Introduction to wireless systems

Wireless Systems a.a. 2014/2015

Un. of Rome "La Sapienza"

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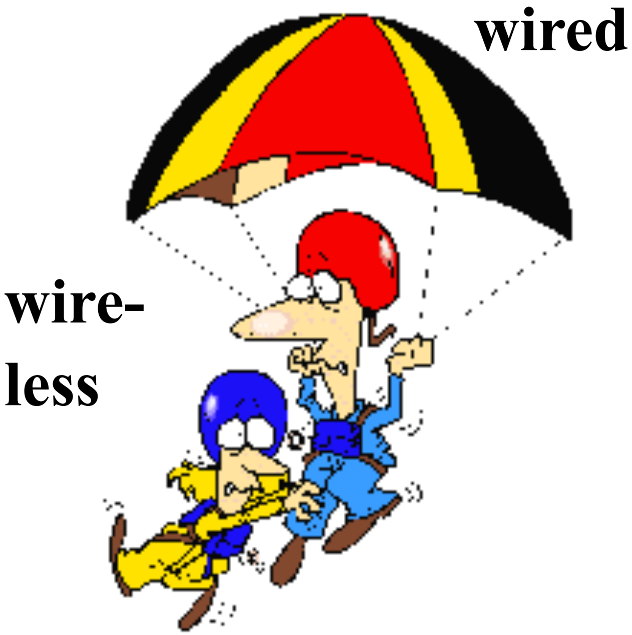
Background-
Wireless Systems

- What is the difference with wired TCP/IP networks? Transmission medium..
  - Unique features of the transmission medium have a big impact on design (e.g., lower reliability, broadcast feature, hidden terminal problems demand for different solutions at the data link and transport layers)
  - Wireless systems have been designed to enable communication anywhere anytime
    - ✓ Mobility must therefore be supported
    - ✓ Portability comes with the fact depends rely on external sources of energy such as batteries to operate

Wireless vs. Wired



Reasons for wireless success:

No cabling

Anywhere/anytime

Cost vs. performance

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Caratteristiche

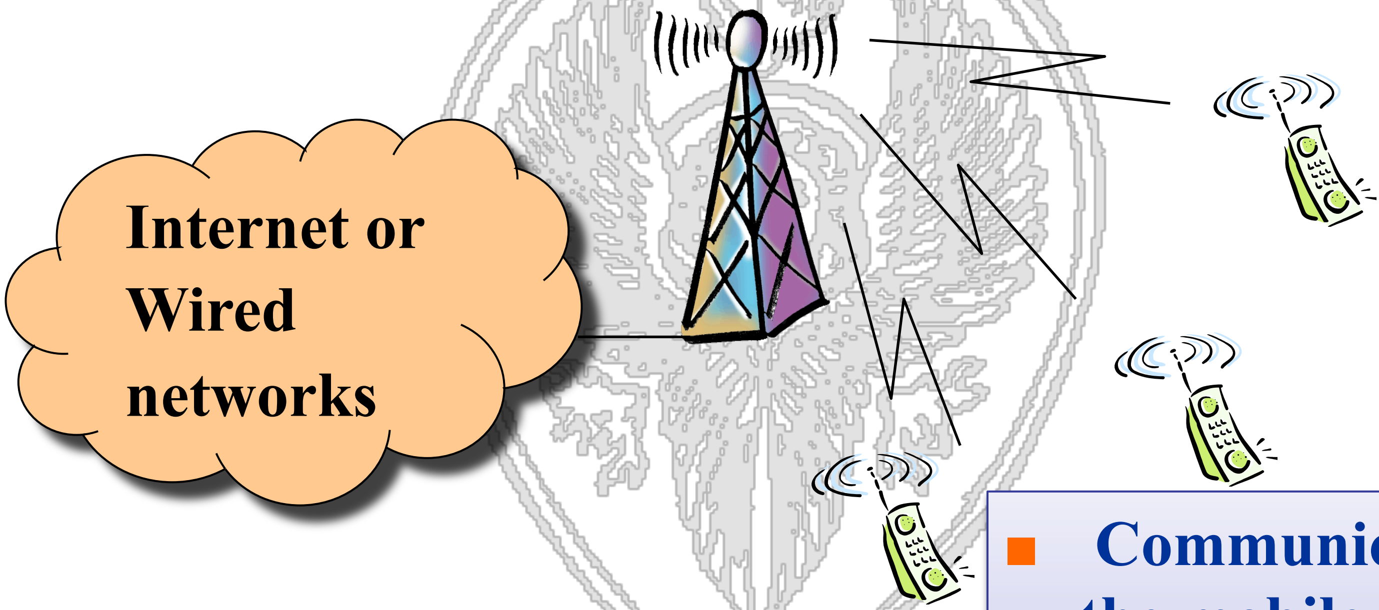
- Broadcast medium- each mobile device transmission is overheard by all other devices within the source 'transmission radius'
  - Poses security challenges
- Shared channel
  - Medium Access Control (MAC)
  - Limited resources must be shared among users
- High bit error rate
  - Error detection, correction & retransmission techniques needed for reliable communication
- Mobility must be supported at design stage
- Portable devices which rely on external sources of energy (batteries) to compute and communicate

  →Low power platforms and energy efficient protocols (green solutions)

  →Computation vs communication trade-offs (e.g., mobile device offloading)

  →Use of HW techniques to limit (wake up radio) energy consumption to the bare minimum and to harvest energy through renewal sources of energy (energy harvesting/scavenging)

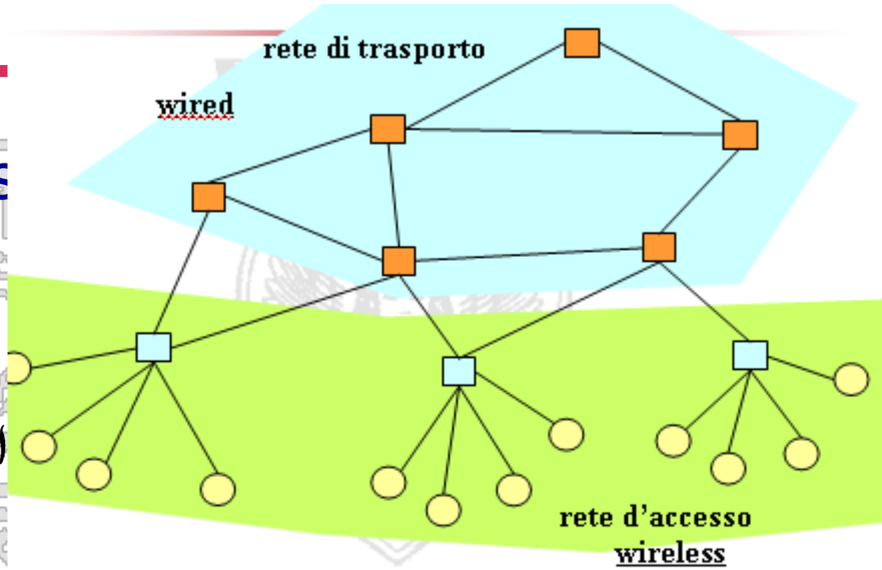
- 1) Infrastructured networks

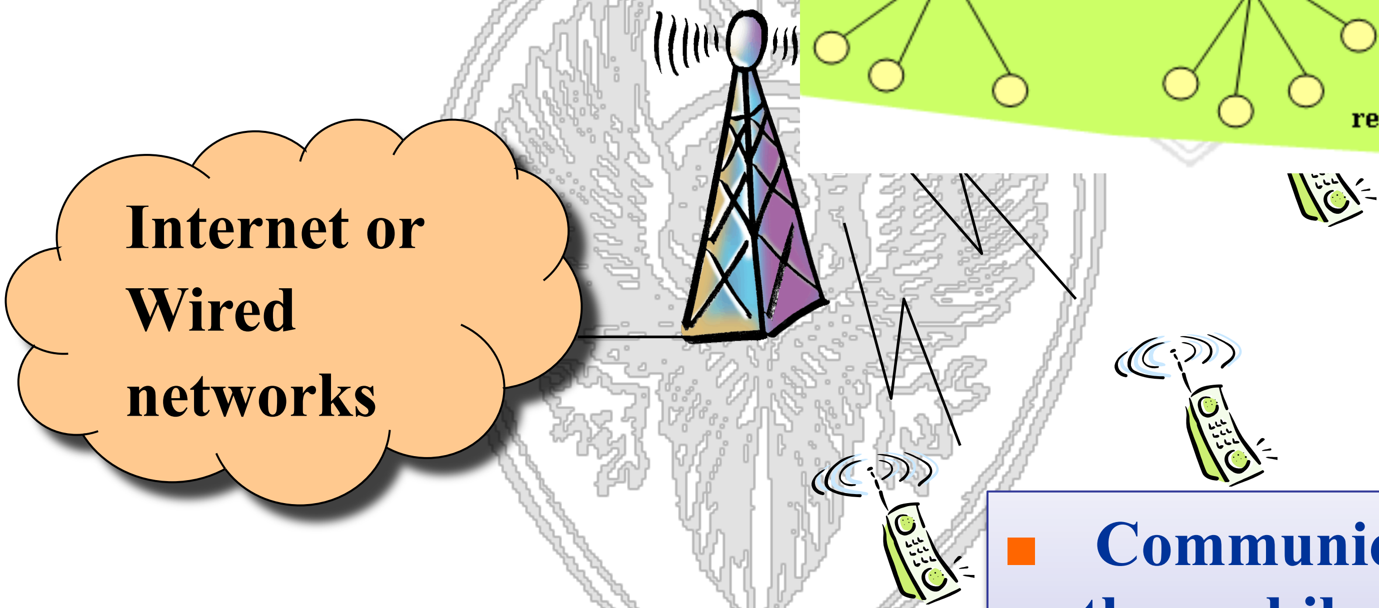


- Communication from the mobile user to the base station/access point and viceversa

Wireless Systems Models

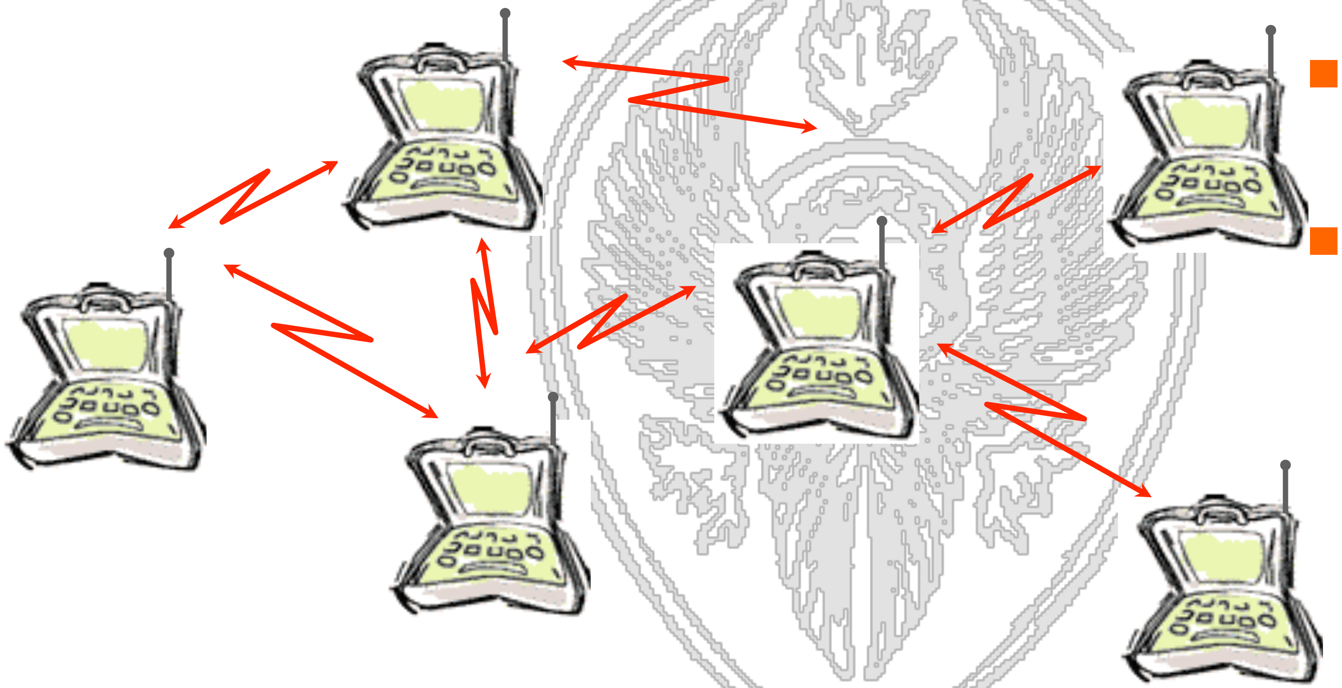
- 1) Infrastructured networks





- **Communication from the mobile user to the base station/access point and viceversa**

- 2) Ad Hoc Wireless Networks (wireless sensor networks, VANET, Mesh Networks,…)



- **Peer to peer communication**
- **Each node can act as source, destination of a packet or as relay**

Transmission Errors

- BER-Bit Error Rate can be significant compared to wired medium
  - Attenuation, reflection, diffraction of the signal + multipath fading

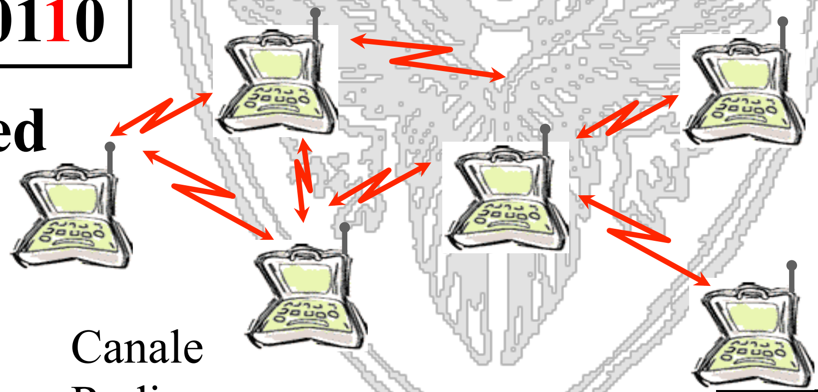
Forward Error Correction

Interleaving

Automatic Repeat Request

100110

◆ **received packet**

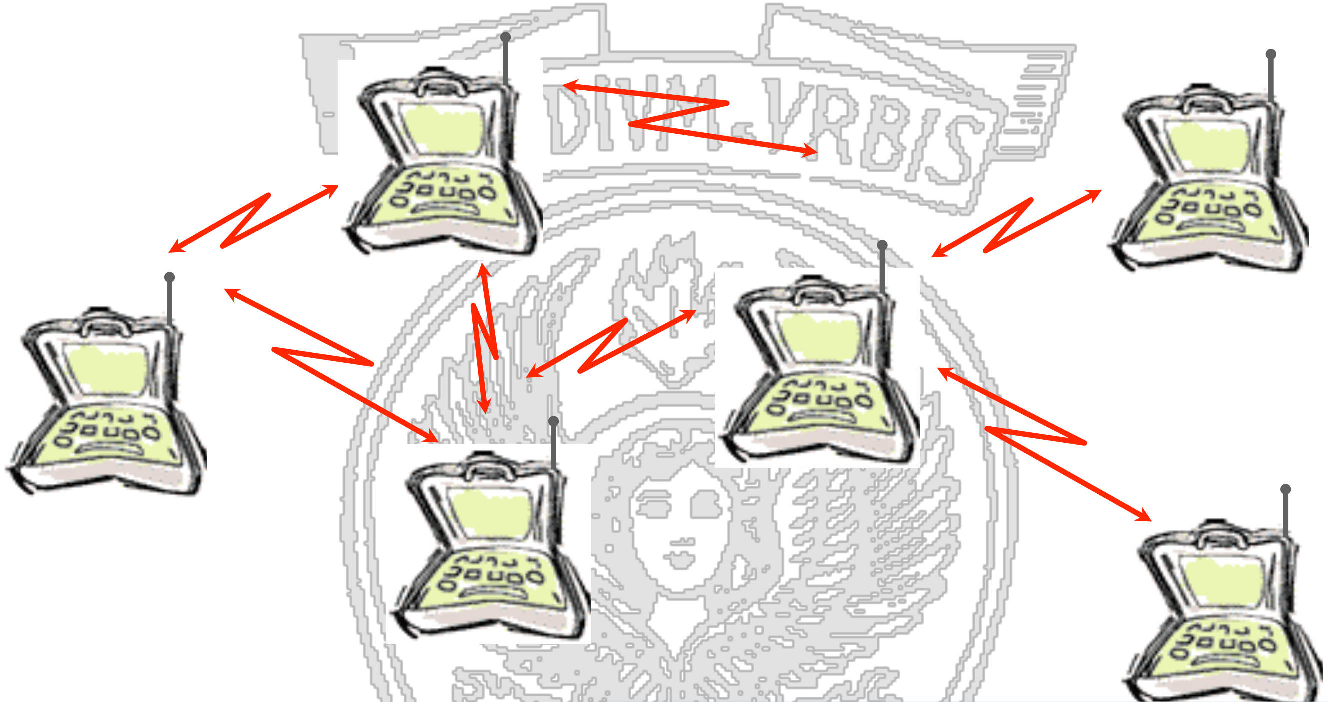


Canale Radio

100100

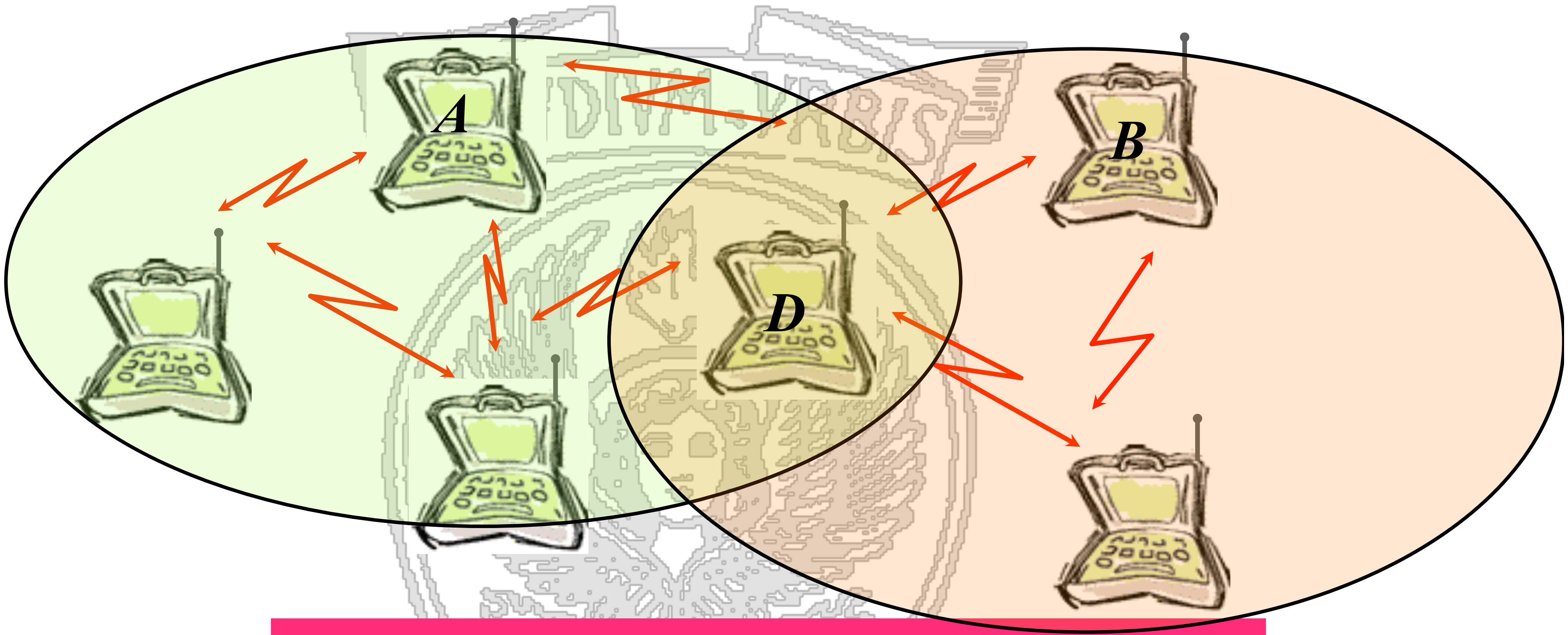
◆ **transmitted packet**

Medium Access Control



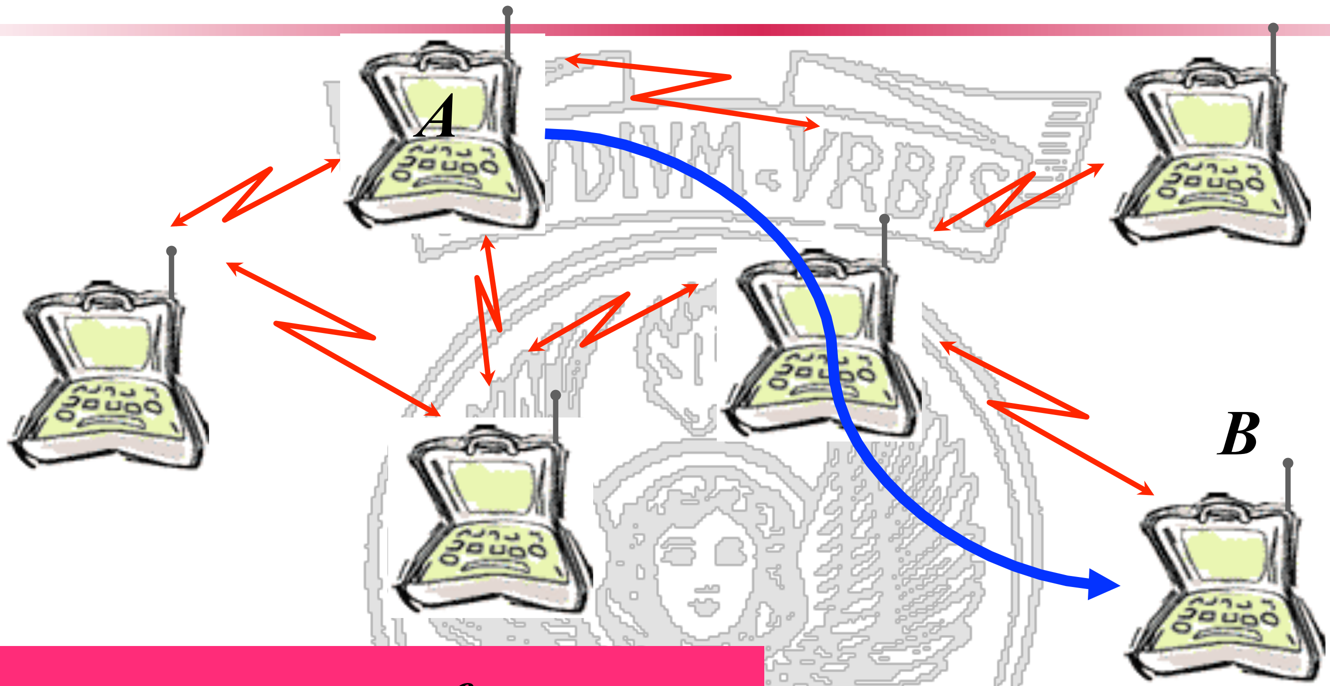
Broadcast channel
Channel access must be arbitrated by a medium access control protocol

Antenna cannot tx and rx simultaneously;
Carrier sense is possible
Collision detection based on ACK/NAK



Hidden terminal
If A and B transmit a packet a collision occurs in D. Neither A nor B can detect such collision directly.

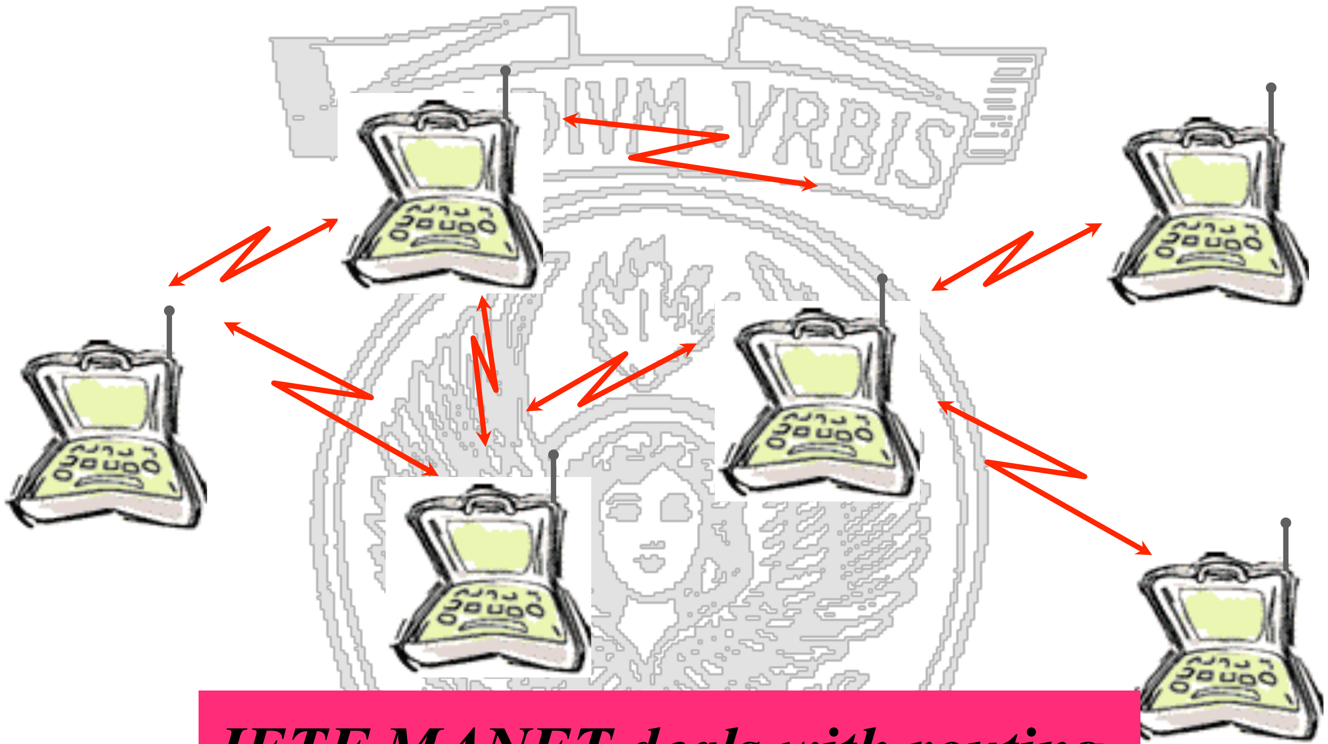
Routing



Routing must account for mobility, dynamicity (e.g., due to varying link quality and nodes alternating between ON and OFF states) and different resources available at the nodes

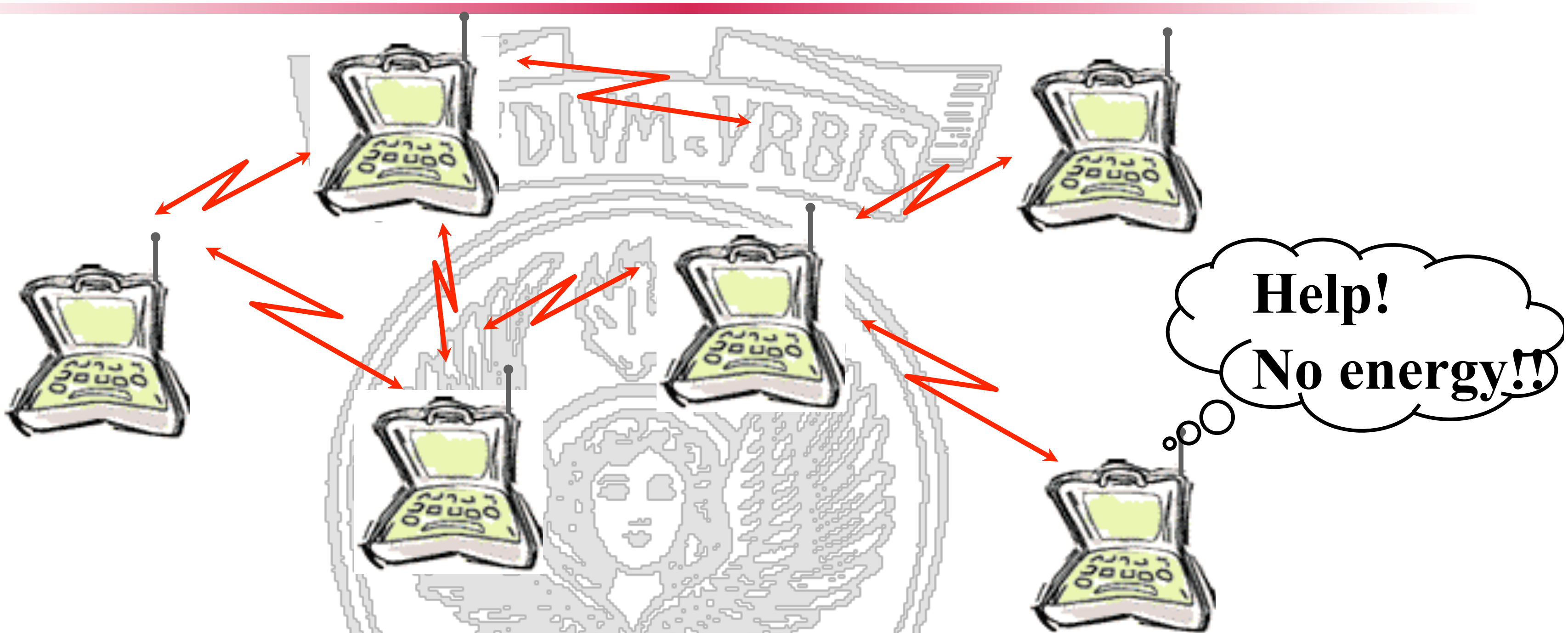
What's the best path between A and B (routing)?

Ad Hoc Networks-Challenges



IETF MANET deals with routing
<u>One of the peculiar aspects introduced by mobile peer to peer ad hoc networking</u>

Ad Hoc Networks-Challenges



Energy efficient solutions at all different layers of the protocol stack: power control, MAC, data link, routing, trasport

How to route packets to minimize energy consumption accounting for the different node residual energy

Introduction

- Backrgound needed to understand the motivations behind current wireless systems design

- Wireless Channel & Signal Propagation – Basic Concepts

- Energy efficient comms. techniques

- Channel Access problems

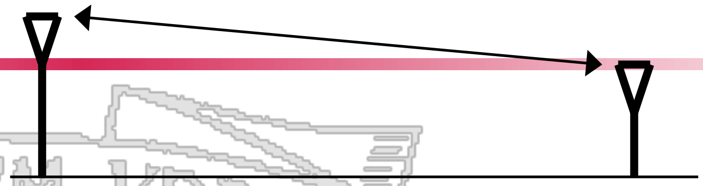
- Mobility management

Wireless channel

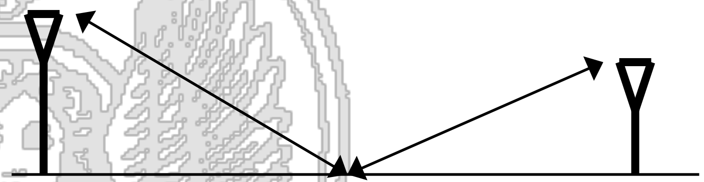
- Much less reliable than wired channels
- While propagating the signal can face
  - Attenuation as function of the distance from transmitter and receiver
  - Attenuation due to obstacles
  - Propagation over multiple paths (resulting in multipath fading)

Signal propagation: challenges

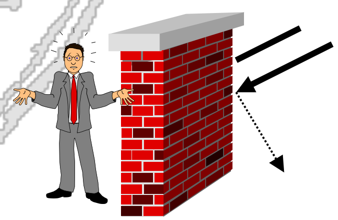
- Line of sight



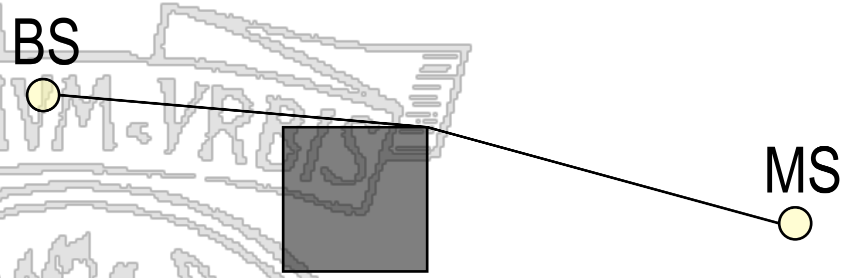
- Reflection



- Shadowing

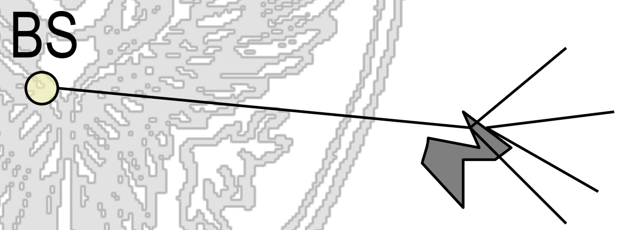


➔Diffraction

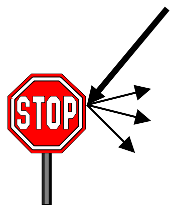


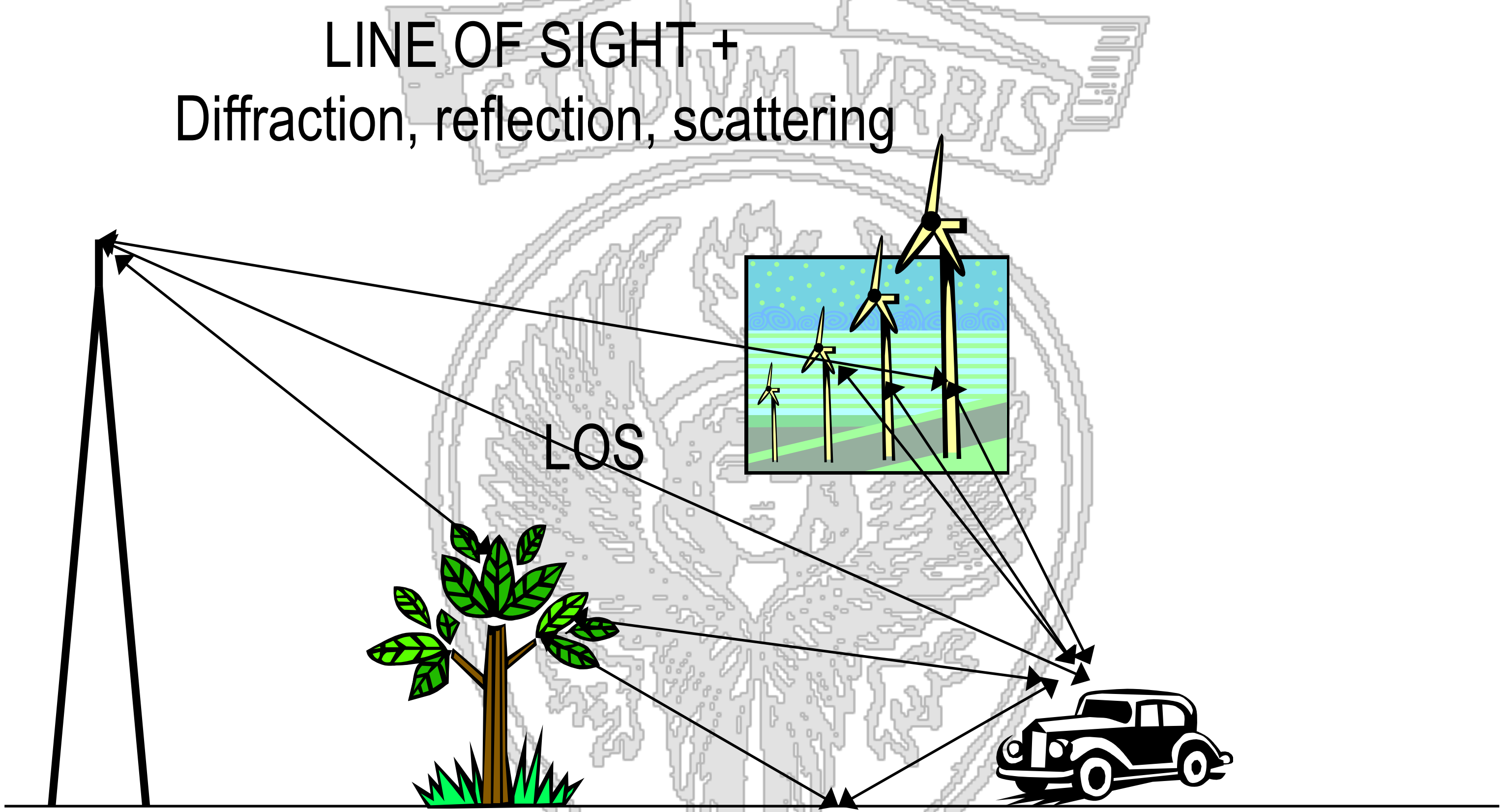
- ➔ When the surface encountered has sharp edges ➔ bending the wave

➔Scattering



- ➔ When the wave encounters objects smaller than the wavelength (vegetation, clouds, street signs)

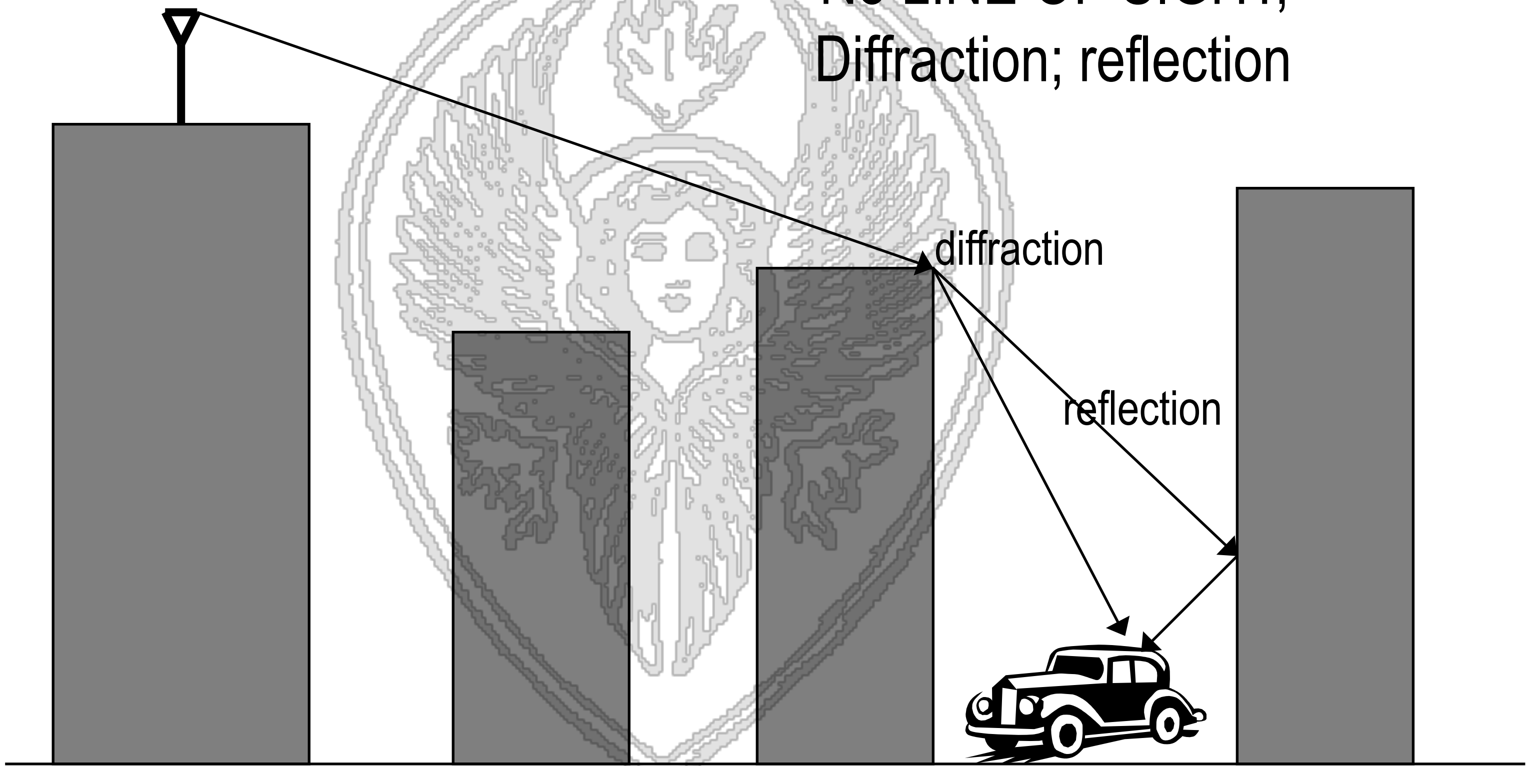



LINE OF SIGHT +
Diffraction, reflection, scattering
LOS

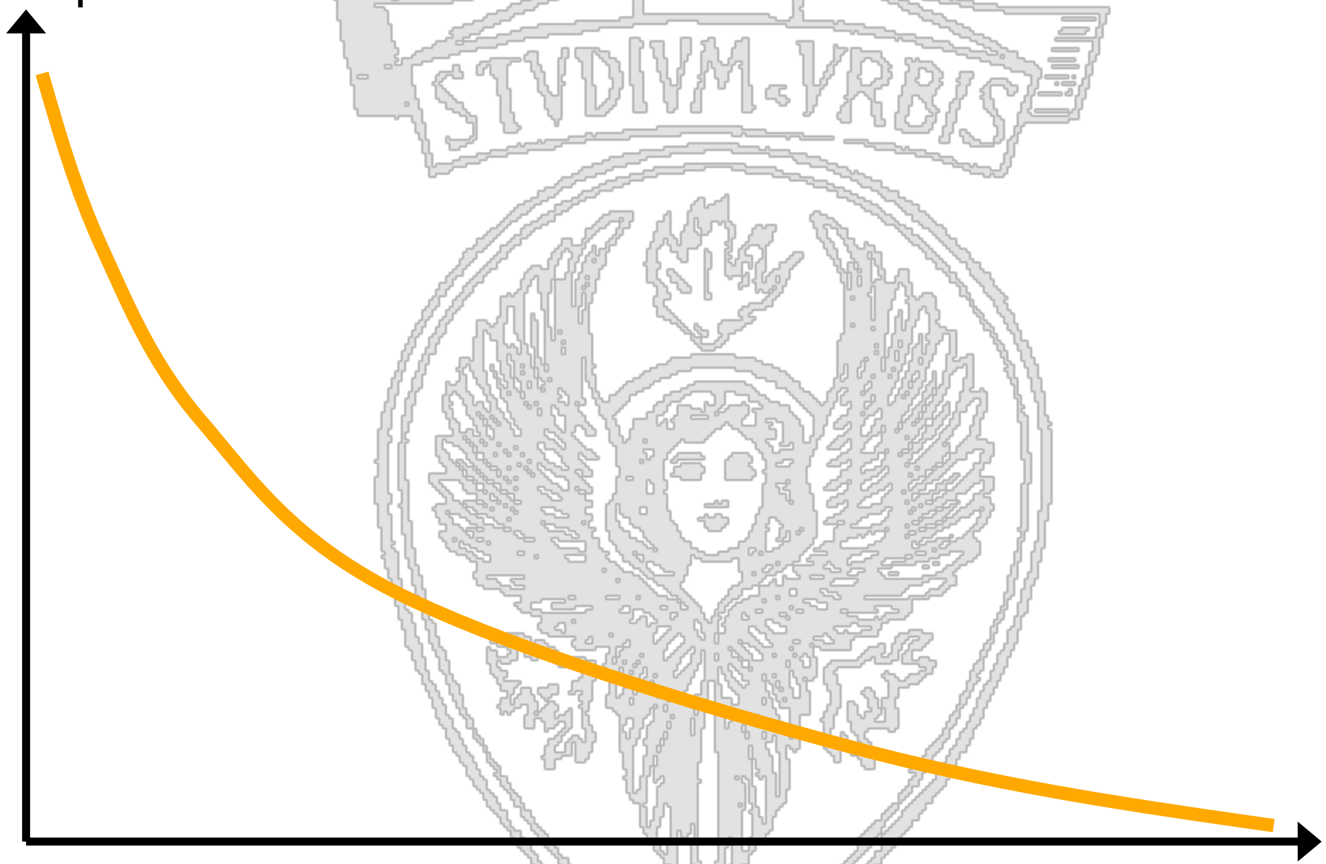
Example scenarios

LOS path non necessarily existing (and unique)

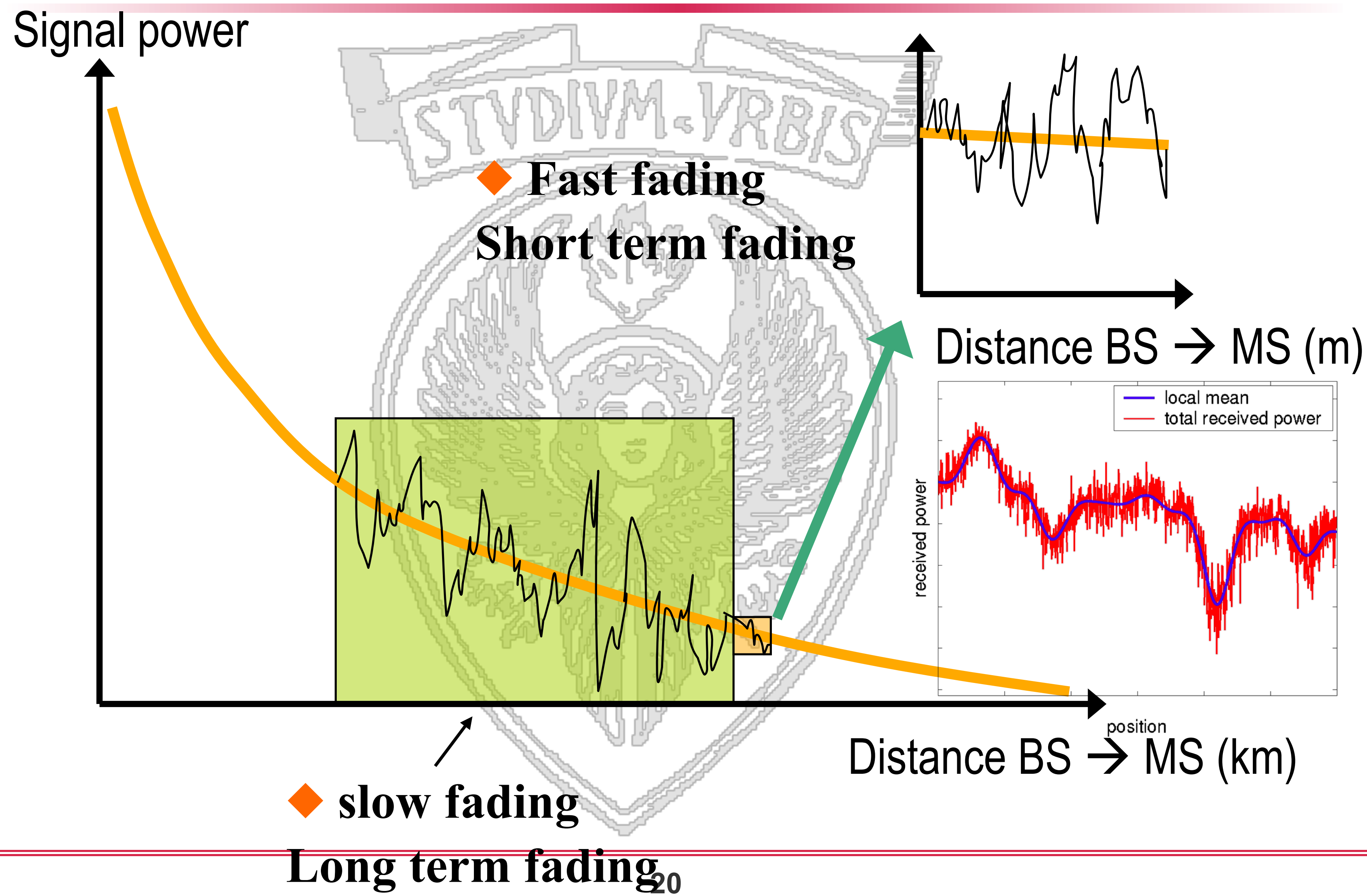
Example: city with large buildings;
No LINE OF SIGHT;
Diffraction; reflection



Signal attenuation

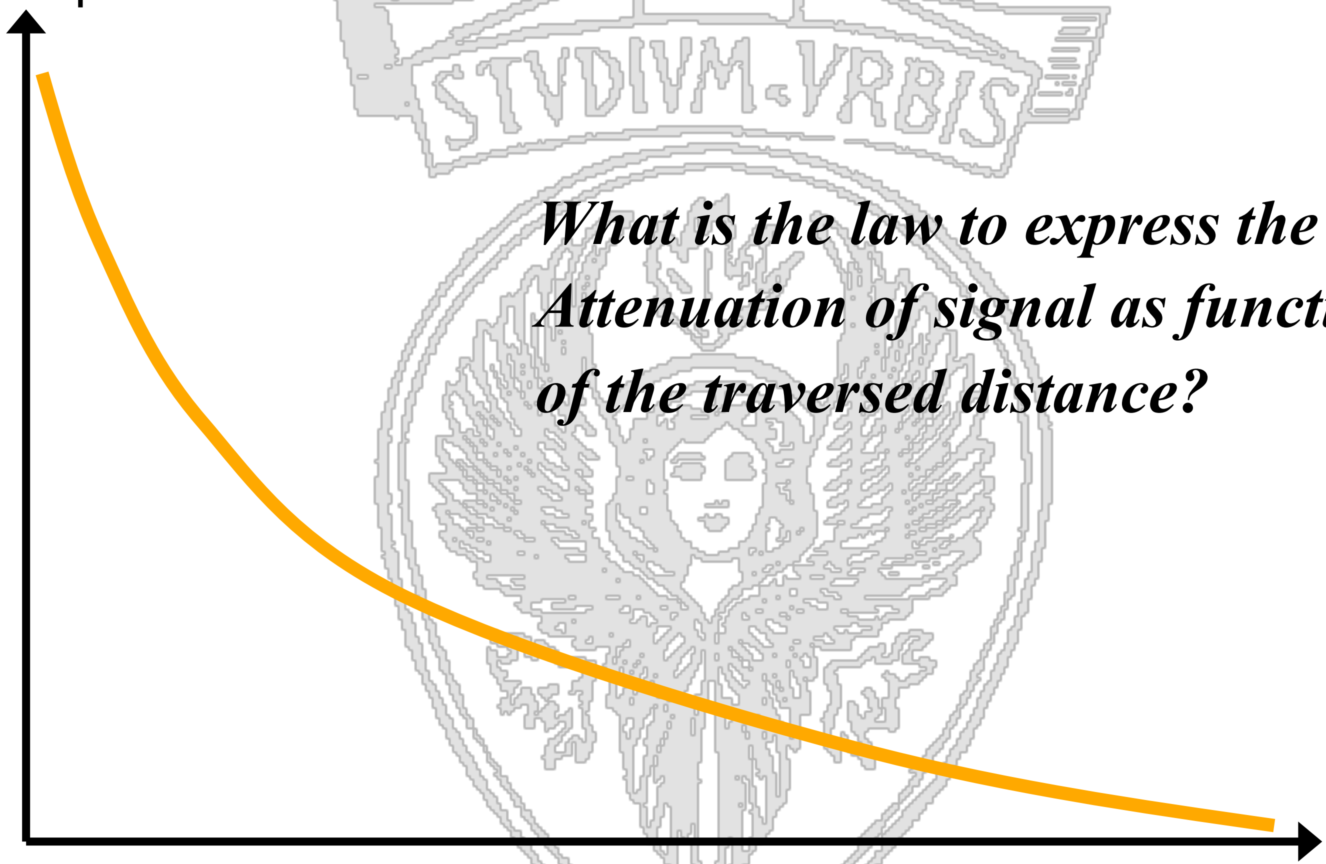


Slow fading – fast fading



Signal attenuation

Signal power

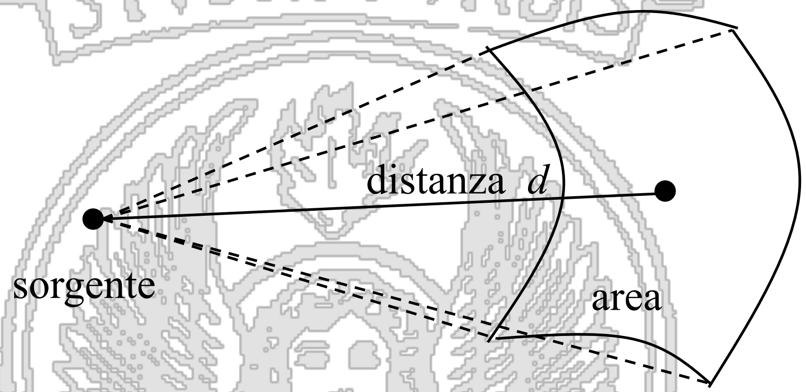


Distance BS → MS

What is the law to express the Attenuation of signal as function of the traversed distance?

Signal attenuation

- Assumption: A point source emits the signal uniformly in all directions (isotropic radiator) with a transmission power P_T

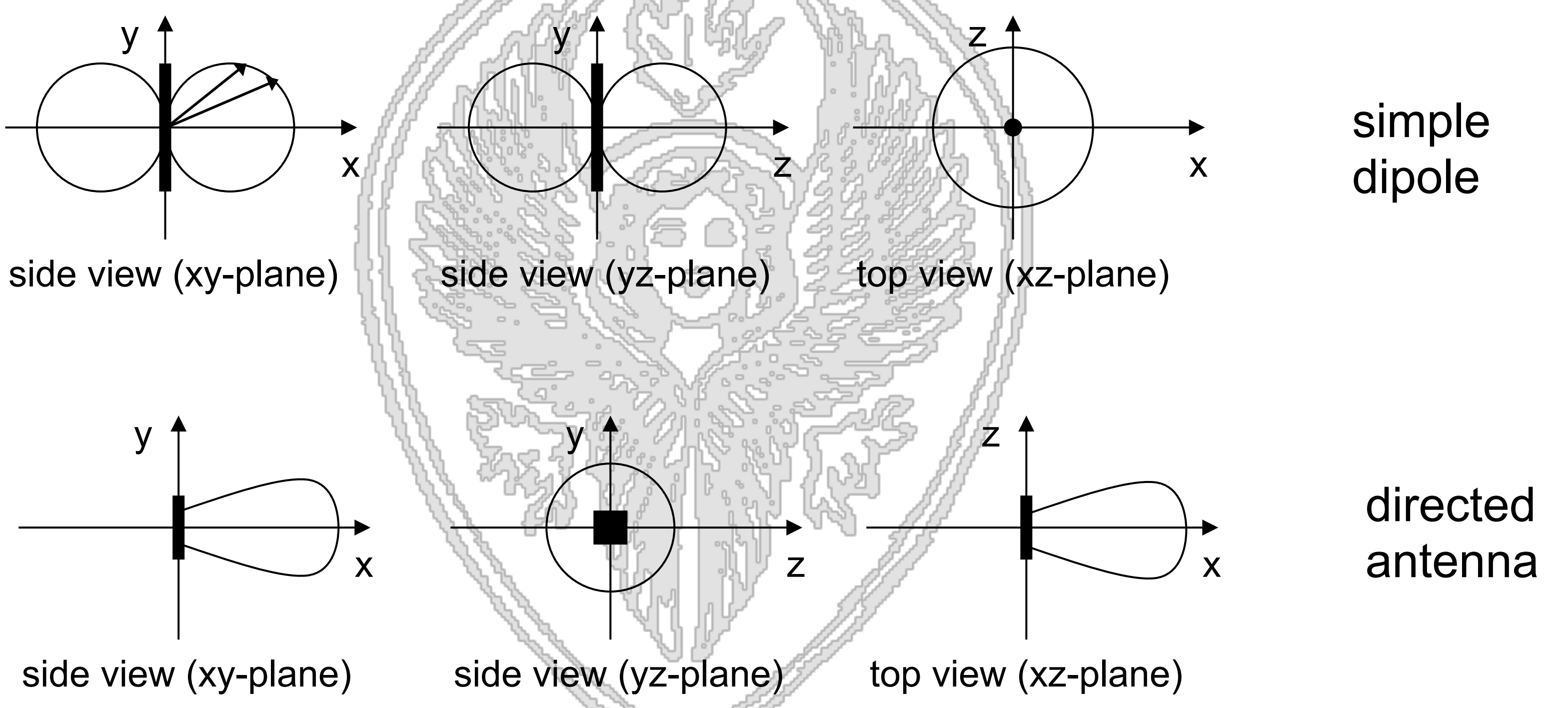


- The power density at distance d is equal to the ratio between the transmission power and the surface area of a sphere centered in the source and with radius d:

$$F = \frac{P_T}{4\pi d^2} \quad [\mathrm{W/m^2}]$$

Antenna types

- Graphical representation of radiation properties of an antenna
- Depicted as two-dimensional cross section



Antenna Gain

- Isotropic antenna (idealized)
  - Radiates power equally in all directions (3D)
  - Real antennas always have directive effects (vertically and/or horizontally)
- Antenna gain
  - Power output, in a particular direction, compared to that produced in any direction by a perfect omni-directional antenna (isotropic antenna)

$$\text{Directivity D} = \frac{\text{power density at a distance d in the direction of maximum radiation}}{\text{mean power density at a distance d}}$$

$$\text{Gain G} = \frac{\text{power density at a distance d in the direction of maximum radiation}}{P_T / 4\pi d^2}$$

- Directional antennas "point" energy in a particular direction
  - Better received signal strength
  - Less interference to other receivers
  - More complex antennas

Wireless channel: attenuation wrt distance

- Let g_T *be* the maximum transmission gain. The received power density in the direction of maximum radiation is given by:

$$F = \frac{P_T g_T}{4\pi d^2} \quad [\mathrm{W/m^2}]$$

- $P_T \, g_T$ is the EIRP (Effective Isotropically Radiated Power) and represents the power at which an isotropic radiator should transmit to reach the same power density of the directional antenna at distance d

Canale wireless: attenuazione da distanza

- The power received by a receiver at distance d from the source, in case of no obstacles and LOS, can be expressed as:

Friis transmission equation

$$P_R = P_T g_T g_R \left(\frac{\lambda}{4\pi d} \right)^2 \frac{\mathbf{1}}{\mathbf{L}}$$

- where P_T is the transmitter radiated power, g_T and g_R the gains og the transmitter and receiver antennas, λ is the wavelength (c/f) and d the distance between the transmitter and the receiver. Finally, parameter L>1 accounts for HW losses.

Power units - decibel

- Decibel (dB): expresses according to a logarithmic scale a ratio among powers

$$10\log\left(P_1 / P_2\right)$$

Log= base-10 logarithm
P_A = 1 Watt
P_B = 1 milliWatt
30 dB→ PA = three orders of magnitudes higher than P_B

◆**Gain of an antenna is expressed in dB**

3dB (una potenza e' il doppio dell'altra), 10dB→ un ordine di grandezza di differenza, 20dB due ordini di grandezza, 30db tre ordini di grandezza

Decibels - dBm

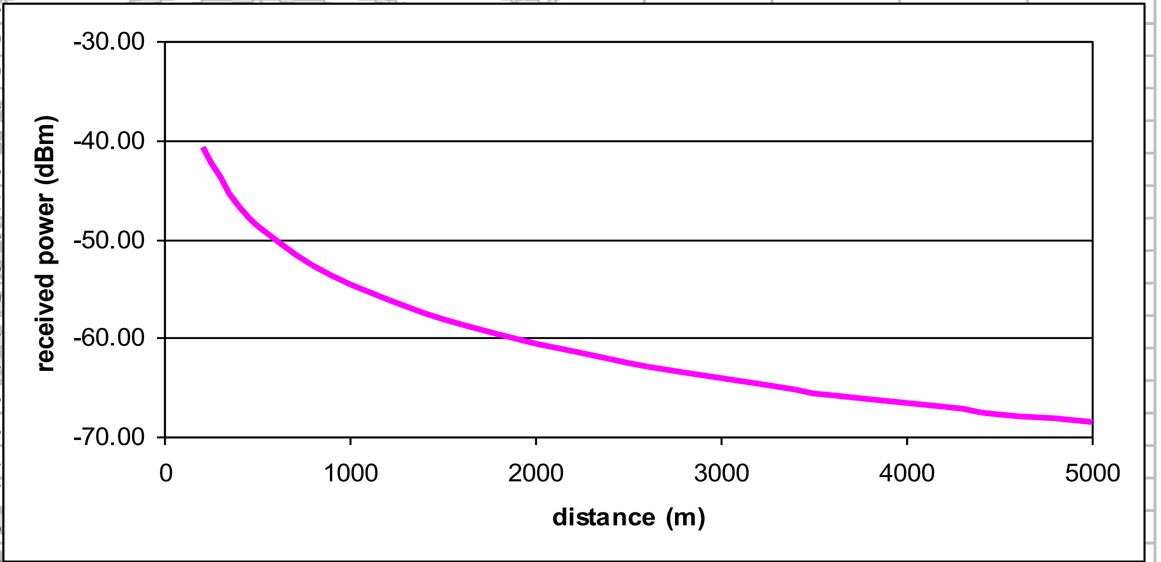
- dBm = ratio between the power and a nominal power of 1mW
  - Power in dBm = 10 log(power/1mW)
  - Power in dBW = 10 log(power/1W)

  Example
  - 10 mW = 10 $\log_{10}$(0.01/0.001) = 10 dBm
  - 10 μW = 10 $\log_{10}$(0.00001/0.001) = -20 dBm
  - S/N ratio = -3dB → S = circa 1/2 N
- Properties & conversions
  - P(dBm) = 10 $\log_{10}$(P (W) / 1 mW) = P (dBW) + 30 dBm
  - (P1 * P2) (dBm) = P1 (dBm) + P2 (dBW)

    P1 * P2 (dBm) = 10 $\log_{10}$(P1(W)*P2 (W)/0.001) = 10$\log_{10}$(P1(W)/0.001) + 10 $\log_{10}$P2(W) = P1 (dBm) + P2 (dBW)

Example

		normalized
frequency [MHz]	900	900000000
speed of light [K	300000	300000000
lambda (m)		0.333333333
gain Tx	1	
Gain Rx	1	
Loss	1	
Ptx [W]	5	
distance (Km)	Prx W	Prx dBm
200	8.80E-08	-40.56
400	2.20E-08	-46.58
600	9.77E-09	-50.10
800	5.50E-09	-52.60
1000	3.52E-09	-54.54
1200	2.44E-09	-56.12
1400	1.79E-09	-57.46
1600	1.37E-09	-58.62
1800	1.09E-09	-59.64
2000	8.80E-10	-60.56
2200	7.27E-10	-61.39
2400	6.11E-10	-62.14
2600	5.20E-10	-62.84
2800	4.49E-10	-63.48
3000	3.91E-10	-64.08
3200	3.44E-10	-64.64
3400	3.04E-10	-65.17
3600	2.71E-10	-65.66
3800	2.44E-10	-66.13
4000	2.20E-10	-66.58
4200	1.99E-10	-67.00
4400	1.82E-10	-67.41
4600	1.66E-10	-67.79
4800	1.53E-10	-68.16
5000	1.41E-10	-68.52



Computation with dB

- Transmit power
  - Measured in dBm
    - Es. 33 dBm
- Receive Power
  - Measured in dBm
    - Es. –10 dBm
- Path Loss
  - Transmit power / Receive power
  - Measured in dB
  - Loss (dB) = transmit (dBm) – receive (dBm)
    - Es. 43 dB = attenuation by factor 20.000

⇒ *If received power is below a given threshold info. cannot be correctly received*

- Path Loss

$$PL = \left(\frac{\lambda}{4\pi d}\right)^{-2}$$

- **Represents free space path loss, due to geometric spreading.**
- **Other attenuations are introduced by obstacles (reflections, diffraction, scattering etc.) and by atmosphere absorption (depending on frequency, water vapor etc).**

Wireless channel-path loss

- Path Loss

$$PL = \left(\frac{\lambda}{4\pi d}\right)^{-2}$$

$$\frac{P_T}{P_R} = \frac{P_T}{P_T g_T g_R \left(\frac{\lambda}{4\pi d}\right)^2 \frac{1}{L}}$$

$$if$$

$$g_T, g_R, L = 1$$

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

Path loss (propagation loss) in dB

Indicata anche con L_{free} nel seguito

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

$= 20$ ...

$= 20$ ... $\log_{10}\frac{c}{4\pi} =$

$= 20$ ... 7.56

$$\frac{P_T}{P_R} = \frac{P_T}{P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \frac{1}{L}}$$

Path loss (propagation loss) in dB (formula generale)

Indicata anche con L_{free} nel seguito

$$PL(d)_{[dB]} = 10\log_{10}\frac{P_t}{P_r} = 10\log_{10}\left\{\frac{L}{G_tG_r}\left(\frac{4\pi d}{\lambda}\right)^2\right\} =$$

$$= 20\log_{10} d - 10\log_{10}\frac{G_tG_r}{L} - 20\log_{10}\frac{\lambda}{4\pi} =$$

$$= 20\log_{10} d + 20\log_{10} f - 10\log_{10}\frac{G_tG_r}{L} - 20\log_{10}\frac{c}{4\pi} =$$

$$= 20\log_{10} d + 20\log_{10} f - 10\log_{10}\frac{G_tG_r}{L} - 147.56$$

It depends on distance but also on frequency

Free space loss

If L=1, gains=1

$$L_{free}(d) = \left(\frac{\lambda}{4\pi d} \right)^{-2}$$

$$L_{free}(d)_{[dB]} = -20\log\left[\frac{\lambda}{4\pi d}\right] = -20\log\left[\frac{c/f}{4\pi d}\right]$$

$$= 20\log_{10} d + 20\log_{10} f - 147.56$$

- **Further comments on Friis transmission equation**

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

L=1

If we know the value at a reference distance d_{ref}…

$P_R(d) = P_R(d_{ref})\ (d_{ref}/d)^2$

$P_R(d)$ dBm= $P_R(d_{ref})$dBm +20 $\log_{10} (d_{ref}/d)$

- $$P_R = P_T g_T g_R \left(\frac{\lambda}{4\pi d} \right)^2$$ ***L=1***

If we know the value at a reference distance d_{ref}…

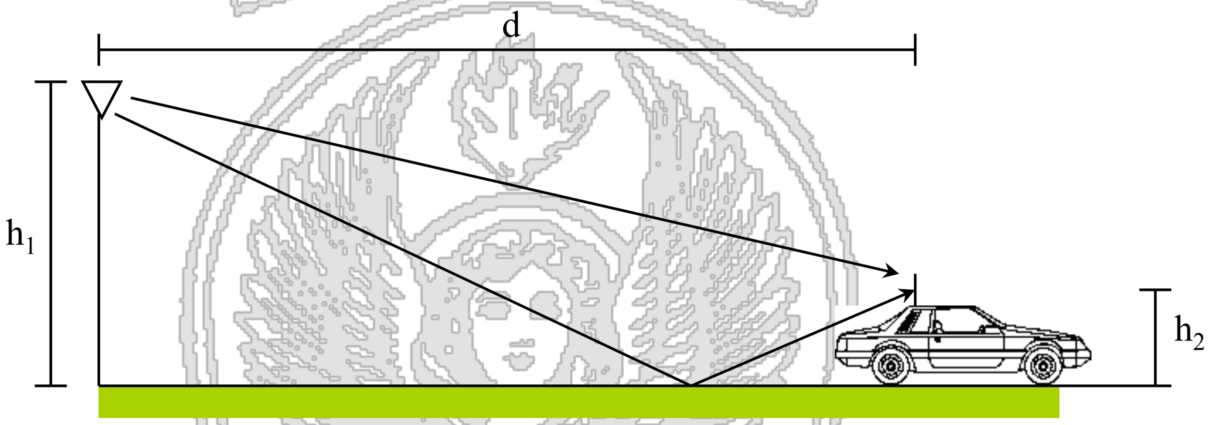
$P_R(d) = P_R(d_{ref})\ (d_{ref}/d)^2$

$P_R(d)$ dBm= $P_R(d_{ref})$dBm +20 $\log_{10} (d_{ref}/d)$

$$\frac{P_R(d)}{P_R(d_{Ref})} = \frac{P_T g_T g_R \left(\frac{\lambda}{4\pi d} \right)^2 \frac{1}{L}}{P_T g_T g_R \left(\frac{\lambda}{4\pi d_{Ref}} \right)^2 \frac{1}{L}} = \left(\frac{d_{Ref}}{d} \right)^2$$

Wireless channel- Two ray propagation model

- In case signal propagates over LOS and one reflected ray..



...the ratio between received power and transmitted power takes the following form:

$$\frac{P_R}{P_T} = g_R g_T \left(\frac{h_1 h_2}{d^2} \right)^2$$

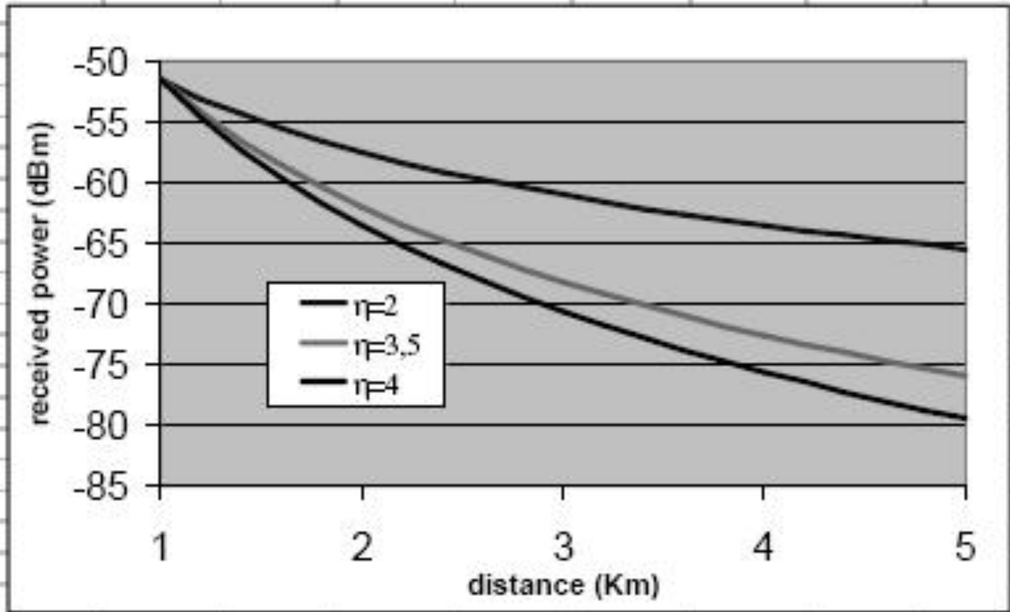
- In the two ray model the received power decreases much faster with distance (~1/d^4) than in the free space model (~1/d^2)
- Real life signal propagation is much more complex than what represented by the two models
- However, mean received power can be often expressed with a generalization of the Friis transmission equation (where the propagation coefficient is η instead of 2) . The propagation coefficient typically assumes values between 2 and 5 (as determined as a function of the propagation environment by empirical studies and models)

$$P_R = P_T g_T g_R \left(\frac{\lambda}{4\pi} \right)^2 \frac{1}{d^\eta}$$

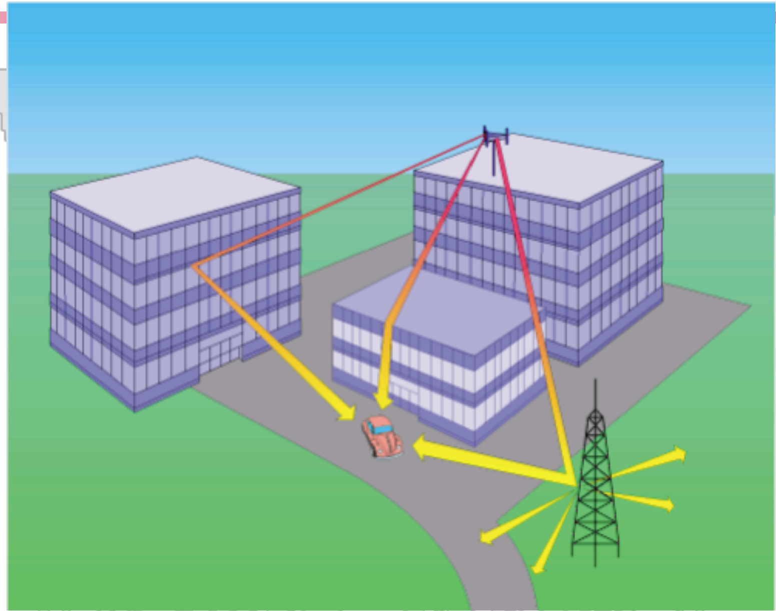
Extended formula

$$P_r(d)(dB) = 10\log_{10} P_r(d_o) + 10\eta \log_{10}\left(\frac{d_o}{d}\right)$$

d_ref	1	Km	
P_ref	-51,5266	dBm	(Ptx=10W; 900 MHz; 1000m)
distance	prx (eta=2	prx (eta=3,5)	prx (eta=4)
1	-51,5266	-51,5266206	-51,5266
1,2	-53,1102	-54,2979642	-54,6939
1,4	-54,4492	-56,6411018	-57,3717
1,6	-55,609	-58,67082	-59,6914
1,8	-56,6321	-60,4611582	-61,7375
2	-57,5472	-62,0626704	-63,5678
2,2	-58,3751	-63,5114144	-65,2235
2,4	-59,1308	-64,834014	-66,7351
2,6	-59,8261	-66,0506877	-68,1256
2,8	-60,4698	-67,1771517	-69,4129
3	-61,069	-68,2258645	-70,6115
3,2	-61,6296	-69,2068698	-71,7326
3,4	-62,1562	-70,1283827	-72,7858
3,6	-62,6527	-70,9972081	-73,7787
3,8	-63,1223	-71,8190464	-74,718
4	-63,5678	-72,5987203	-75,609
4,2	-63,9916	-73,3403457	-76,4566
4,4	-64,3957	-74,0474642	-77,2647
4,6	-64,7818	-74,7231447	-78,0369
4,8	-65,1514	-75,3700639	-78,7763
5	-65,506	-75,9905707	-79,4854

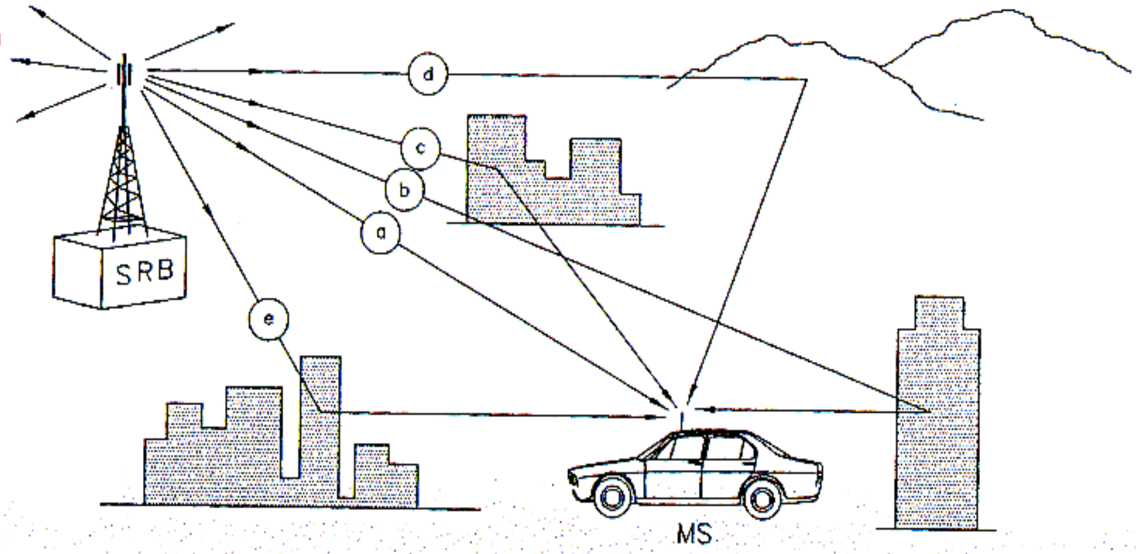


Wireless channel: multipath fading



- While propagating from source to destination the signal can follow multiple paths. At the receiver different components (received over different paths, with different phases and amplitudes) are combined.
- Signal can be reflected, diffracted, scattered based on the obstacles it founds over its path towards destination.
- Low frequencies can traverse without or with low attenuation many objects; when frequency increases waves tend to be absorbed or reflected by obstacles (at very high frequency– over 5 GHz – communication is LOS).

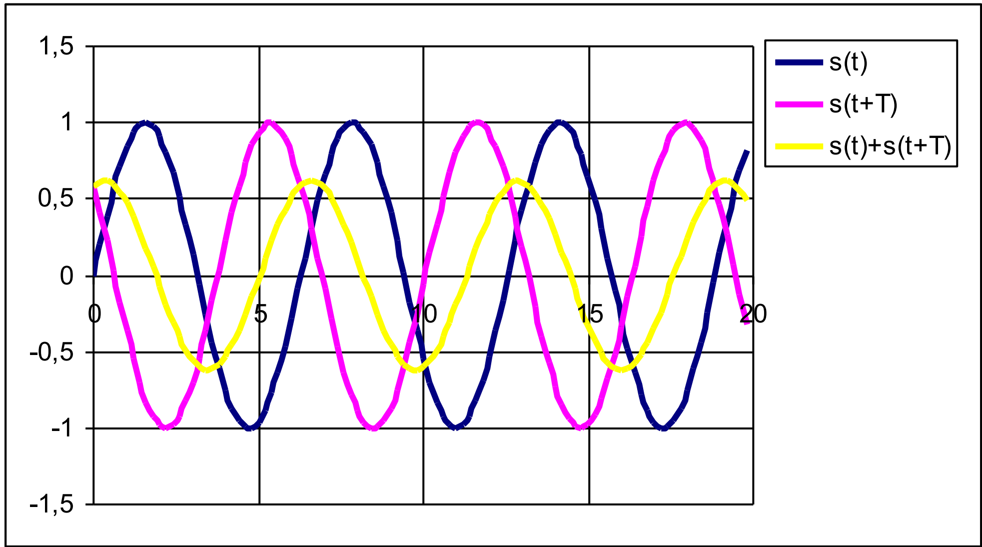
Multipath fading



- Signal replicas received via different propagation paths are combined at the receiver
- The results depends on
  - The number of replicas
  - Their phases
  - Their amplitudes
  - Frequency

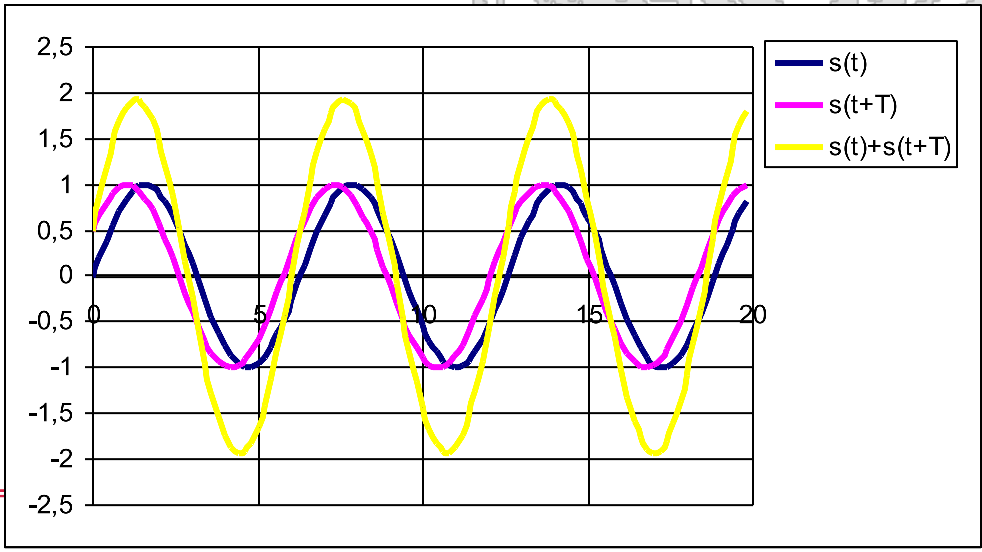
- **Received power differs, as a result**
  - **from place to place, from time to time!**

Multipath fading



- Resulting signal can be attenuated

$T=4/5\pi$



- Or amplified

$T= \pi /6$

Rayleight fading

$$e_r(t) = \sum_{k=1}^{N} a_k \cos(2\pi f_0 t + \phi_k) =$$

recall that : $\cos(2\pi f_0 t + \phi_k) =$
$= \cos(2\pi f_0 t)\cos(\phi_k) - \sin(2\pi f_0 t)\sin(\phi_k)$

$$= \cos(2\pi f_0 t)\sum_{k=1}^{N} a_k \cos\phi_k - \sin(2\pi f_0 t)\sum_{k=1}^{N} a_k \sin\phi_k =$$

$$= X\cos(2\pi f_0 t) - Y\sin(2\pi f_0 t)$$

In the assumptions:

- N large (many paths)
- ϕ_k uniformly distributed in $(0,2\pi)$
- a_k comparable (no privileged path such as LOS)

X,Y are gaussian, identically distributed random variables

Sigma² is the Variance of The X,Y variables

Rayleigh fading power distribution

$$f_p(x) = \frac{1}{2\sigma^2} e^{-x/2\sigma^2}$$

Rayleight fading

$$e_r(t) = \sum_{k=1}^{N} a_k \cos(2\pi f_0 t + \phi_k) =$$

recall that: $\cos(2\pi f_0 t + \phi_k) =$

$= \cos(2\pi f_0 t)\cos(\phi_k) - \sin(2\pi f_0 t)\sin(\phi_k)$

$= c$

$= X$

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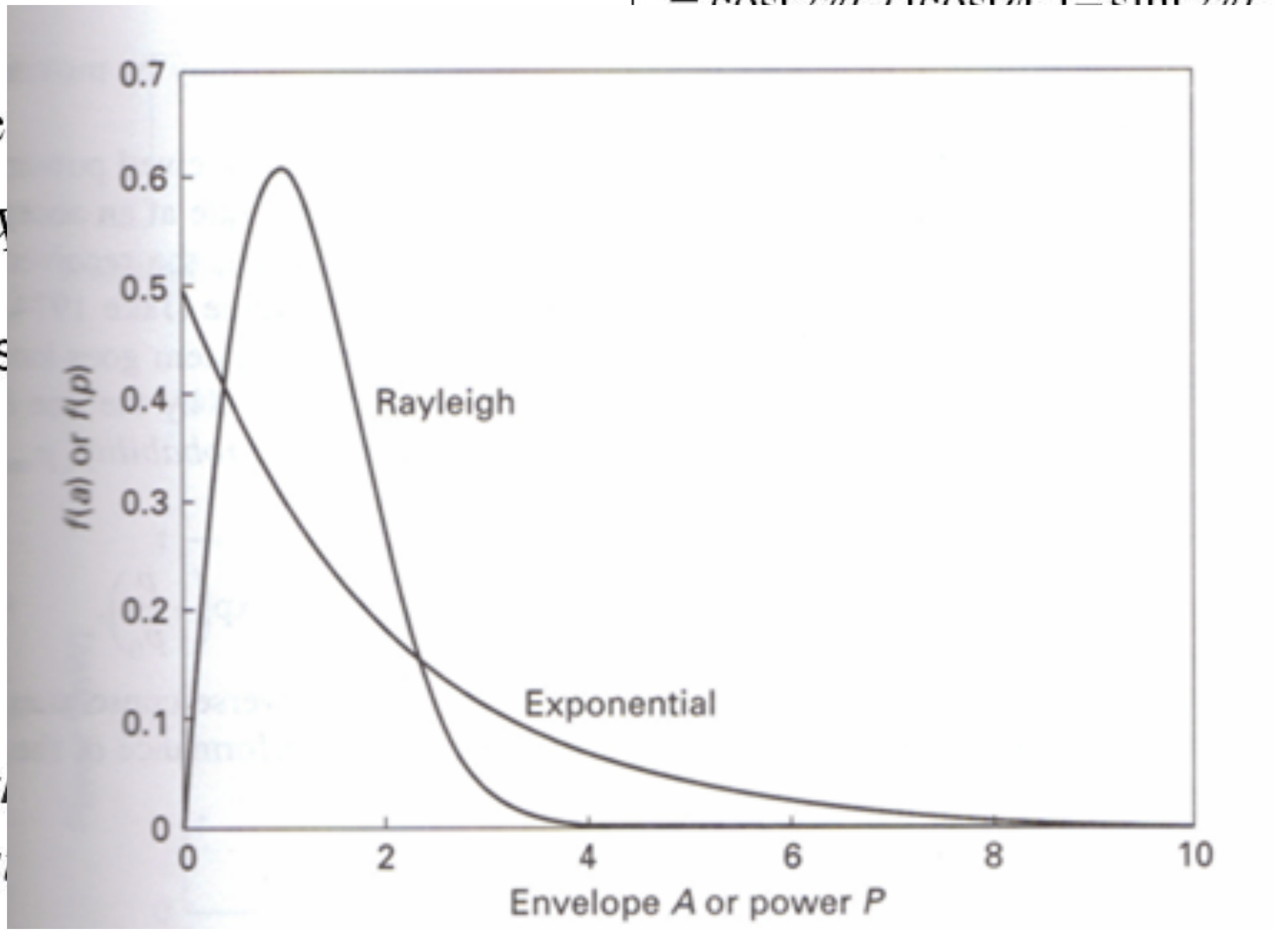


Rayleight fading

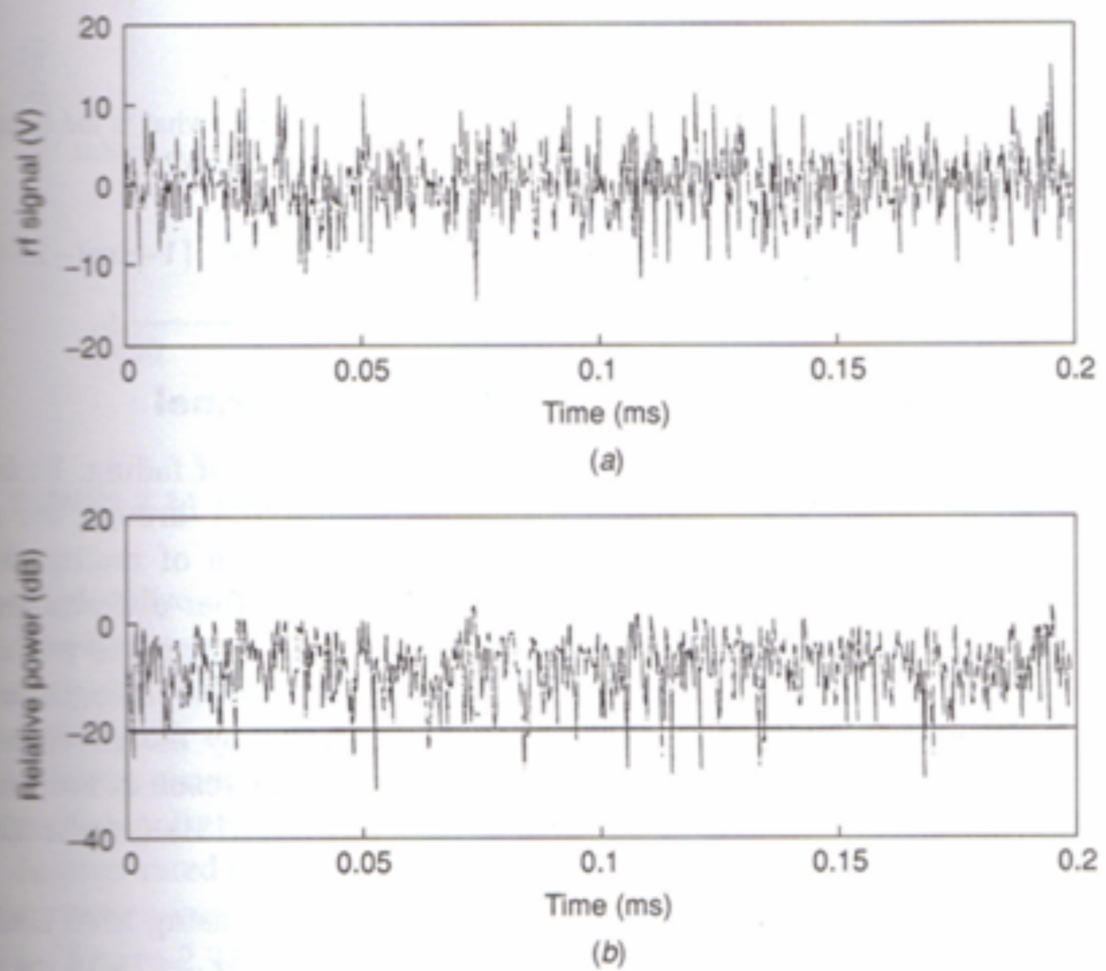


FIGURE 2.19 Rayleigh-faded rf signal (*a*) and its power (*b*). The plots were generated from 11 multiple paths. The envelope was obtained by demodulating the rf signal.

Fading-why is it important?

Answer1:

Outage Probability→Probability that received power is lower than a given threshold

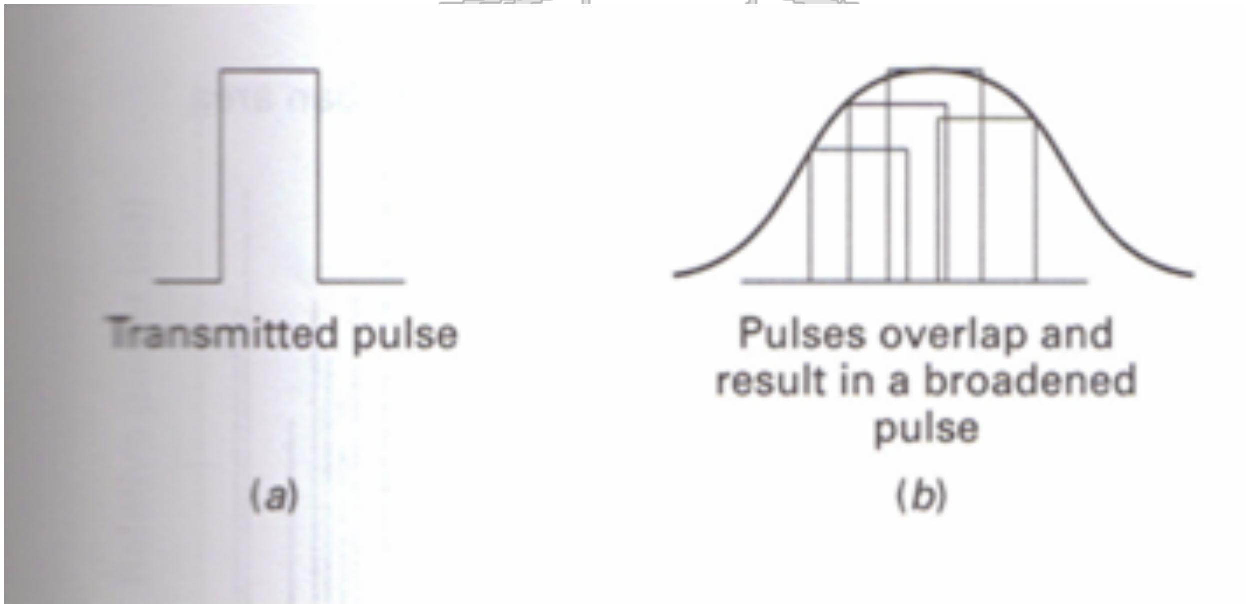
⇨Below which signal cannot be correctly received

$$P_{out}=\int_{o}^{pthr} f(p)\,dp$$

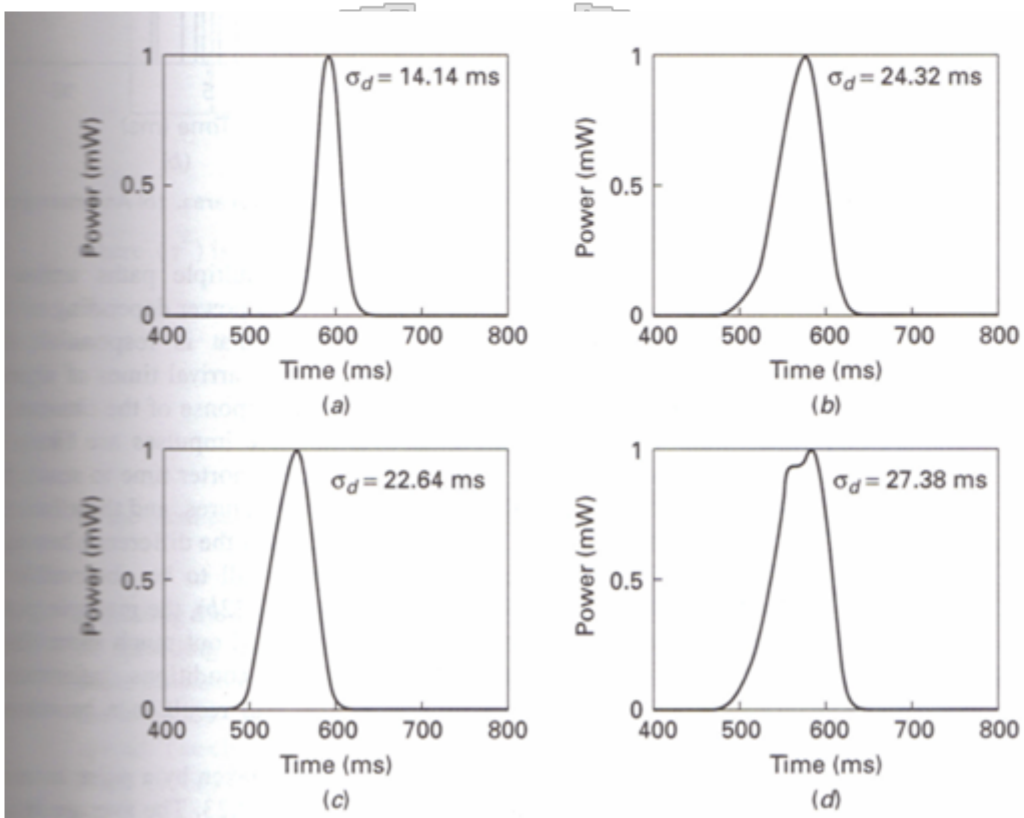
Multipath fading

- Different delays experienced by the different signal replicas (*delay spread*) can widen the channel impulse response leading to intersymbol interference (ISI – Inter-Symbol Interference)

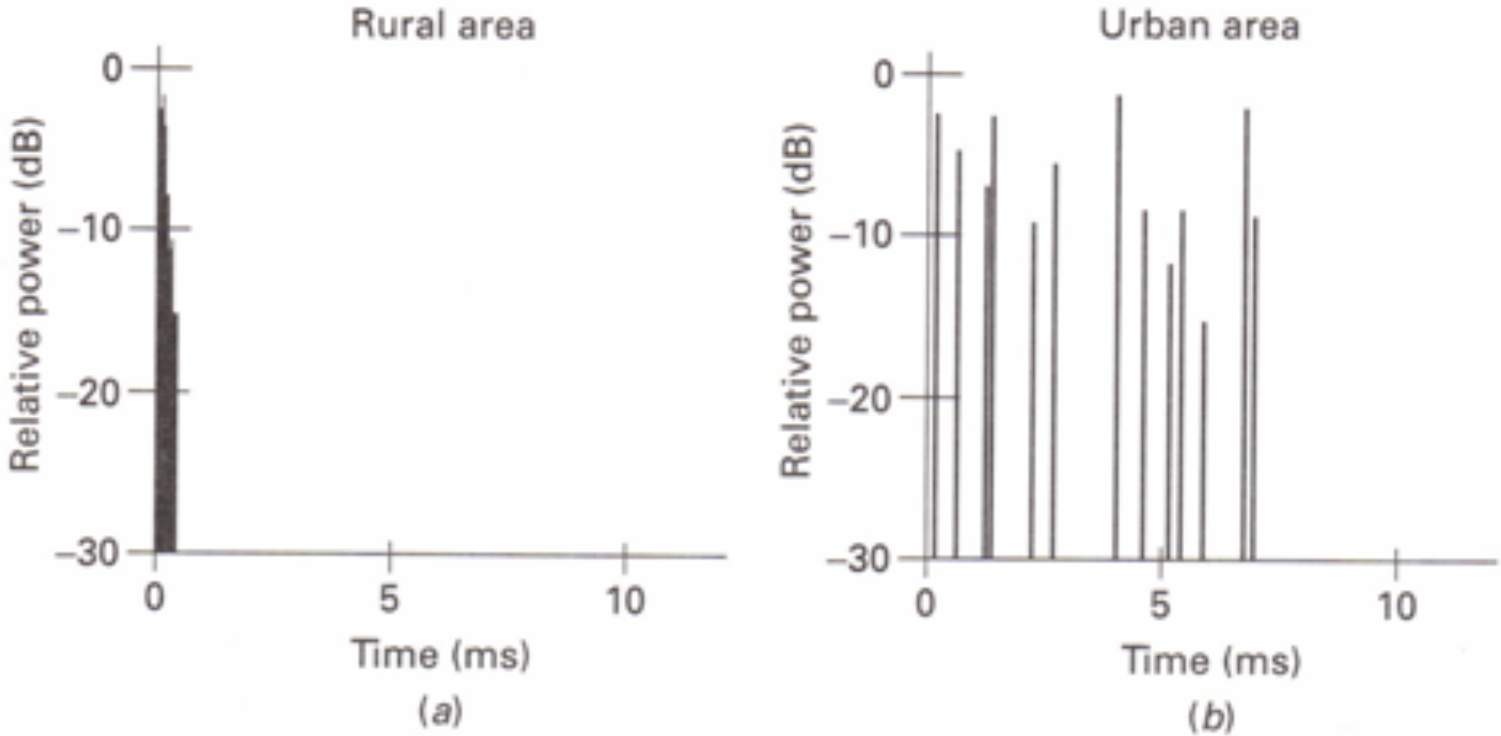
Examples


Transmitted pulse
(a)
Pulses overlap and
result in a broadened
pulse
(b)

Examples



Impulse response



Multipath fading

- Impact of delay spread can be quantified by computing the root mean square (RMS Delay Spread):

$$\tau_{RMS} = \sqrt{\frac{1}{\sum_{i=1}^{n} P_i} \sum_{i=1}^{n} \left(\tau_i^2 P_i\right) - \tau_d^2}$$

- **with**

$$\tau_d = \frac{\sum_{i=1}^{n} \left(\tau_i P_i\right)}{\sum_{i=1}^{n} P_i}$$

- τ_{RMS} **RMS delay spread**
- τ_i **delay on path i**
- P_i **power received on path i**
- n **number of paths**

Multipath fading

- The coherence bandwidth, which is a statistical measurement of the bandwidth interval over which the channel is ‘flat’ is approximated by the inverse of the delay spread
- If coherence bandwidth is >> signal bandwidth the channel is flat
- If coherence bandwidth is comparable to the signal bandwidth then delay spread results into intersymbol interference and reception errors

In case of intersymbol interference equalization is used, introducing complexity.