

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 \rightarrow Receive SNR

RF System Design

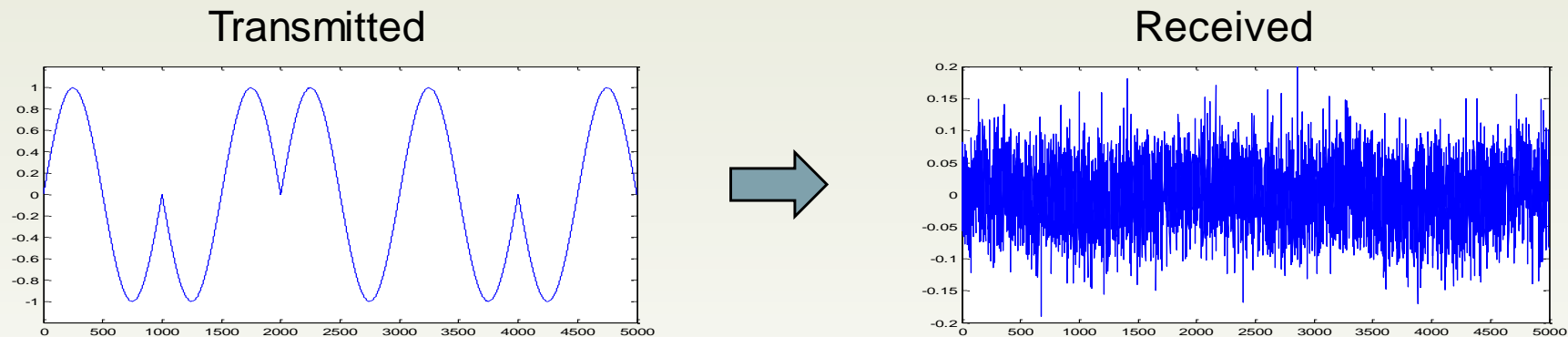
- RF components
- Baseband processing and Channel Estimation
- SNR \rightarrow Link Performance (Probability of error)
- Modulation tradeoffs – Spectral/Power Efficiency
- MIMO, Satellite Comms

This Video : Large Scale Propagation

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

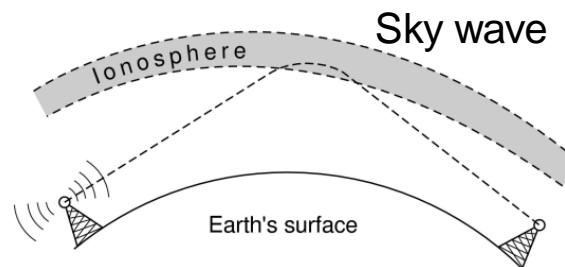
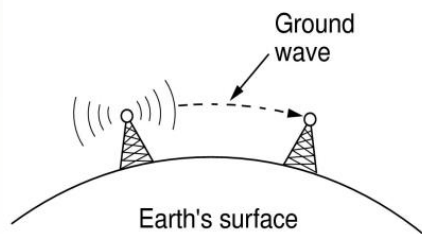
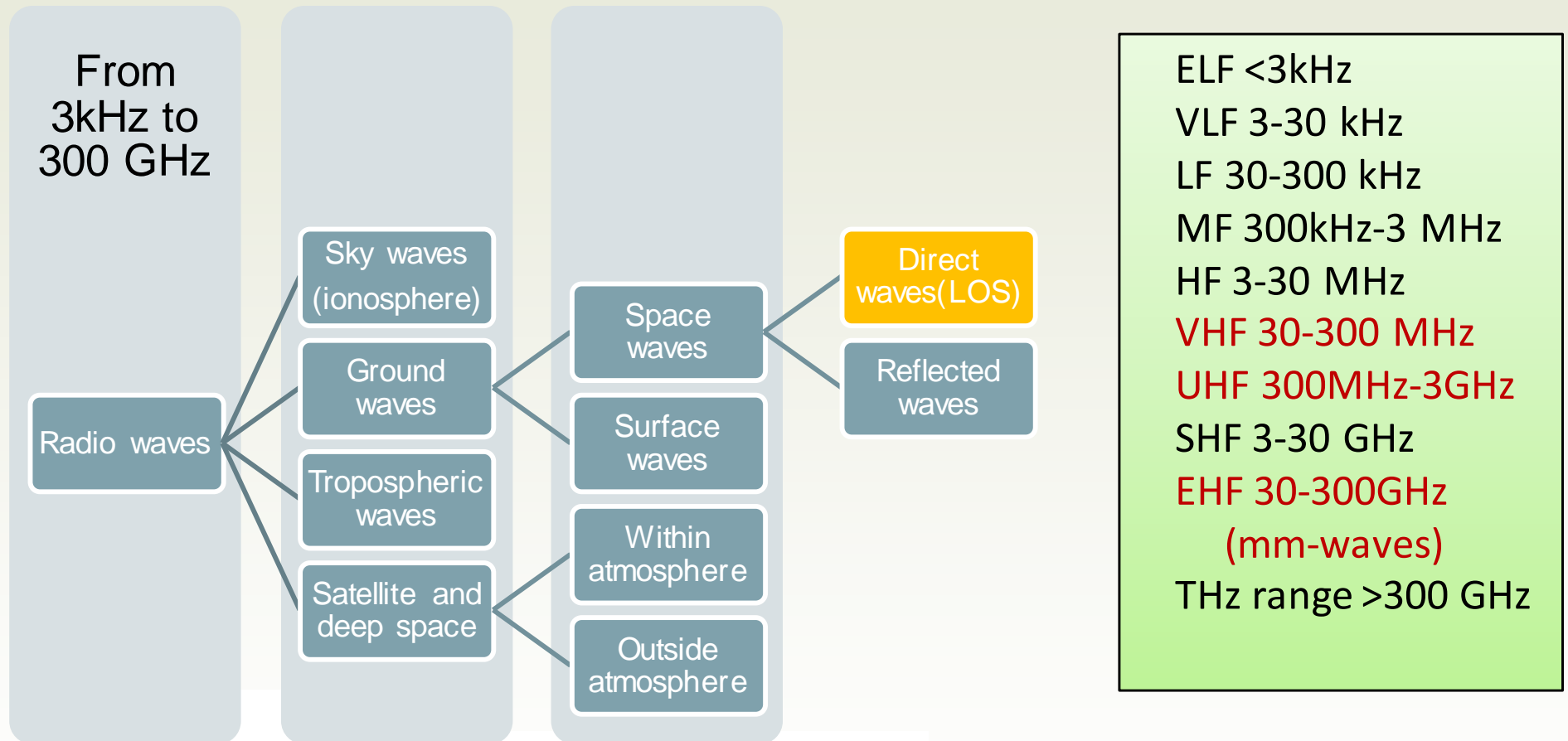
The radio channel

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



- 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.

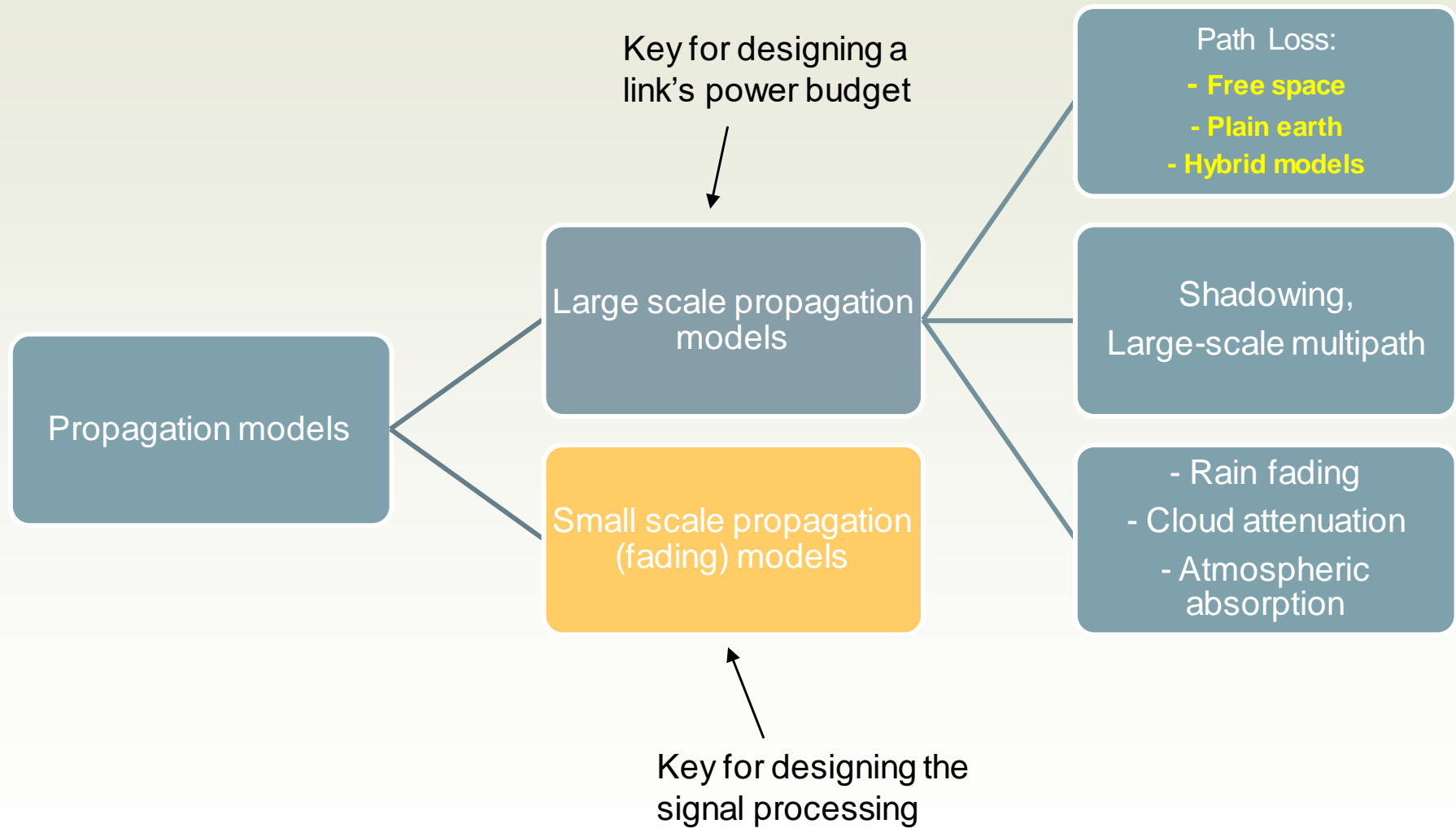
Radio propagation modes and frequencies



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

LTE bands within 700 MHz - 3.8 GHz
 WiFi, BlueTooth: 2.4 GHz (5 GHz)

Fading



LARGE SCALE PROPAGATION: ANTENNA GAIN – PATH LOSS

Antenna Directivity

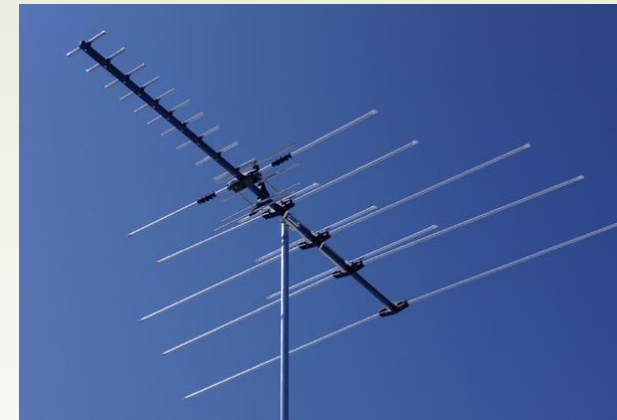
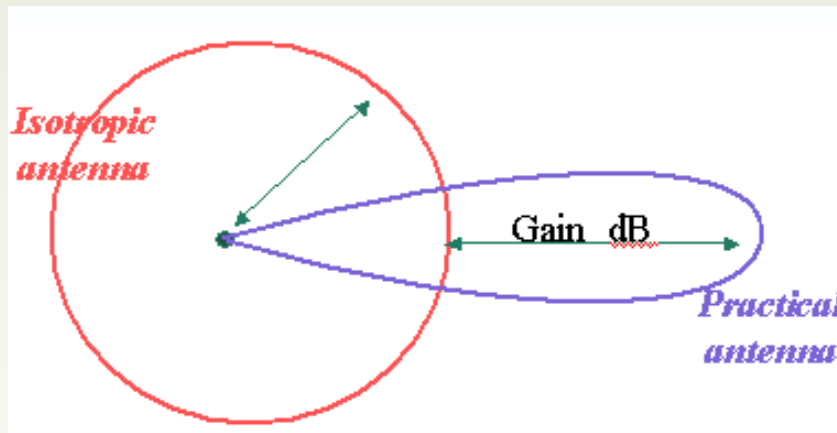
Transmit
Directivity



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:

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

η : antenna ohmic efficiency

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

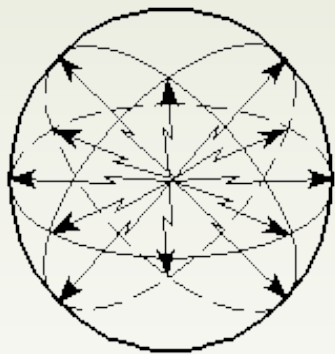


Antenna radiation pattern

Directivity \rightarrow Gain

Power flux density (P_D) W/m^2

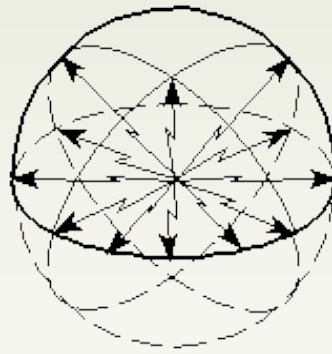
(a) SPHERE (Isotropic source)



$$P_D = \frac{P_{in}}{4 \pi R^2}$$

$$G = 0 \text{ dB}$$

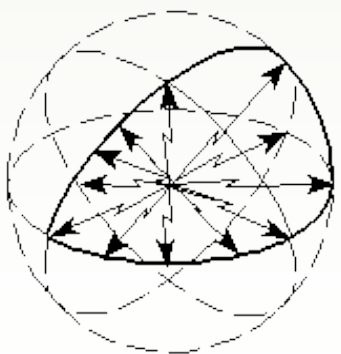
(b) HEMISPHERE



$$P_D = \frac{2 P_{in}}{4 \pi R^2}$$

$$G = +3 \text{ dB}$$

(c) QUARTER SPHERE

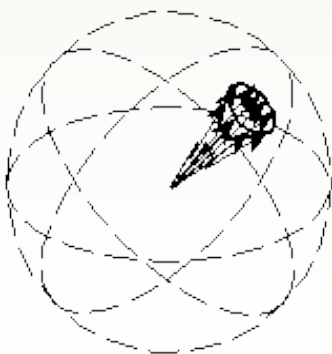


$$P_D = \frac{4 P_{in}}{4 \pi R^2}$$

$$G = +6 \text{ dB}$$

$10 \cdot \log_{10}(P)$

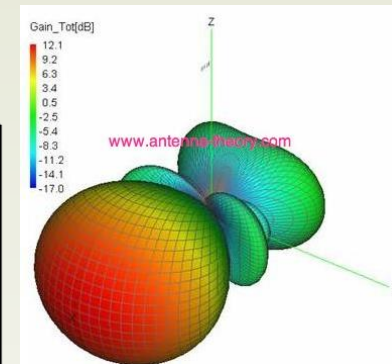
(d) 1.5° SEGMENT



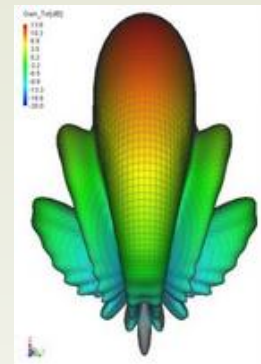
$$P_D = \frac{18334 P_{in}}{4 \pi R^2}$$

$$G = +43 \text{ dB}$$

Yagi-Uda



Horn antenna



Satellite dish

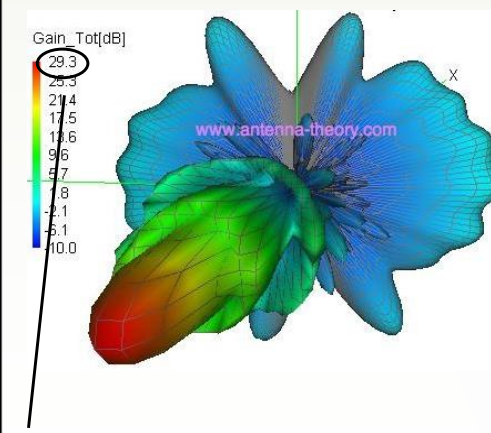


Figure 2. Antenna Gain

$\sim 30\text{dB} \rightarrow \times 1000$ 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

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

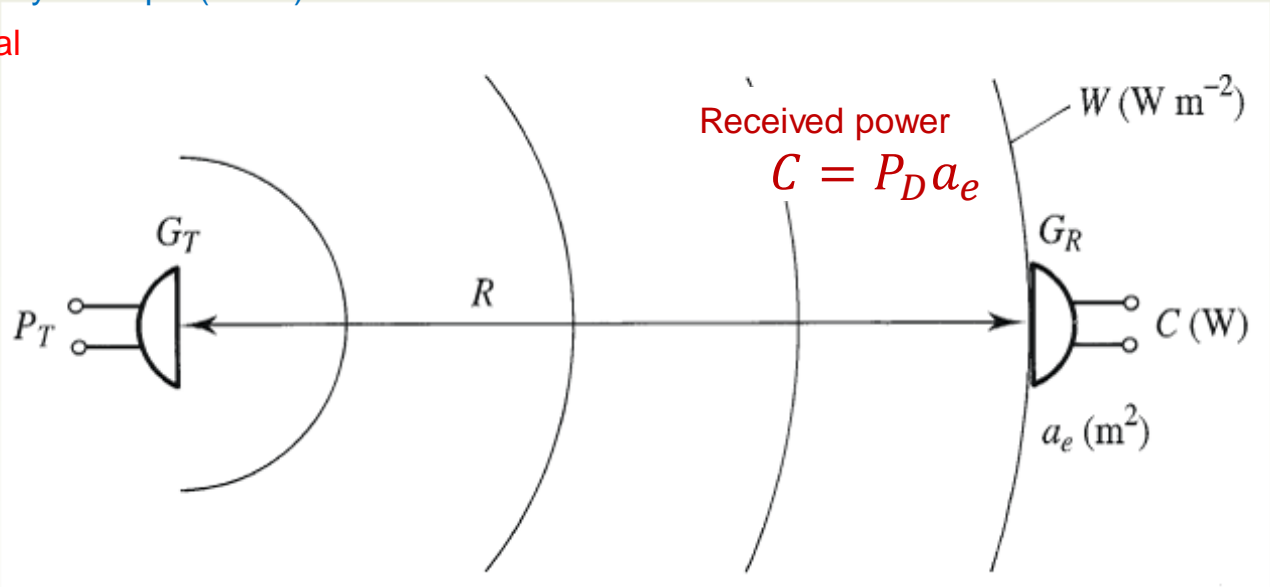
Power density: Radiated by isotropic (W/m²)

Radiated by directional

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

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

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



Received power
 $C = P_D a_e$

W (W m⁻²)

C (W)

a_e (m²)

Assumptions:

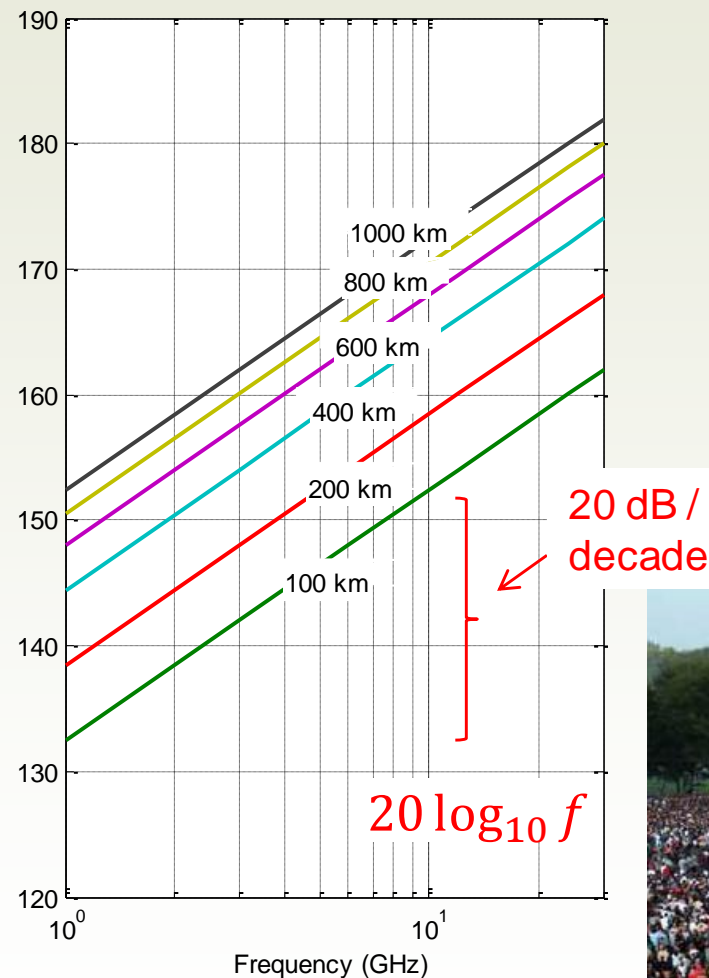
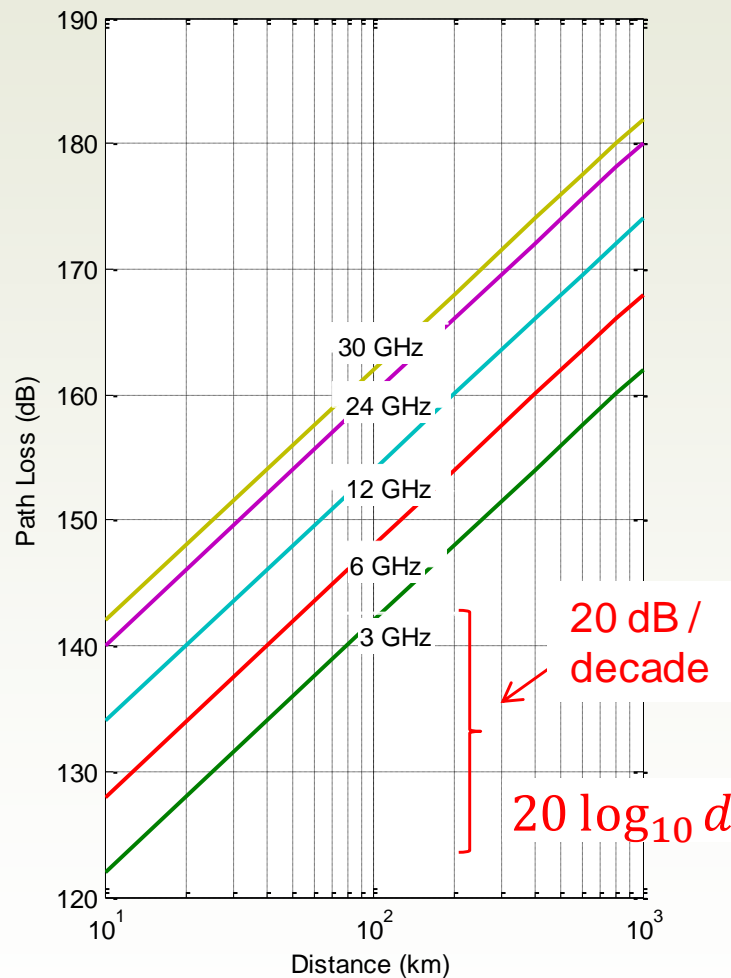
- single path
- in vacuum

Path Loss:

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

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

Path loss as a function of d and f



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

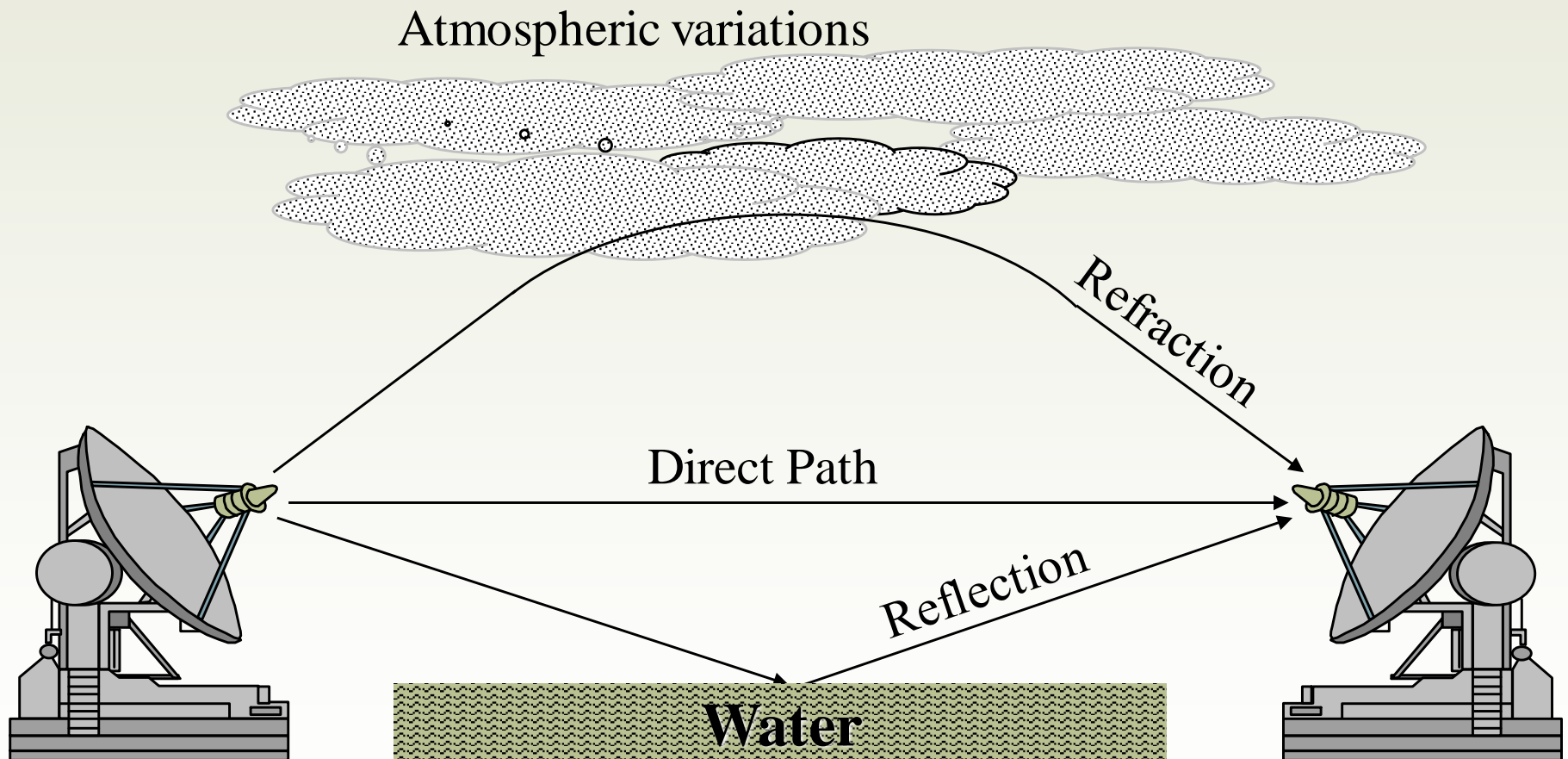
The 'concert effect'



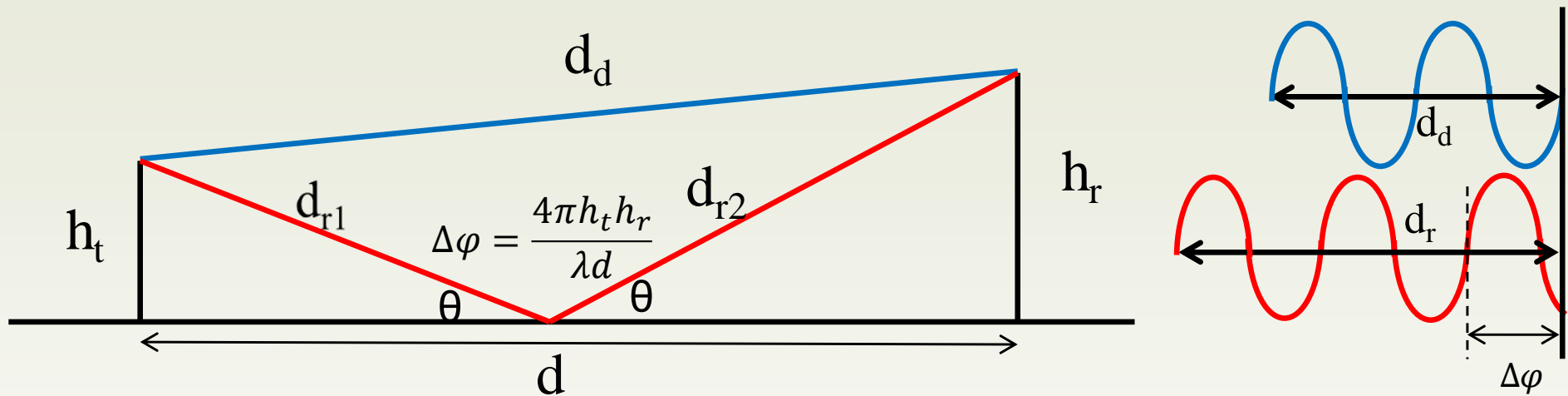
Ref. JPL report 2005;

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



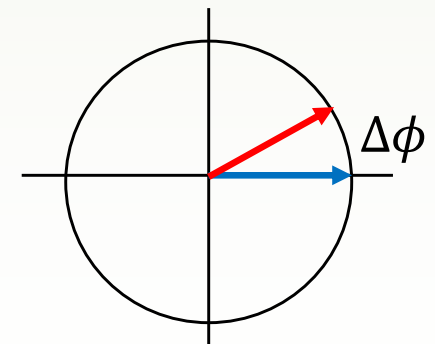
- When θ is small, the earth acts as a reflector
- The reflected signal is 180° out of phase with the incident

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

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

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

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

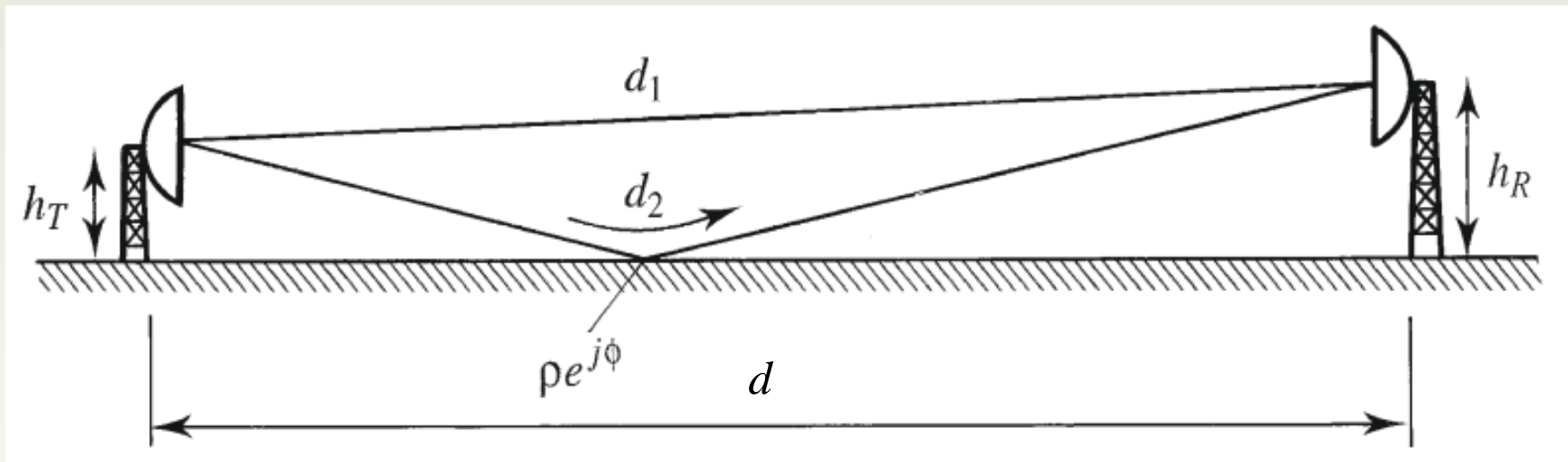


$$\Delta\phi_{tot} = \Delta\phi + 180$$

Assumptions:

- two paths
- in vacuum

Two ray fading (Plane Earth Propagation)



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

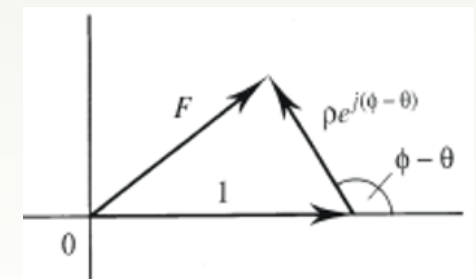
Received free-space field strength modified by factor F :

$$F = \left| \underbrace{1}_{\text{d1 path}} + \underbrace{\rho e^{j\phi}}_{\text{d2 path}} \right|^2 = \left| 4 \sin^2 \left(\frac{2\pi h_T h_R}{\lambda d} \right) \right| \cong \left(\frac{4\pi h_T h_R}{\lambda d} \right)^2$$

ρ is the reflection coefficient, for earth ~ 1

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

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



for small argument

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

When $d \gg h_t$ and h_r

Plane-Earth propagation

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

For $R > R_{\max}$:

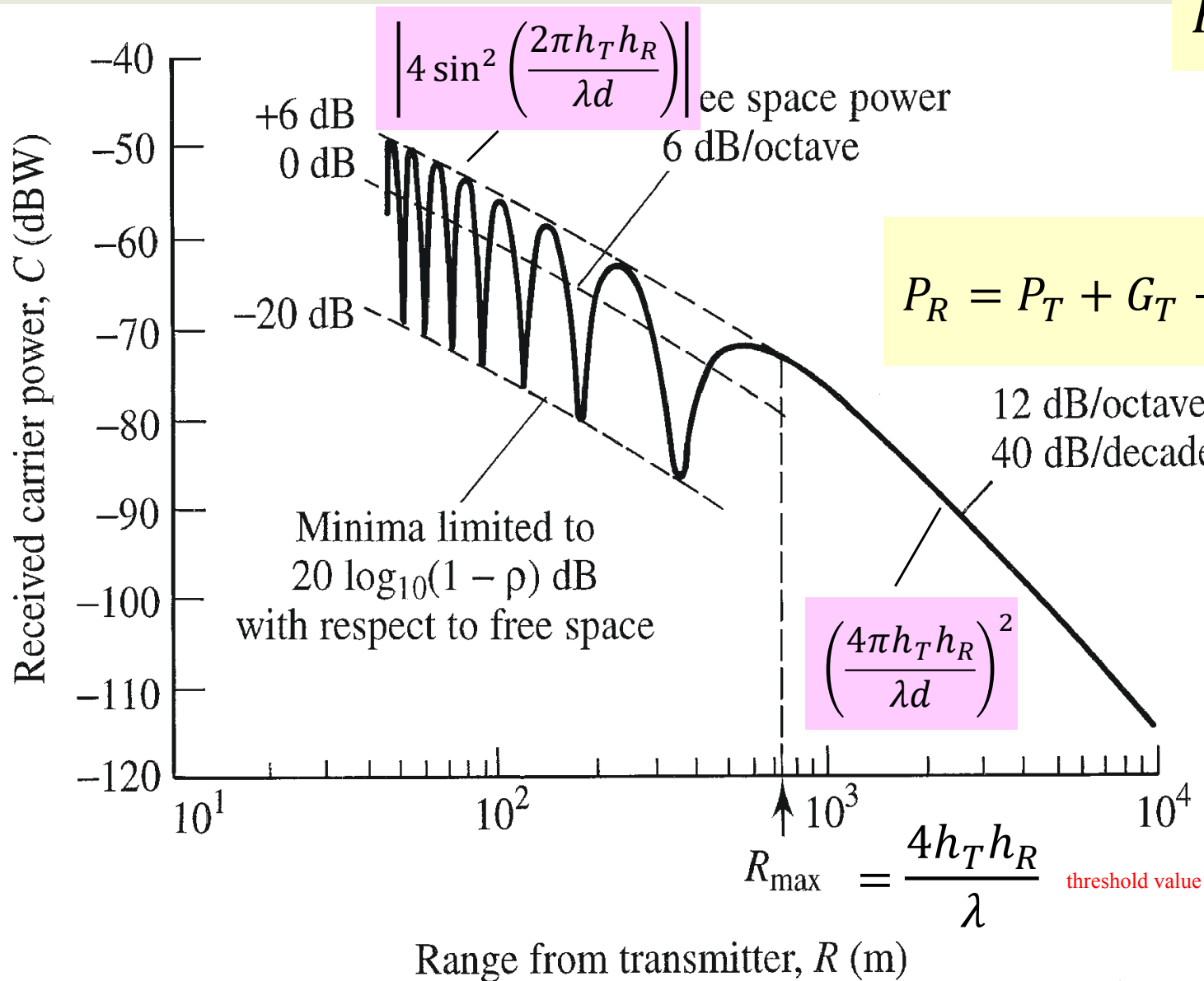
$$P_R = P_T + G_T - 20 \log_{10} \left(\frac{R^2}{h_T h_R} \right) + G_R$$

L_{PEPL}

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

Assumptions:

- two paths
- in vacuum

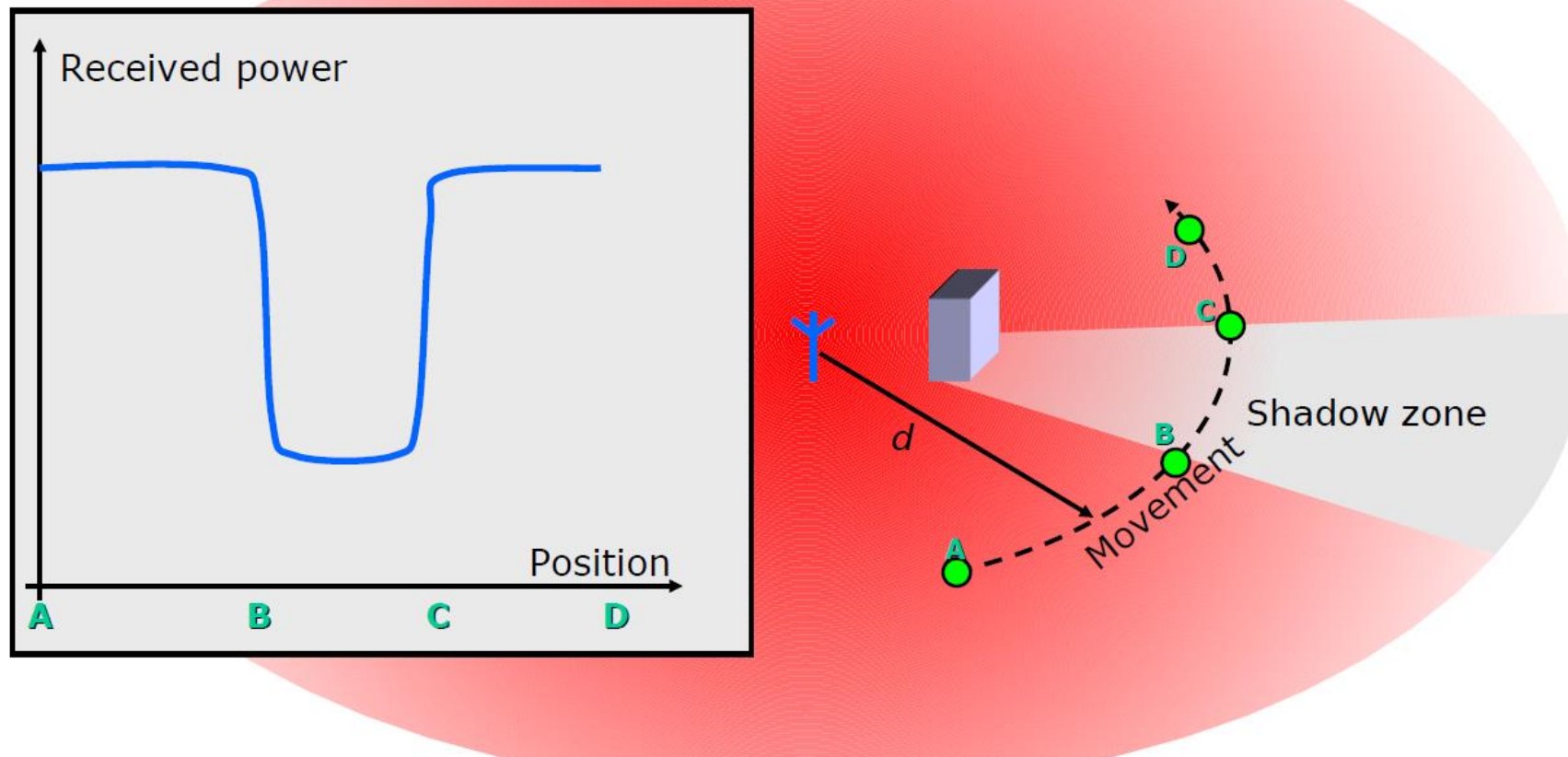


[Note the path loss is *subtracted*]

This Video : Large Scale Propagation

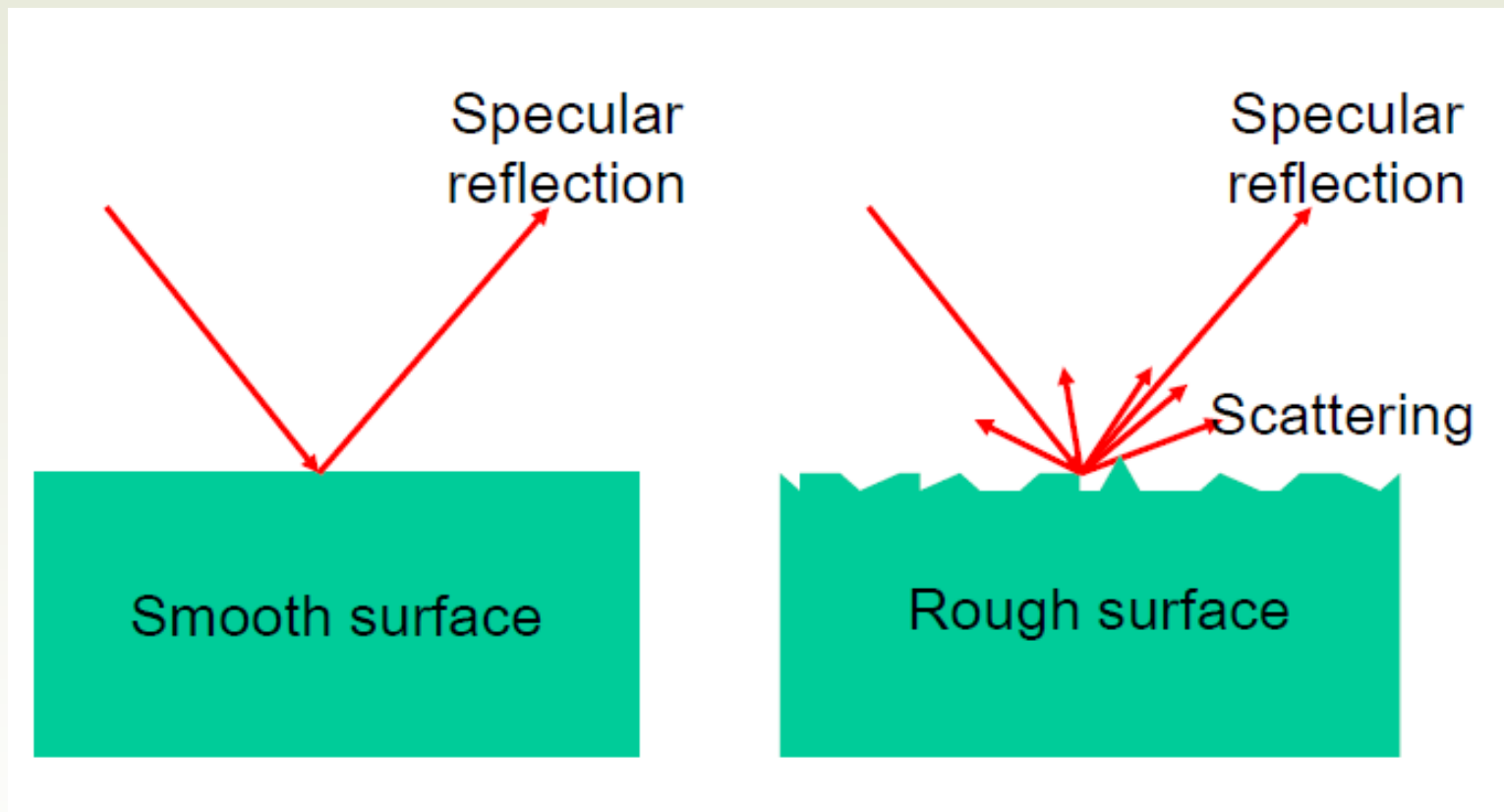
- Shadowing and geometrical effects
- Atmospheric effects
- Advanced propagation models

Shadowing



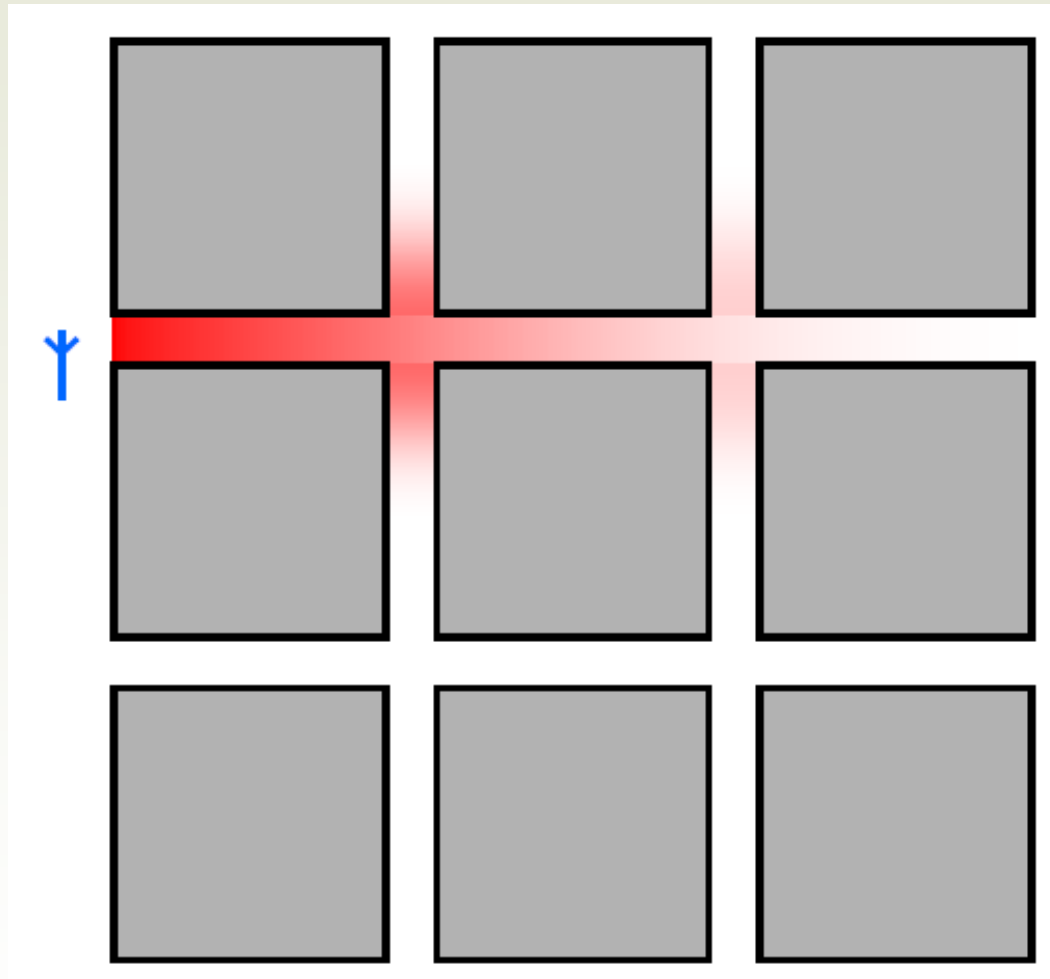
Not accounted for, in the previous models!

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 (α) becomes greater than 2 (e.g. cellular radio systems)
- Can now write the path loss expression as

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

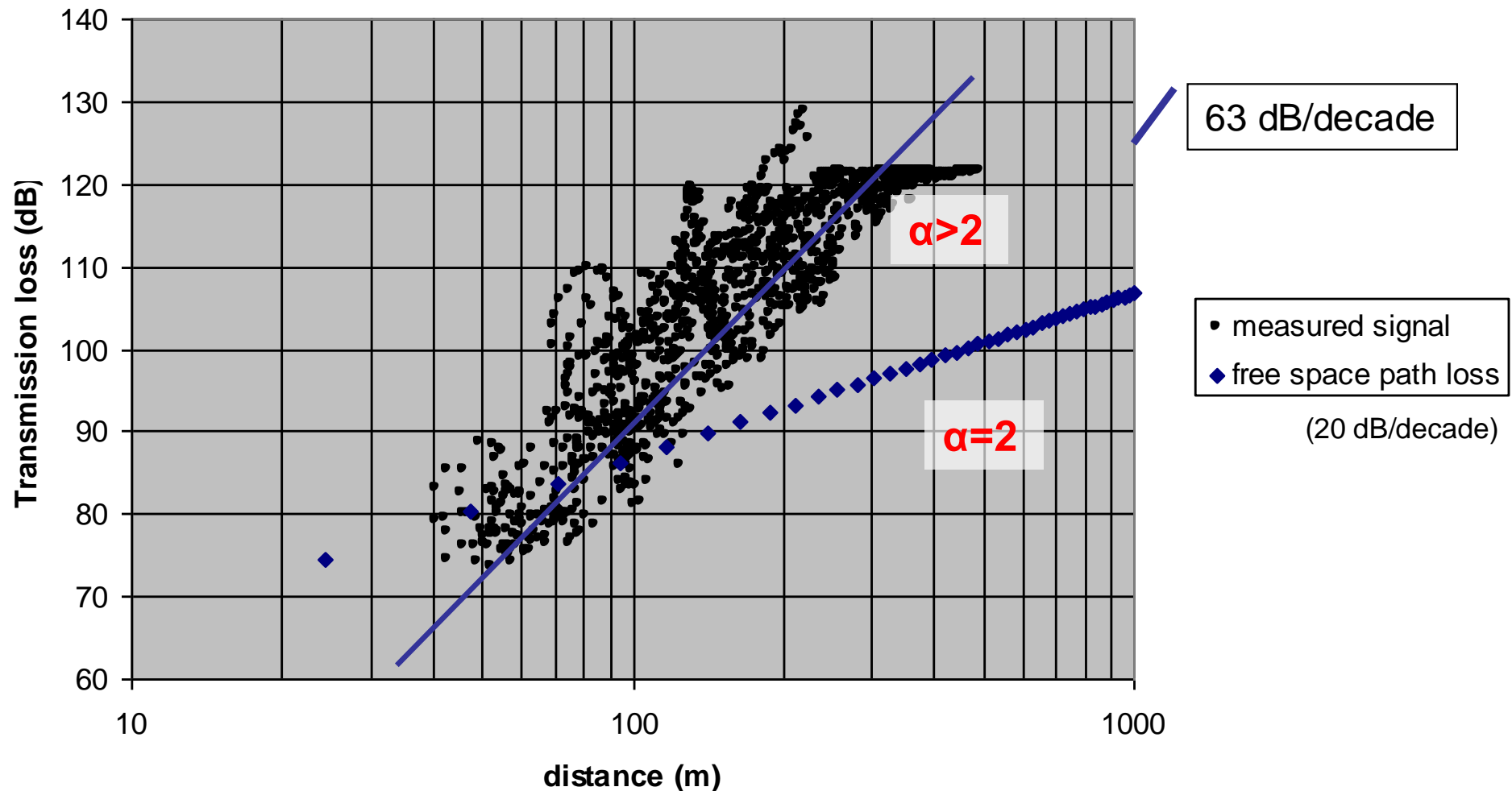
- Typical values for the loss exponent α are 3 to 5 in outdoor environments

• 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

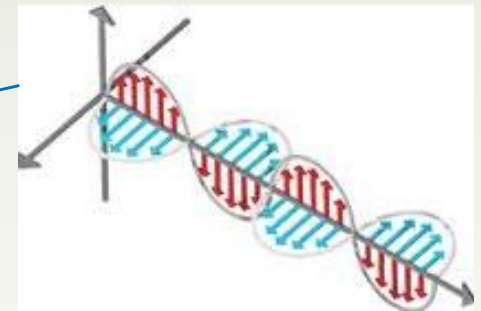
$$L_{dB} = 20 \log_{10} f_{MHz} + 10\alpha \log_{10} d_{km} + 32.44$$

Wide area 5 GHz received signal strength validation results

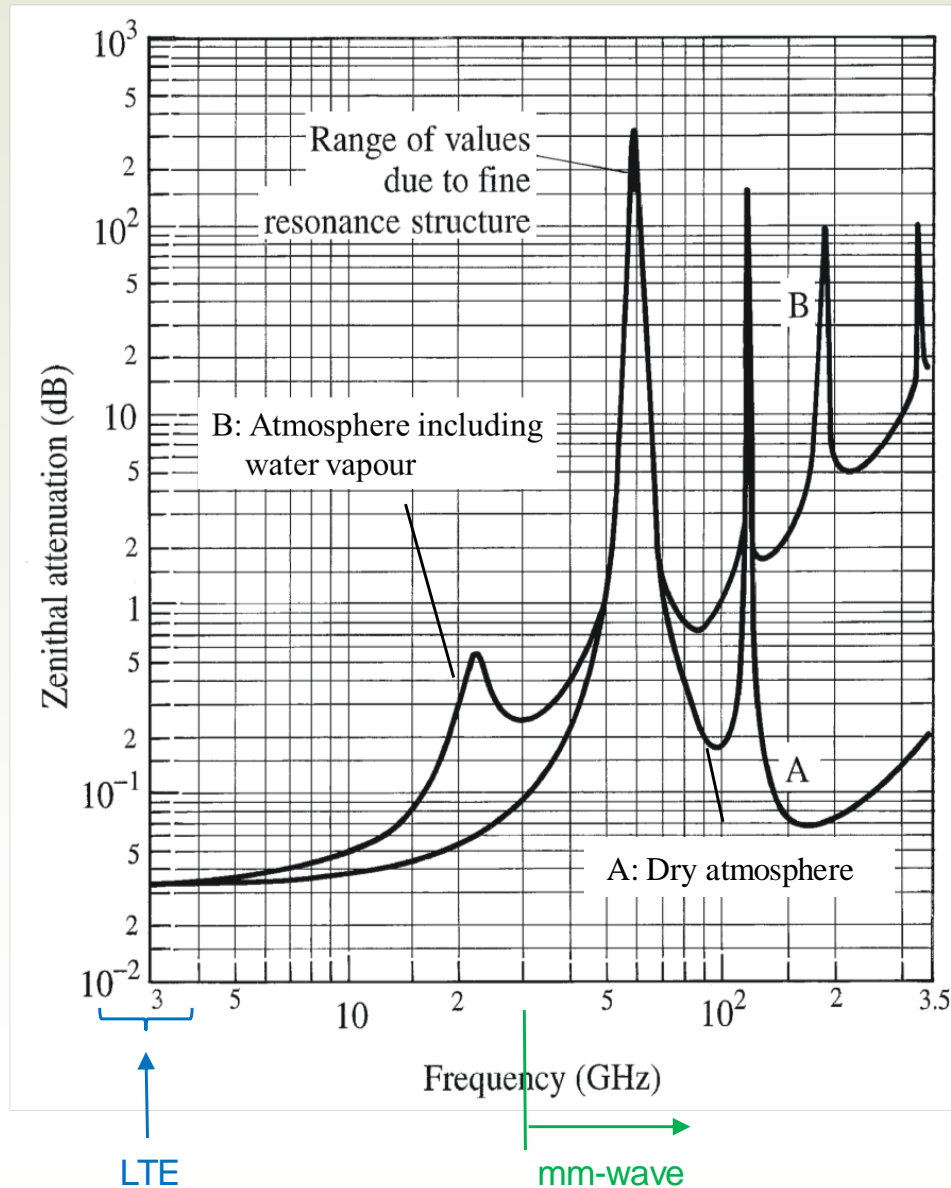


Atmospheric effects

- 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

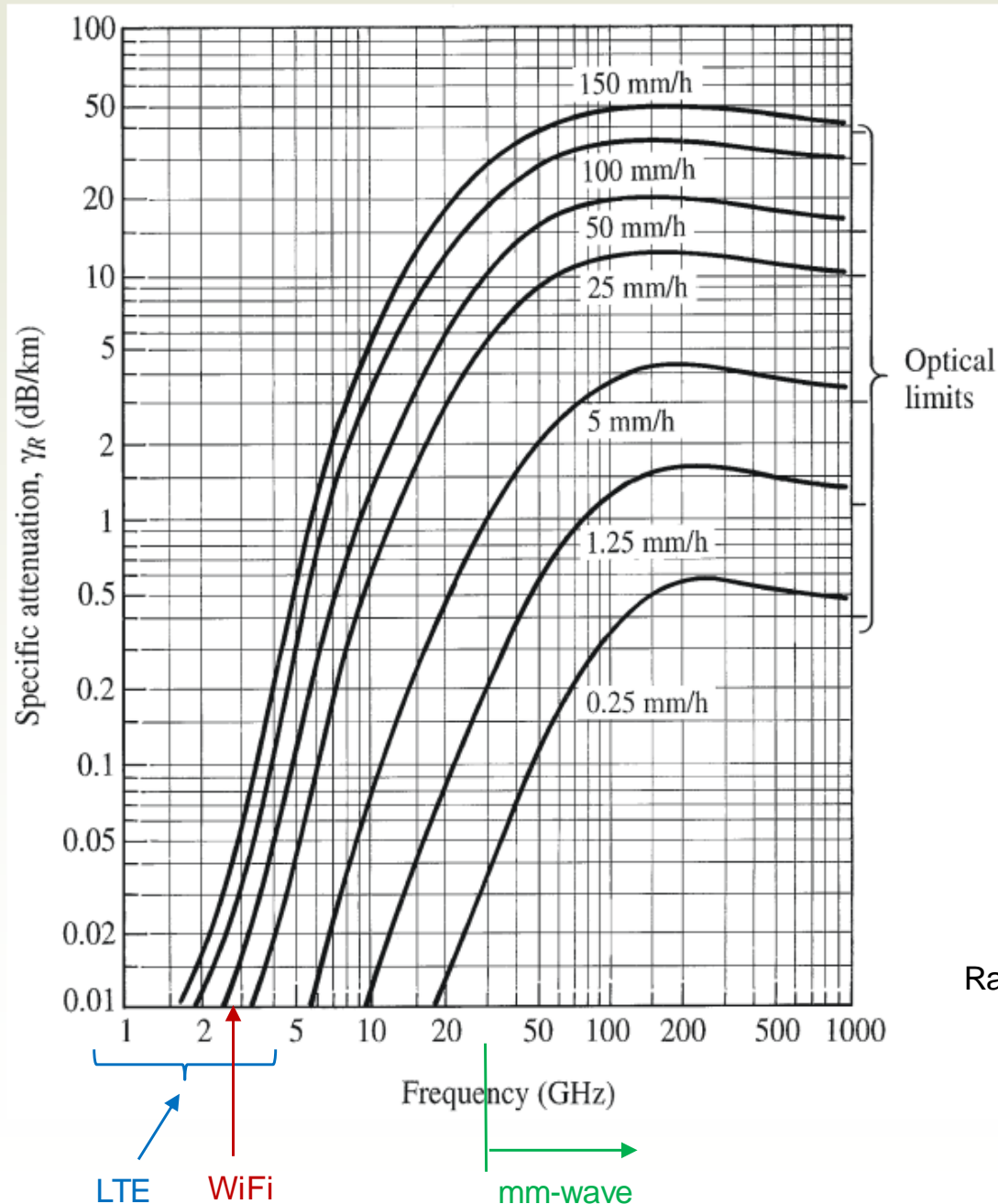


Reference atmosphere surface parameters:

temperature	15°C
pressure	1013 mBars
water vapour	7.5 g/m ³

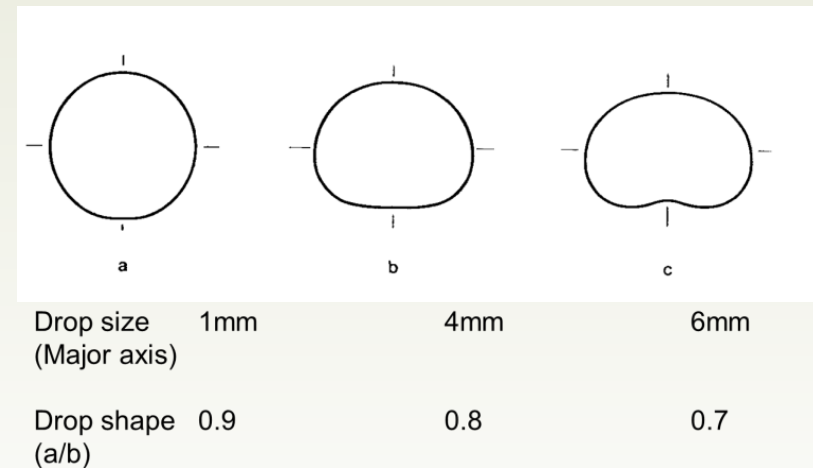
- Peak of water vapour absorption ~ 22 GHz
- Peak of oxygen absorption ~ 60 GHz

2. Specific attenuation due to rain



[After ITU-R, 1996]

Spherical raindrops assumed
(therefore no polarisation dependence)

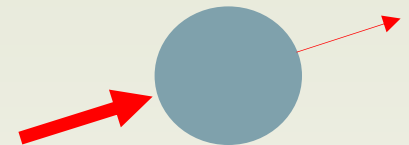


Rain intensity (mm/h)

3. Cloud attenuation

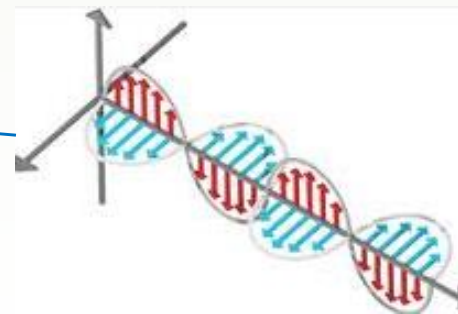
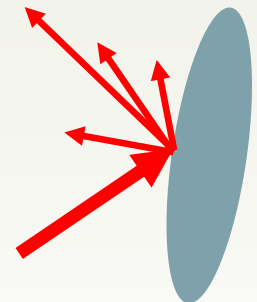
- Liquid clouds

- 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/m³)

4. Scintillation

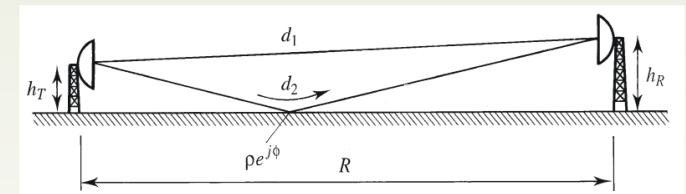
- Rapid fluctuation of signal amplitude and phase due to spatial and temporal variations in refractive index of atmosphere (thickness/density of atmosphere, vapour content, temperature)
- Fluctuation time scale - seconds to minutes
- Fluctuation amplitude - up to several decibels
- May result in signal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

Channel and propagation models

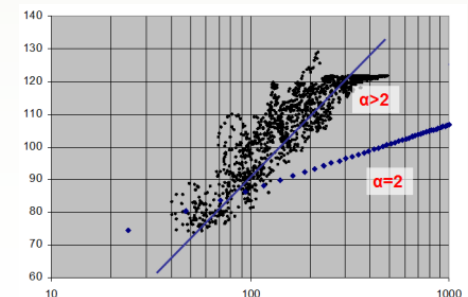
- **Channel model** describes *what* happens
 - gives channel output for a particular input
 - black box
 - requires appropriate parameter (e.g. loss, fading, dispersion statistics)

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

- **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

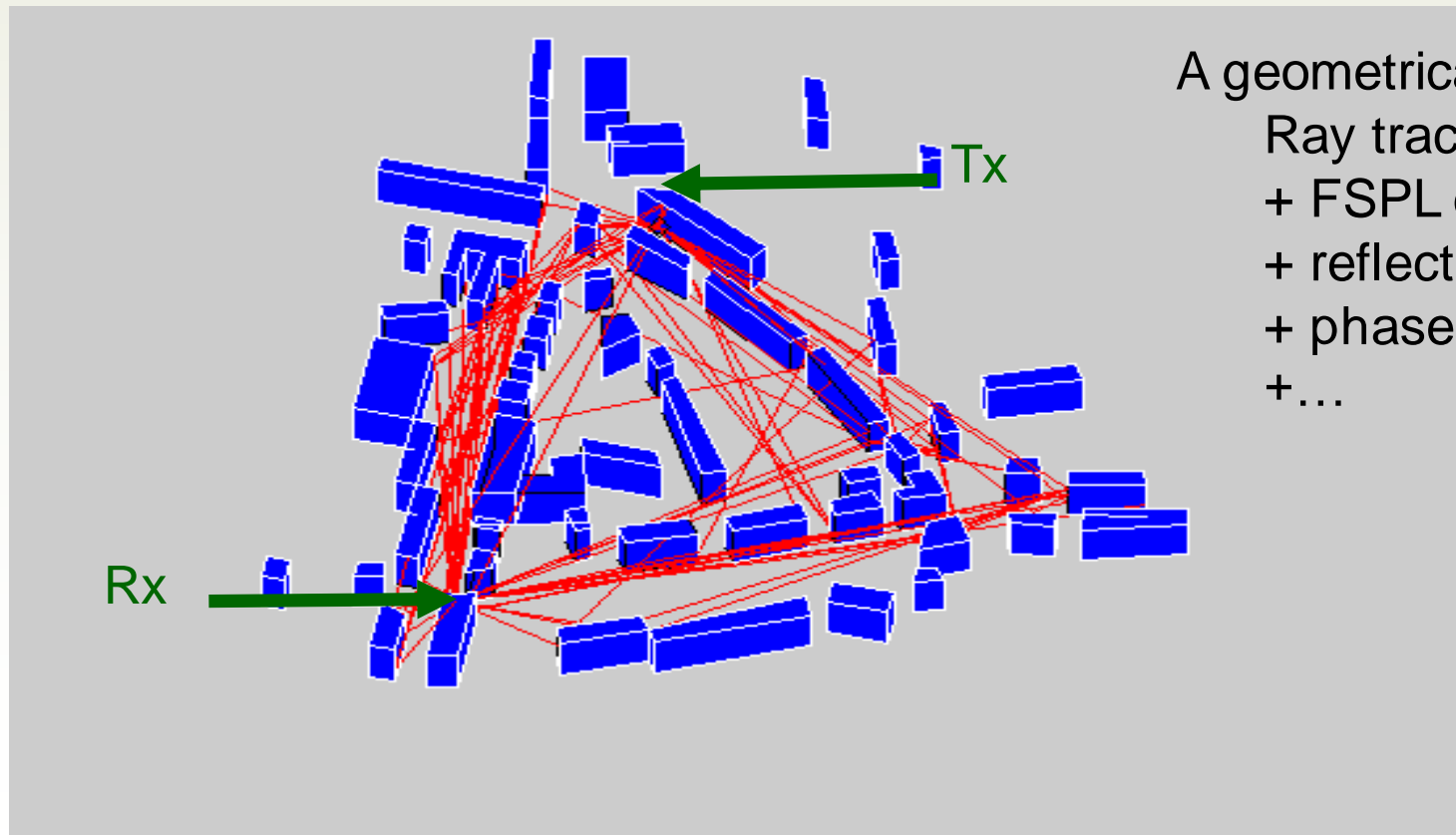


- **Measurement based (semi-empirical) models**
 - Based on simple physical model (e.g. free-space path loss) plus a correction factor derived from measurements
 - Valid for specific channels and ranges of variables (antenna heights, frequencies etc.)
 - Sensitive to changes in environment but probably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



Example propagation model

- Geometric optics (Snell's laws (reflection) + 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

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

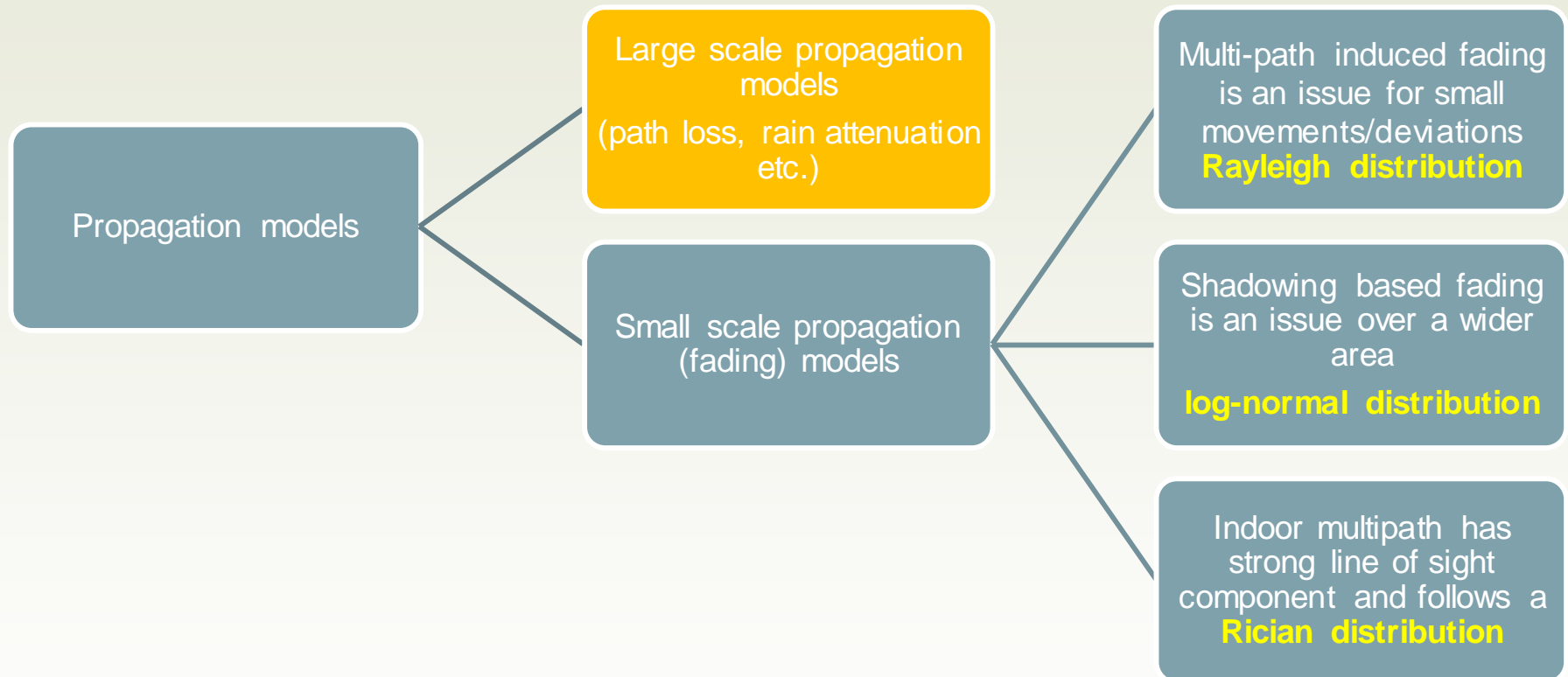
Gives median path loss (L_{ur}) as a function of
 frequency in MHz (f_{MHz})
 height of the base station in m (h_{TX})
 height of the mobile station in m (h_{RX})
 range in km (d_{km})

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

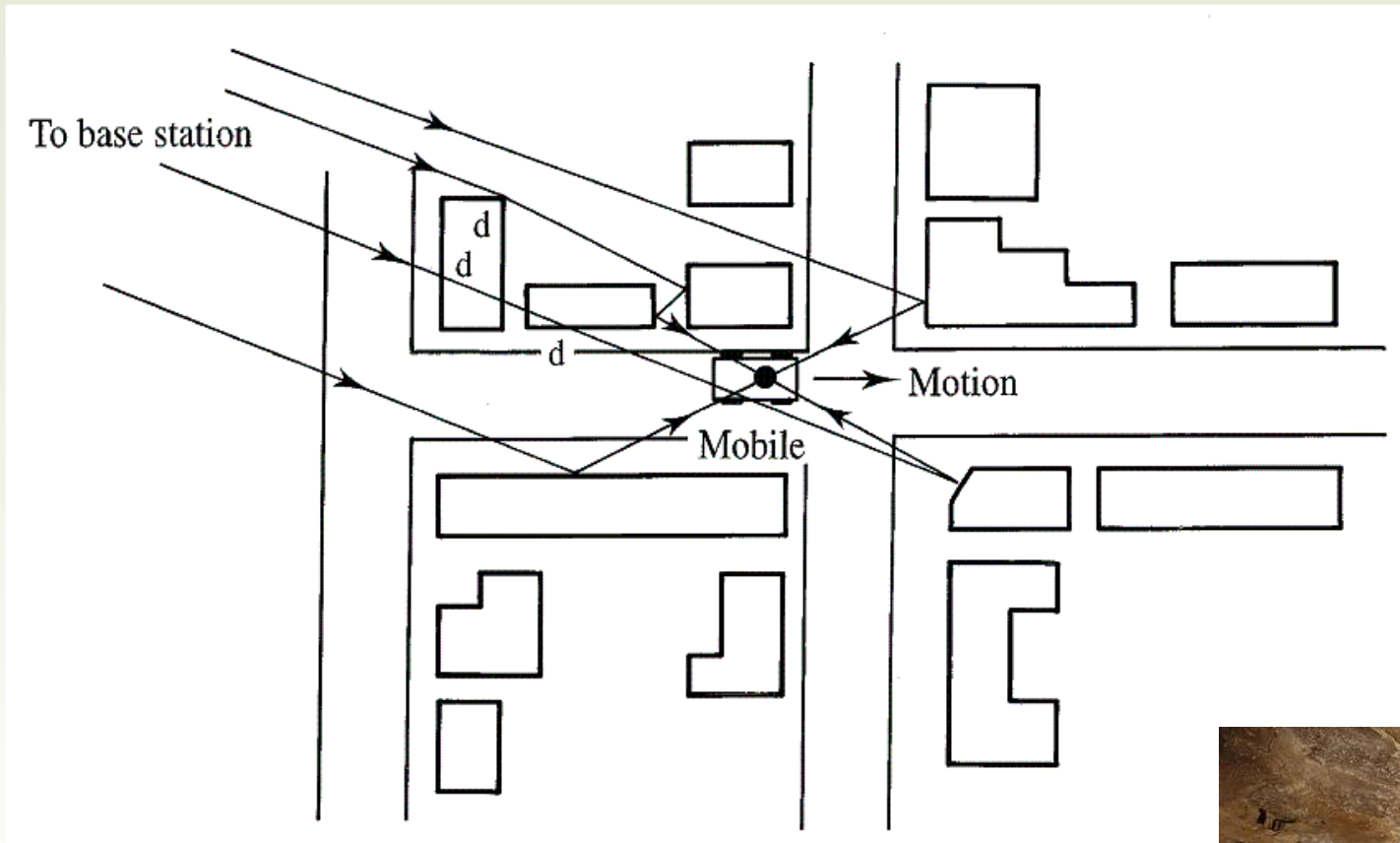
This Video : Small Scale Propagation

- Multipath
- Channel response
- Frequency Selectivity

Fading



Urban multipath propagation



d: denotes diffraction

Excess delays up to say $10 \mu\text{s}$ for flat rural areas

Effect of shouting inside a cave



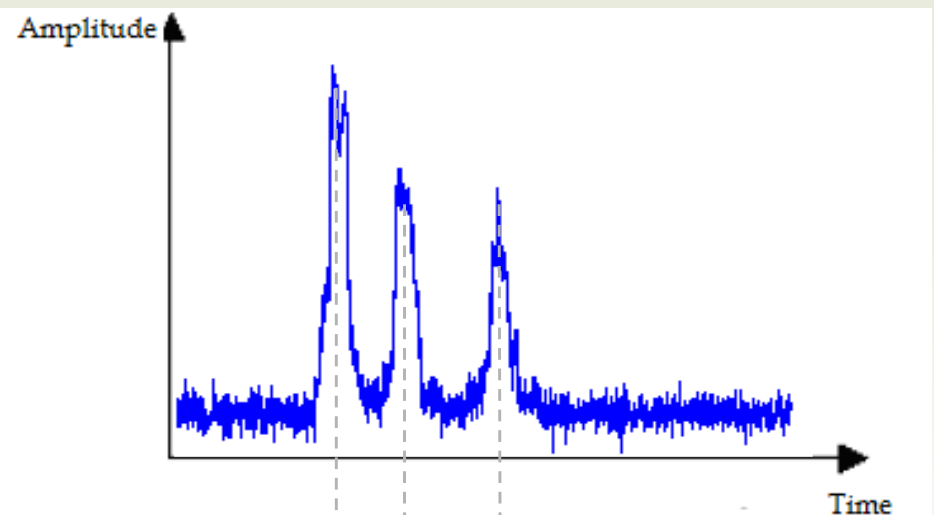
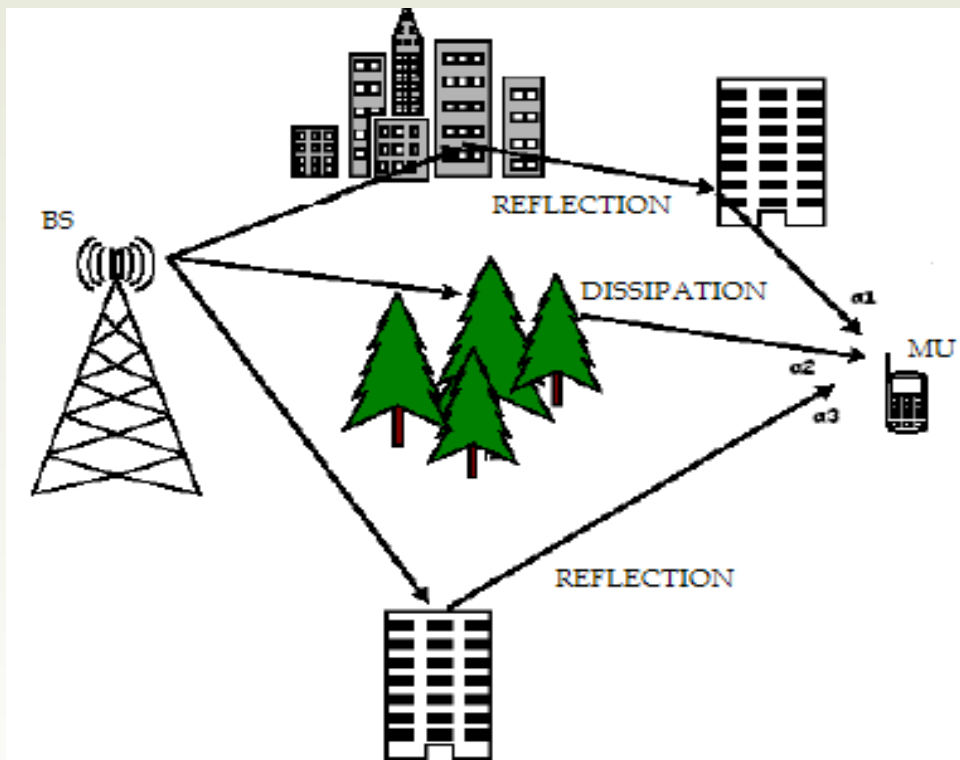
Fading effects of multipath propagation

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

The Multipath Channel

Typical urban multipath channel

Channel impulse response

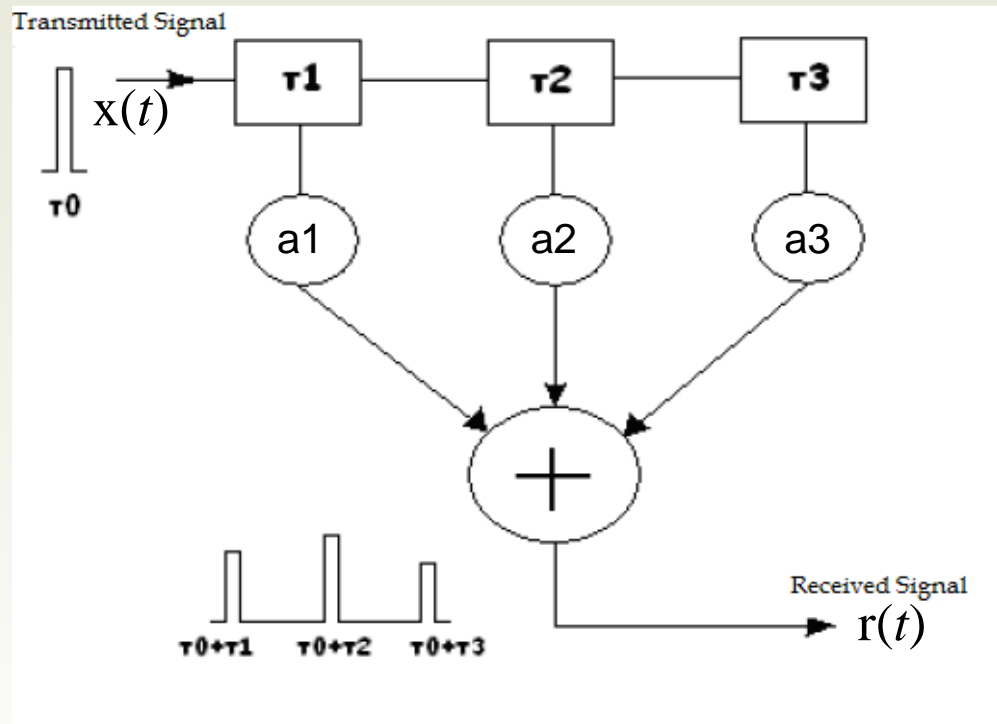


Hi! my name is Chris
 + Hi! my name is Chris
 Hi! my name is Chris
 —————
 Hi! my name is Chris Chris
 ISI

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

Multipath Channel Mathematical Model

Channel model – tap delay line

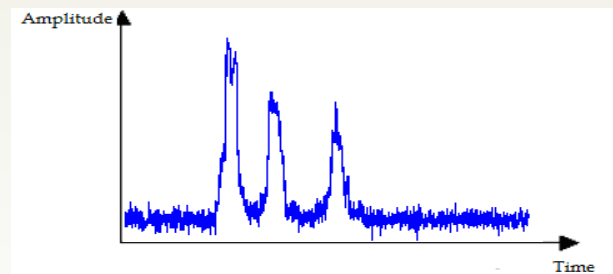


$x(t)$: transmitted

τ_i : delay of path i

a_p : coefficient of channel path p

$r(t)$: received



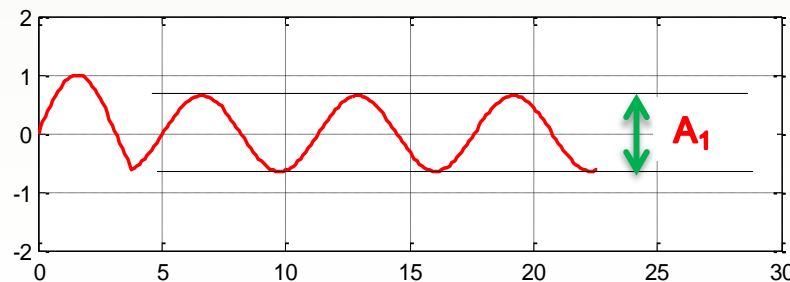
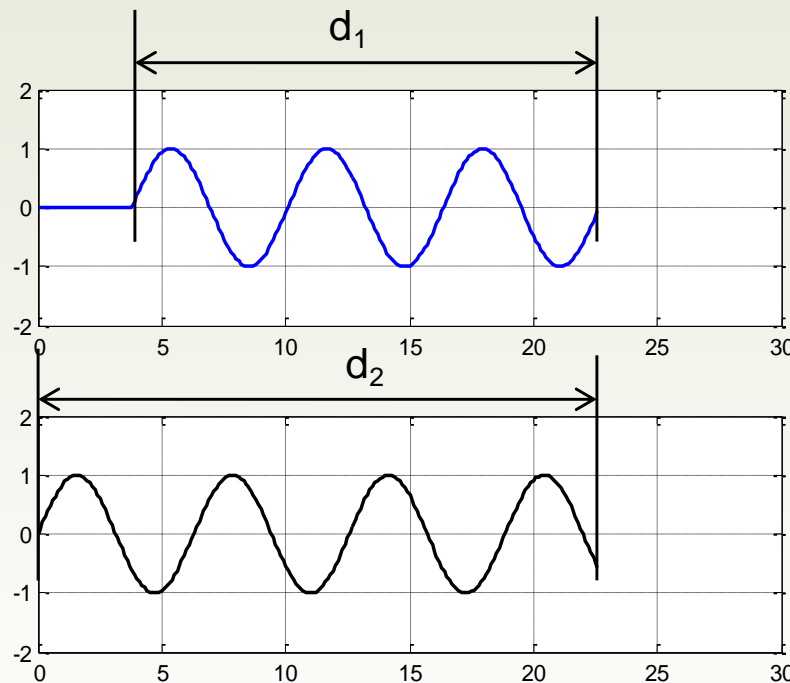
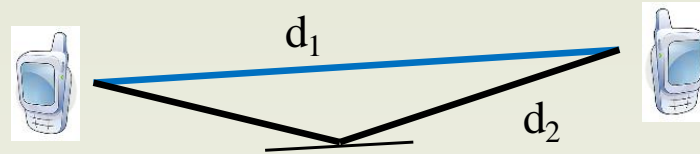
$$h(t) = \alpha_1 \delta(t - \tau_1) + \alpha_2 \delta(t - \tau_2) + \alpha_3 \delta(t - \tau_3)$$

$$r(t) = a_1 x(t - \tau_1) + a_2 x(t - \tau_2) + a_3 x(t - \tau_3) = h(t) \otimes x(t)$$

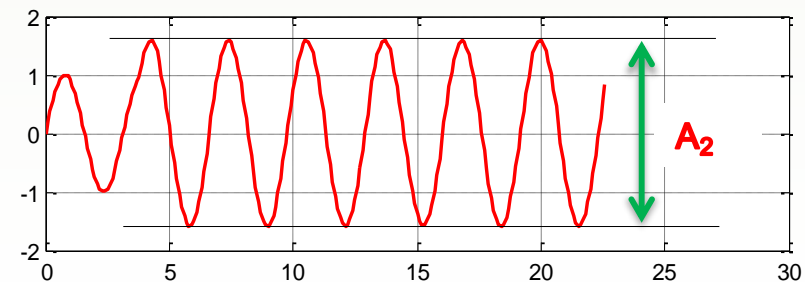
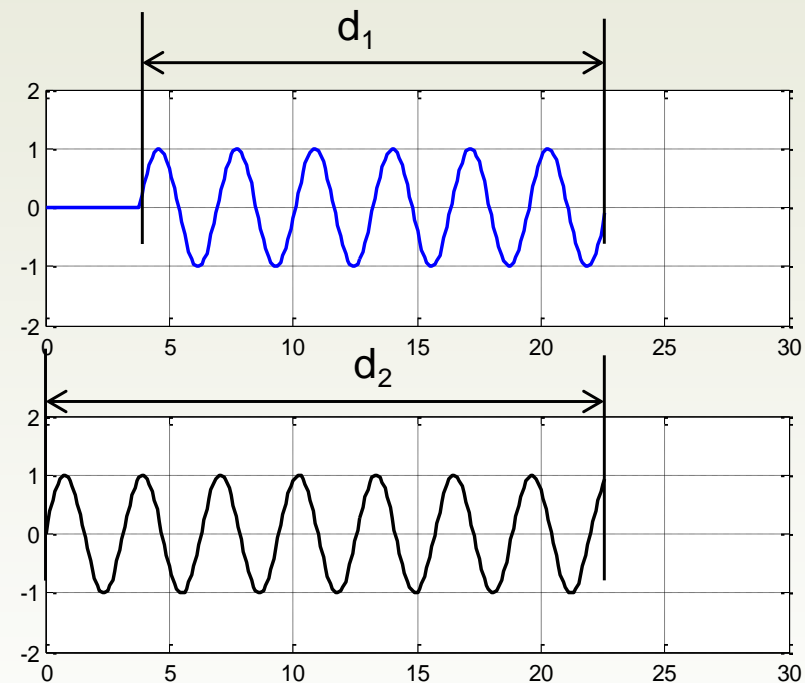
Desired

ISI

Where does the frequency selectivity come from??

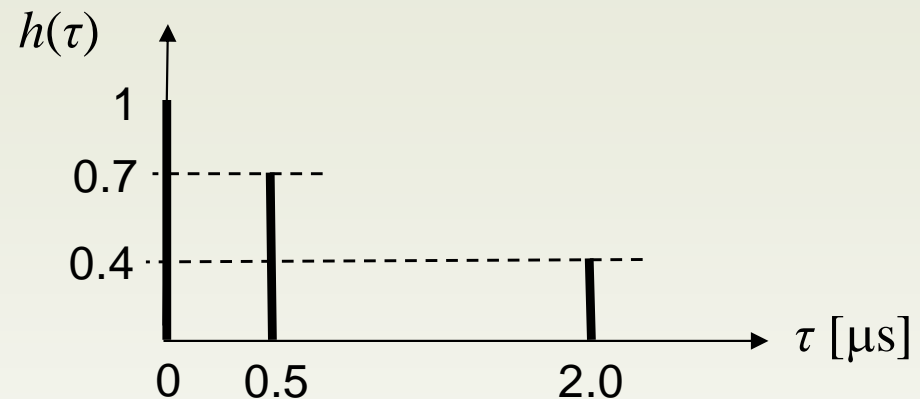
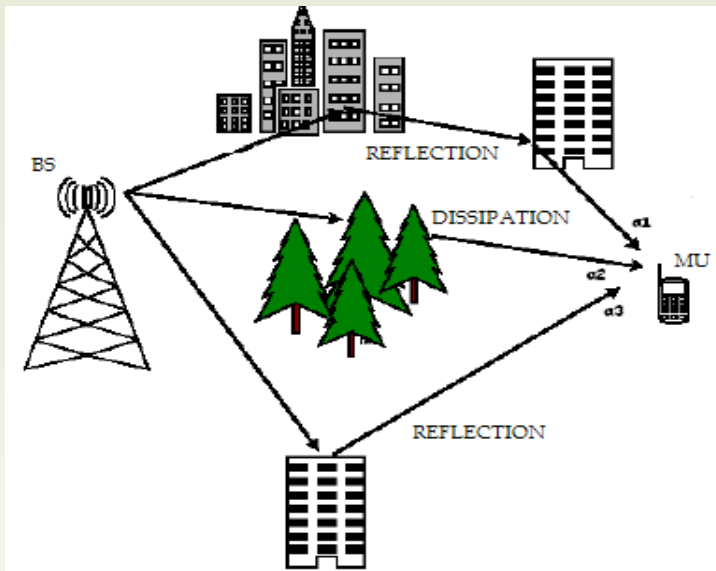


Frequency 1



Frequency 2

Where does the frequency selectivity come from??



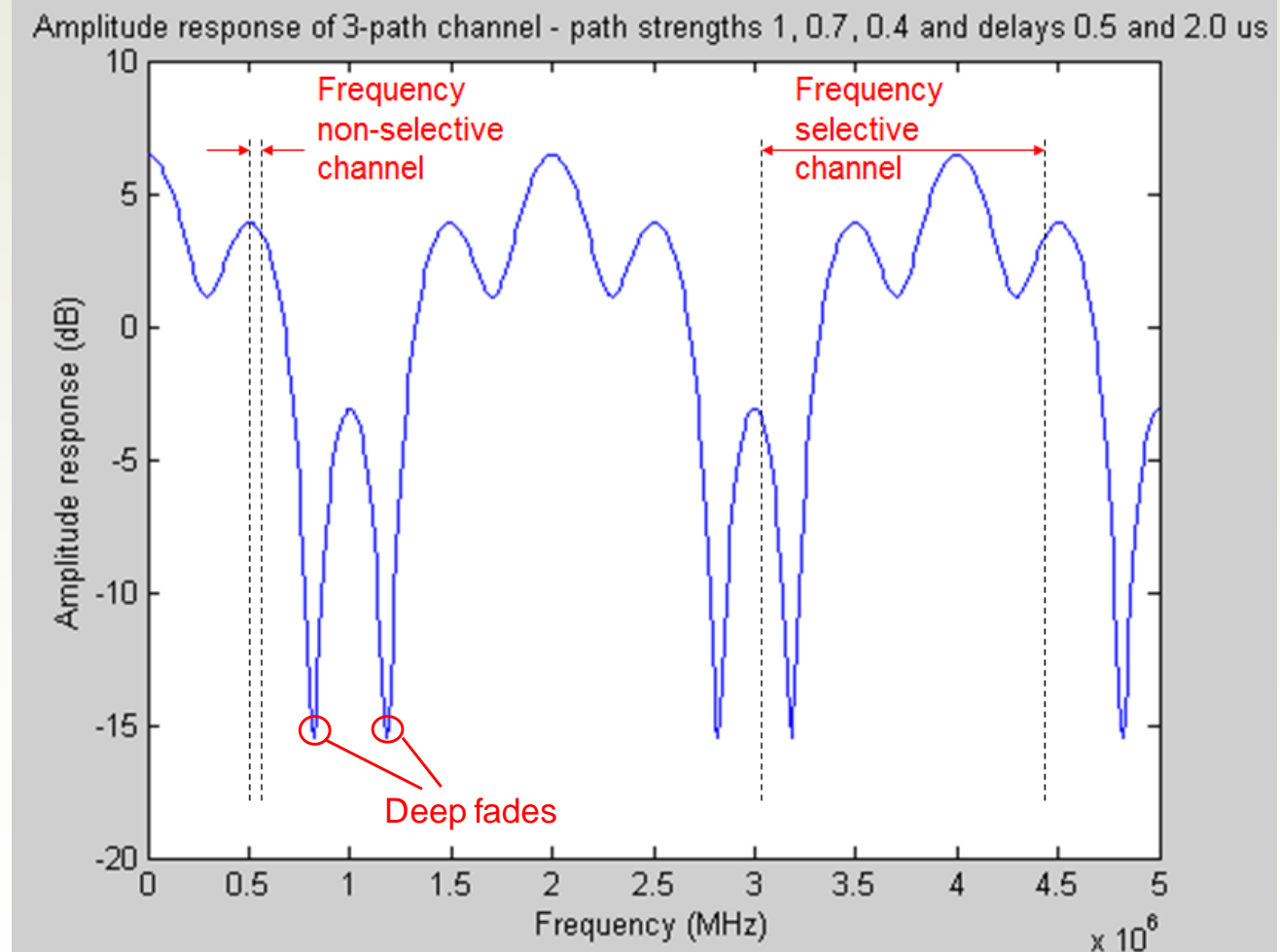
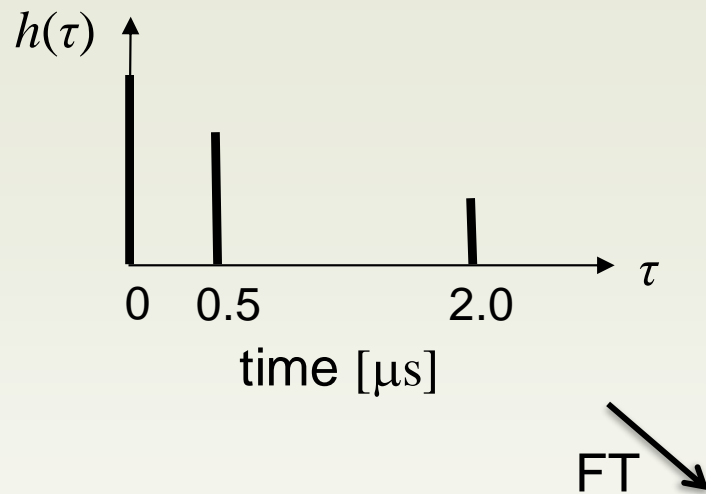
- Three ray channel with impulse response:

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

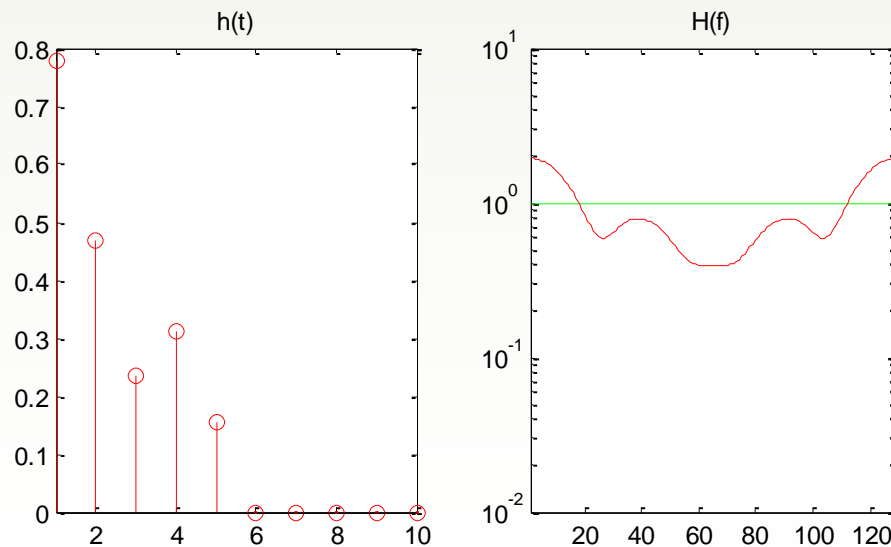
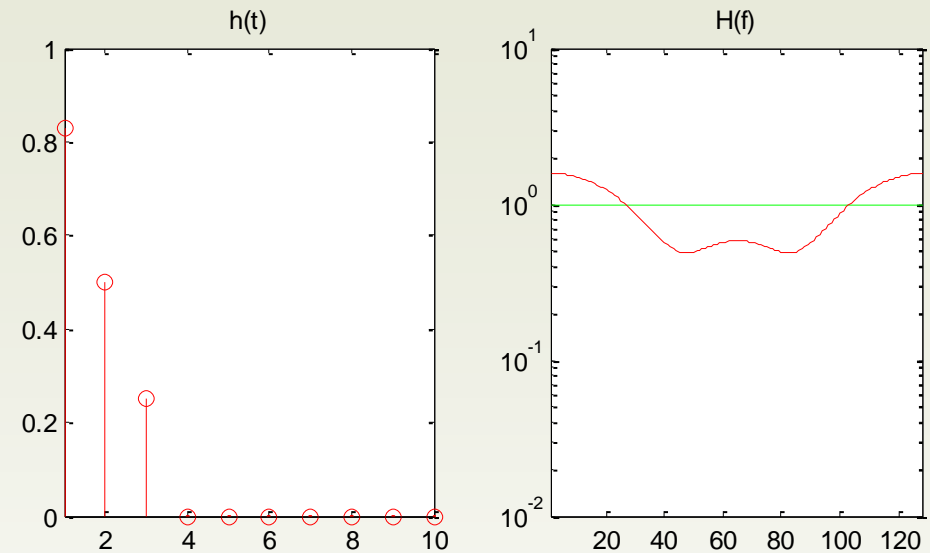
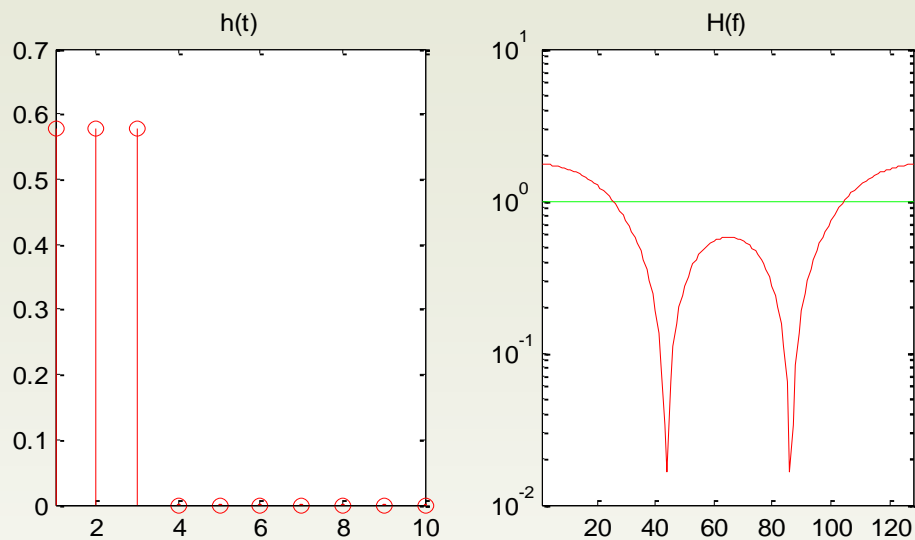
- Has the frequency response:

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

Three-path example



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



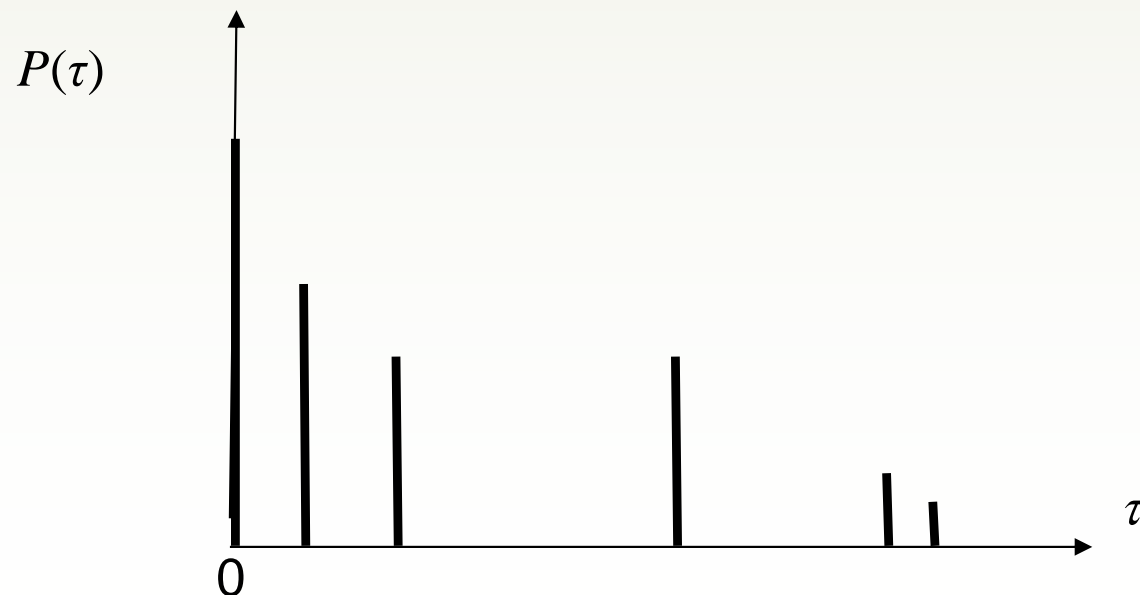
↑ #paths → ↑ variation

More equally distributed path power → deeper fades

Power delay profile (PDP)

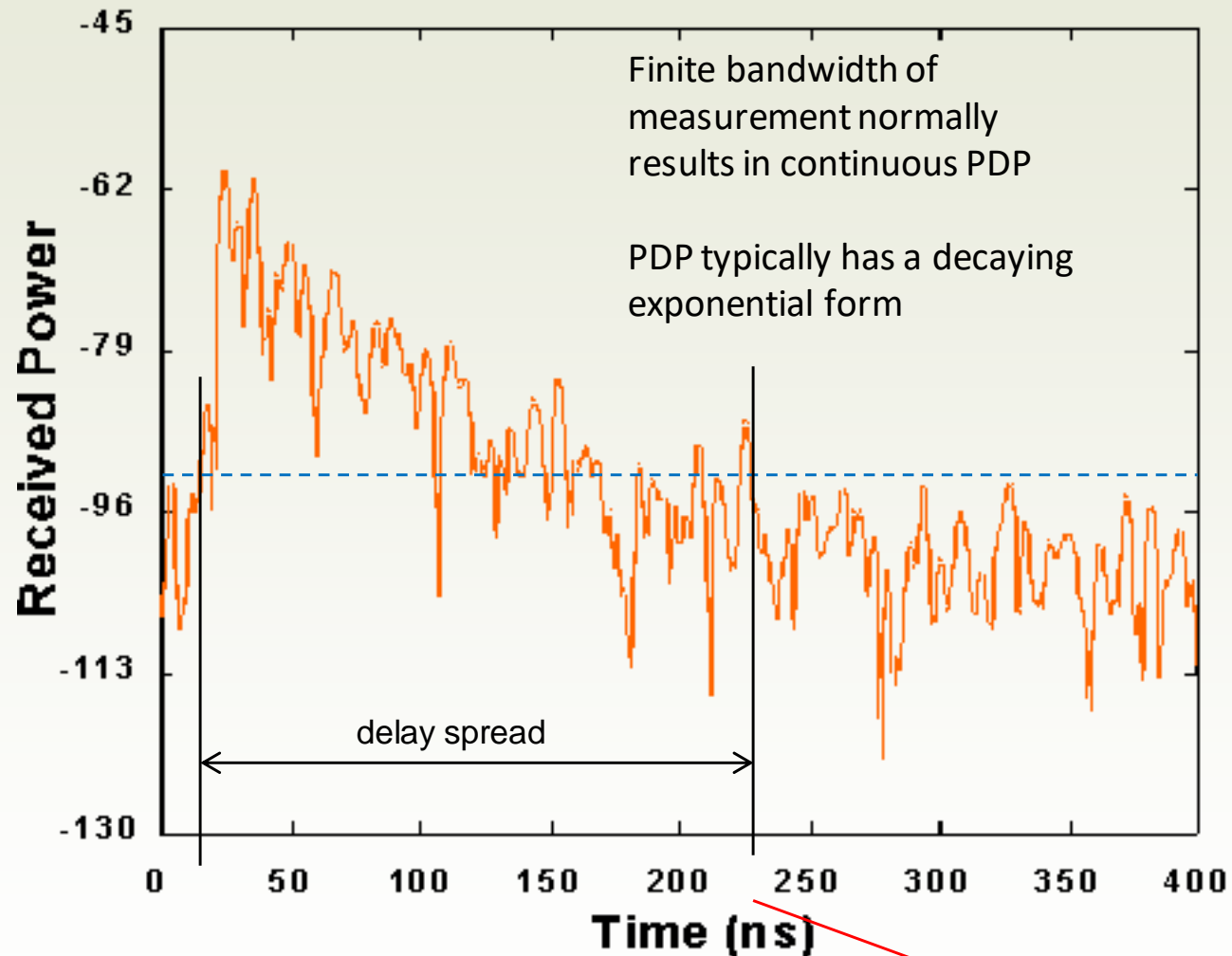
- Power received via the path with excess time delay τ_i is the value (height) of the discrete PDP component at t_i

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



Example indoor PDP measurement

Instantaneous Impulse Response



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

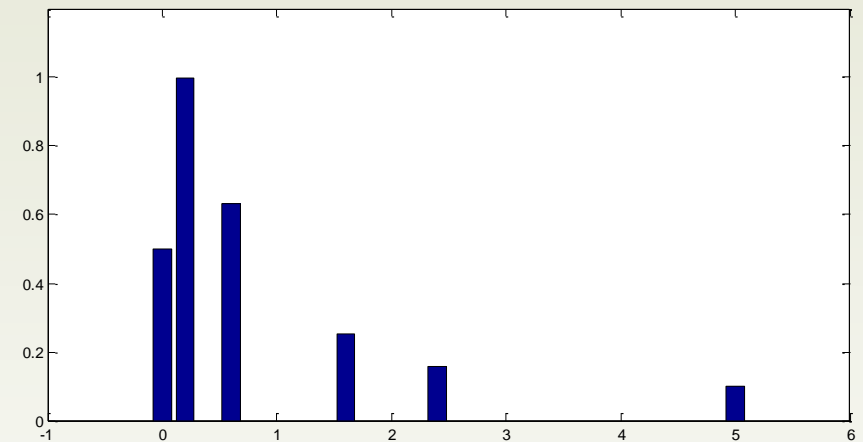
$\sim 0.23\mu\text{s}$ – is this important?

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

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

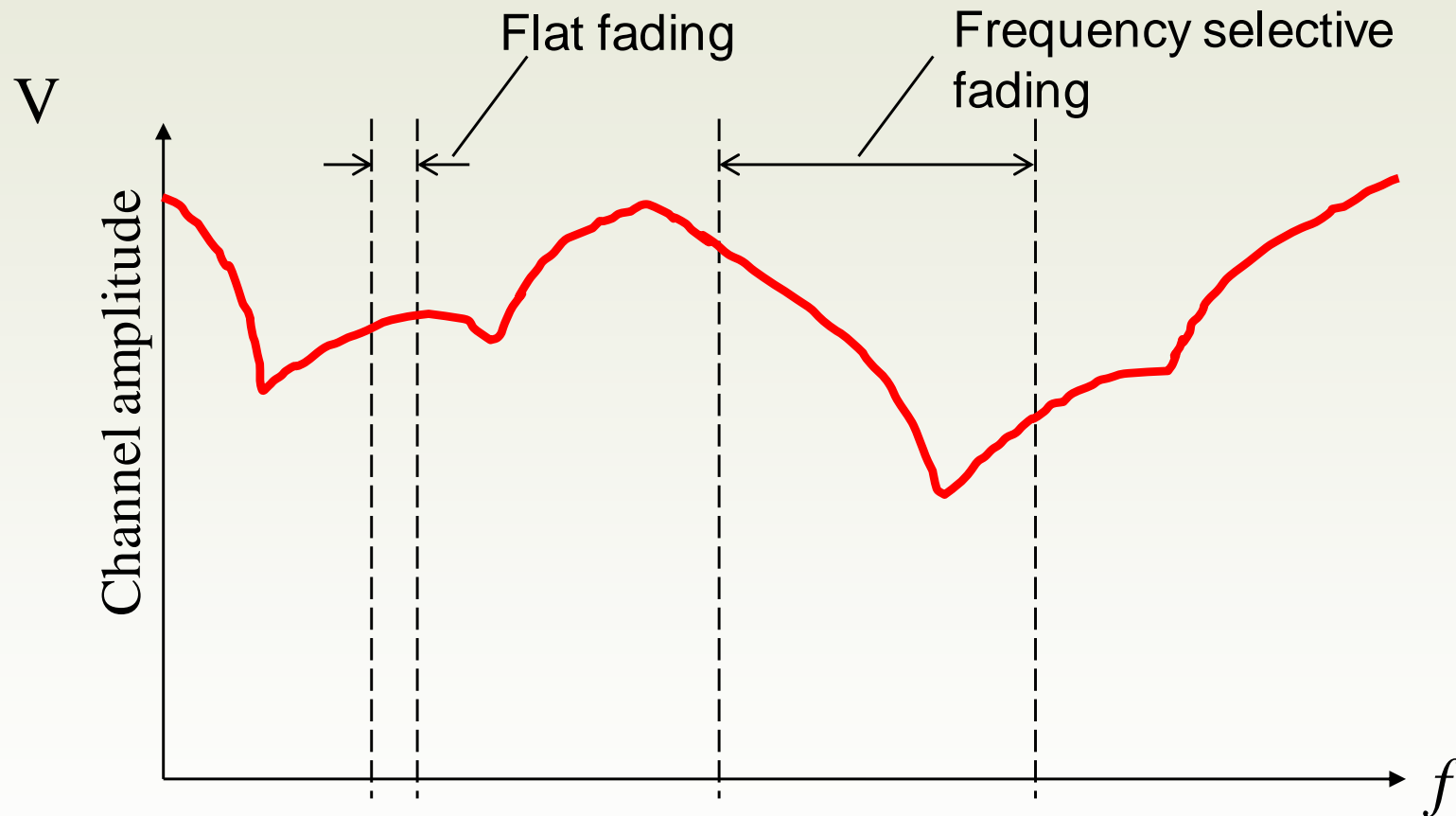
from COST 207 Management Committee: *Digital land mobile radio communications*, Final Report of COST Action 207, Office for Official Publications of the European Communities, 1989.

Tap no.	Delay (μs)	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

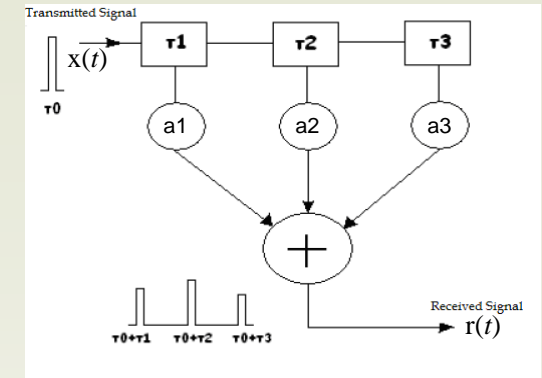
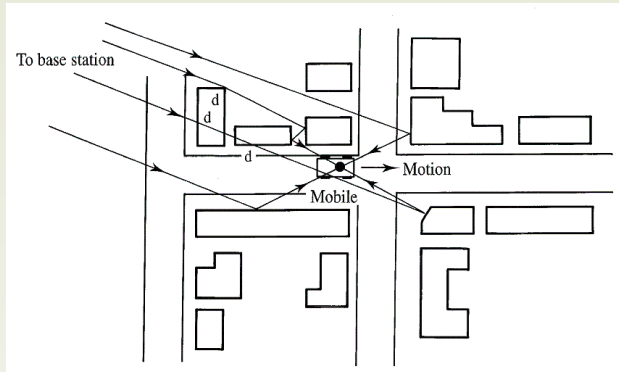


Frequency selective: When the amplitude of the **channel response** varies significantly ($> 3\text{dB}$) within the **signal bandwidth**

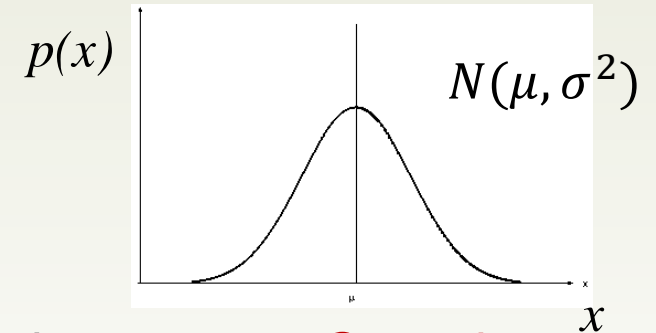
This Video : Small Scale Propagation

- Rayleigh-Rice distribution
- Doppler effect

Rayleigh fading model – rich multipath



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

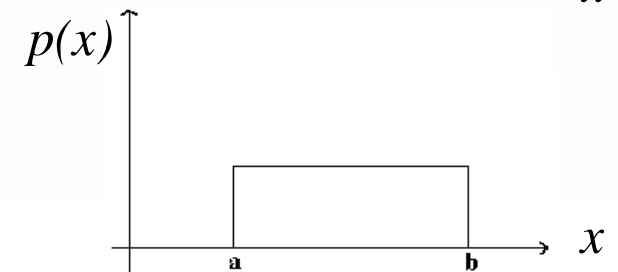
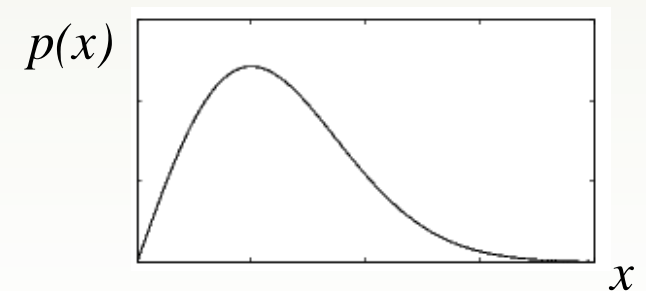


- I and Q components are **statistically independent** and **zero-mean Gaussian** distributed
- Then, amplitude is Rayleigh distributed

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

- 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 σ 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**

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

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

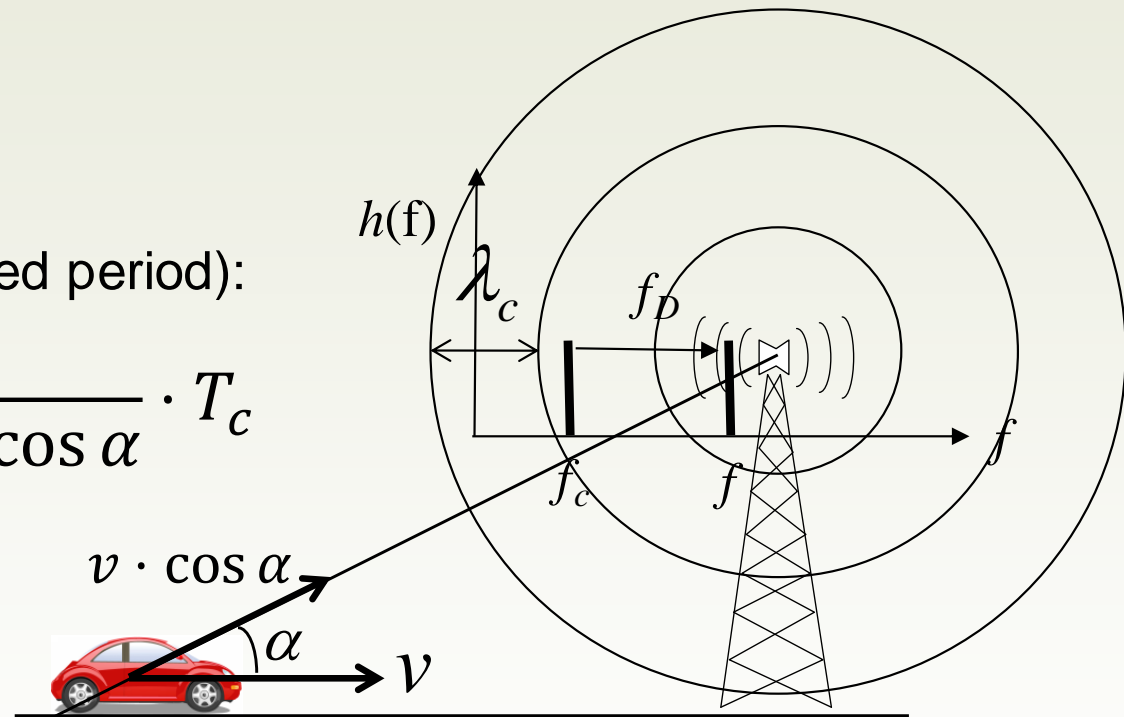
Carrier period: $T_c = \frac{\lambda_c}{c}$

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:

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

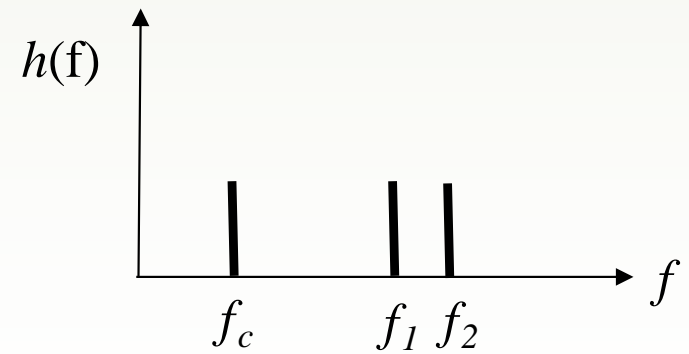
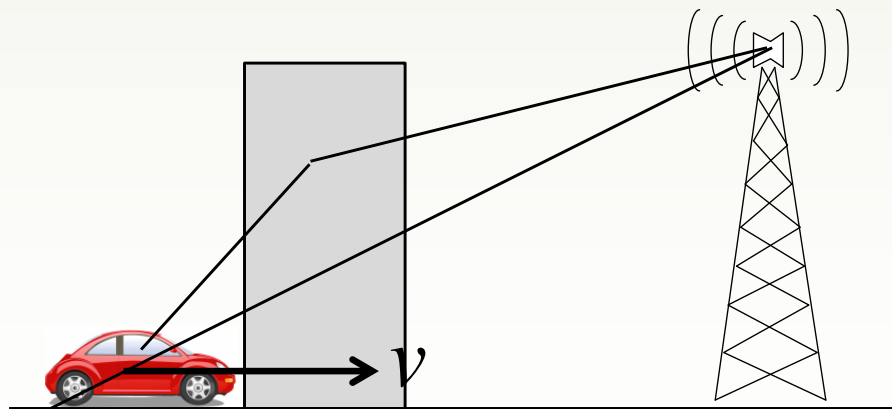
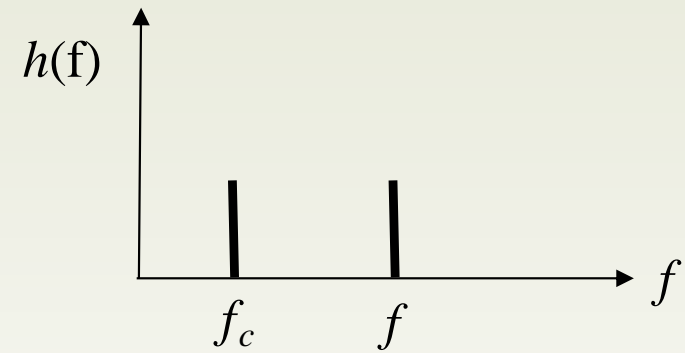
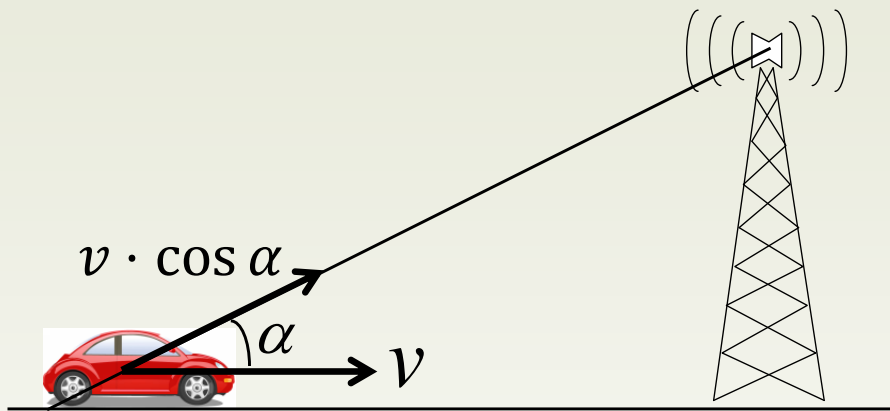


Doppler shift
(frequency shift):

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



Doppler shift from obliquely incident ray

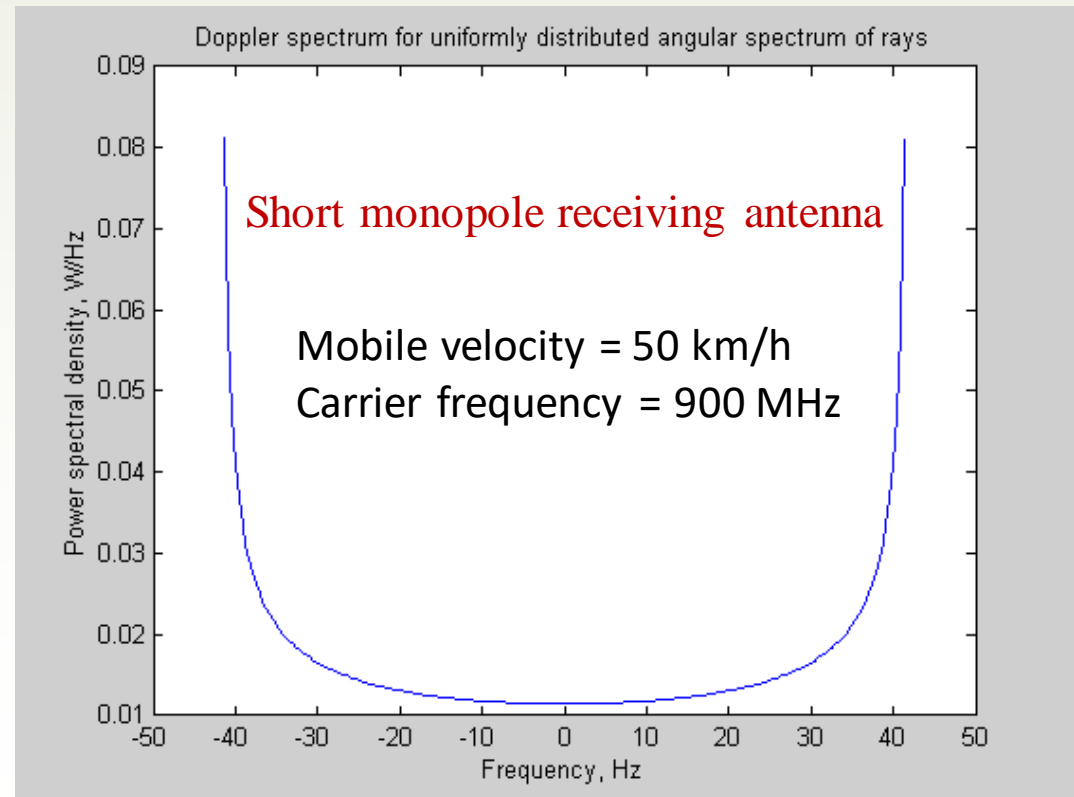
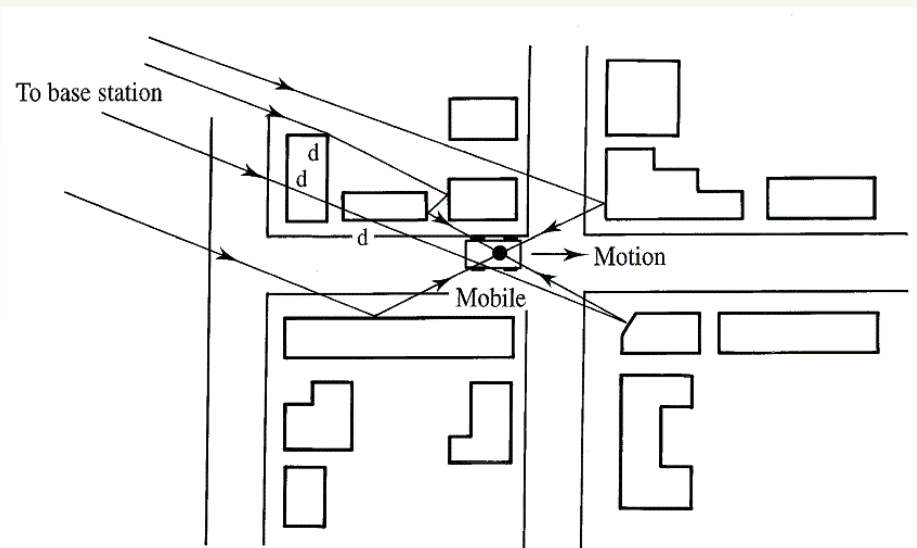


Doppler spectrum

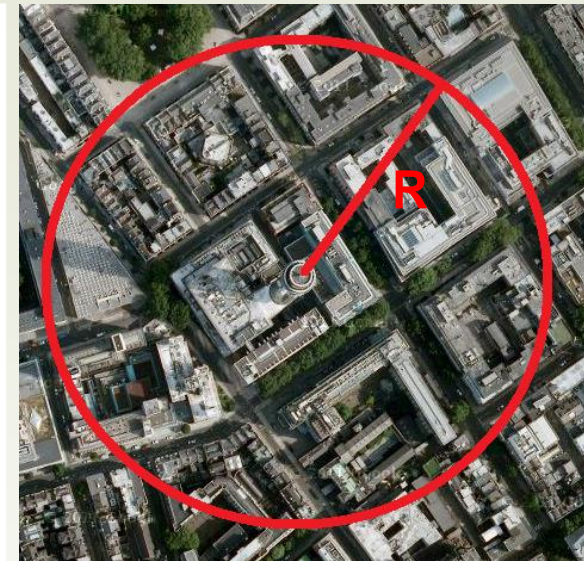
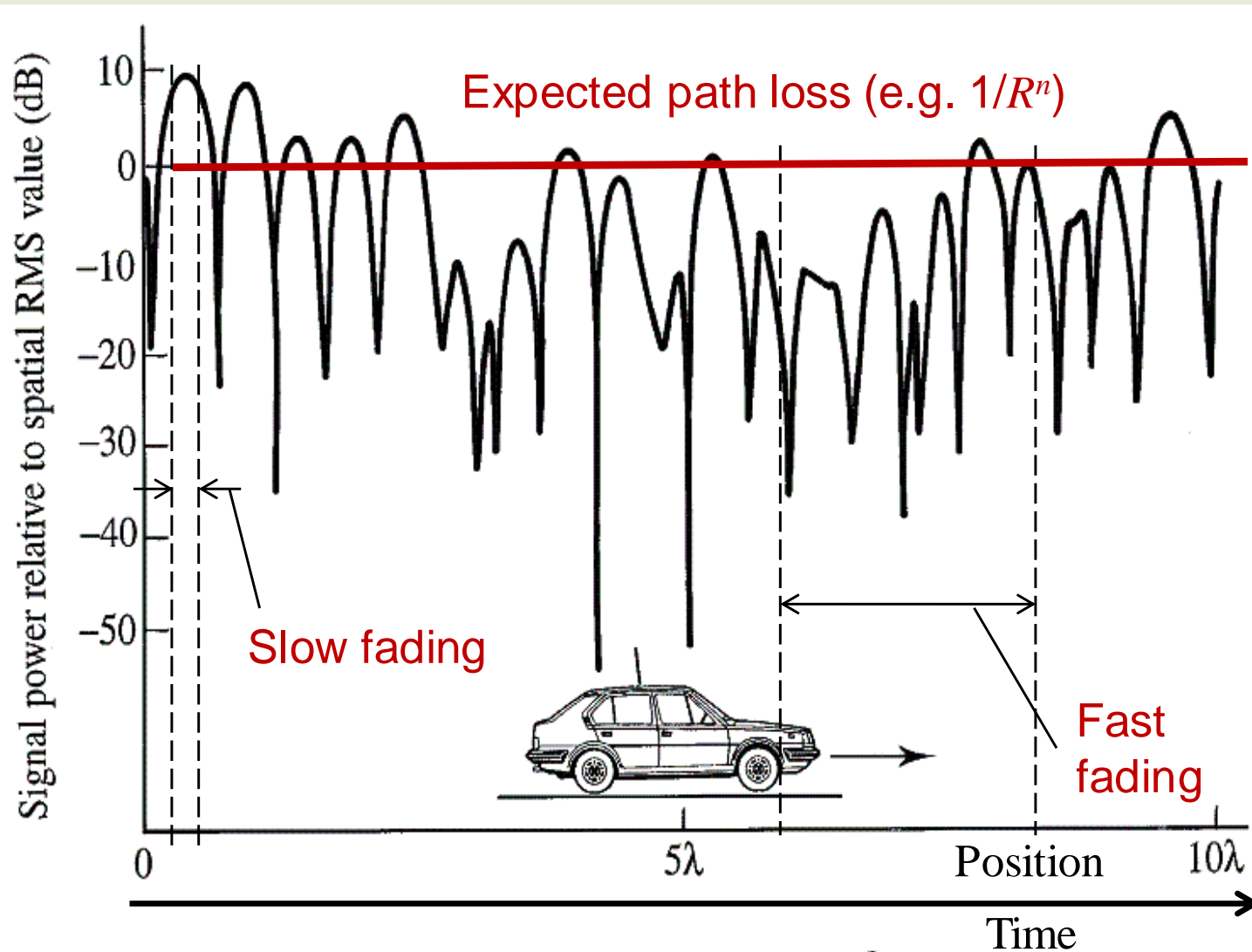
In a multipath with many arriving rays, with uniformly distributed random angles of arrival α , a number of frequency shifted waveforms arrive, with random frequency shifts

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

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

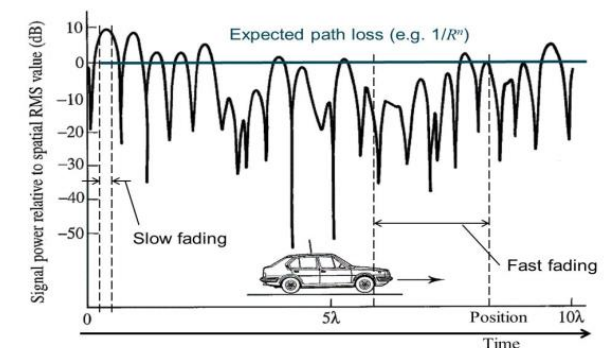
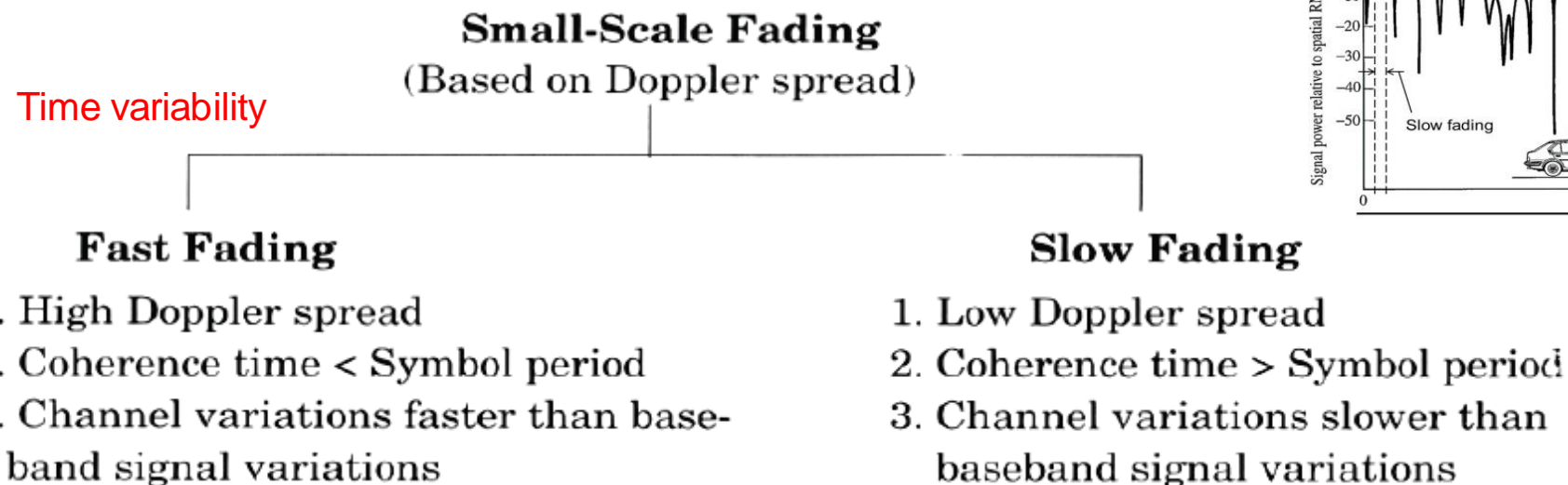
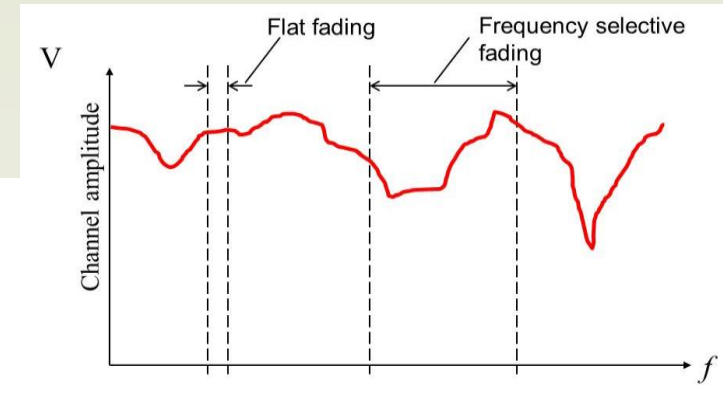
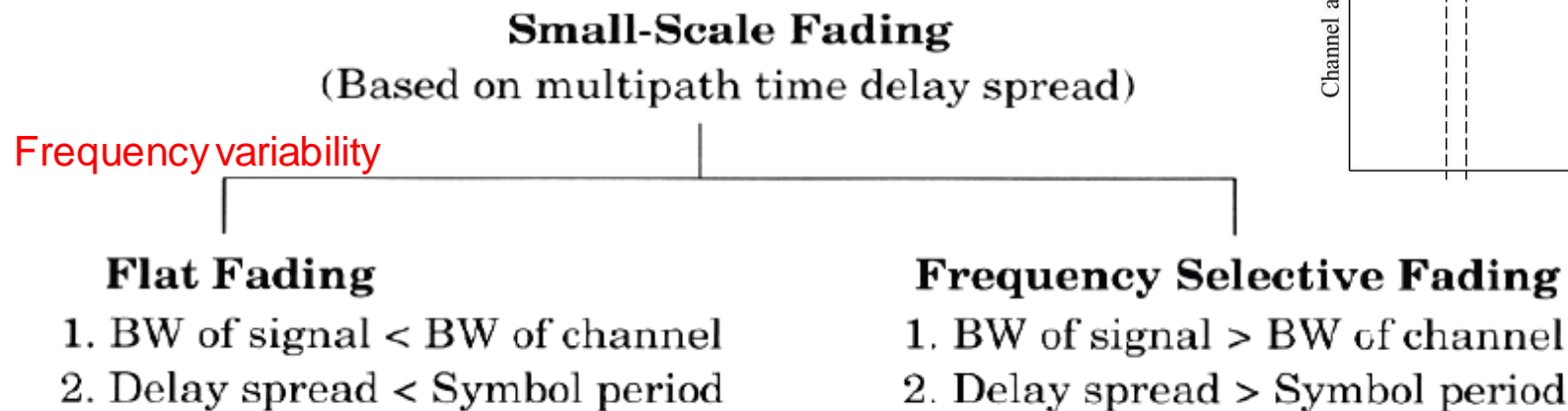


Time-Varying multipath fading

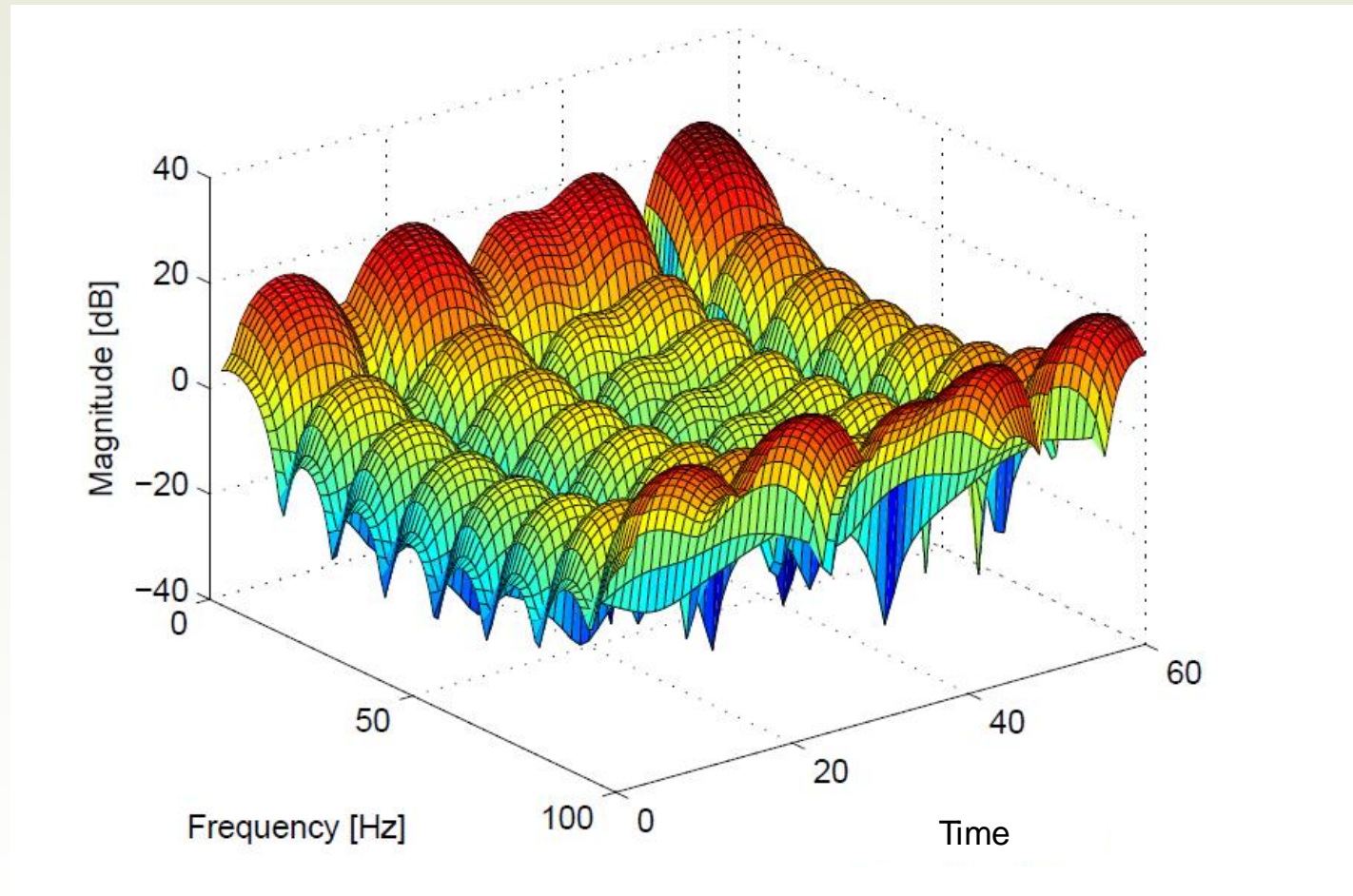


* Fixed range from transmitter R

4 types of fading



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, ($= 1.38 \times 10^{-23}$ Joule/Kelvin)

T : temperature in Kelvin ($0^\circ\text{C} = 273 \text{ K}$) $C = K - 273$

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

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

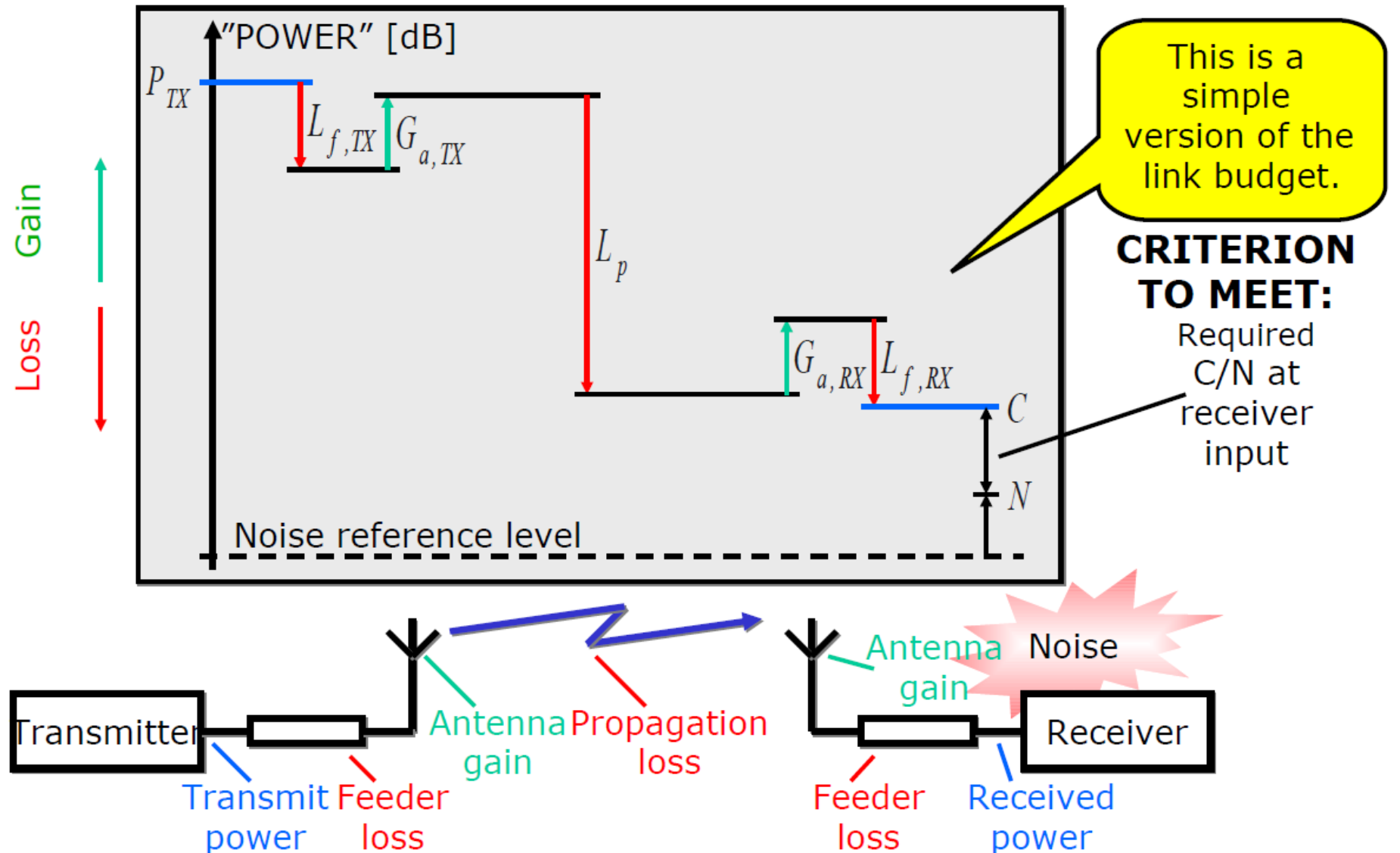
- As an example, consider the above system where the power at the RX was -72 dBW, if the system had a bandwidth of 500 MHz, a NF of 5 dB and was operating at a room temperature (27°C) the SNR would be 40 dB

k : Boltzmann's Constant, ($= 1.38 \times 10^{-23}$ Joule/Kelvin)

T : temperature in Kelvin ($0^{\circ}\text{C} = 273 \text{ K}$)

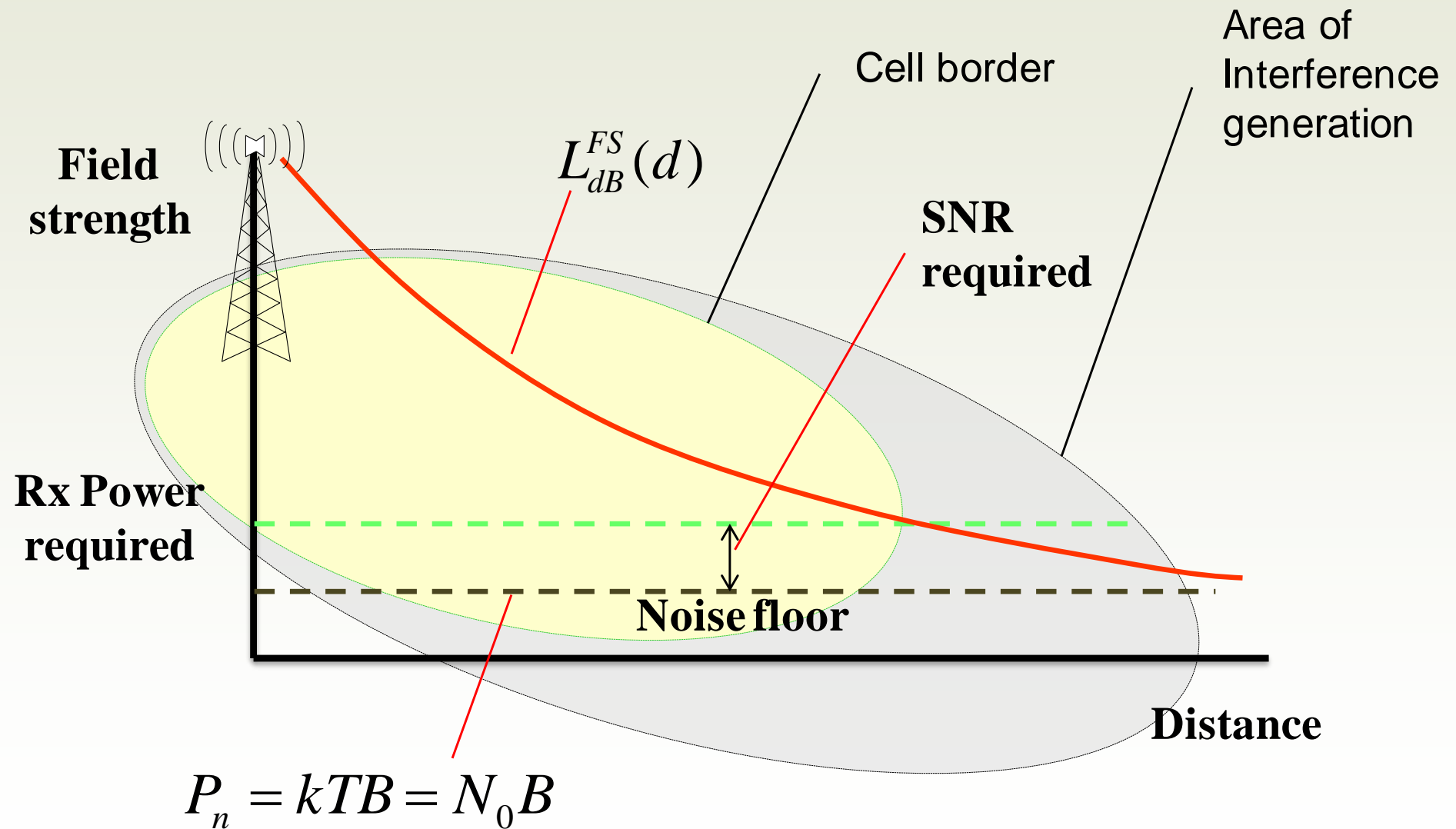
B : Bandwidth (in Hz)

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



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 \rightarrow Probability of error
- Modulation tradeoffs
- MIMO, Satellite Comms