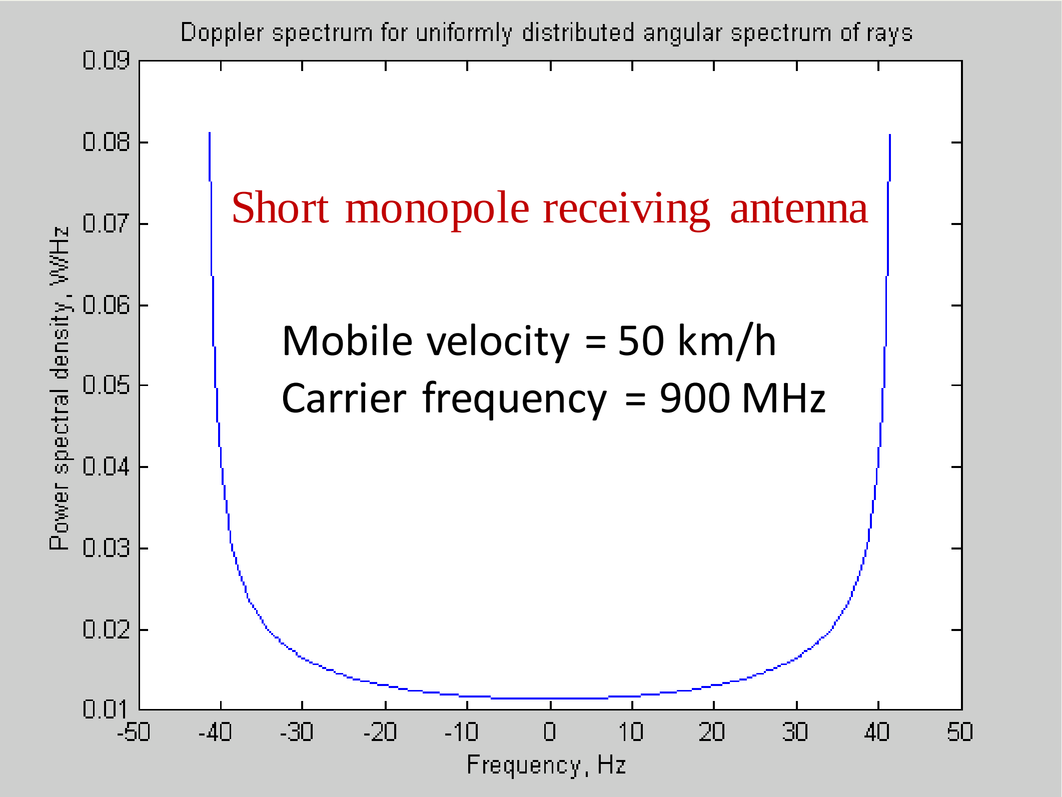
# Doppler spectrum

In a multipath with many arriving rays, with uniformly distributed random angles of arrival α, a number of frequency shifted waveforms arrive, with random frequency shifts

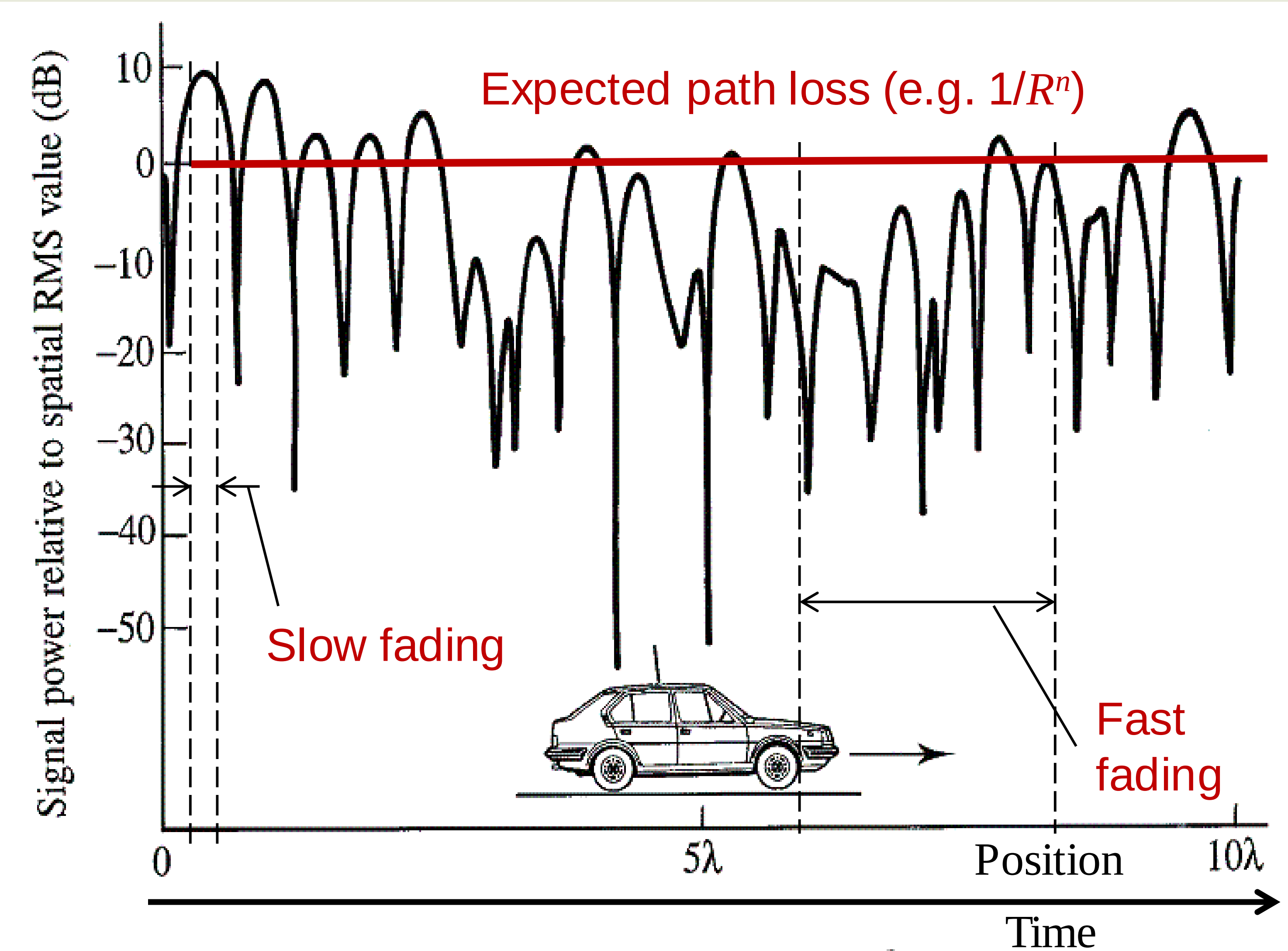
Typical received frequency spectrum, for a transmission of a sinewave (a single frequency):

$$f_{\max} = \pm \max f_c \frac{v}{c} cos\alpha = \pm f_c \frac{v}{c}$$



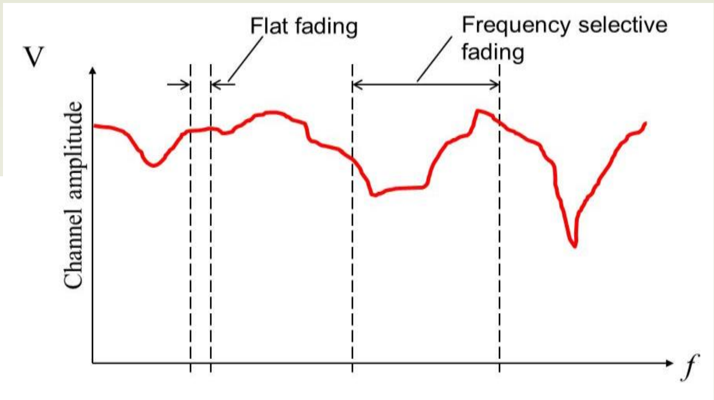
# Time-Varying multipath fading





* Fixed range from transmitter *R*

# 4 types of fading

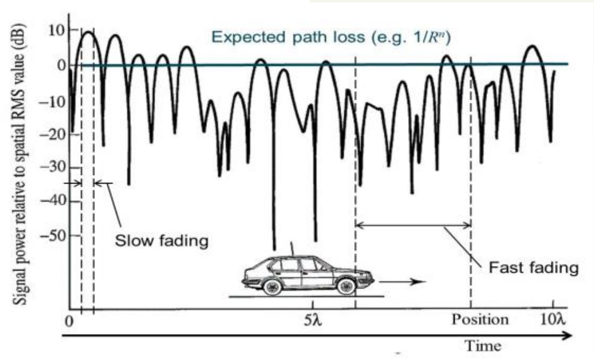



**Small-Scale Fading**
(Based on multipath time delay spread)

Frequency variability

**Flat Fading**
1. BW of signal < BW of channel
2. Delay spread < Symbol period

**Frequency Selective Fading**
1. BW of signal > BW of channel
2. Delay spread > Symbol period



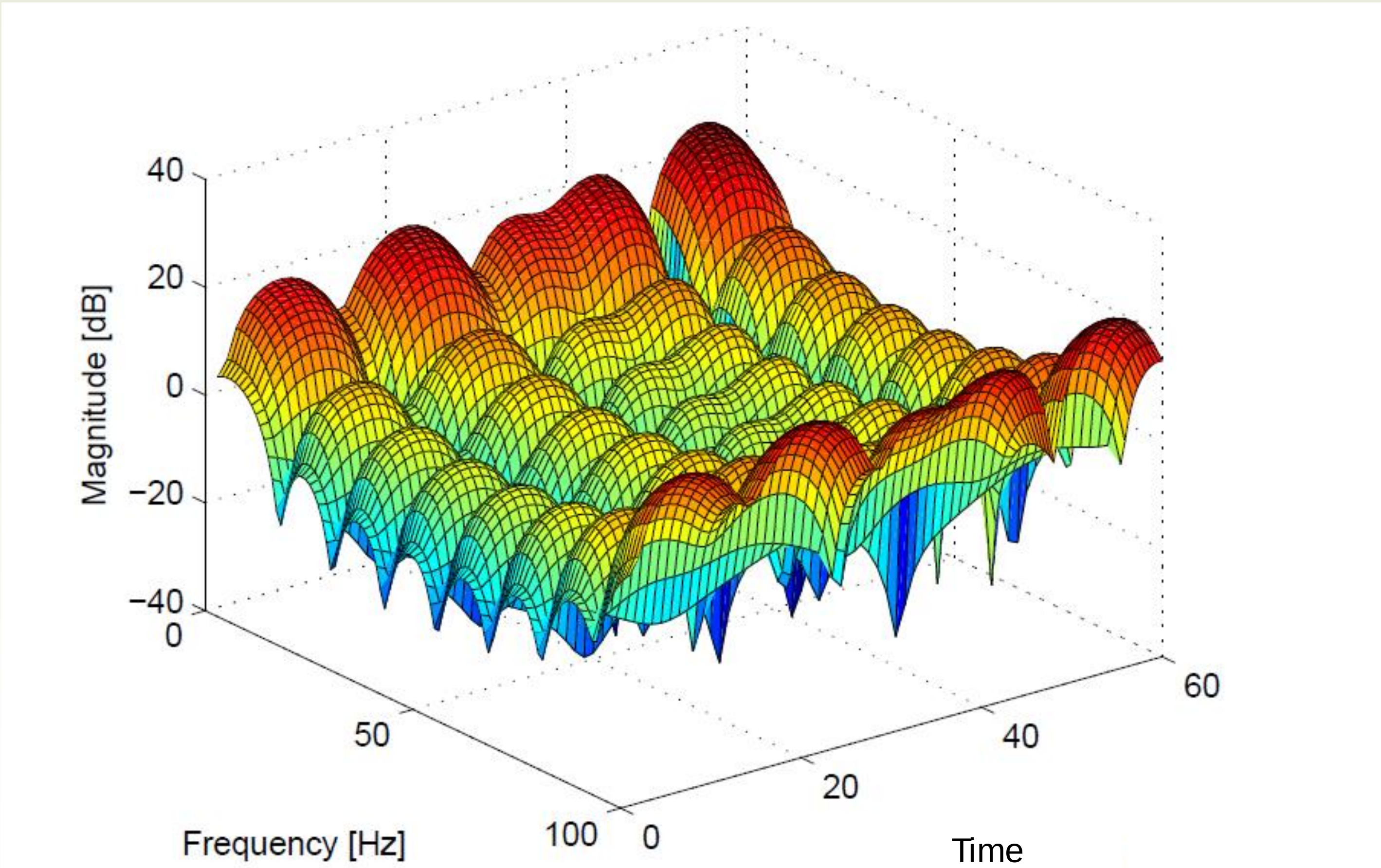

**Small-Scale Fading**
(Based on Doppler spread)

Time variability

**Fast Fading**
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than base-band signal variations

**Slow Fading**
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

# The mobile channel is time varying and frequency dependent



# This Video : Link budget

- Receive power
- Noise power
- SNR

# Link budget calculation

- Using the path loss formula we can easily calculate the received signal strength at a receiver (in dBx)

$$P_{RX} = P_{TX} - L_{dB} + G_{TX} + G_{RX} + 10\log_{10}\eta_{TX} + 10\log_{10}\eta_{RX}$$

- For example, if we have :
  - a LOS path of length of 2 km,
  - a 10W - 1 GHz transmitter,
  - a TX antenna gain of 10 dB and a RX antenna gain of 12dB and
  - 50% coupling efficiency at both ends,
- then the received power is…? -72 dBW (-42 dBm) [0.000063 mW]

FSPL: $$L_{dB} = 20\log_{10} f_{MHz} + 20\log_{10} d_{km} + 32.44$$

# Noise

- Thermal noise: produced by random motion of electrons (small random currents)

$$P_n = kTB = N_0 B$$

*k:* Boltzmann's Constant, (= 1.38 x $10^{-23}$ Joule/Kelvin )
T: temperature in Kelvin (0°C = 273 K)
B: Bandwidth
$N_0$: Noise power spectral density

- Noise Figure: measure of degradation of the signal-to-noise ratio (SNR), caused by components in an RF signal chain.

$$F = \frac{\text{Actual output noise power}}{\text{Output noise power if device is noiseless}} = \frac{\text{Actual output noise power}}{\text{Device Gain} \times \text{Input noise power}}$$

A measure of the amplification of noise through the RF components

$$P_n^{total} = P_n F$$

# SNR calculations

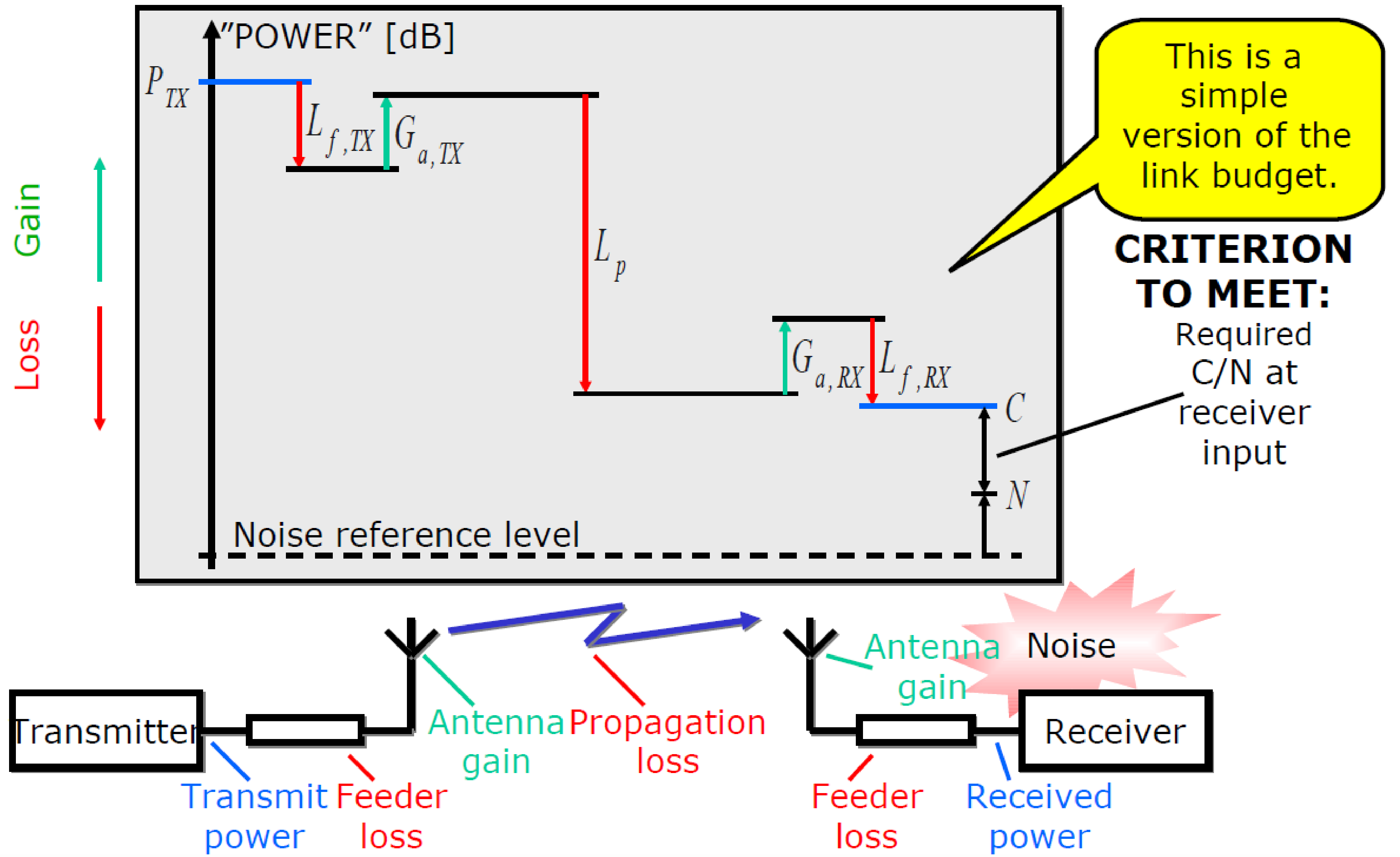
- It is relatively easy to extend the above to calculate a SNR at the receiver - this can then be used to predict BER for a digital system

$$SNR_{dB} = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right) = P_{RX} - F_{dB} - 10\log_{10}(kTB)$$

- As an example, consider the above system where the power at the RX was -72 dBW, if the system had a bandwidth of 500 MHz, a NF of 5 dB and was operating at a room temperature (27°C) the SNR would be 40 dB

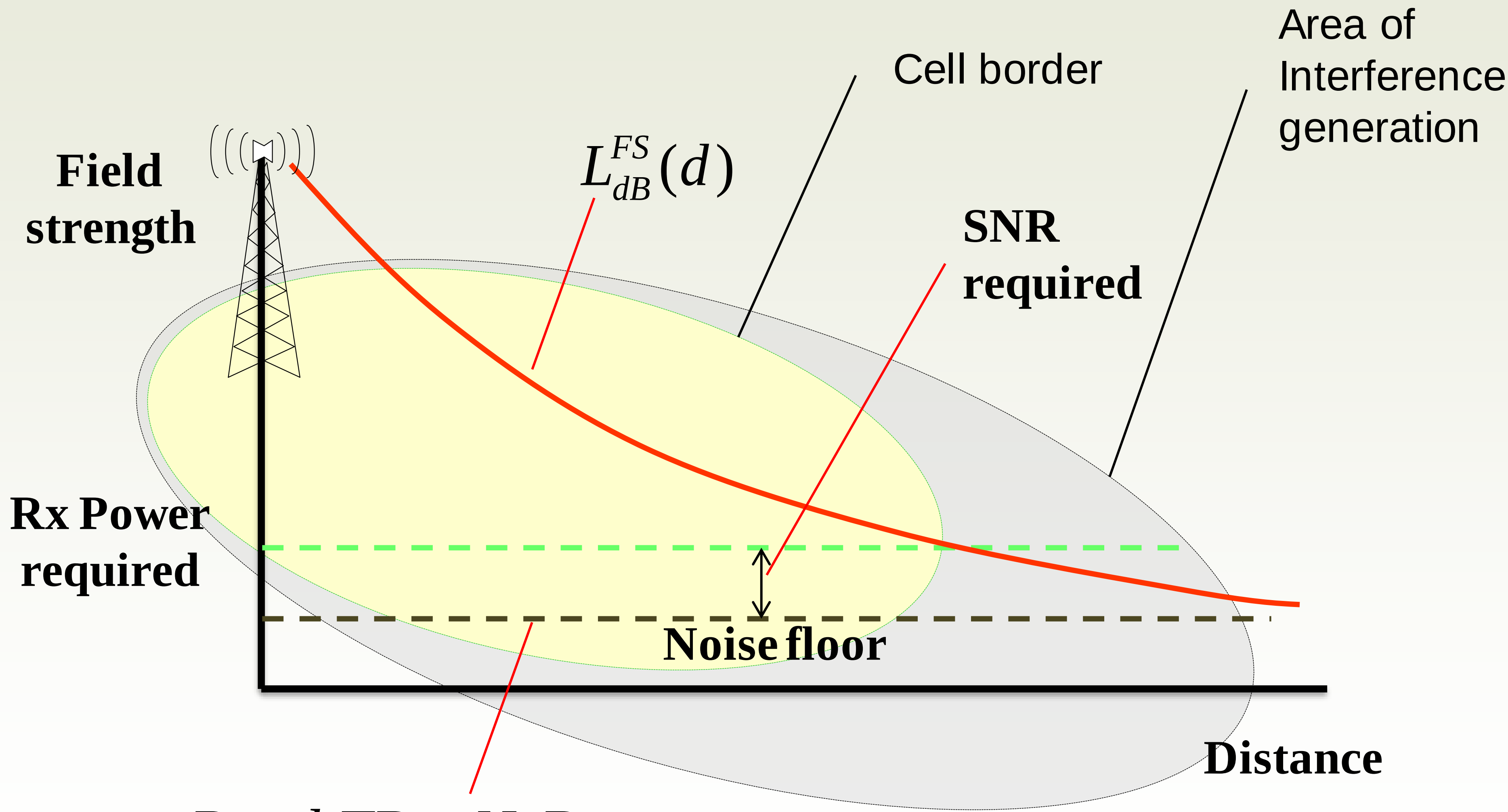
*k:* Boltzmann's Constant, (= $1.38 \times 10^{-23}$ Joule/Kelvin )
T: temperature in Kelvin (0°C = 273 K)
B: Bandwidth (in Hz)

# Link Power Budget Summary




$$P_{RX} = P_{TX} + 10\log_{10}\eta_{TX} + G_{TX} - L_{dB} + G_{RX} + 10\log_{10}\eta_{RX}$$

# Noise limited service area




$$P_n = kTB = N_0 B$$

# Summary

- Looked at the basic ideas behind radio propagation
- Seen how signal strength may vary and factors for such variation
- Looked at the causes and effects of fading
- Calculation of link budget

# Next

- RF equipment
- Baseband processing
- SNR $\longrightarrow$ Probability of error
- Modulation tradeoffs
- MIMO, Satellite Comms