



# IoT, Course introduction

Internet of Things a.a. 2021/2022

Un. of Rome “La Sapienza”

Chiara Petrioli

Department of Computer Science – University of Rome “Sapienza” – Italy

# The instructor

- *Prof.ssa Chiara Petrioli*
- Office: Dip. di Ingegneria Informatica Automatica e Gestionale
- E-mail: [petrioli@diag.uniroma1.it](mailto:petrioli@diag.uniroma1.it)
- What I do:
  - Director of the Sensor Networks and Embedded Systems laboratory (SENSES lab);
  - Founding partner of "La Sapienza" spinoff WSENSE S.r.l.
  - Research interests: design and optimization of wireless, embedded and cyber physical systems; design of solutions for the Future Internet. Over a hundred papers published in international journals and conferences (h-index 46, 7600+ citations).
  - International activities: Chair of the steering committee of **IEEE SECON**, general co-chair of **ACM MobiHoc 2019**, **TPC co-chair of EWSN 2021** and **IEEE ICCCN 2020**; program co-chair of **IEEE INFOCOM 2016**, general chair of **ACM SenSys 2013**. She has been member of the steering committee and associate editor of IEEE Transactions on Mobile Computing, associate editor of IEEE Transactions on Vehicular Technology, member of the executive committee of ACM SIGMOBILE and of ACM Europe Council, of the steering committee of ACM Sensys, and has been program co-chair of leading conferences in the field such as **ACM MobiCom** and **IEEE SECON**. She is currently among the 5 members of ASN.



# The instructor

- *Prof.ssa Chiara Petrioli*
- Office: Dip. di Ingegneria Informatica Automatica e Gestionale
- E-mail: [petrioli@diag.uniroma1.it](mailto:petrioli@diag.uniroma1.it)
- What I do:
  - Research Projects: PI of over twenty national and international research projects. Coordinator of FP7 EC projects GENESI and SUNRISE and of EASME ArcheoSub and SesStar.
  - Regularly serves as reviewer for the European Commission and other international research funding institutions.
- SENSES lab web page: [senseslab.di.uniroma1.it](http://senseslab.di.uniroma1.it)
- Web page : <http://twiki.di.uniroma1.it> → laurea magistrale → IoT
- Orario di ricevimento/office hours:
  - Send me an email to agree on a schedule (fast answer)
- We would like to be able to contact all registered students fast.
- Please provide contact info and register on



# IoT Students



Career Aspirations



Background



Status



Interests





# What we will do

## Why a class on Internet of Things?

Wireless systems are becoming the usual way to connect to the Internet, and communicate...

WiFi

Std: IEEE 802.11

Mesh networks



Sensor  
web

Std: GSM/UMTS/  
LTE/5G

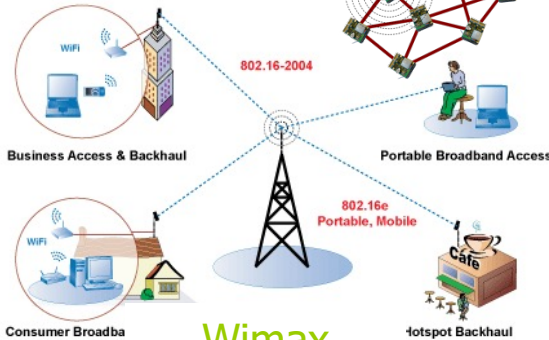
Cellular Networks

Internet of Things

Std: IEEE 802.15.4

IETF ROLL

Narrow IoT



Wimax

Std: IEEE 802.16



VANET

Std: IEEE 802.11p

5G



Personal Area

Network

Std: IEEE 802.15.1/  
IEEE 802.15.3



# What we will do

## Why a class on Internet of Things?

Wireless systems are becoming the usual way to connect to the Internet, and communicate...

WiFi

Std: IEEE 802.11

Mesh networks

Internet

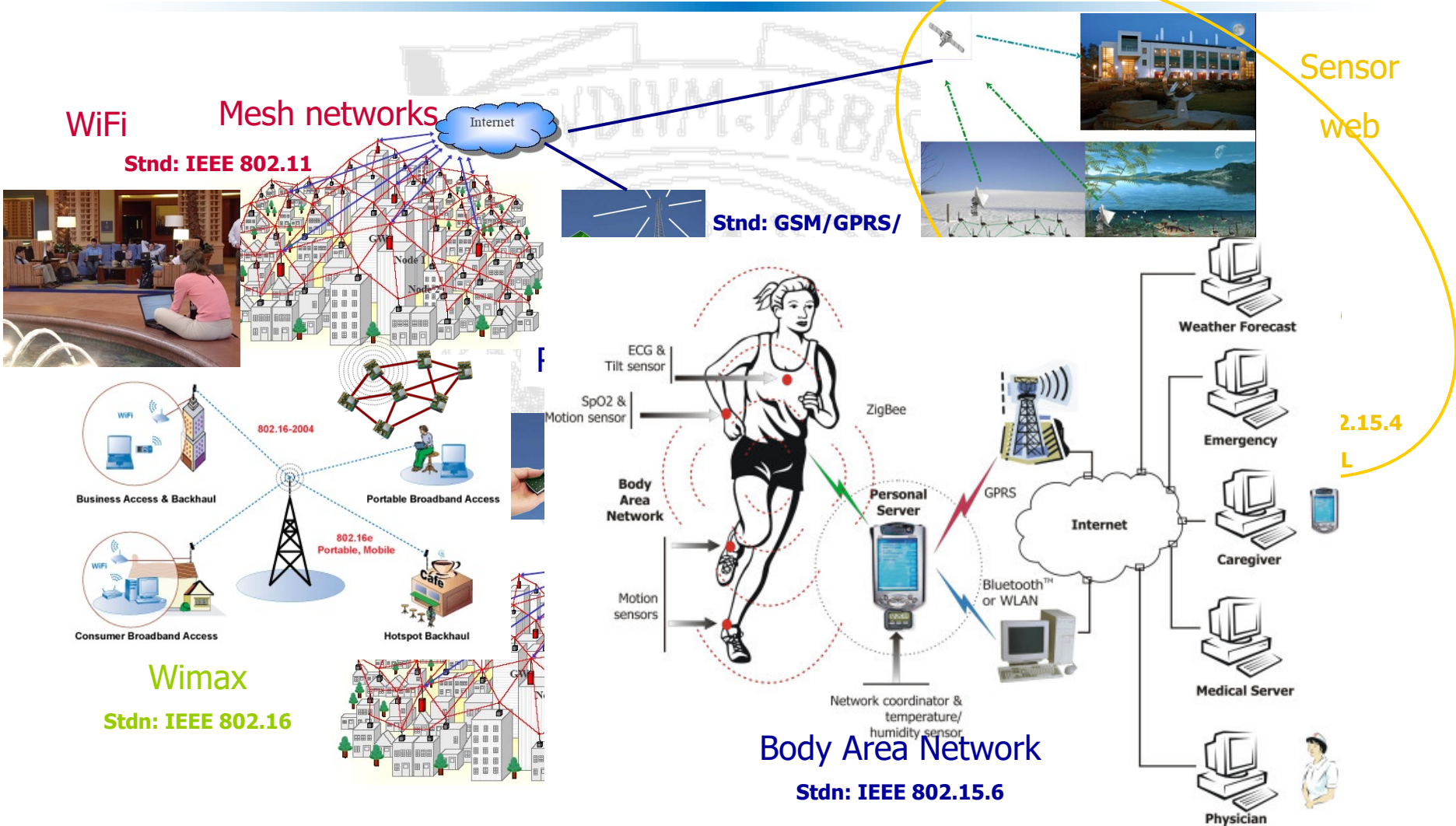
Std: GSM/GPRS/

Sensor web

2.15.4 L

Body Area Network

Std: IEEE 802.15.6



# What we will do

## Why a class on Internet of Things?

Wireless systems are becoming the usual way to connect to the Internet, and communicate...

WiFi

Std: IEEE 802.11

Mesh networks

Internet

Std: GSM

Data Analytics  
(over the cloud)  
+  
Green computing  
and comms.

Internet of Things

Std: IEEE 802.15.4

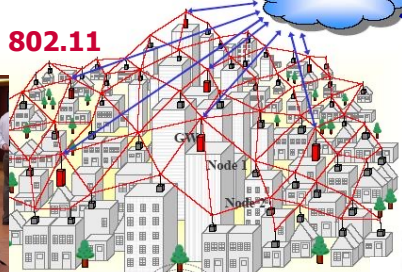
IETF ROLL

Personal Area  
Network

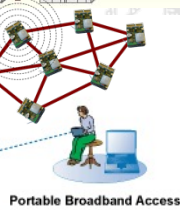
Std: IEEE 802.15.1/  
IEEE 802.15.3

Wimax

Std: IEEE 802.16

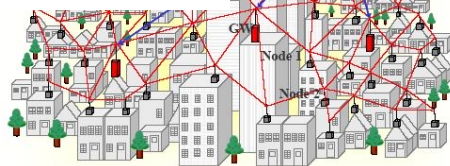


802.16-2004

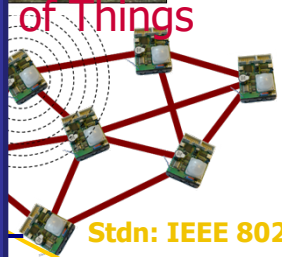


802.16e  
Portable, Mobile

Hotspot Backhaul

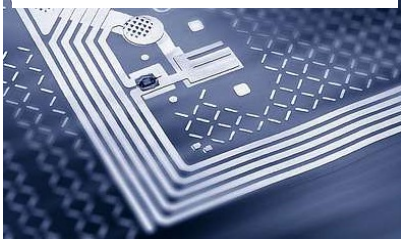


Sensor  
web





## CHIRON project



## RFID Anticollision Protocols



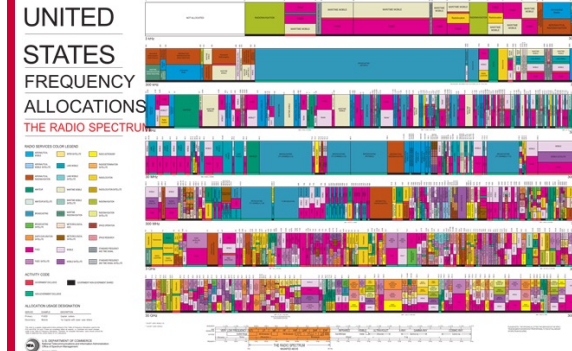
## GENESI Project



## Green sensing systems



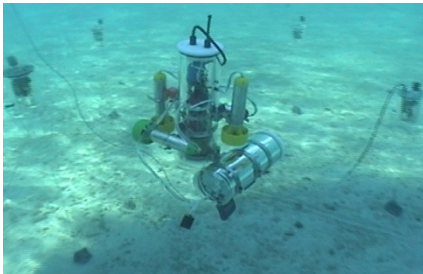
## SENDORA project



## Cognitive networks



## CLAM Project; SUNRISE project



## Underwater Monitoring systems



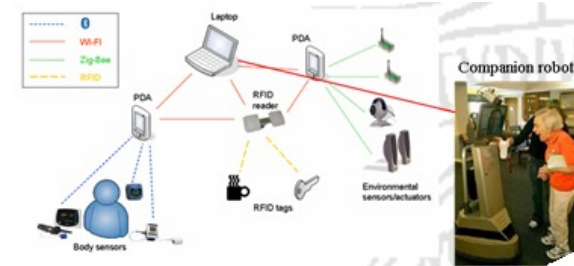
## TROPIC Project



## Cloud Computing

## LTE Advanced

## CHIRON project



## Assisted living

## WSN security



# Syllabus

A The course will make students aware of the challenges behind the design, implementation and field use of Wireless system, Sensing systems and the Internet of Things. The course will present both the theoretical foundations and practical aspects you need to know to develop such systems.

The course will cover the following topics:

## **Part 1, Prerequisites**

Fundamentals of wireless systems

Fundamental of ad hoc and cellular networks

From 2G to 5G

## **Part 2, Internet of Things Core**

Internet of Things applications, architectures, enabling technologies and protocols

# Syllabus

A The course will make students aware of the challenges behind the design, implementation and field use of Wireless system, Sensing systems and the Internet of Things. The course will present both the theoretical foundations and practical aspects you need to know to develop such systems.

## **Part 3, Emerging Technological Trends in Internet of Things**

Wake Up Radio, energy harvesting, passive backscattering

Blockchain and ledger technologies for Internet of Things

Machine learning for Internet of Things lsystems

## **Part 4, From technologies to Applications**

Internet of Things for smart planet and smart cities

Smart Transportation systems

## **Transversal Topics**

Performance evaluation of Internet of Things systems

How to model, what to model

Simulators for Internet of Things systems

How to move from an idea to a validated idea to a solution

# Exam sessions

Teaching material will comprise book chapters, articles, standards,...

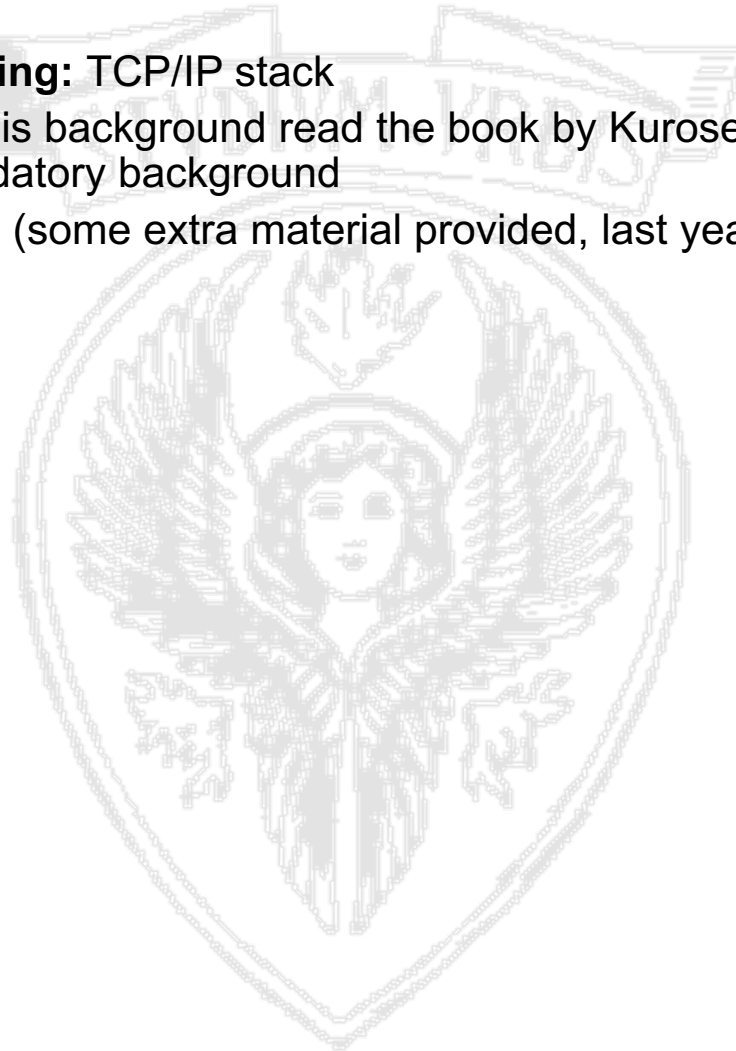
Midterm and Final during the class (including some questions on the lab part, providing extra points; Lab extra points available only with midterm and first session-June/July). Lab very important to provide you with skills that are recognized as important for your future career.

Rules: If a student passes at least one of the (midterm/final) tests he/she will be allowed to take the missing one in the June/July exam sessions. In such sessions it will also be possible to take a complete written exam on the topics covered during the course. In the fall and winter exam sessions students will have to take the complete written exam to pass the class.



# Required background

- **Computer Networking:** TCP/IP stack
- If you do not have this background read the book by Kurose Ross «Computer Networking» → mandatory background
- C/C++ programming (some extra material provided, last year videoregistered classes)



# How To Get Additional Info

Sources of relevant information:

IEEE and IETF Standards

IEEE and ACM Digital Libraries (articles)

Books (main library)

Title ACM CONFERENCE ON APPLICATIONS, TECHNOLOGIES, ARCHITECTURES, AND PROTOCOLS FOR COMPUTER COMMUNICATION	Acronym SIGCOMM	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					
Title ACM CONFERENCE ON COMPUTER AND COMMUNICATIONS SECURITY	Acronym CCS	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					
Title ACM CONFERENCE ON EMBEDDED NETWORKED SENSOR SYSTEMS	Acronym SENSYS	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A+	Collected Classes A++, A++, A+
Detailed Ratings (click to expand)					
Title ACM CONFERENCE ON OBJECT ORIENTED PROGRAMMING SYSTEMS LANGUAGES AND APPLICATIONS	Acronym OOPSLA	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A+, MA:A++	Collected Classes A++, A++, A+
Detailed Ratings (click to expand)					
Title ACM INTERNATIONAL CONFERENCE ON KNOWLEDGE DISCOVERY AND DATA MINING	Acronym KDD	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					
Title ACM INTERNATIONAL CONFERENCE ON MOBILE COMPUTING AND NETWORKING	Acronym MOBICOM	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					
Title ACM INTERNATIONAL CONFERENCE ON RESEARCH AND DEVELOPMENT IN INFORMATION RETRIEVAL	Acronym SIGIR	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					
Title ACM INTERNATIONAL SYMPOSIUM ON COMPUTER ARCHITECTURE	Acronym ISCA	GGG Class 1	GGG Rating A++	Qualified Classes CORE:A++, LiveSHINE:A++, MA:A++	Collected Classes A++, A++, A++
Detailed Ratings (click to expand)					

ACM MobiCom,  
IEEE Infocom,  
ACM MobiHoc,  
ACM SenSys,  
IEEE IPSN

# College experience





# College experience



+

Transversal  
Skills



Seminars of international experts



Internship

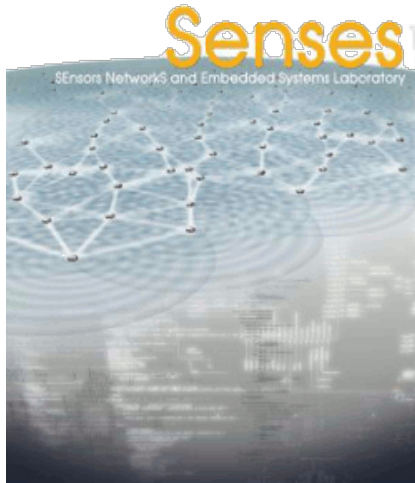
Large projects, EXPLOIT Labs

Spinoff





# College experience



GRANTS “borsa di studio per attività di ricerca”

Contact me AT petrioliATdiDOTuniroma1DOTit

5 in the last years to top class students

<http://senseslab.di.uniroma1.it>

Possibility to do also the AFC



# Fundamental of wireless systems

Internet of Things a.a. 2021/2022

Un. of Rome “La Sapienza”

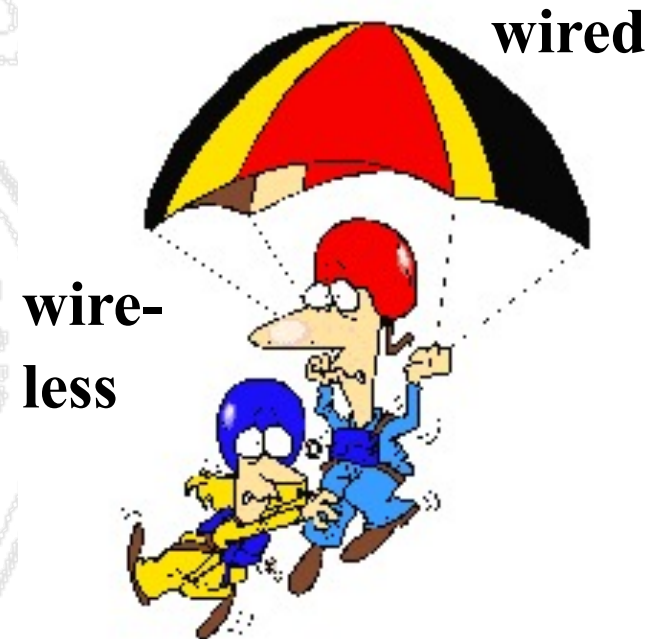
Chiara Petrioli

Department of Computer Science – University of Rome “Sapienza” – Italy

# Background- Wireless Systems

- What is the difference wrt 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 devices 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

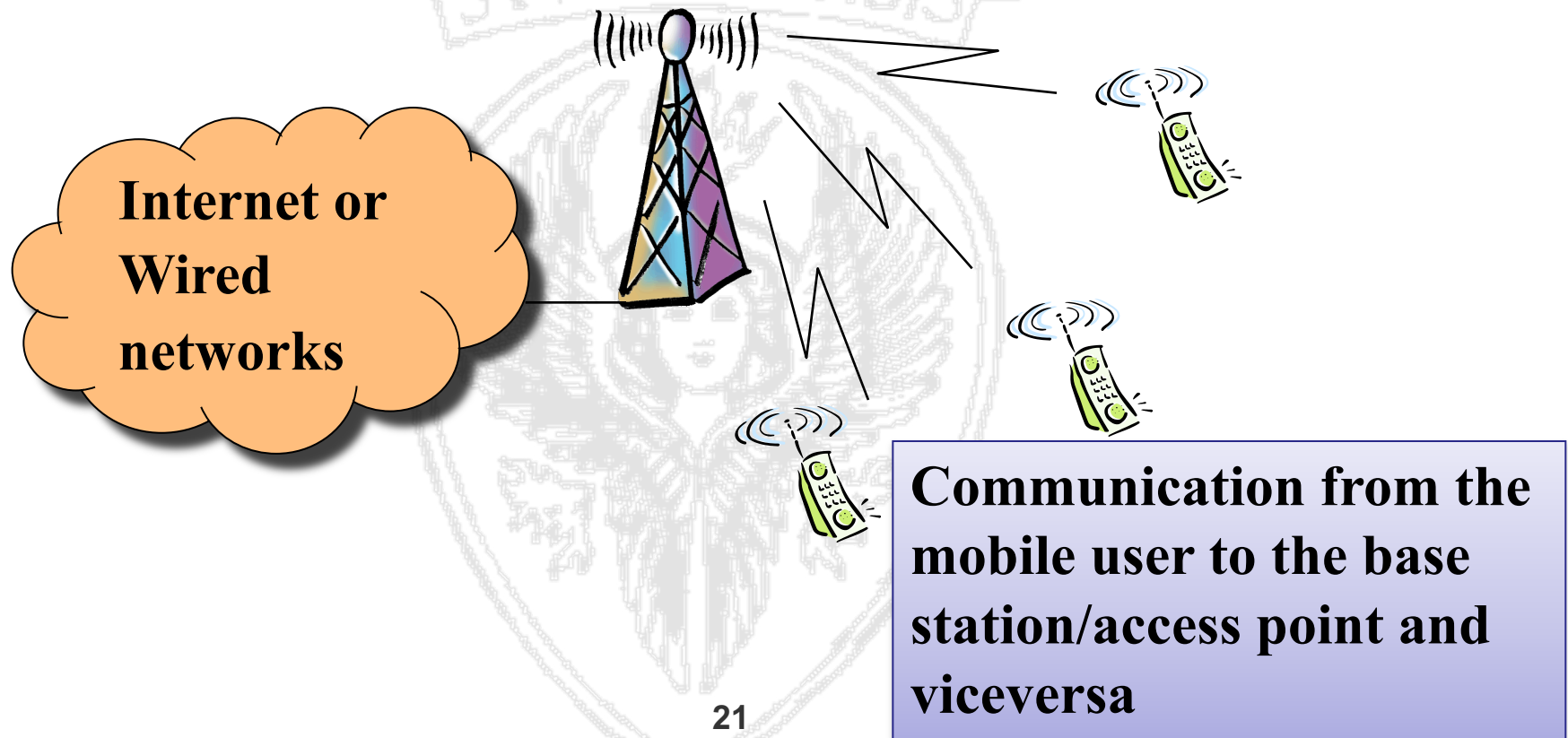
# Wireless systems- Features

- 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)



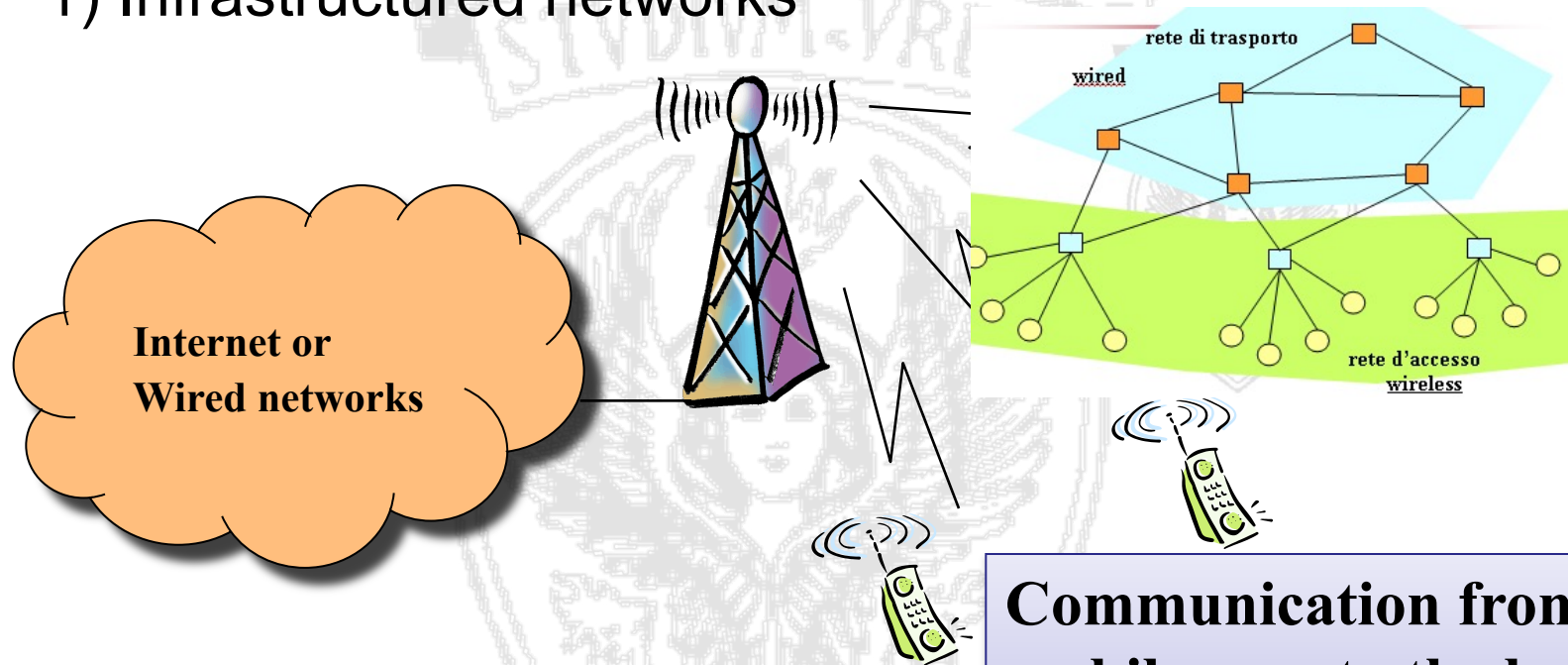
# Wireless Systems Models

- Infrastructured networks



# Wireless Systems Models

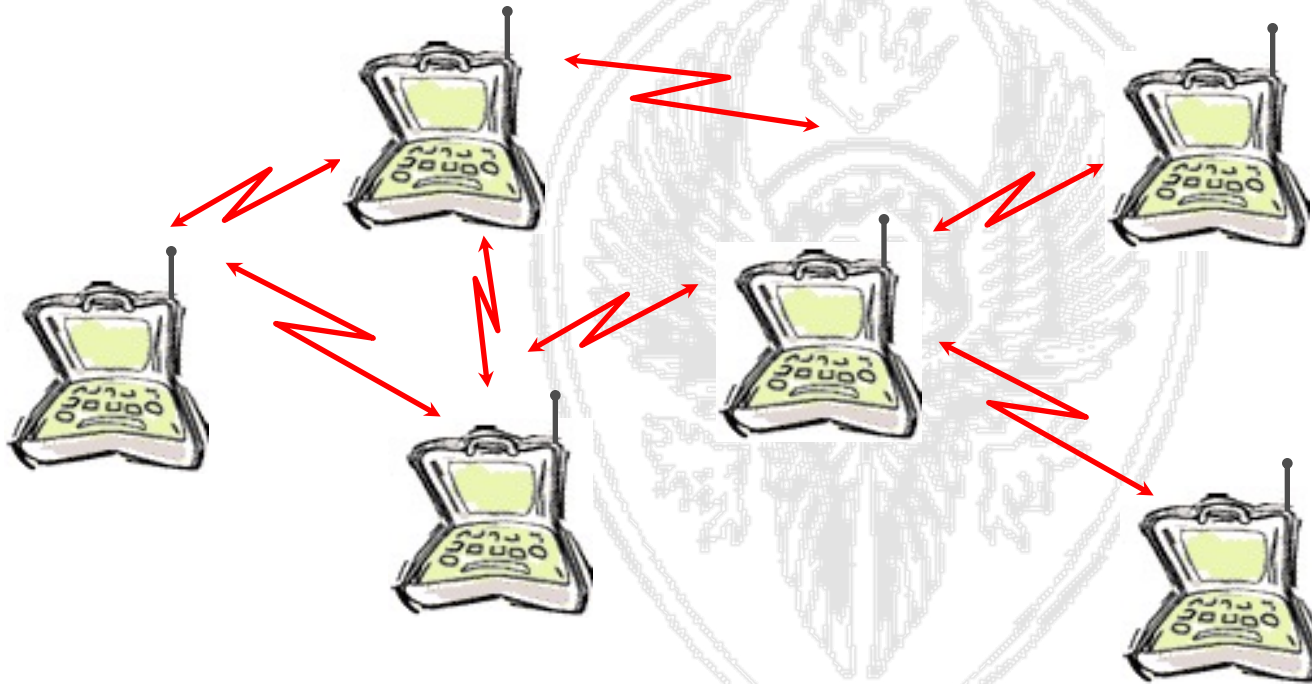
- 1) Infrastructured networks



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

# Wireless Systems models

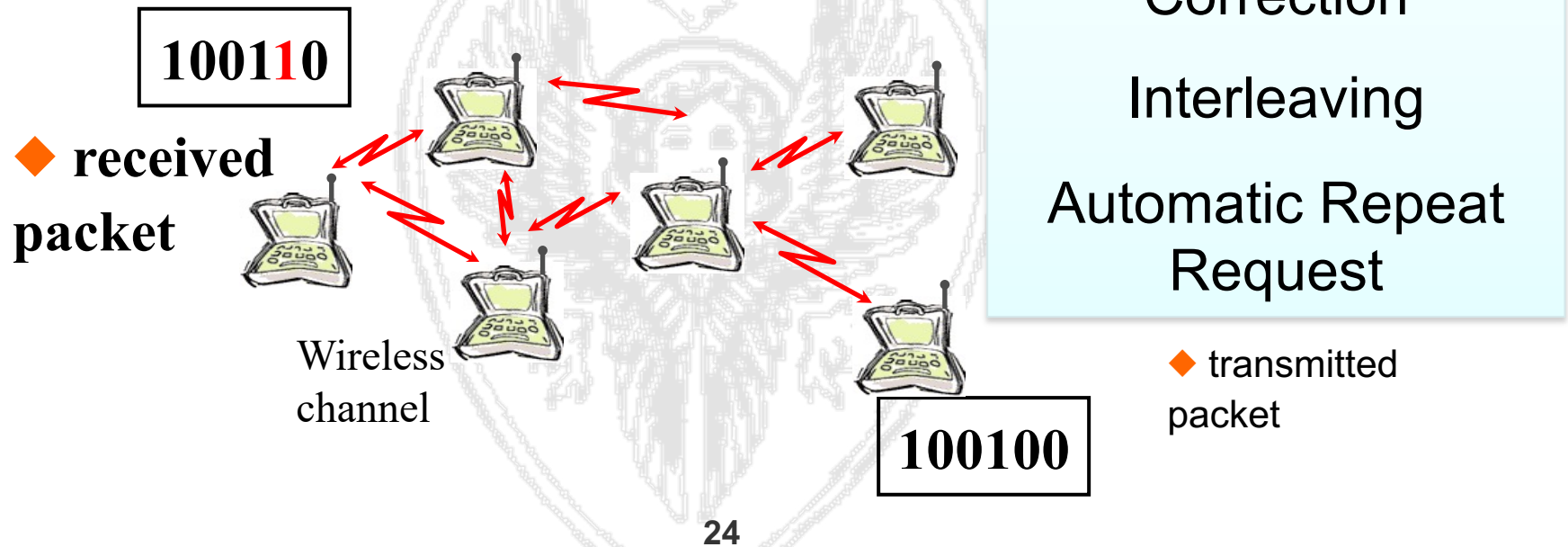
- 2) Ad Hoc Wireless Networks (wireless sensor networks, VANET, Mesh Networks,...)



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

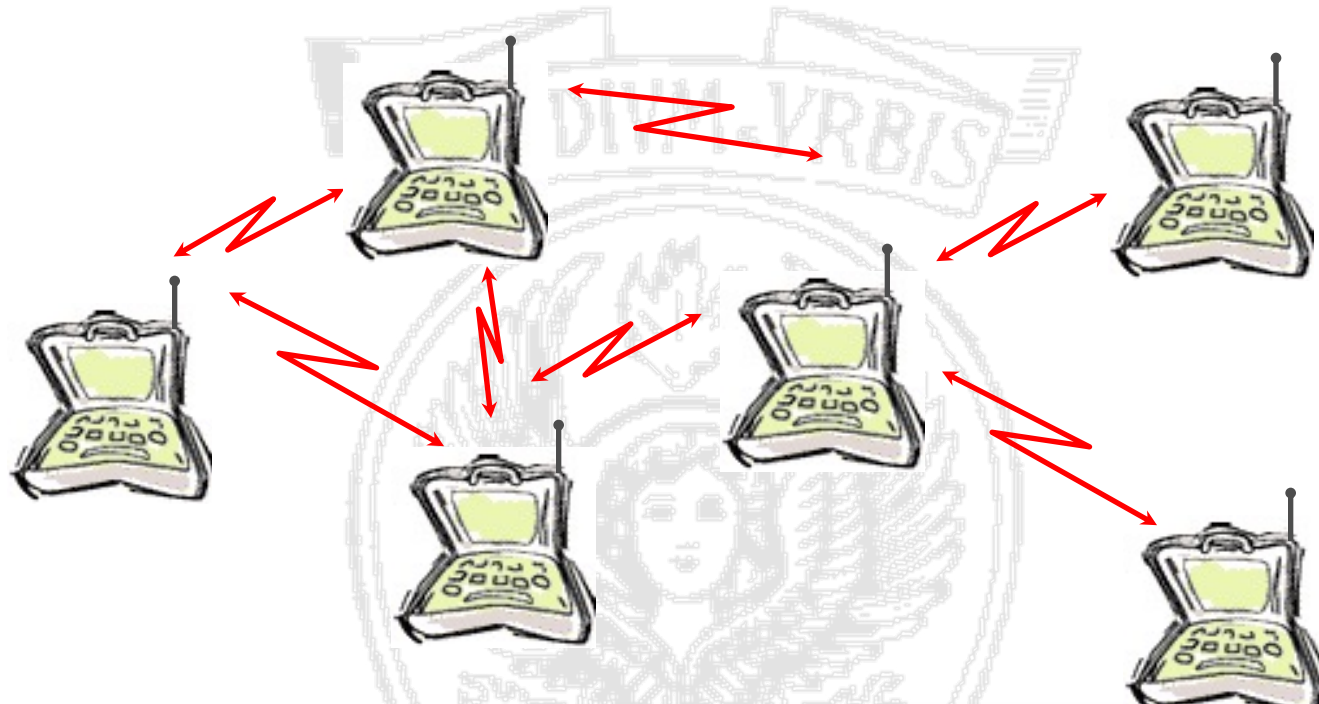
# Transmission Errors

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





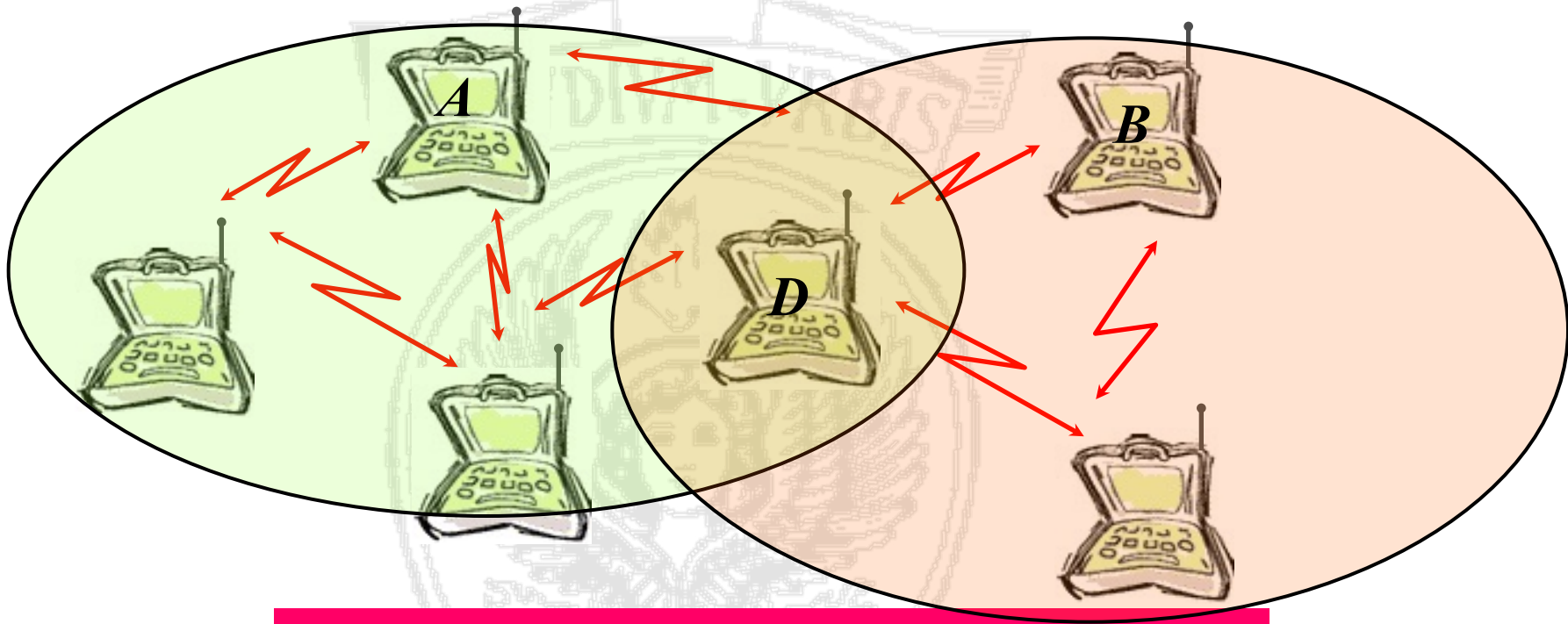
# Medium Access Control



*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*

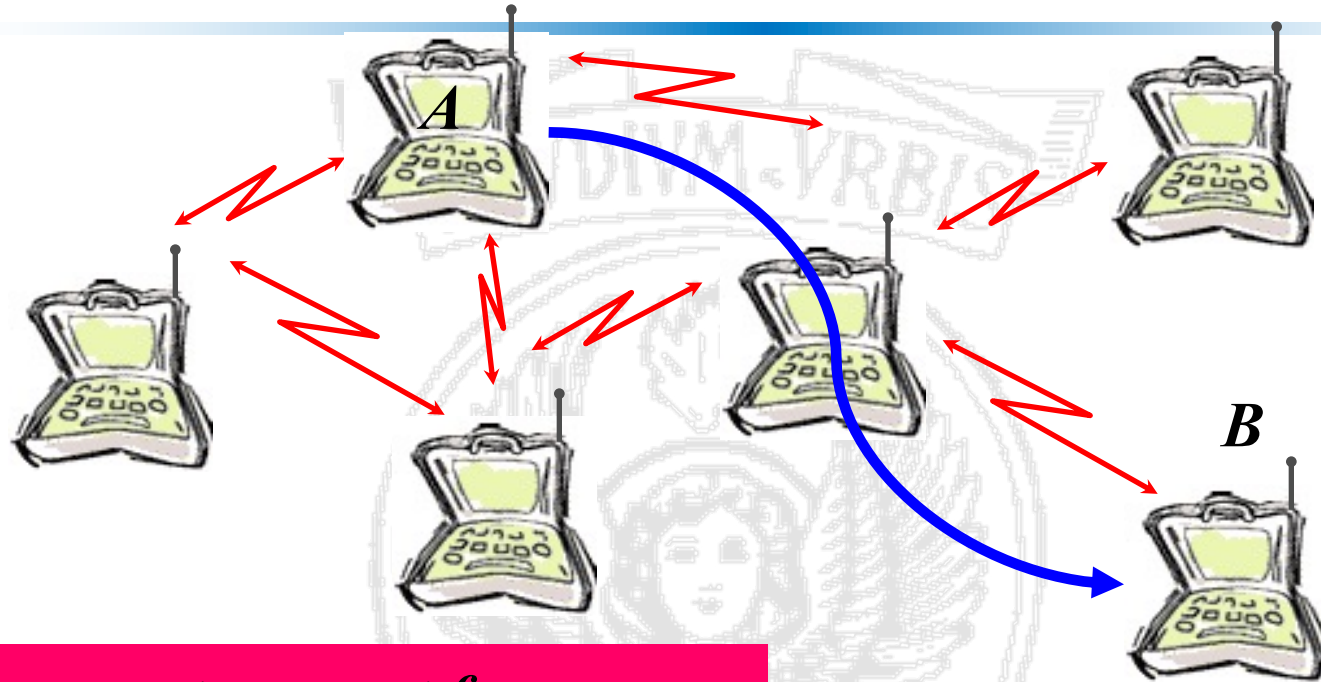
# Medium Access Control



***Hidden terminal***

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

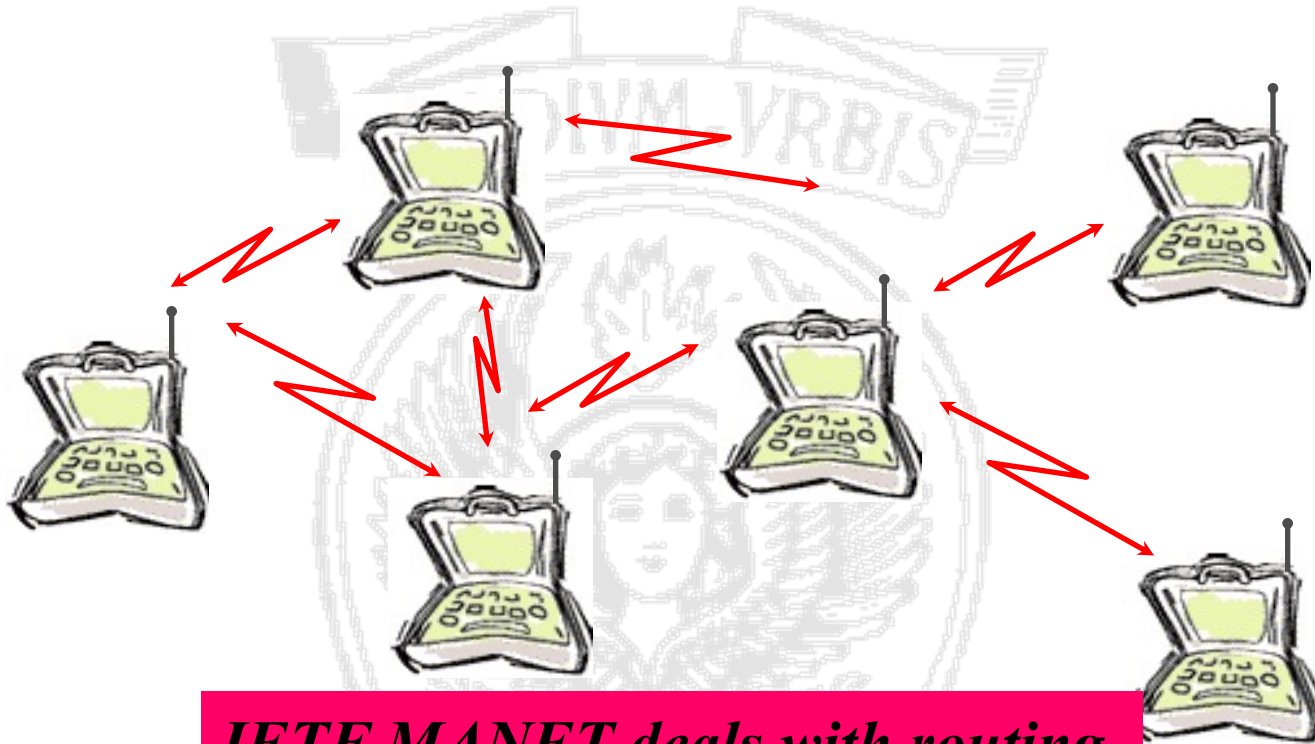
# Routing



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

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

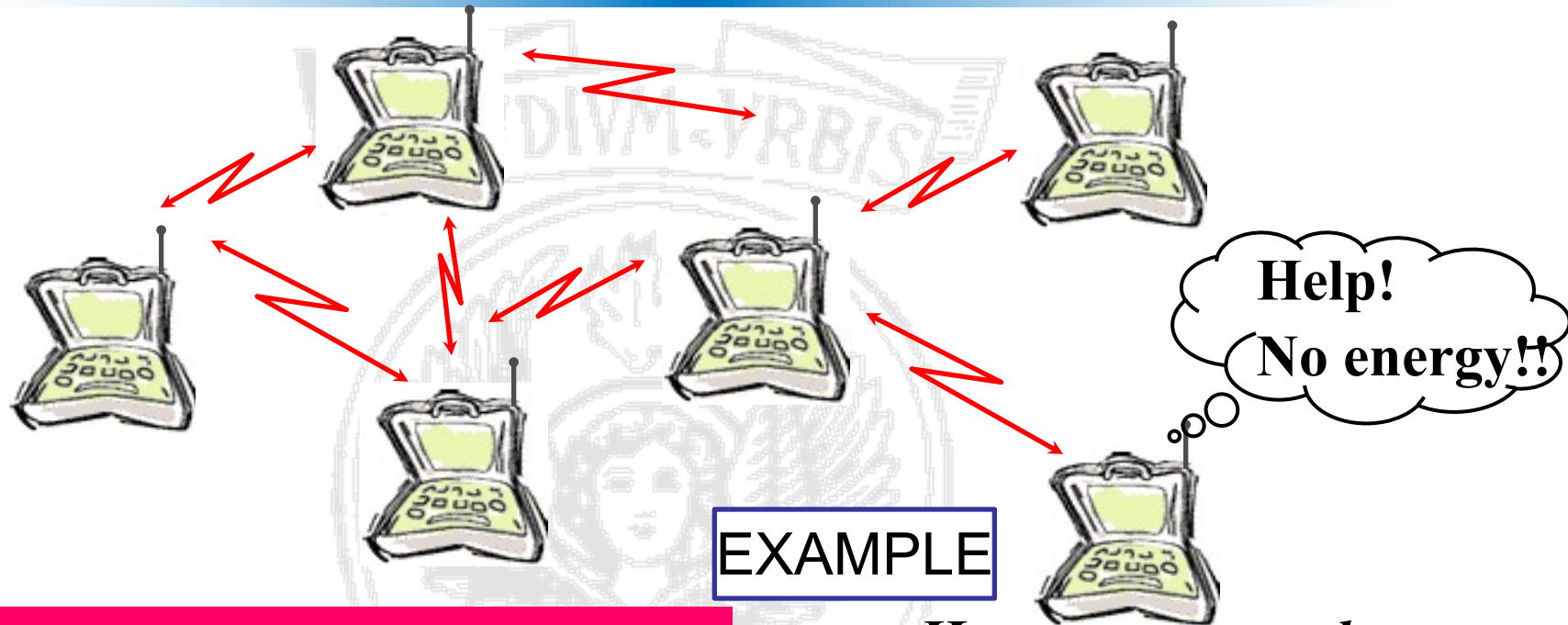
# Ad Hoc Networks -Challenges



*IETF MANET deals with routing*  
*One of the key challenges behind*  
*mobile peer to peer ad hoc*  
*networking*



# Ad Hoc Networks- Challenges



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

*How to route packets minimizing energy consumption, accounting for the (heterogeneous) node residual energy*

# Introduction

- ✓ Background needed to understand the motivations behind current wireless systems design

- Wireless Channel & Signal Propagation – Basic Concepts

- Energy efficient comms. techniques

- Channel Access problems

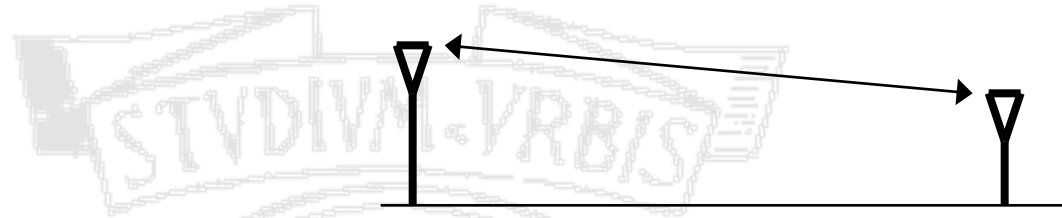
- Mobility management

# Wireless channel

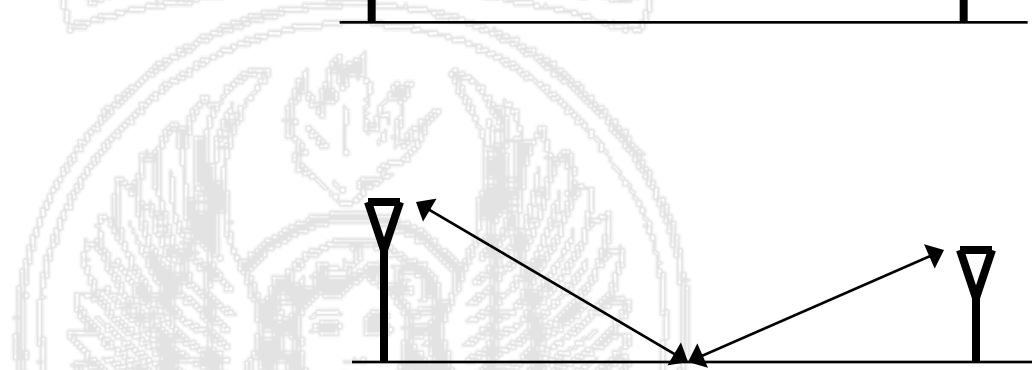
- Much less reliable than wired channels
- While propagating the signal can face
  - Attenuation as function of the distance from transmitter and receiver
  - Attenuation due to obstacles
  - Propagation over multiple paths (resulting in multipath fading)

# Radio signal propagation

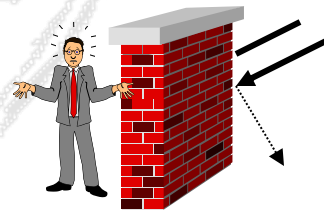
- Line of sight



- Reflection



- Shadowing

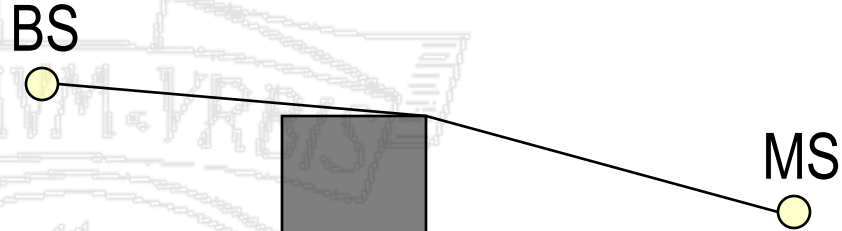




# Radio signal propagation

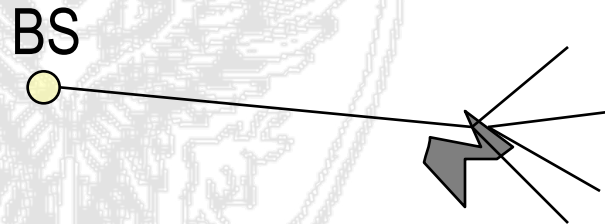
## → Diffraction

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



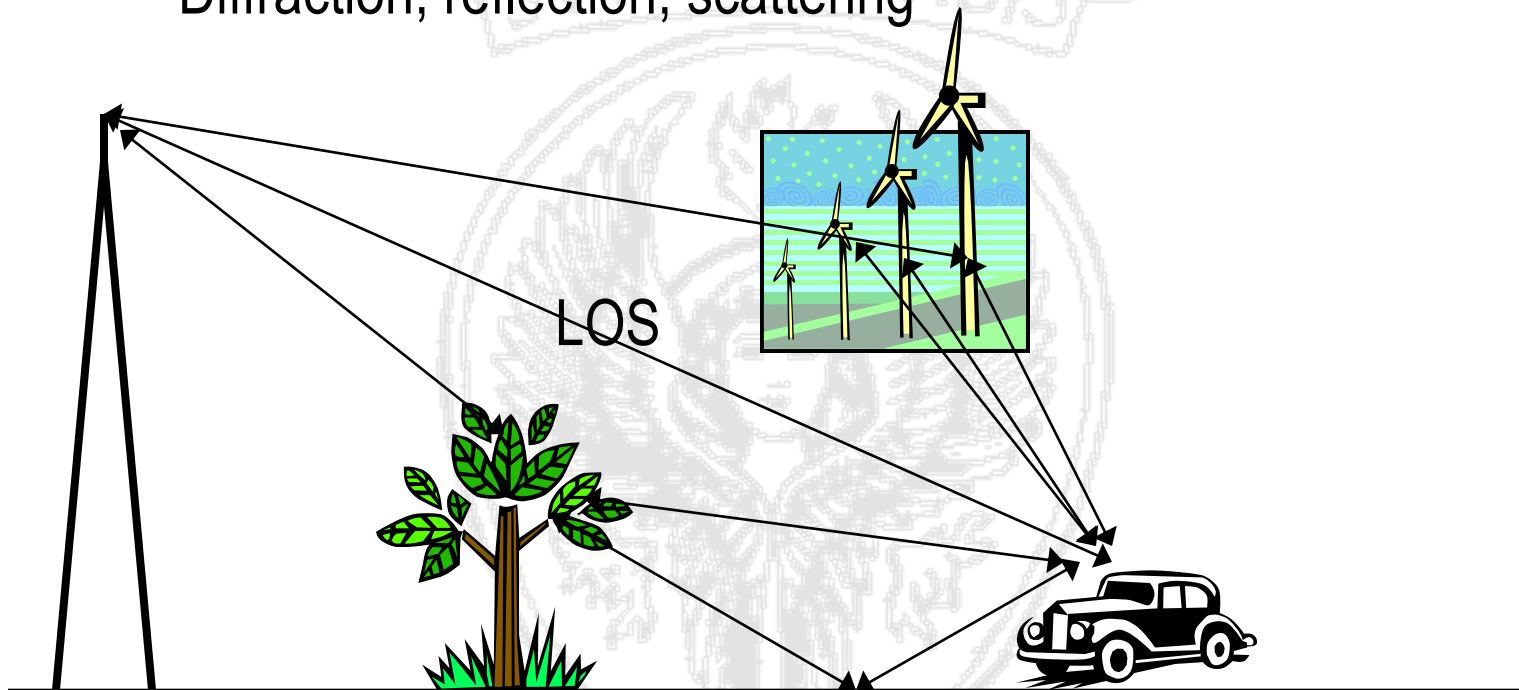
## → Scattering

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



# Radio signal propagation

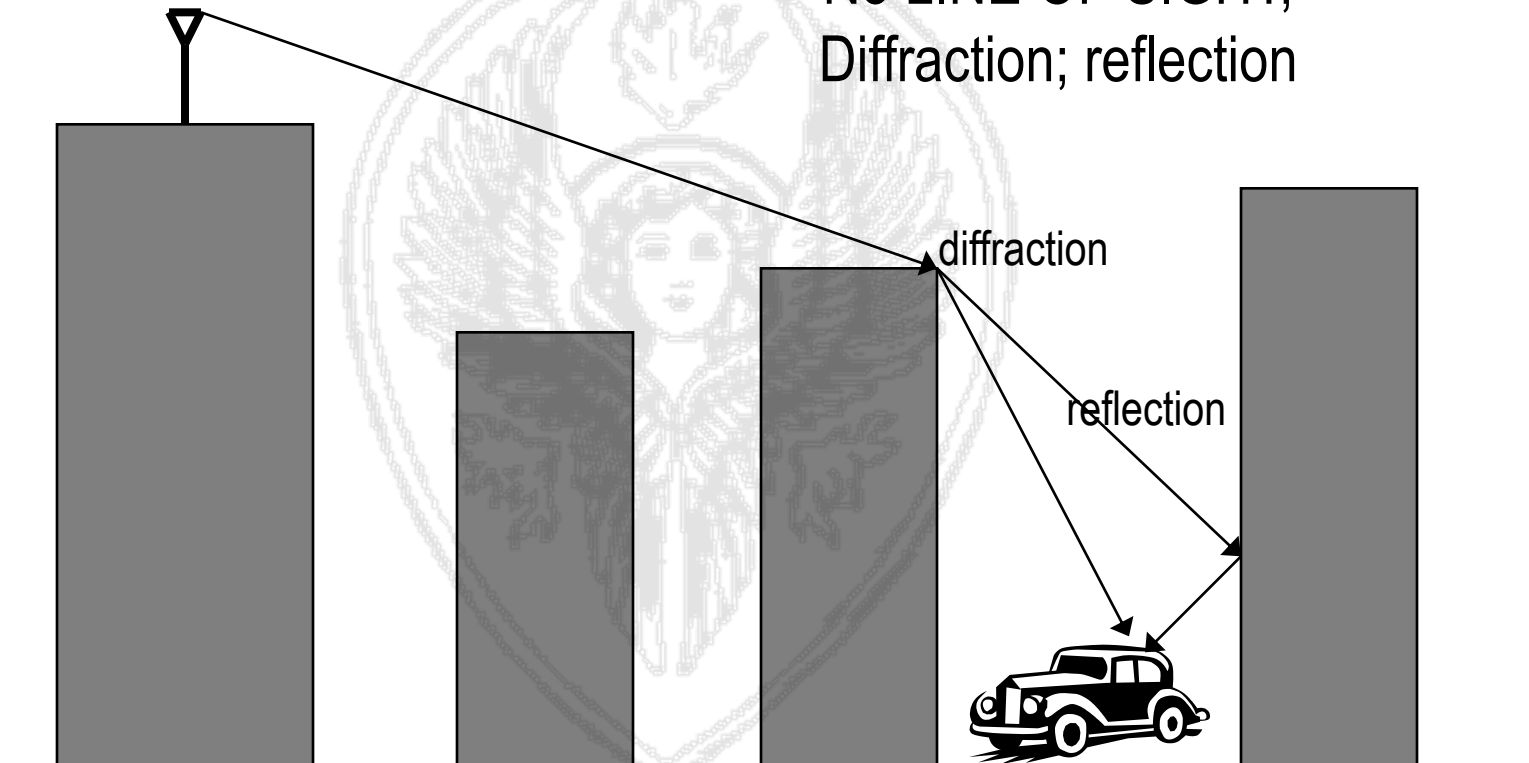
LINE OF SIGHT +  
Diffraction, reflection, scattering



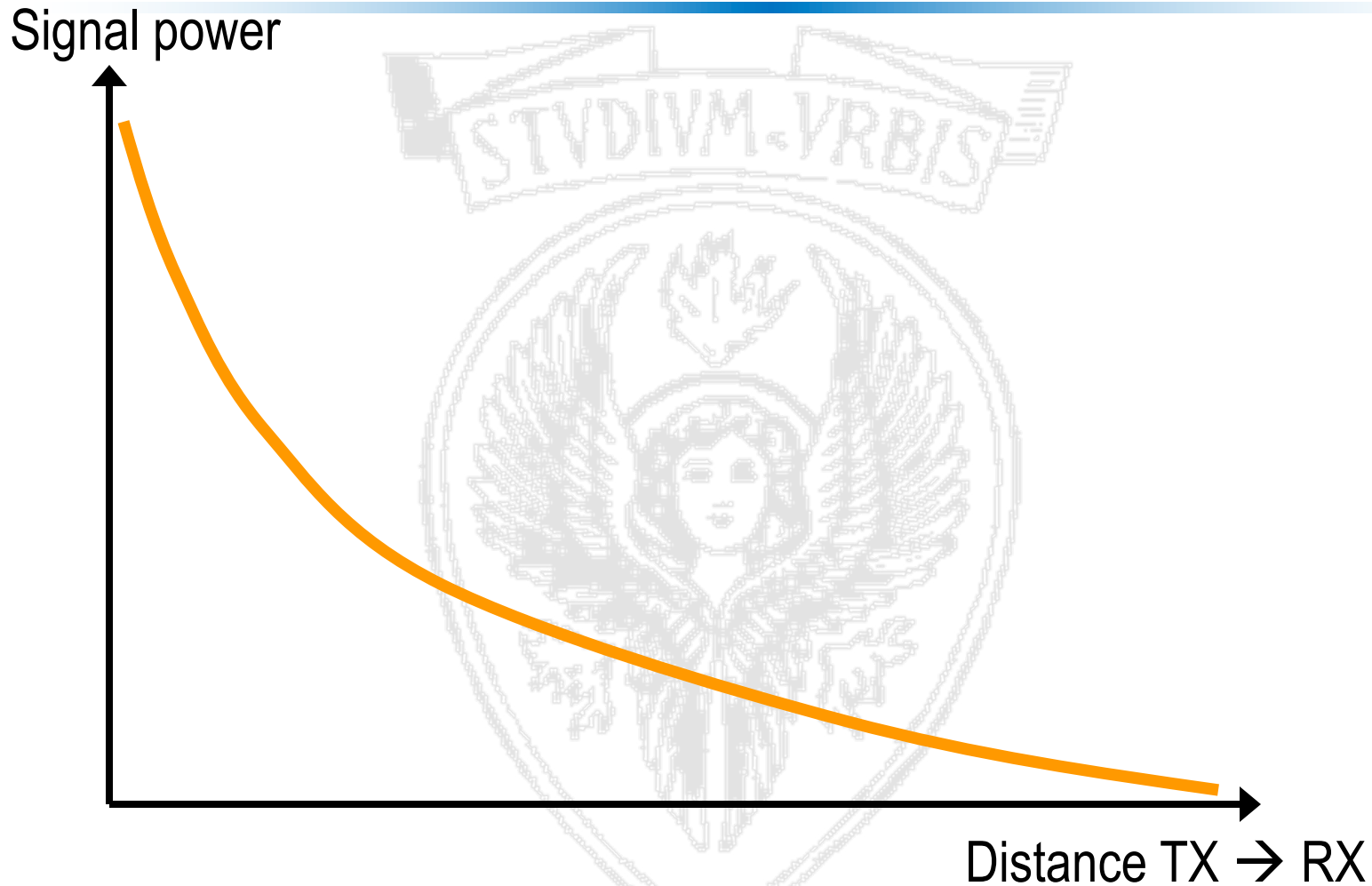
# Radio signal propagation

## *LOS path non necessarily existing*

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

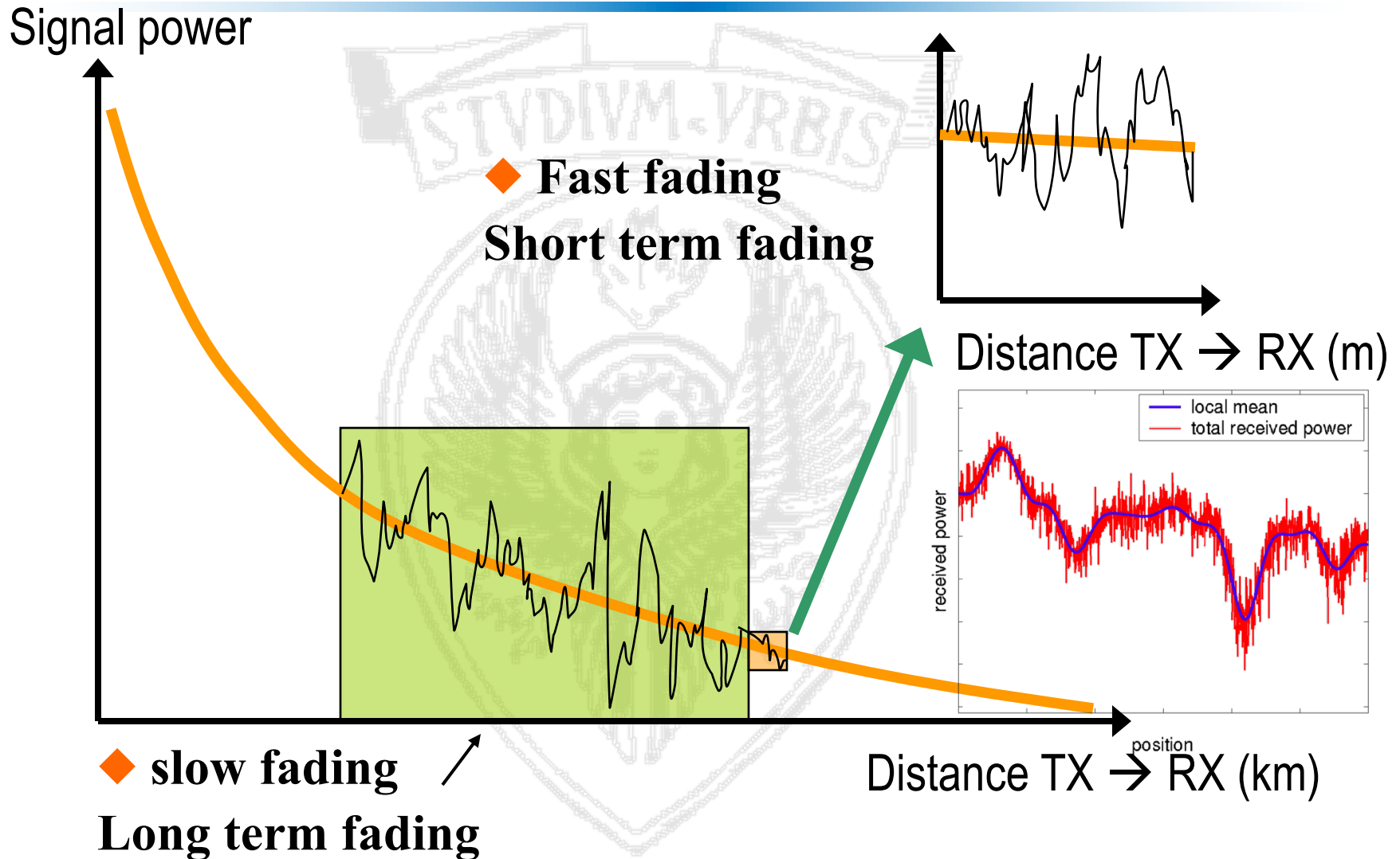


# Radio signal attenuation



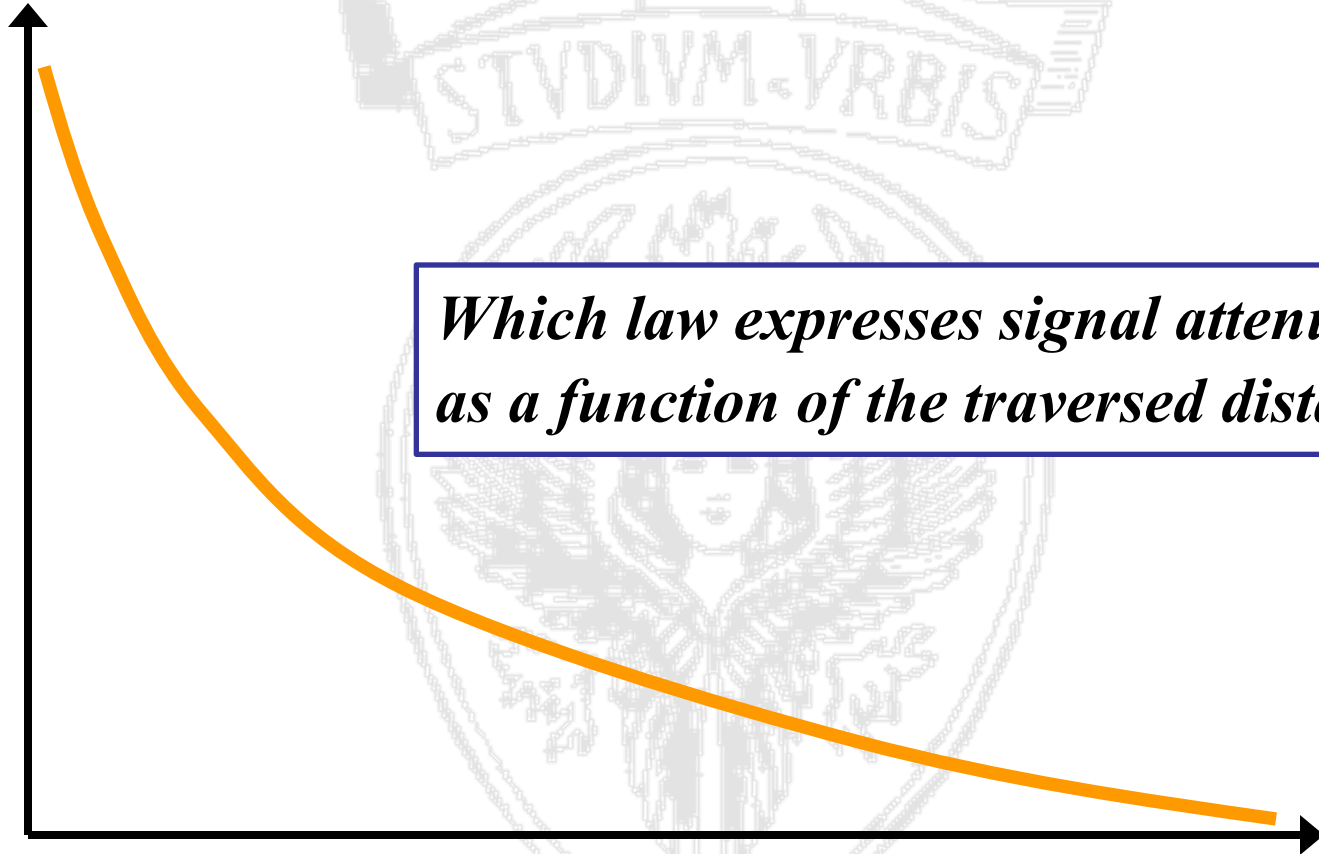


# Slow fading – fast fading



# Radio signal attenuation

Signal power

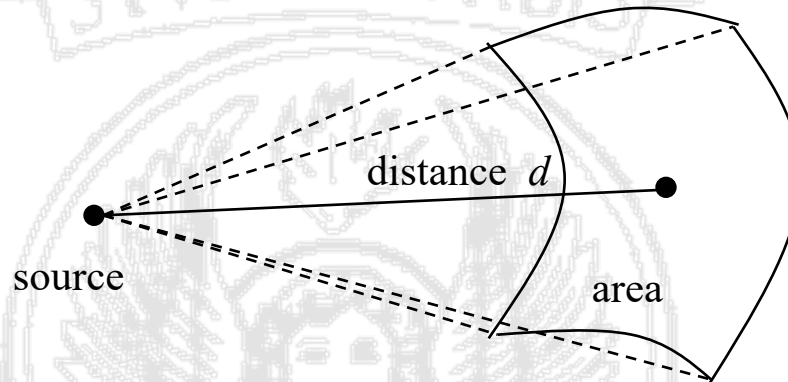


*Which law expresses signal attenuation as a function of the traversed distance?*

Distance TX → RX

# Radio signal attenuation geometrical spreading

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

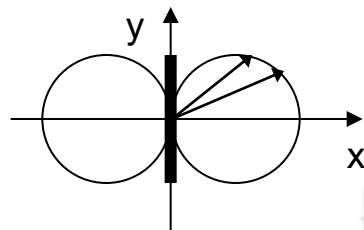


- The power density at distance  $d$  is equal to the ratio between the transmission power and the surface area of a sphere centered in the source and with radius  $d$ :

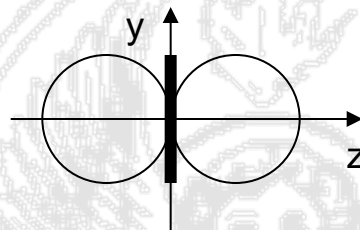
$$F = \frac{P_T}{4\pi d^2} \quad [\text{W/m}^2]$$

# Antenna types

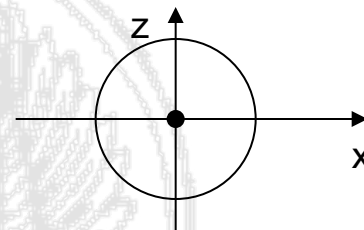
- Graphical representation of radiation properties of an antenna
- Depicted as two-dimensional cross section



side view (xy-plane)

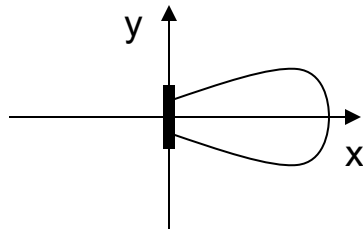


side view (yz-plane)

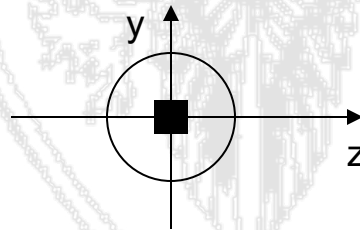


top view (xz-plane)

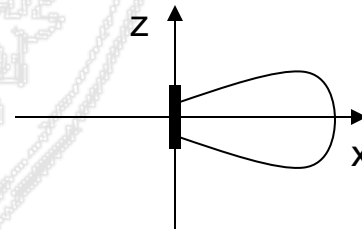
simple  
dipole



side view (xy-plane)



side view (yz-plane)



top view (xz-plane)

directional  
antenna

# 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)

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

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

- k antenna efficiency factor ( $\leq 1$ )
- 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:

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

- $P_T g_T$  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  $d$

# Wireless channel: attenuation wrt distance

- 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

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

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

- where  $P_T$  is the transmitter radiated power,  $g_T$  and  $g_R$  the gains of the transmitter and receiver antennas,  $\lambda$  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

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

Log= base-10 logarithm

$P_A = 1$  Watt

$P_B = 1$  milliWatt

30 dB  $\rightarrow$   $P_A$  = three orders of magnitudes higher than  $P_B$

## ◆ Gain of an antenna is expressed in dB

3dB  $\rightarrow$   $P_1$  is twice  $P_2$ , 10dB  $\rightarrow$   $P_1$  is one order of magnitude higher than  $P_2$

20dB  $\rightarrow$   $P_1$  is two orders of magnitude higher than  $P_2$

30dB  $\rightarrow$   $P_1$  is three orders of magnitude higher than  $P_2$

# Decibels - dBm

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

## Example

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

# Example

frequency [MHz]	900	normalized
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

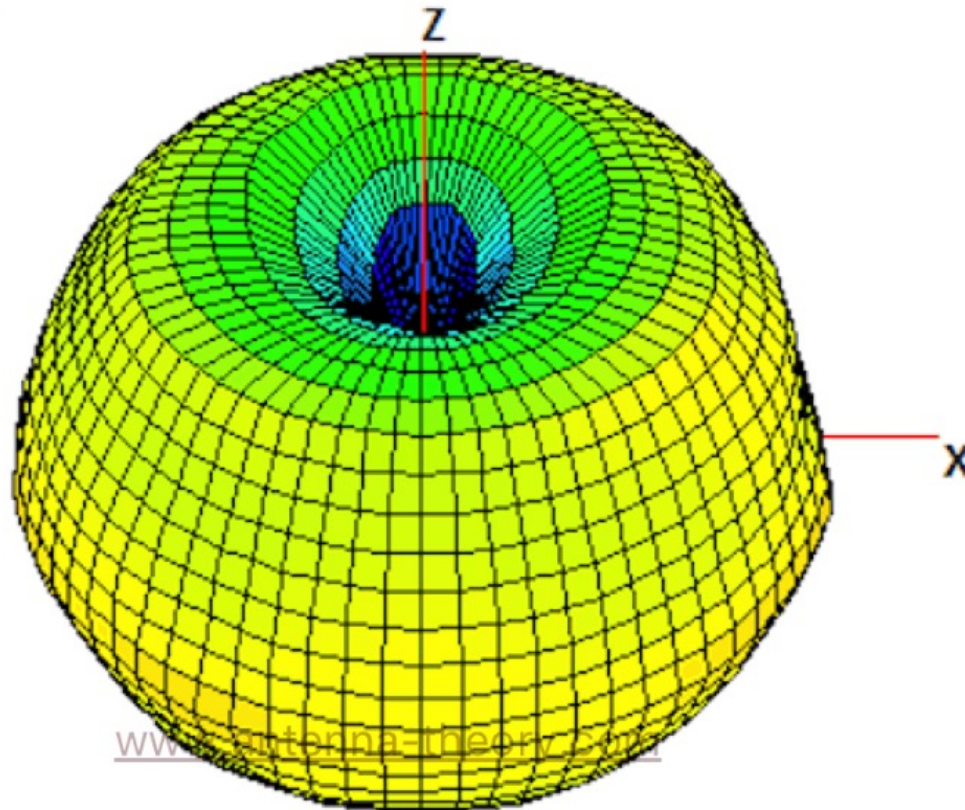
The graph illustrates the relationship between distance and received power. The x-axis is labeled 'distance (m)' and ranges from 0 to 5000. The y-axis is labeled 'received power (dBm)' and ranges from -70.00 to -30.00. A red curve shows the power decreasing as distance increases, starting at approximately -40.56 dBm at 200m and ending at approximately -68.52 dBm at 5000m.



## Radiation Pattern (Gain in dB)

Azimuth = 0.0  
Elevation = 45.0  
Roll = 0.0

[www.antenna-theory.com](http://www.antenna-theory.com)



Response (dB)

5

0

-5

-10

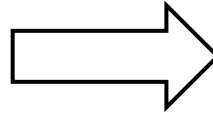
-15

-20

[www.antenna-theory.com](http://www.antenna-theory.com)

# 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
- $\text{Loss (dB)} = \text{transmit (dBm)} - \text{receive (dBm)}$ 
  - Es. 43 dB = attenuation by factor 20.000

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

# Wireless channel: path loss

- Path Loss

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

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

- 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

*Denoted also as  $L_{free}$  in what follows*

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

= 20

$$\frac{P_T}{P_R} = \frac{P_T}{P_T G_T G_R \left( \frac{\lambda}{4\pi d} \right)^2 \frac{1}{L}} \quad 10 \log_{10} \frac{c}{4\pi} =$$

= 20

7.56



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

*Denoted also as  $L_{free}$  in what follows*

$$\begin{aligned} PL(d)_{[dB]} &= 10 \log_{10} \frac{P_t}{P_r} = 10 \log_{10} \left\{ \frac{L}{G_t G_r} \left( \frac{4\pi d}{\lambda} \right)^2 \right\} = \\ &= 20 \log_{10} d - 10 \log_{10} \frac{G_t G_r}{L} - 20 \log_{10} \frac{\lambda}{4\pi} = \\ &= 20 \log_{10} d + 20 \log_{10} f - 10 \log_{10} \frac{G_t G_r}{L} - 20 \log_{10} \frac{c}{4\pi} = \\ &= 20 \log_{10} d + 20 \log_{10} f - 10 \log_{10} \frac{G_t G_r}{L} - 147.56 \end{aligned}$$

*It depends on distance but also on frequency*

# Free space loss

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

*If  $L=1$ , gains=1*

$$\begin{aligned} L_{free}(d)_{[dB]} &= -20 \log \left[ \frac{\lambda}{4\pi d} \right] = -20 \log \left[ \frac{c/f}{4\pi d} \right] \\ &= 20 \log_{10} d + 20 \log_{10} f - 147.56 \end{aligned}$$

# Further comments on Friis transmission equation

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

*If we know the value at a reference distance  $d_{ref}$ ...*

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

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

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

*If we know the value at a reference distance  $d_{ref}$ ...*

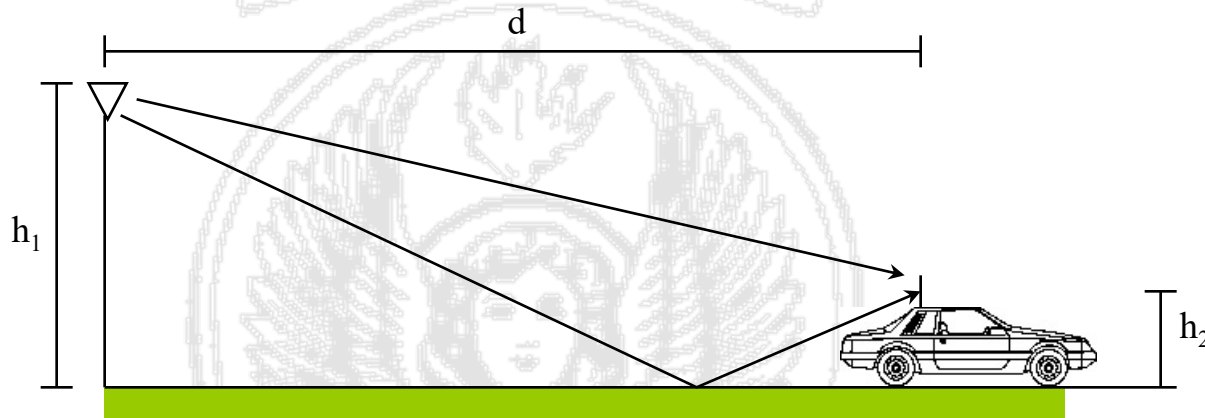
$$P_R(d) = P_R(d_{ref}) (d_{ref}/d)^2$$

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

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

# ***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:**

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



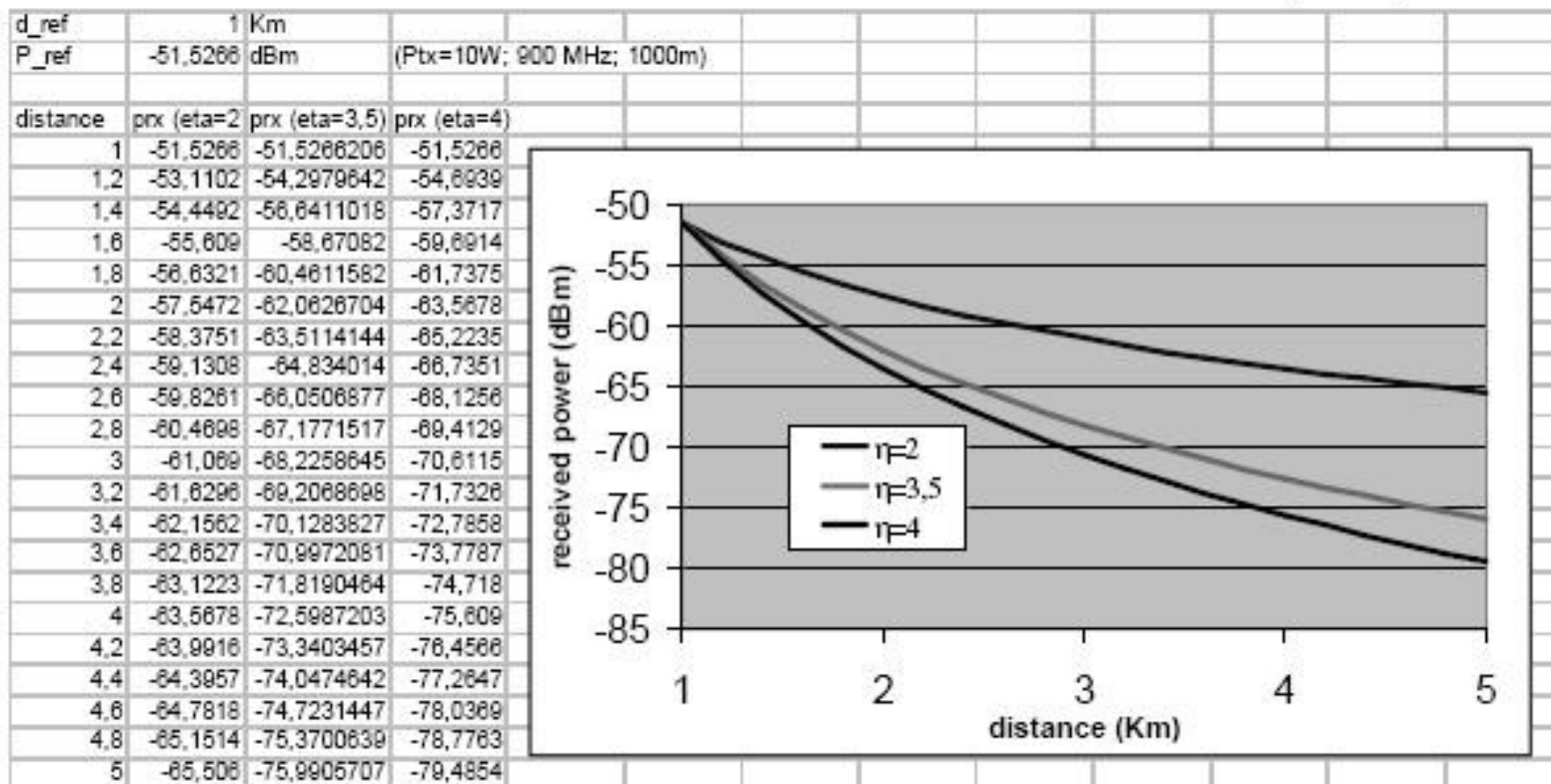
# Wireless signal propagation

- In the two ray model the received power decreases much faster with distance ( $\sim 1/d^4$ ) than in the free space model ( $\sim 1/d^2$ )
- 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  $\eta$  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)

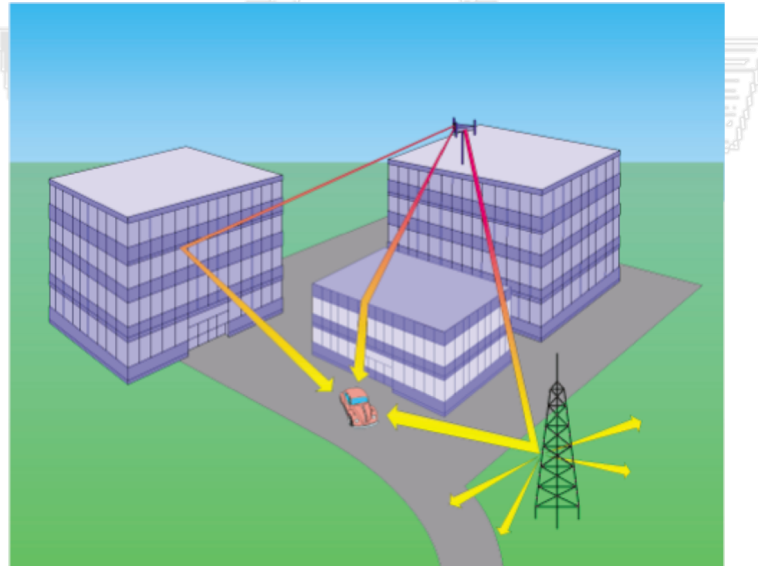
$$P_R = P_T g_T g_R \left( \frac{\lambda}{4\pi} \right)^2 \frac{1}{d^\eta}$$

# Extended formula

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

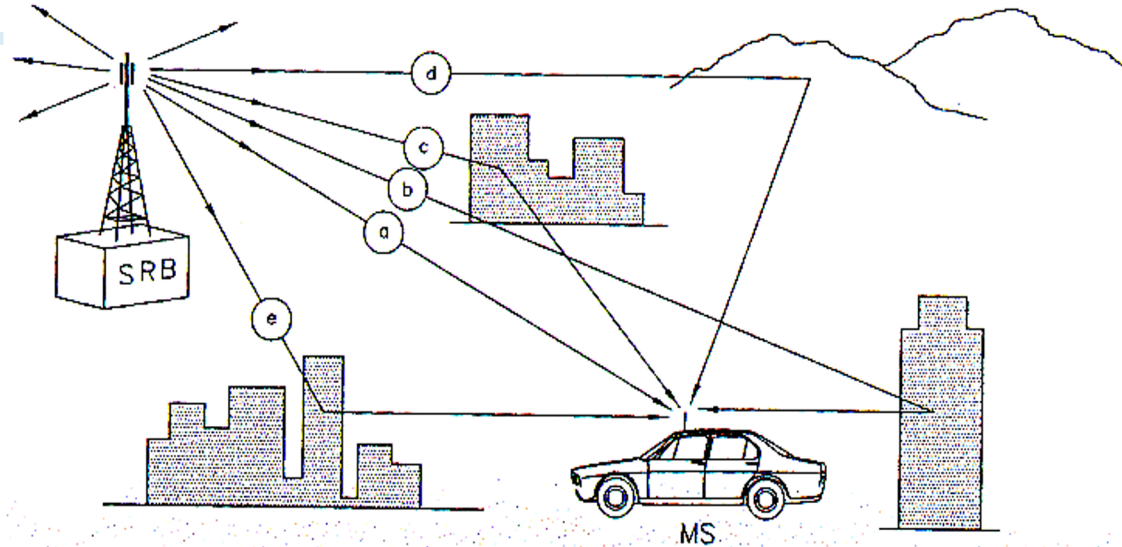


# Wireless channel: multipath fading



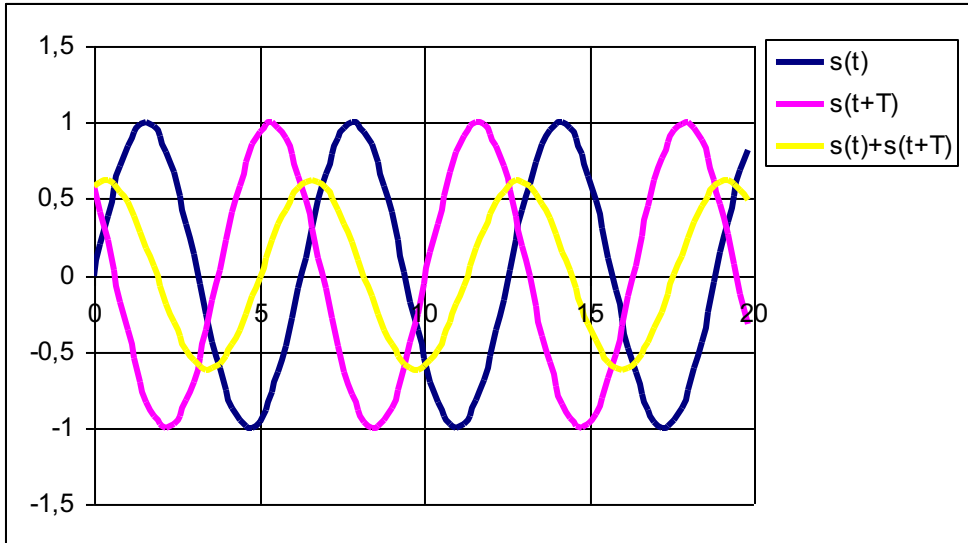
- While propagating from source to destination the signal can follow multiple paths. At the receiver different components (received over different paths, with different phases and amplitudes) are combined.
- Signal can be reflected, diffracted, scattered based on the obstacles it finds over its path 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



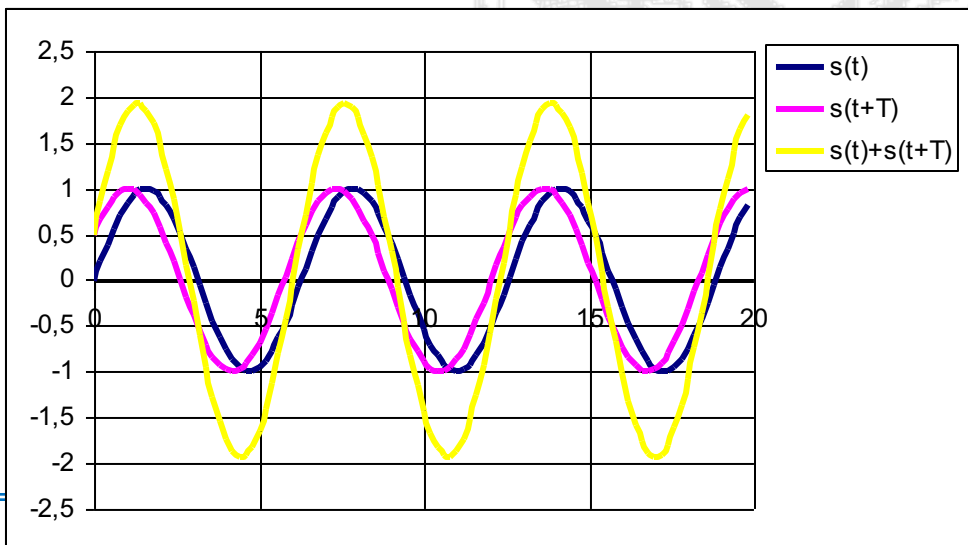
- Signal replicas received via different propagation paths are combined at the receiver
  - The results depends on
    - The number of replicas
    - Their phases
    - Their amplitudes
    - Frequency
- Received power differs, as a result  
from place to place, from time to time!

# Multipath fading



- Resulting signal can be attenuated

$$T = 4/5\pi$$



- Or amplified

$$T = \pi / 6$$

# Rayleigh 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)
- $\phi_k$  uniformly distributed in  $(0, 2\pi)$
- $a_k$  comparable (no privileged path such as LOS)

X, Y are gaussian, identically distributed random variables

**Rayleigh fading power  
distribution**

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

*Sigma<sup>2</sup> is the  
Variance of  
The X, Y variables*



# Rayleigh fading

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

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

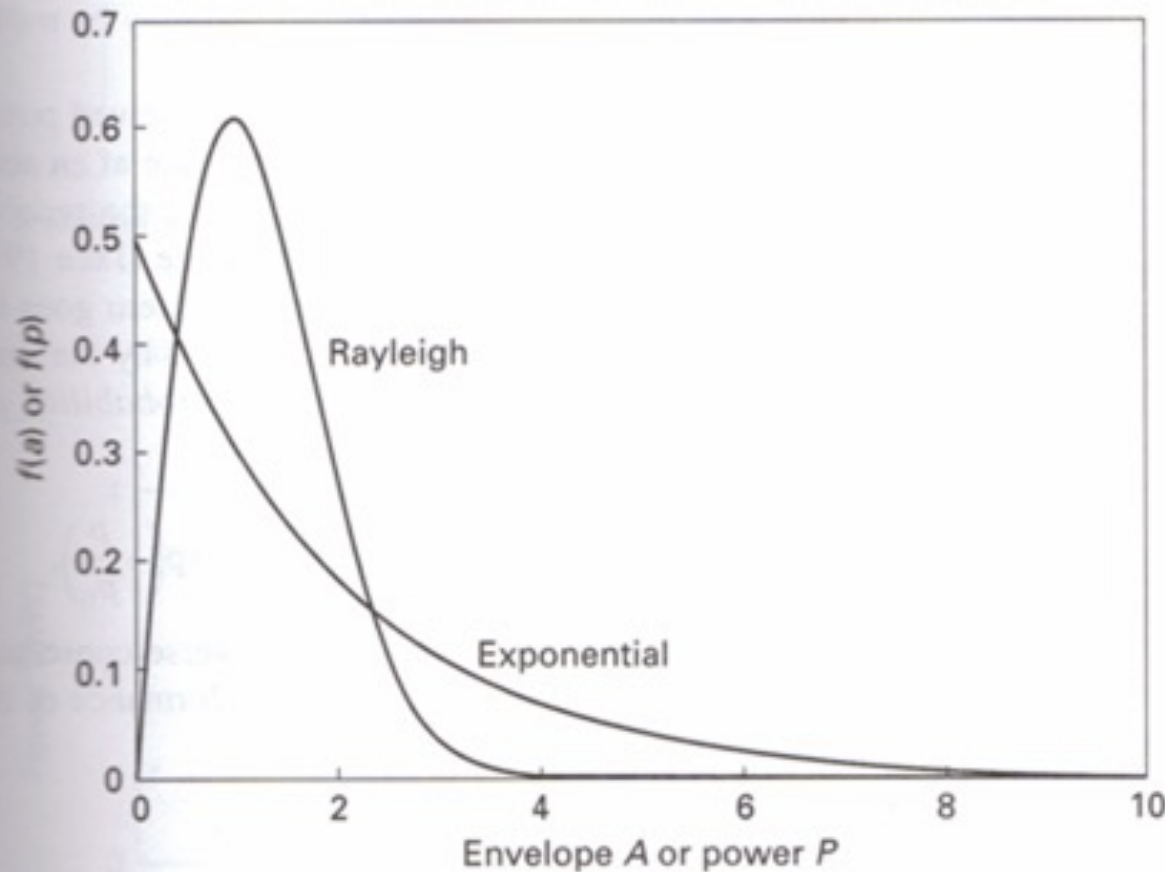
= c

= X

In the as

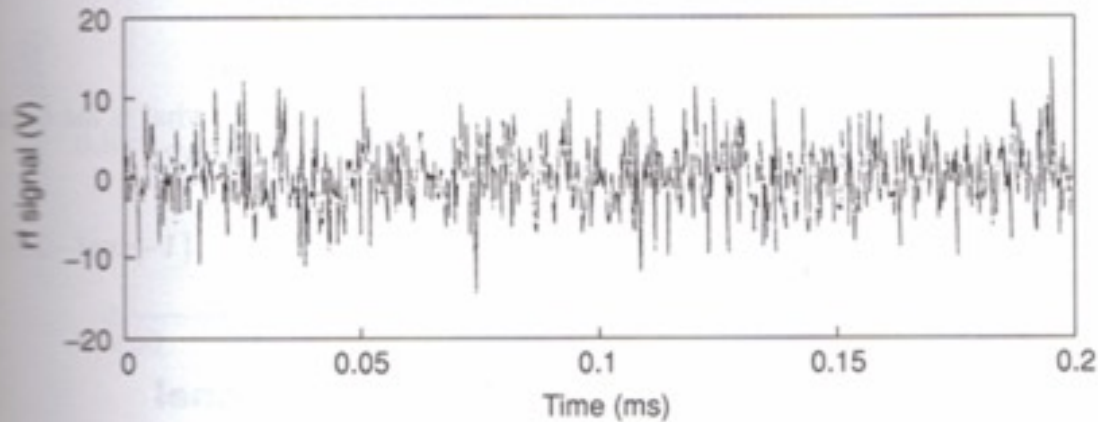
X,Y are

Rayleigh  
distribu

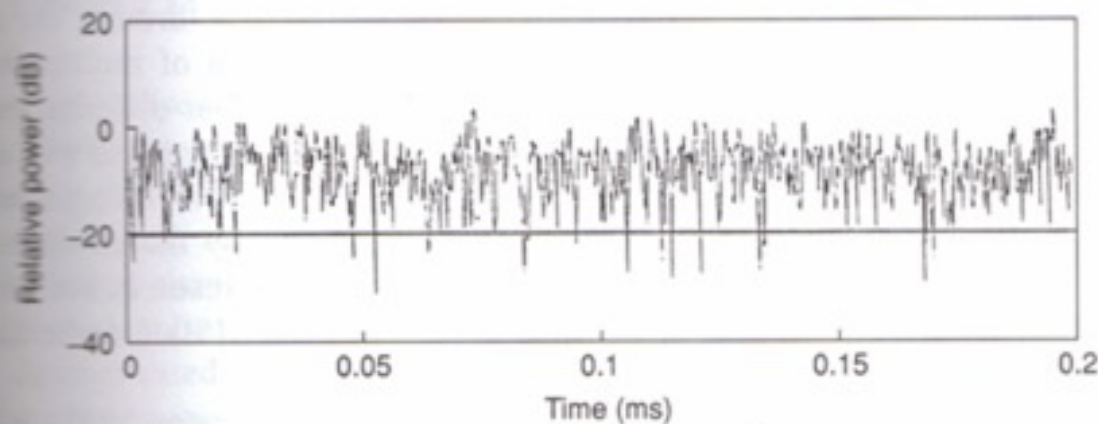


s the  
of  
variables

# Rayleigh fading



(a)



(b)

**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:

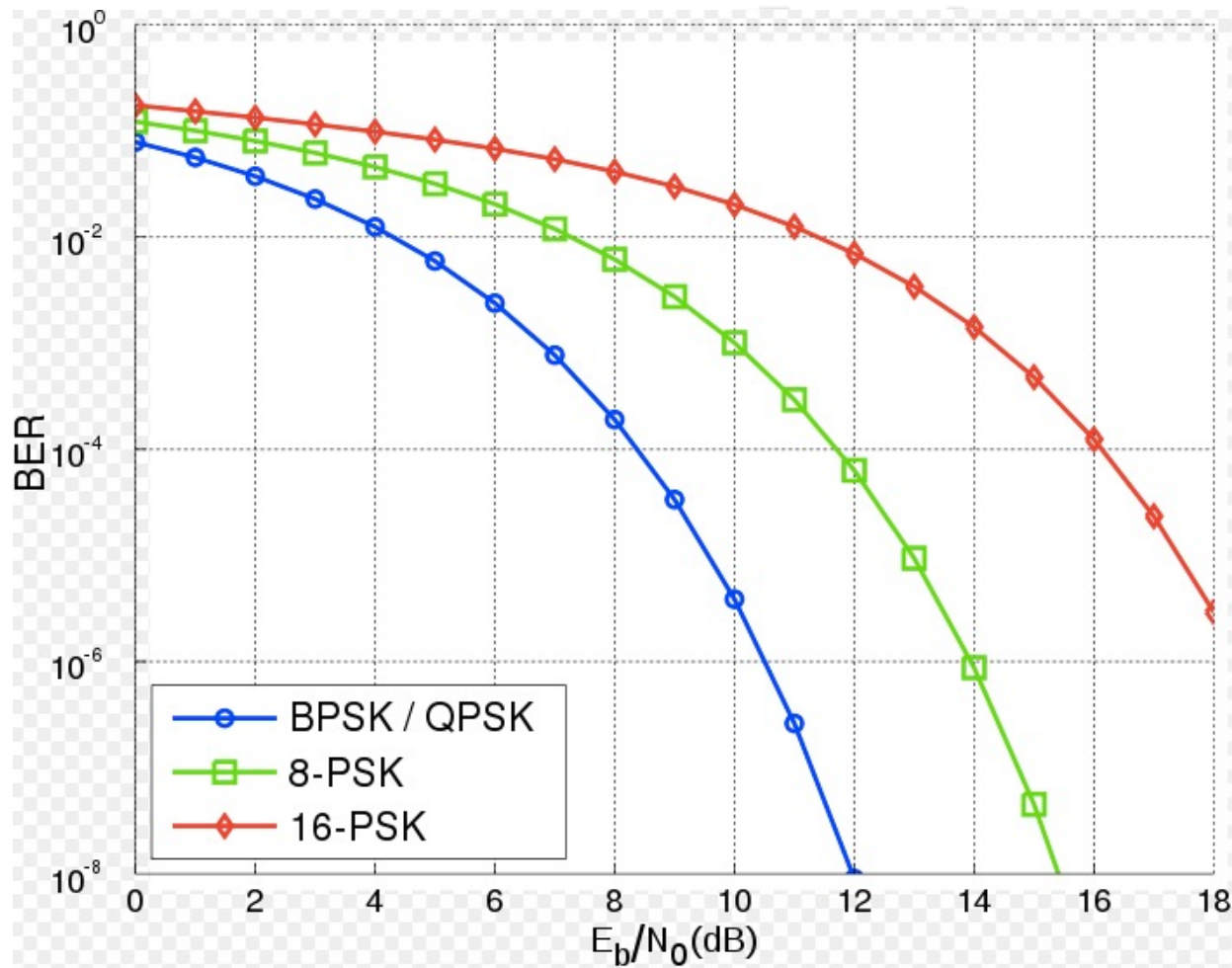
**Outage Probability**→Probability that received power is lower than a given threshold

⇒Below which signal cannot be correctly received

$$P_{\text{out}} = \int_0^{p_{\text{thr}}} f(p) dp$$

Pay attention: making the assumption the network topology is a unit disc graph is a strong approximation to be aware of. Solutions relying heavily on this approximation sometimes fail completely in real life

# BER performance

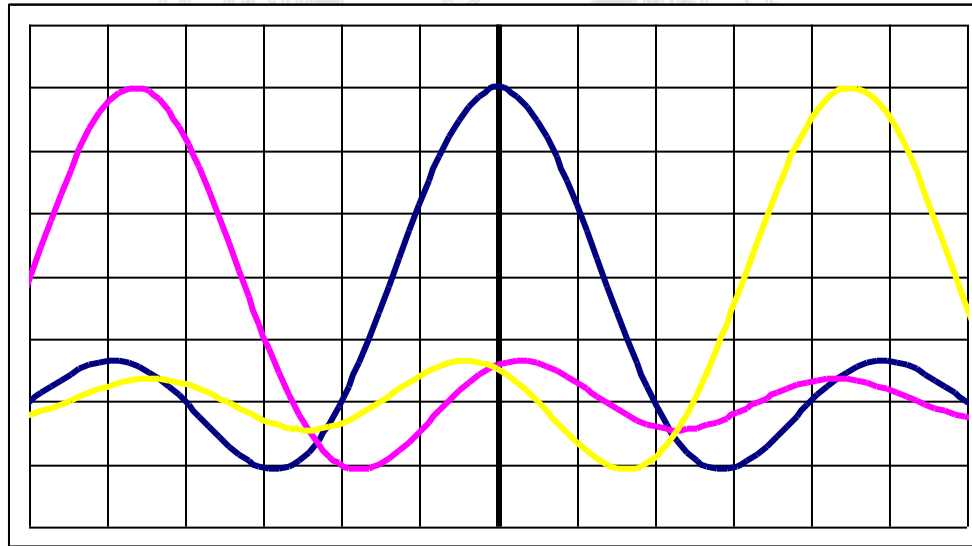


BER performance  
also depends  
on modulation  
Given a S/N and a  
Modulation  $\rightarrow$  BER

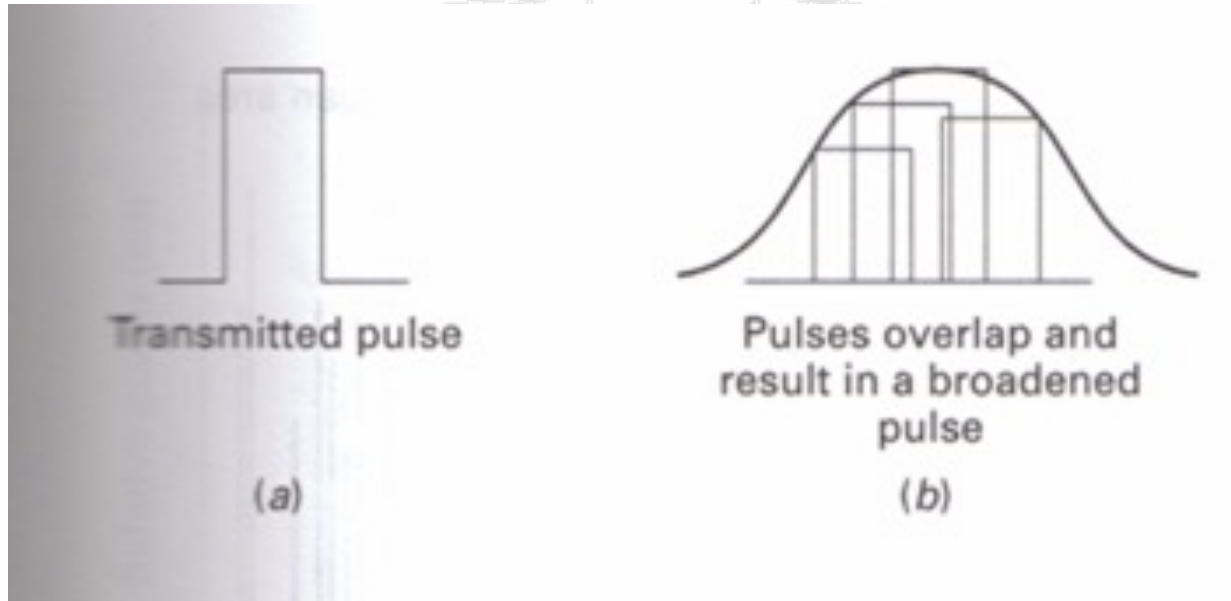
Using FEC BER  
Performance can  
be improved

# 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)

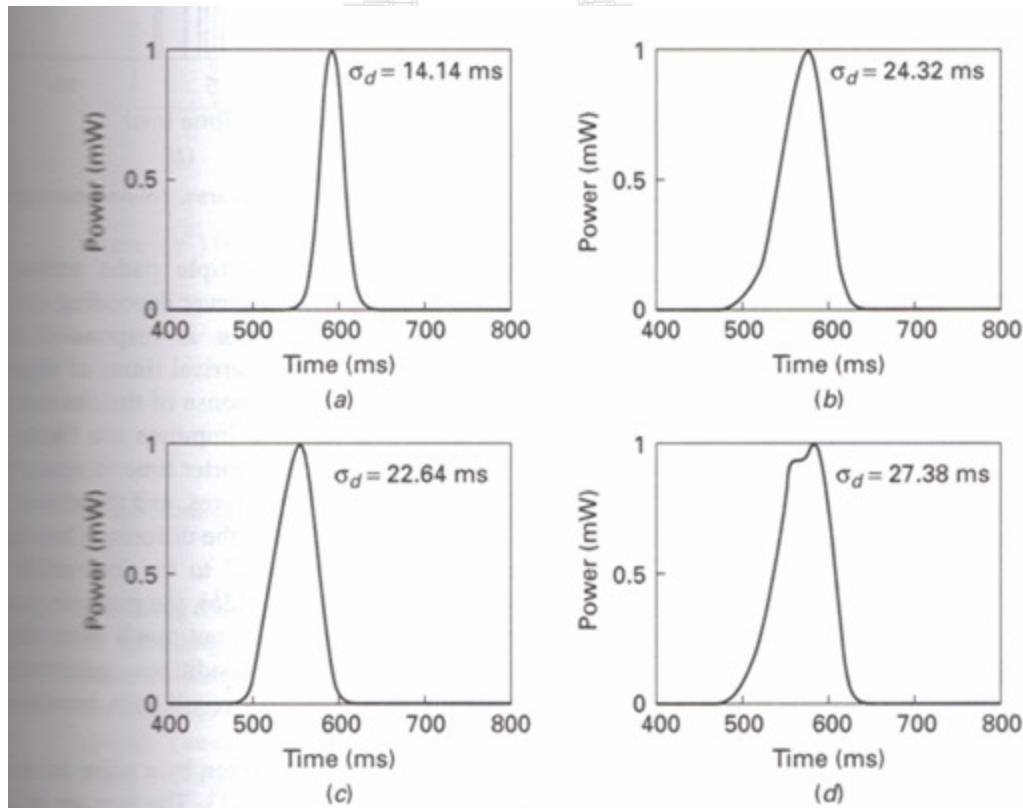


# Examples

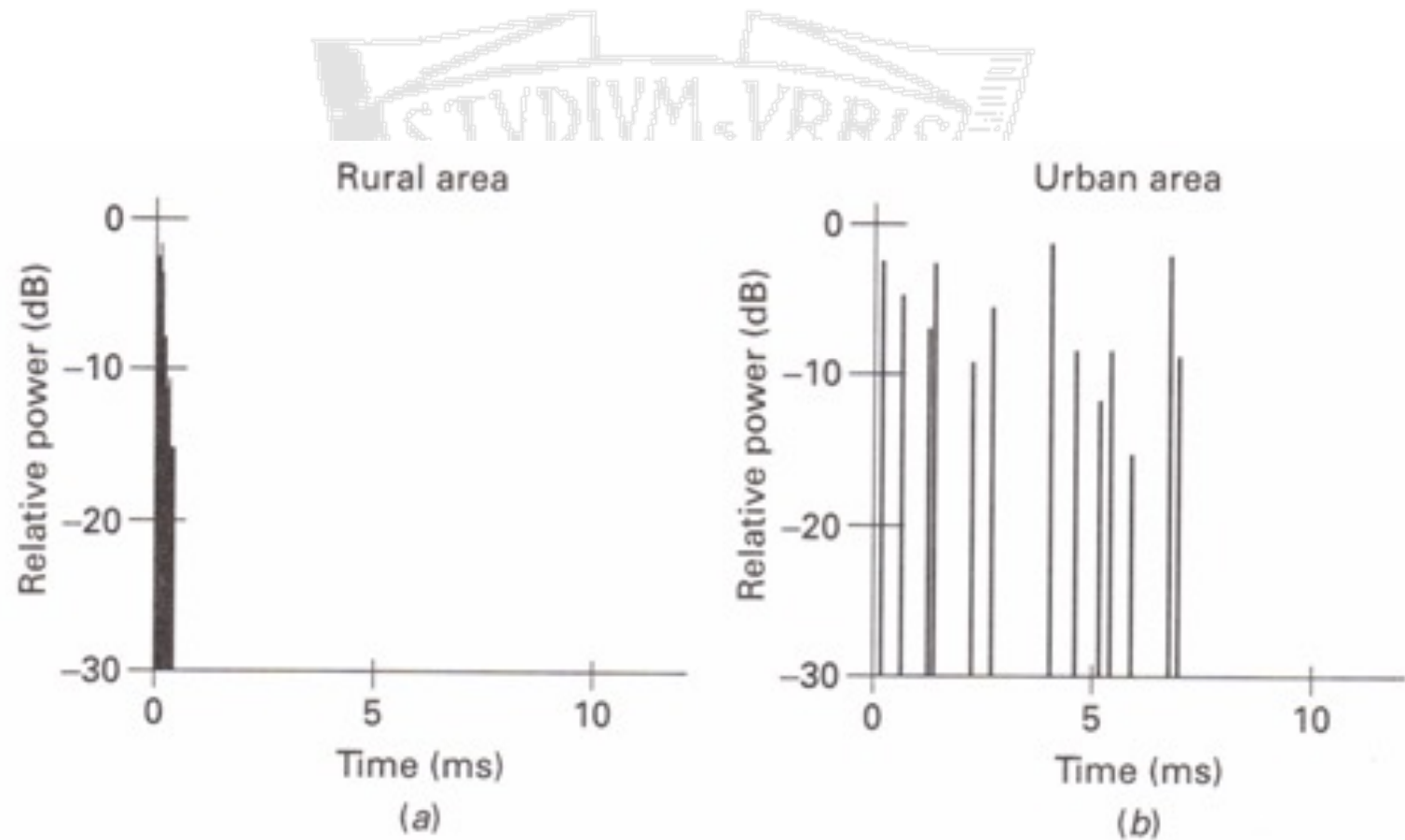




# Examples



# Impulse response



# Multipath fading

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

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

■ with

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



$\tau_{RMS}$

RMS delay spread



$\tau_i$

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  $\gg$  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.