IoT, Course introduction

Internet of Things a.a. 2020/2021

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 Informatica, Via Salaria 113, 3° piano, room n. 311, Tel: 06 4991 8354
- E-mail: petrioli@di.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 45, 7000+ 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 Informatica, Via Salaria 113, 3° piano, room n. 311, Tel: 06 4991 8354
- E-mail: petrioli@di.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
- 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)

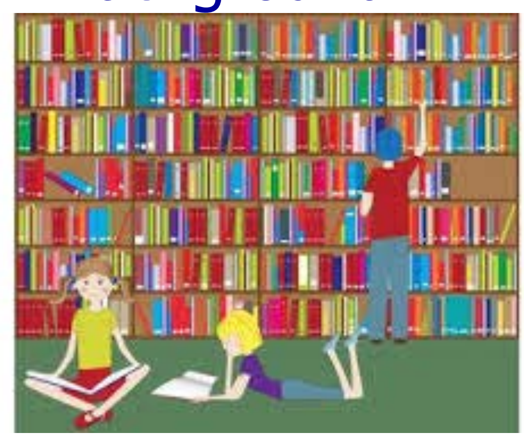
- We would like to be able to contact all registered students fast.
- Please provide contact info and register on

IoT Students

Career Aspirations

Background

Status

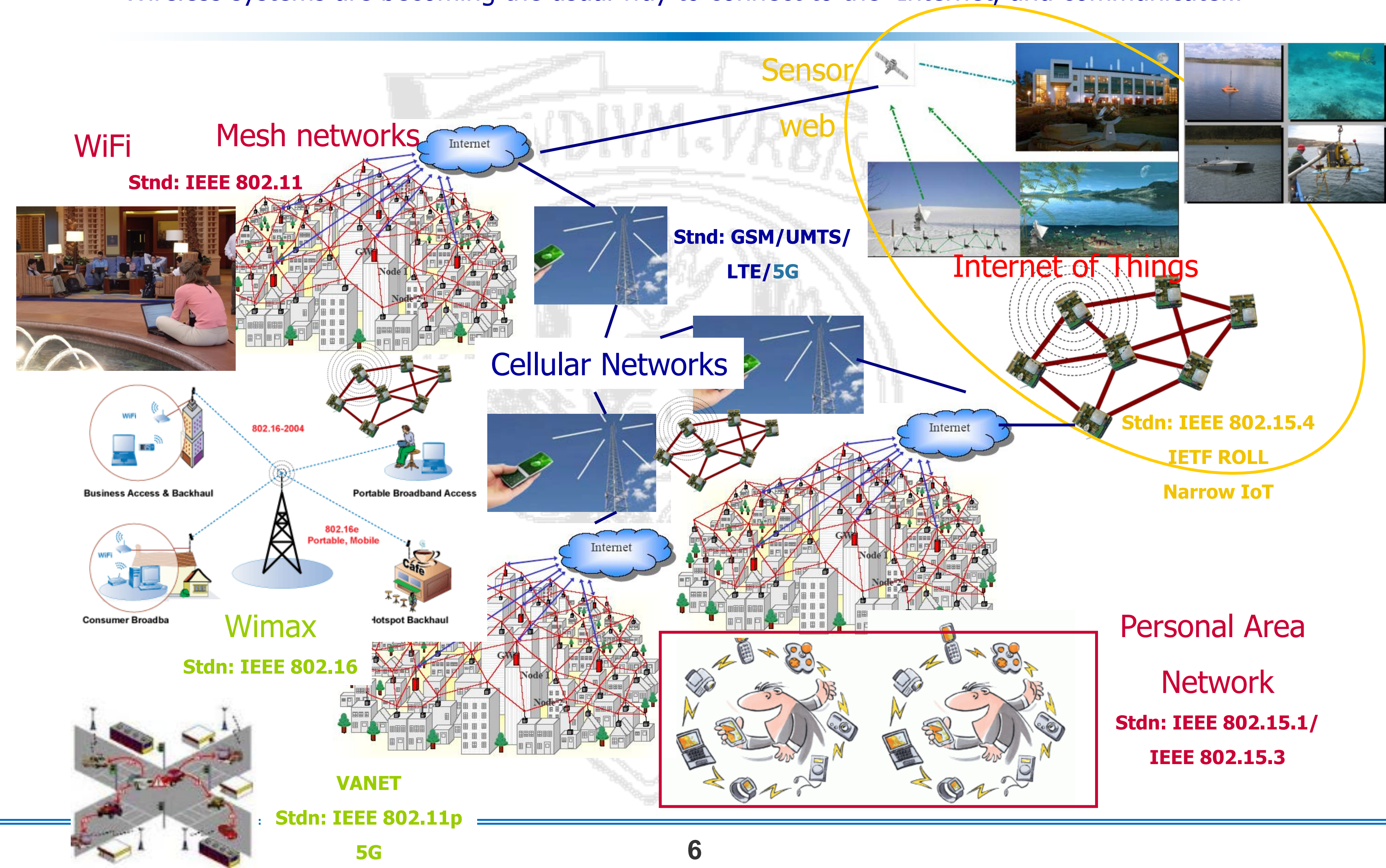


Interests

What we will do

Why a class on Internet of Things?

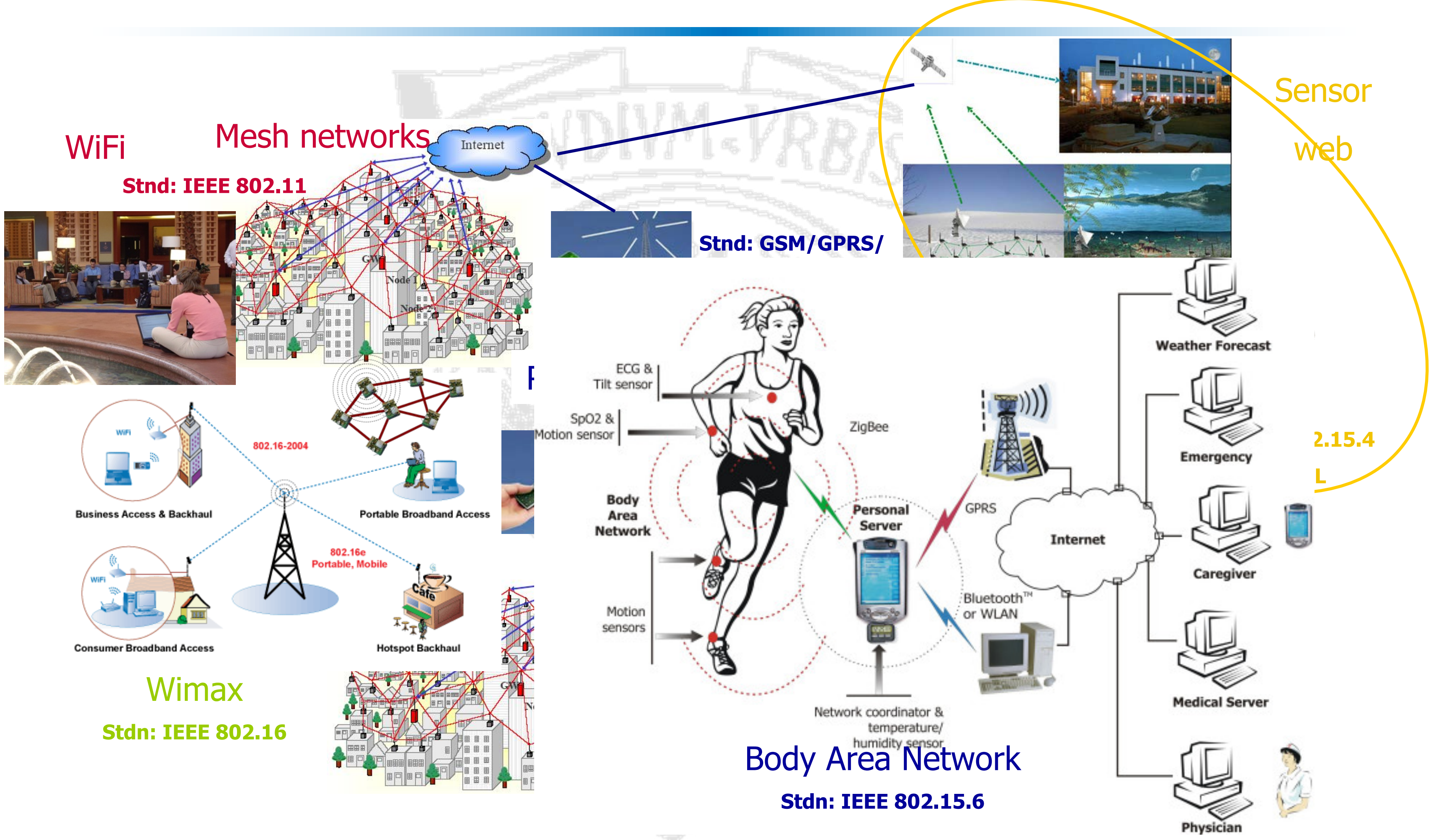
Wireless systems are becoming the usual way to connect to the Internet, and communicate…



What we will do

Why a class on Internet of Things?

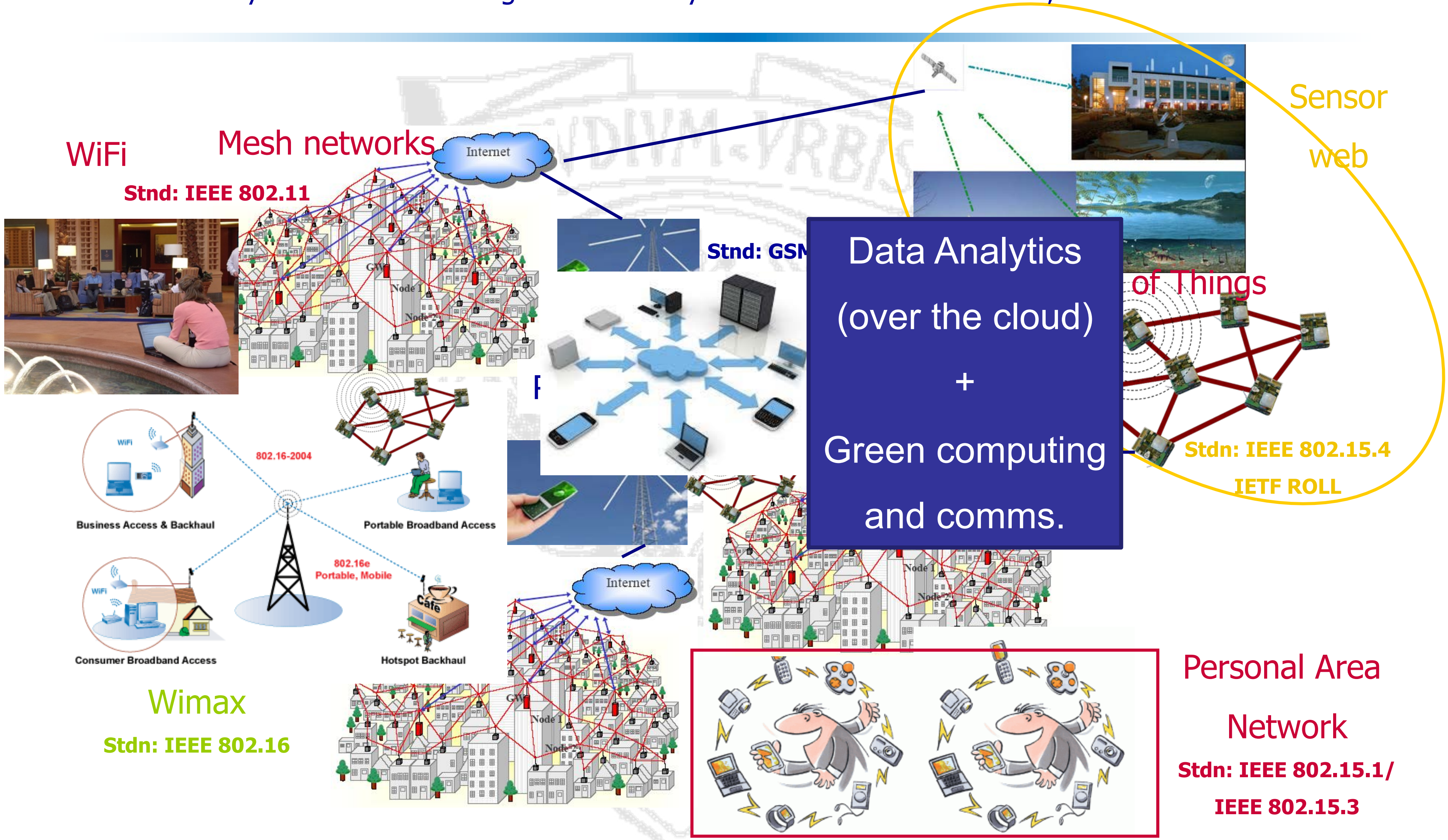
Wireless systems are becoming the usual way to connect to the Internet, and communicate…



What we will do

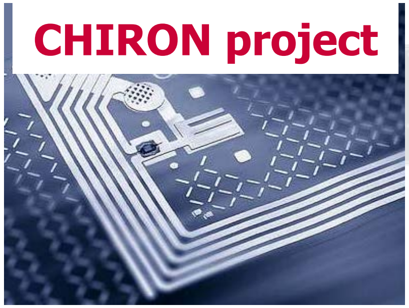
Why a class on Internet of Things?

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



SENSES lab

CHIRON project

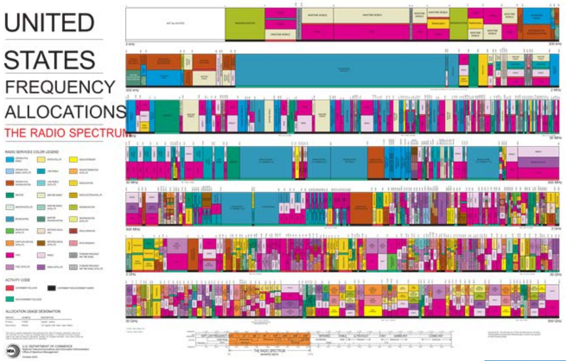


RFID Anticollision Protocols

GENESI Project

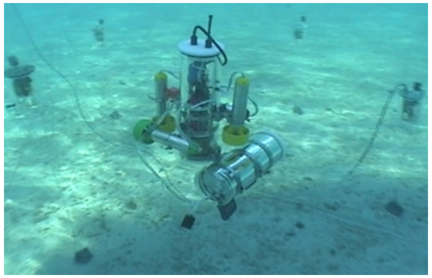
Green sensing systems

SENDORA project



Cognitive networks

CLAM Project; SUNRISE project



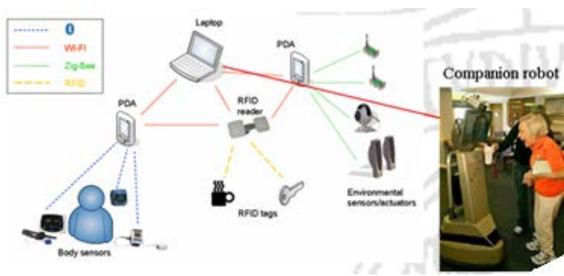
Underwater Monitoring systems

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 Thigs 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 Isystems

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.

<u>WE ARE CHECKING WHETHER IT WILL BE ALLOWED TO HAVE MIDTERM OR NOT</u>

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 Libaries (articles)
Books (main library)

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

ACM MobiCom,

IEEE Infocom,

ACM MobiHoc,

ACM SenSys,

IEEE IPSN

College experience

College experience

+ Transversal Skills

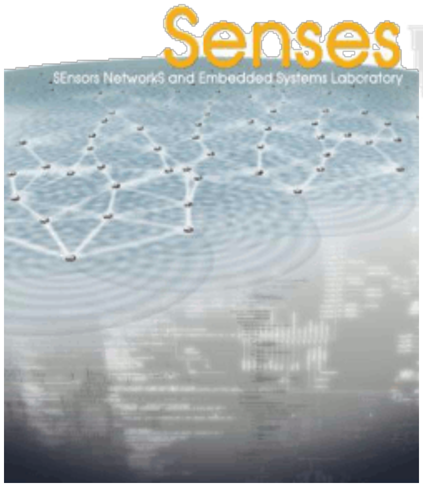
<u>Seminars of international experts</u>

<u>Large projects, EXPLOIT Labs</u>

Internship

Spinoff

College experience



GRANTS “borsa di studio per attività di ricerca”

Contact me AT petrioliATdiDOTuniroma1DOTit

5 in the last year to top class students

http://senseslab.di.uniroma1.it

Possibility to do also the AFC

Fundamental of wireless systems

Internet of Things a.a. 2020/2021

Un. of Rome “La Sapienza”

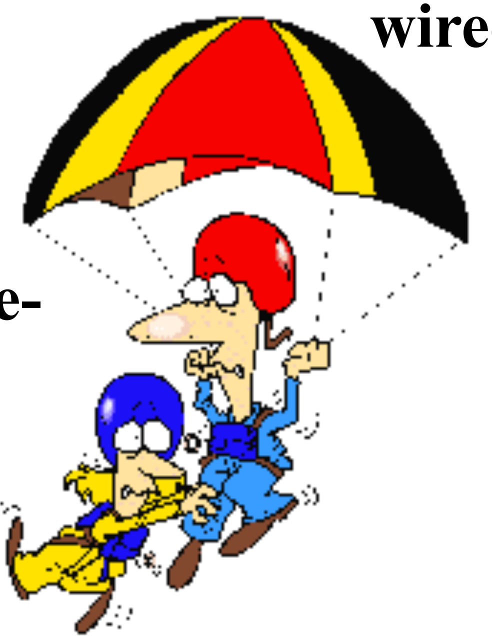
Chiara Petrioli

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

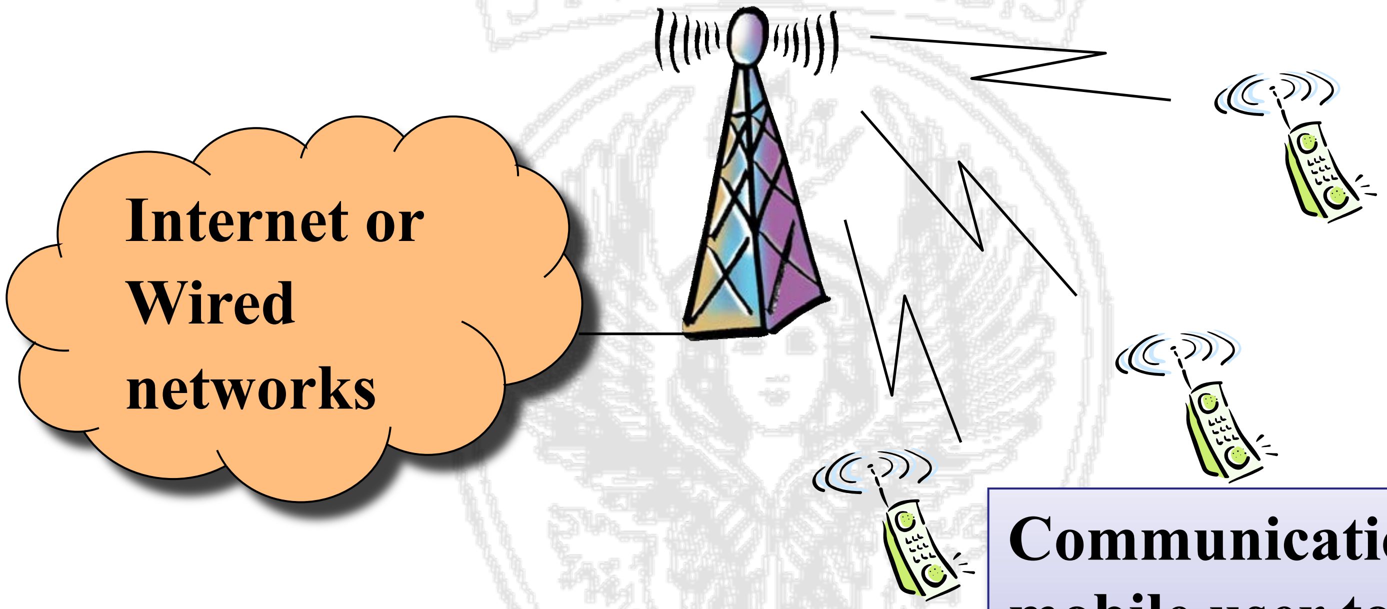
  →Low power platforms and energy efficient protocols (green solutions)

  →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

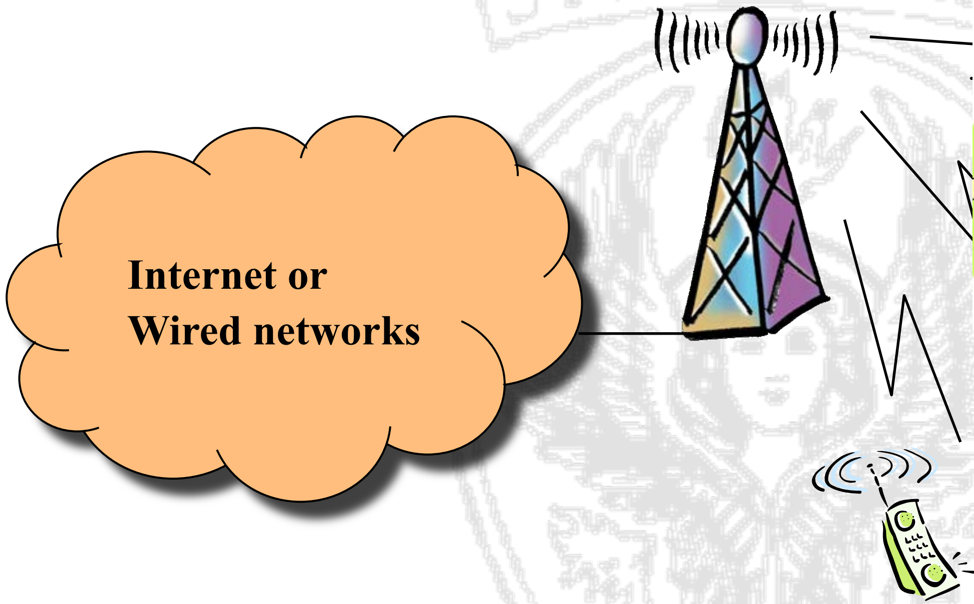
- Infrastructured networks

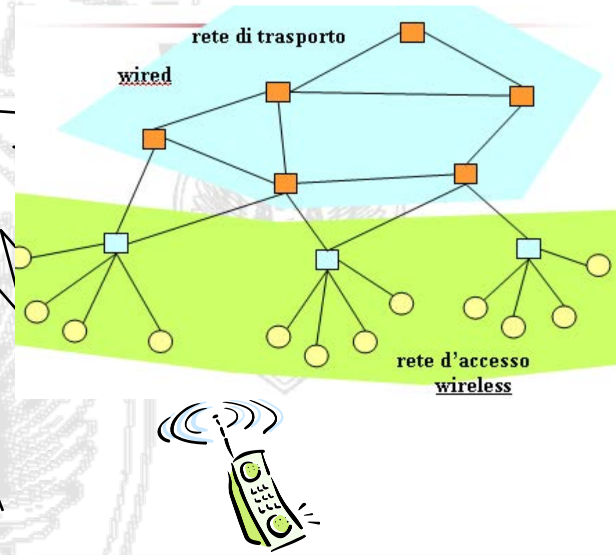


Communication from the mobile user to the base station/access point and viceversa

Wireless Systems Models

- 1) Infrastructured networks

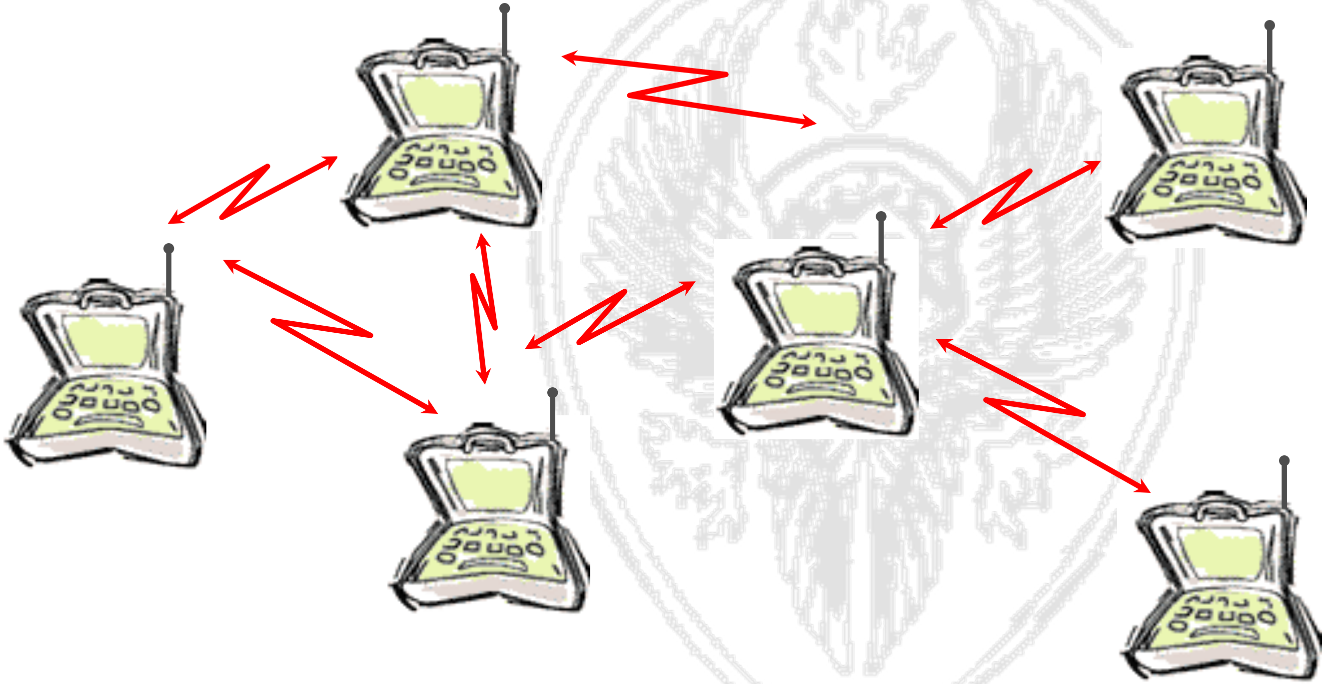




Communication from the mobile user to the base station/access point and viceversa

Wireless Systems models

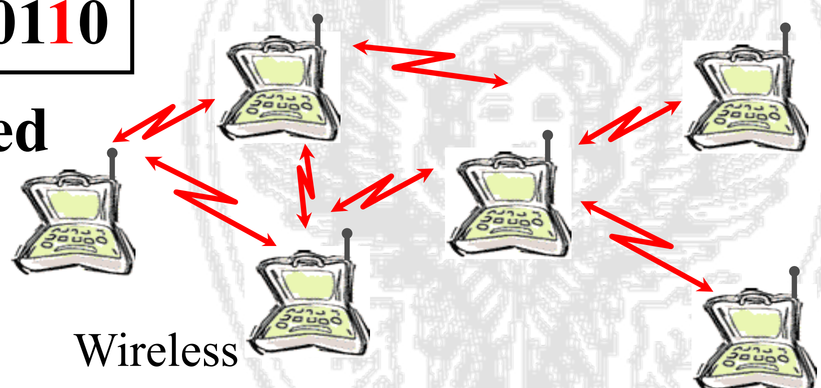
- 2) Ad Hoc Wireless Networks (wireless sensor networks, VANET, Mesh Networks,…)



- 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

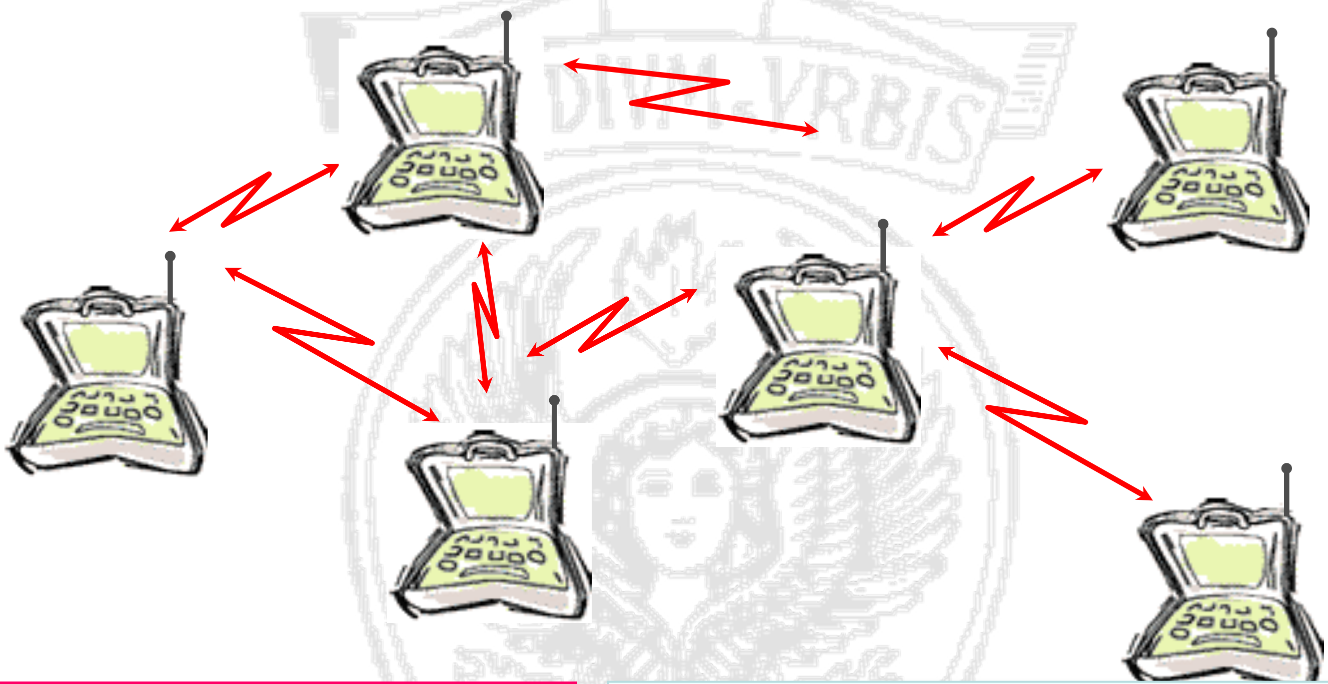


Forward Error Correction

Interleaving

Automatic Repeat Request

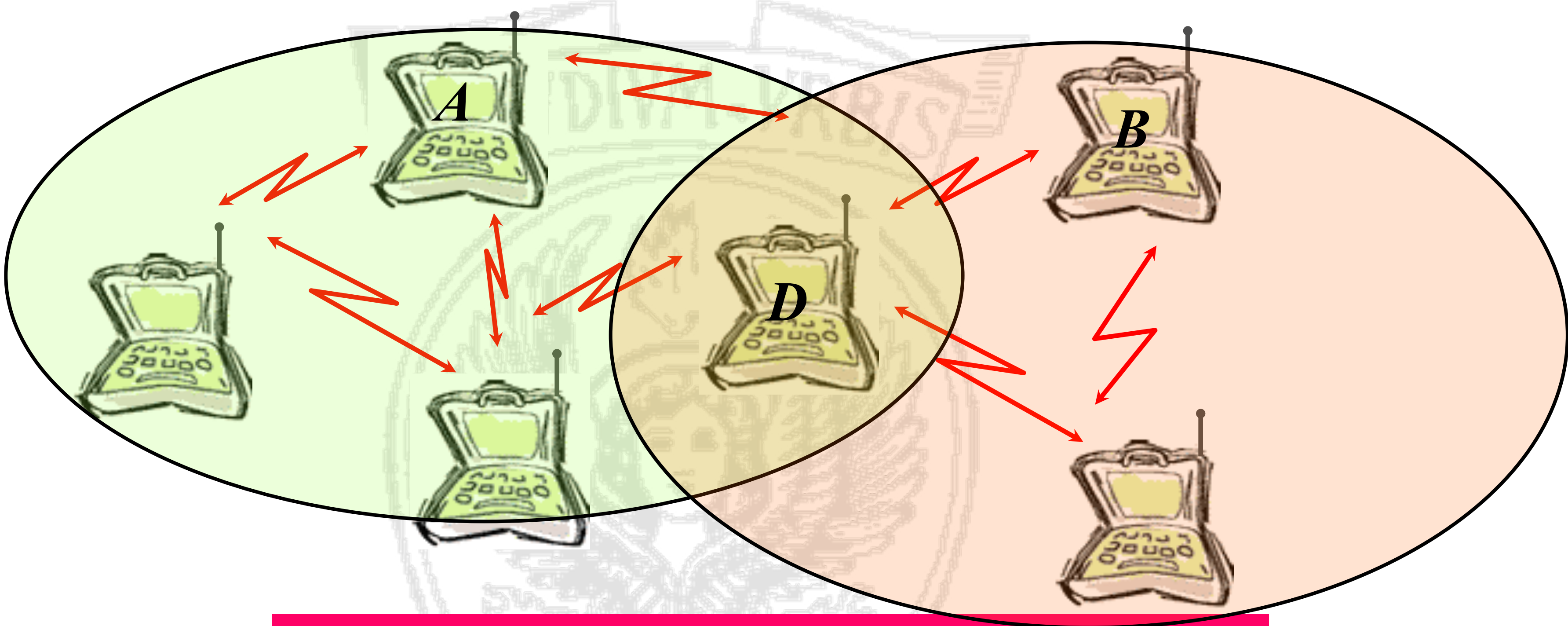
Medium Access Control



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

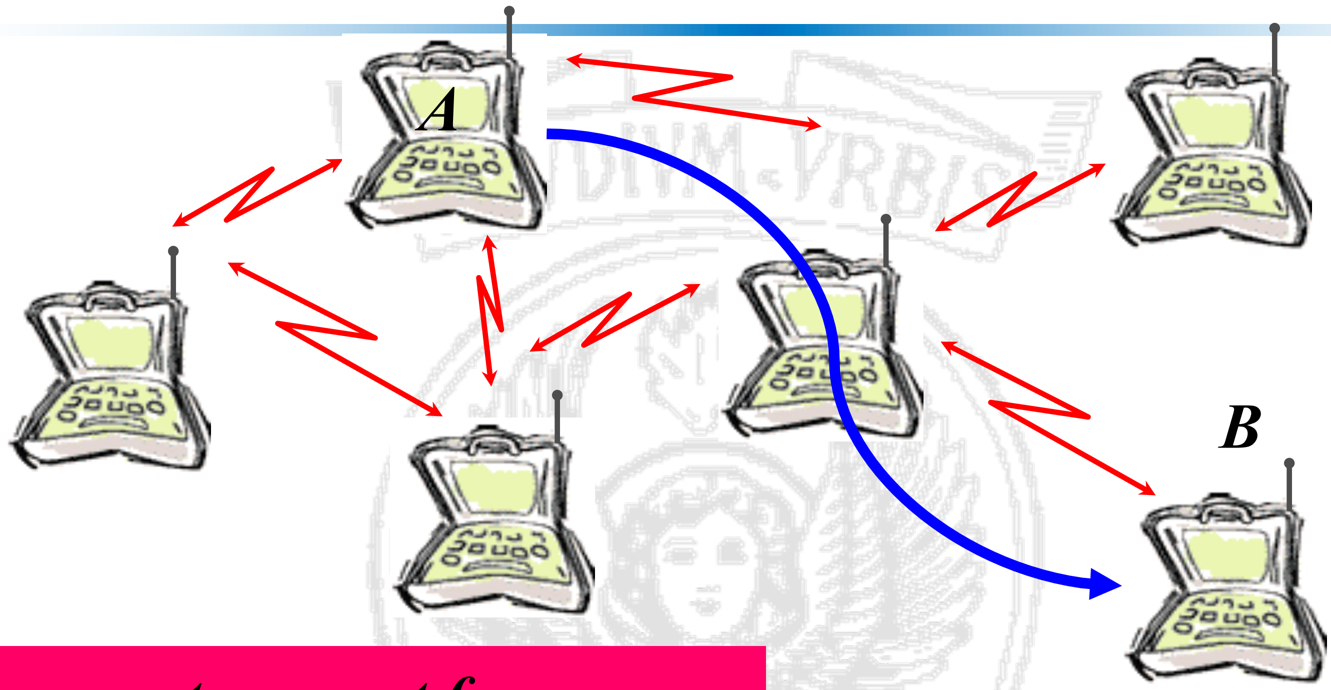
Antenna cannot tx and rx simultaneously;
Carrier sense is possible
Collision detection based on ACK/NAK

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.

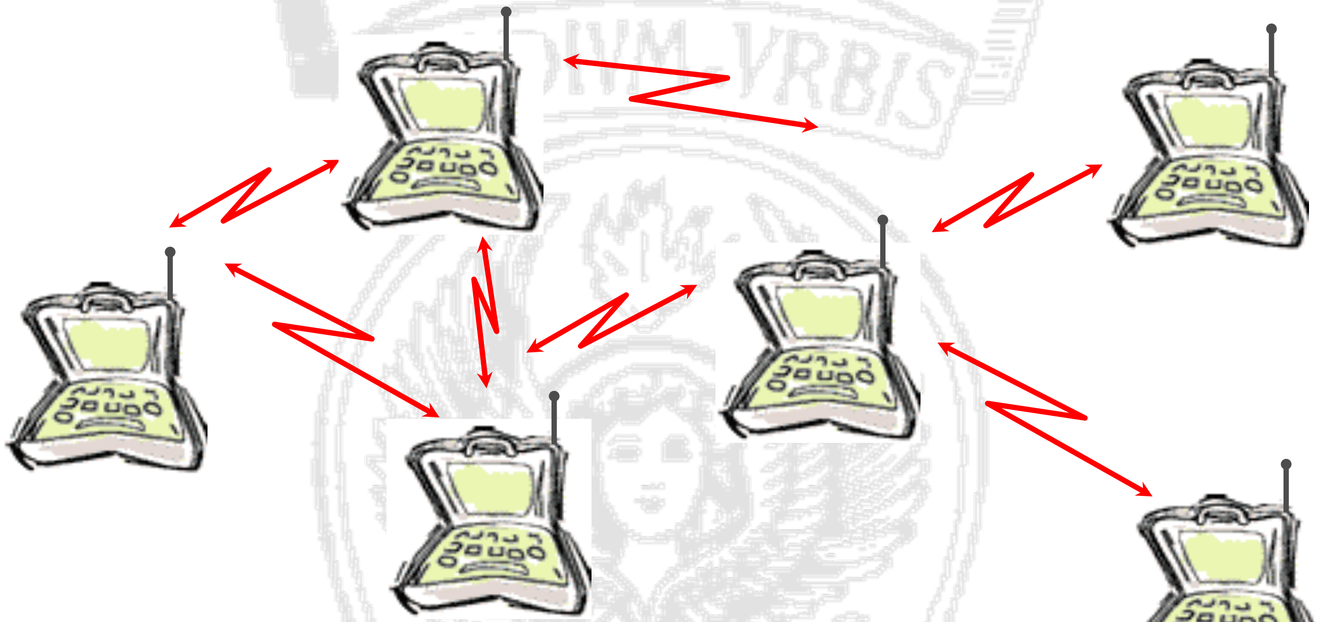
Routing



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)?

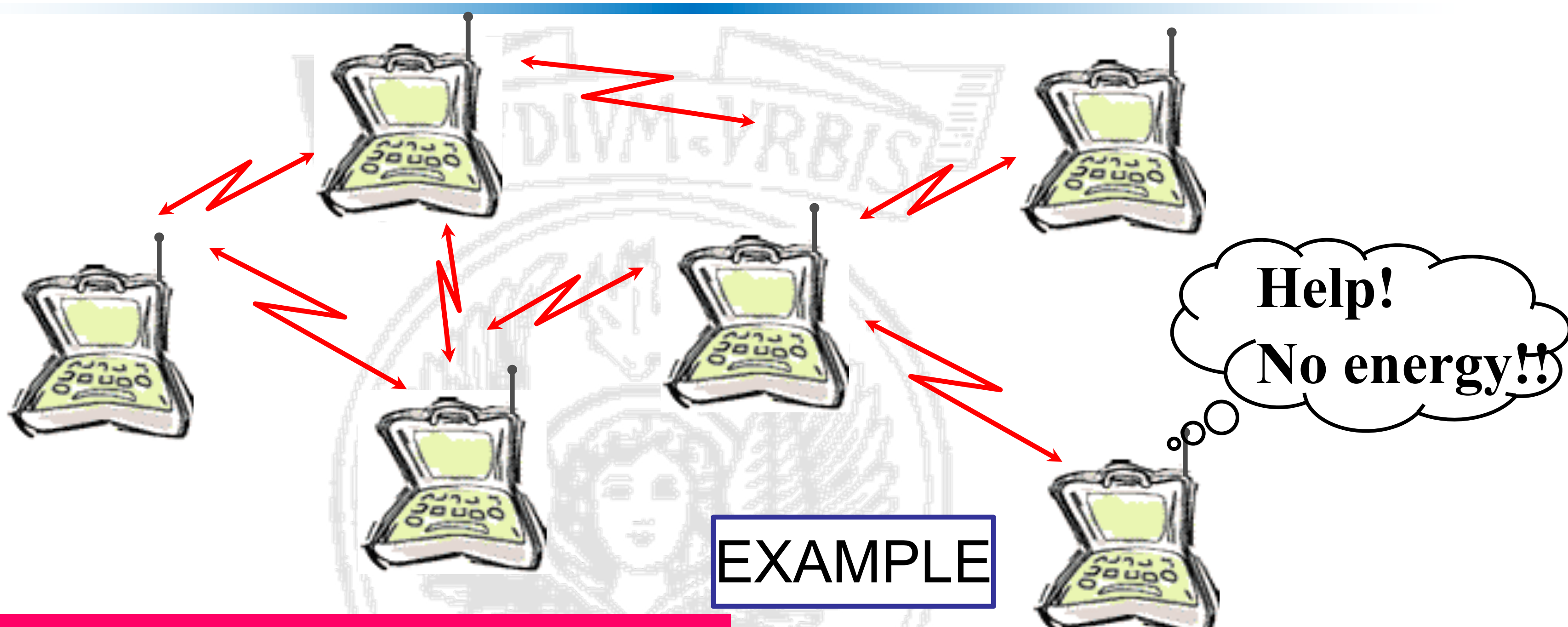
Ad Hoc Networks -Challenges



IETF MANET deals with routing

<u>One of the key challenges behind mobile peer to peer ad hoc networking</u>

Ad Hoc Networks-Challenges



EXAMPLE

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

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

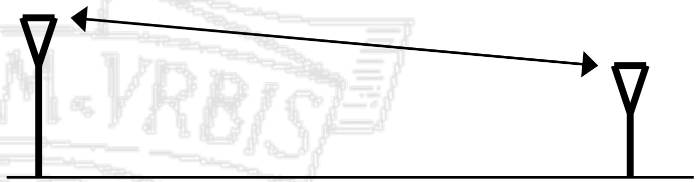
- Mobility management

Wireless channel

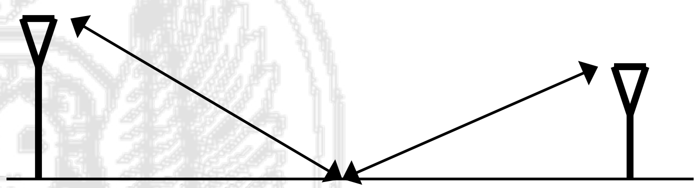
- Much less reliable than wired channels
- While propagating the signal can face
  - Attenuation as function of the distance from transmitter and receiver
  - Attenuation due to obstacles
  - Propagation over multiple paths (resulting in multipath fading)

Radio signal propagation

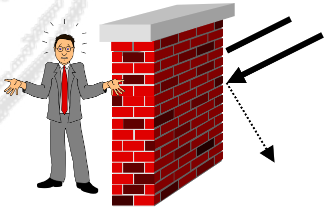
- Line of sight



- Reflection

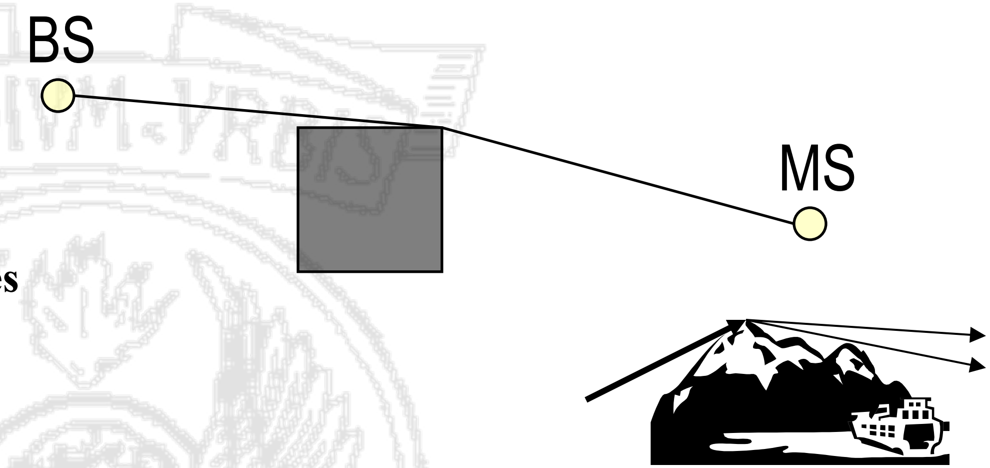


- Shadowing



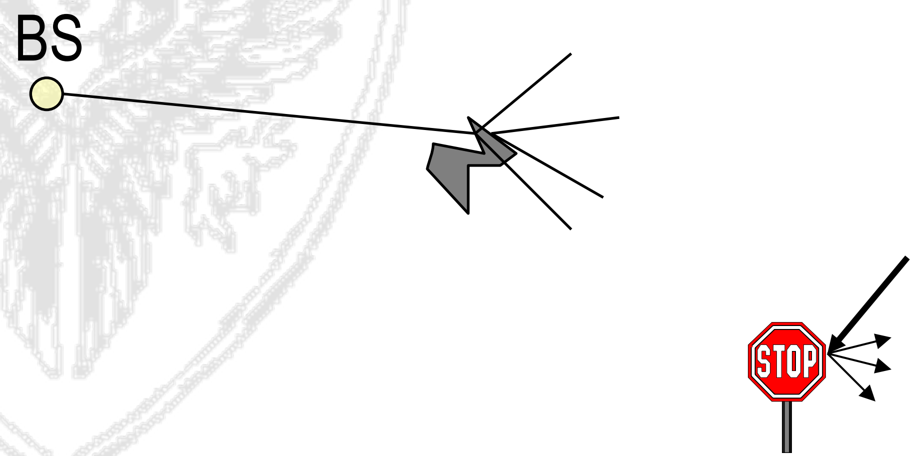
Radio signal propagation

➔Diffraction



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

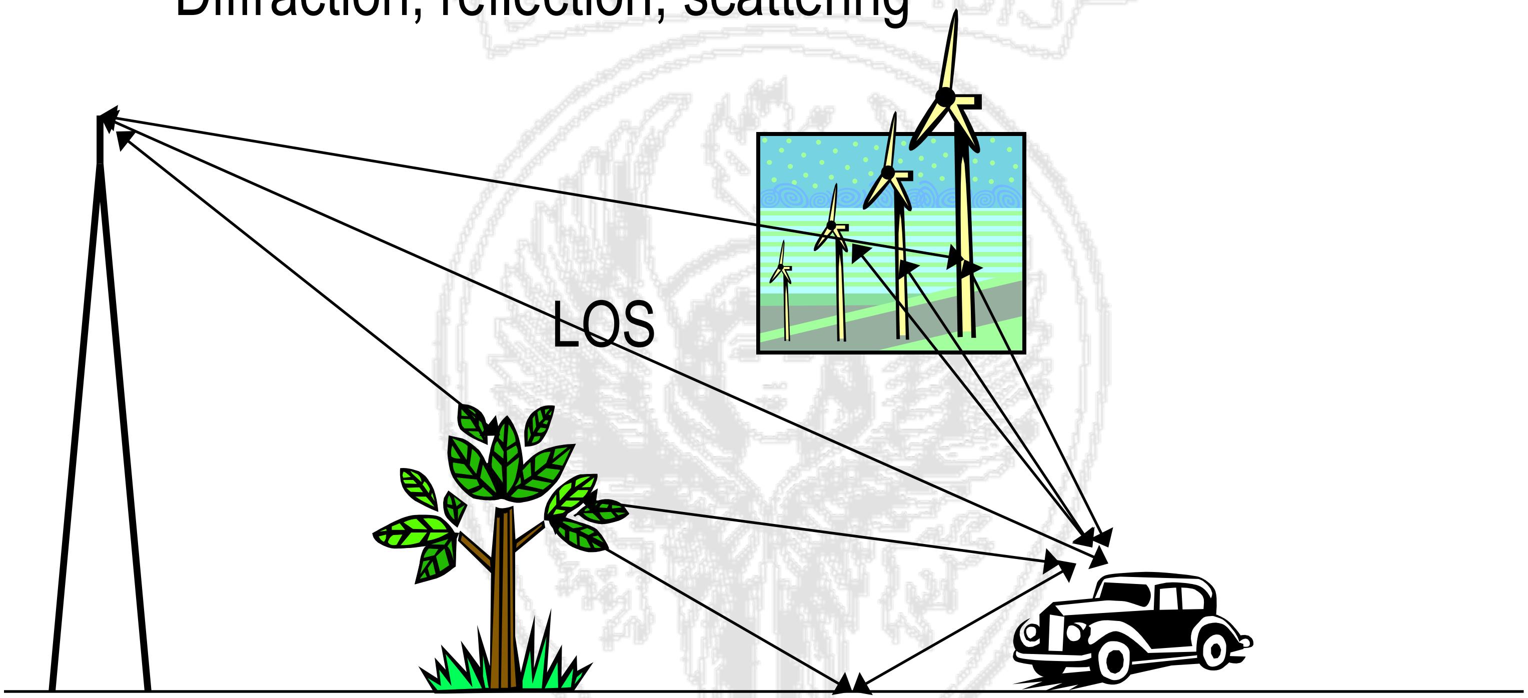
➔Scattering



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

Radio signal propagation

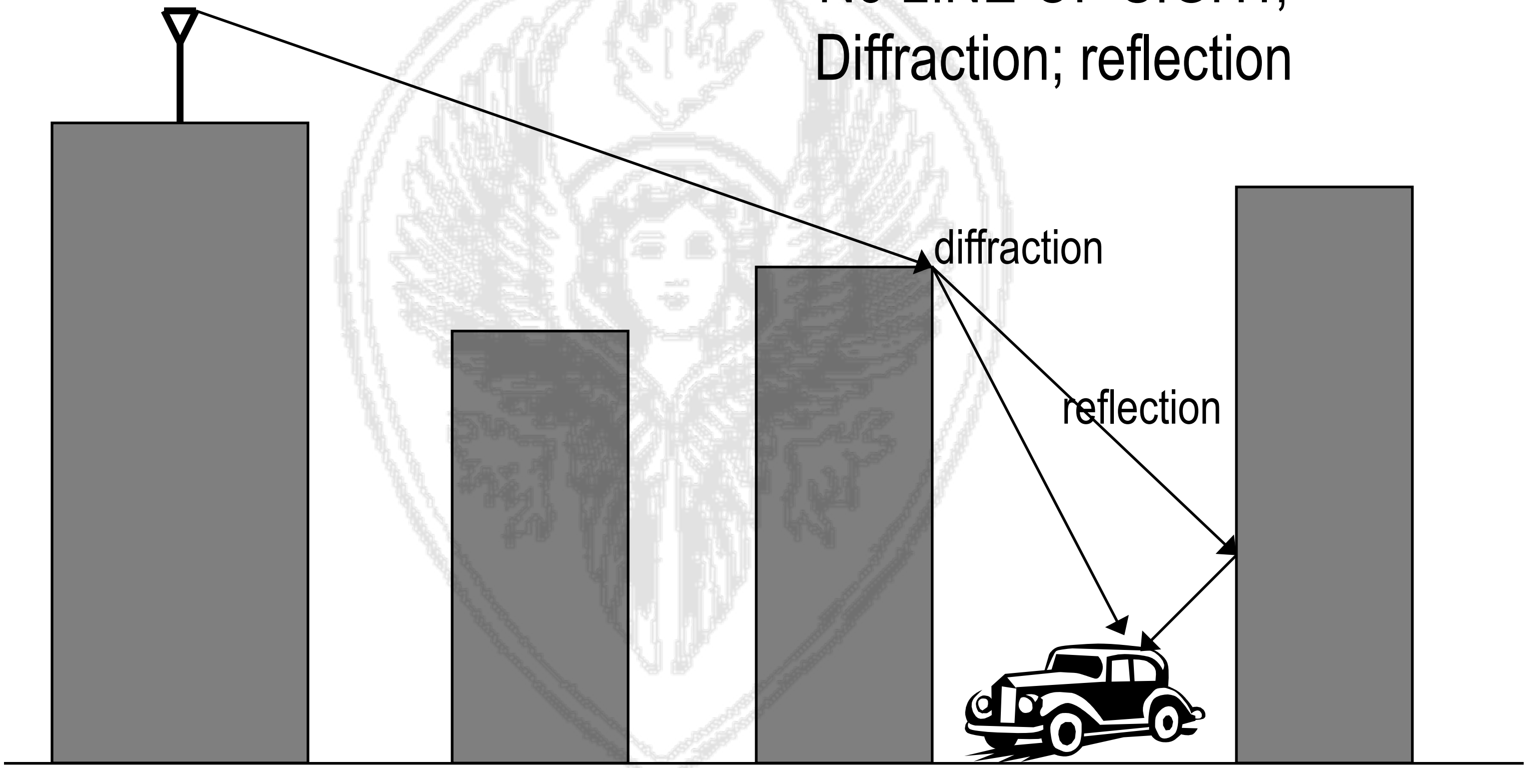
LINE OF SIGHT +
Diffraction, reflection, scattering



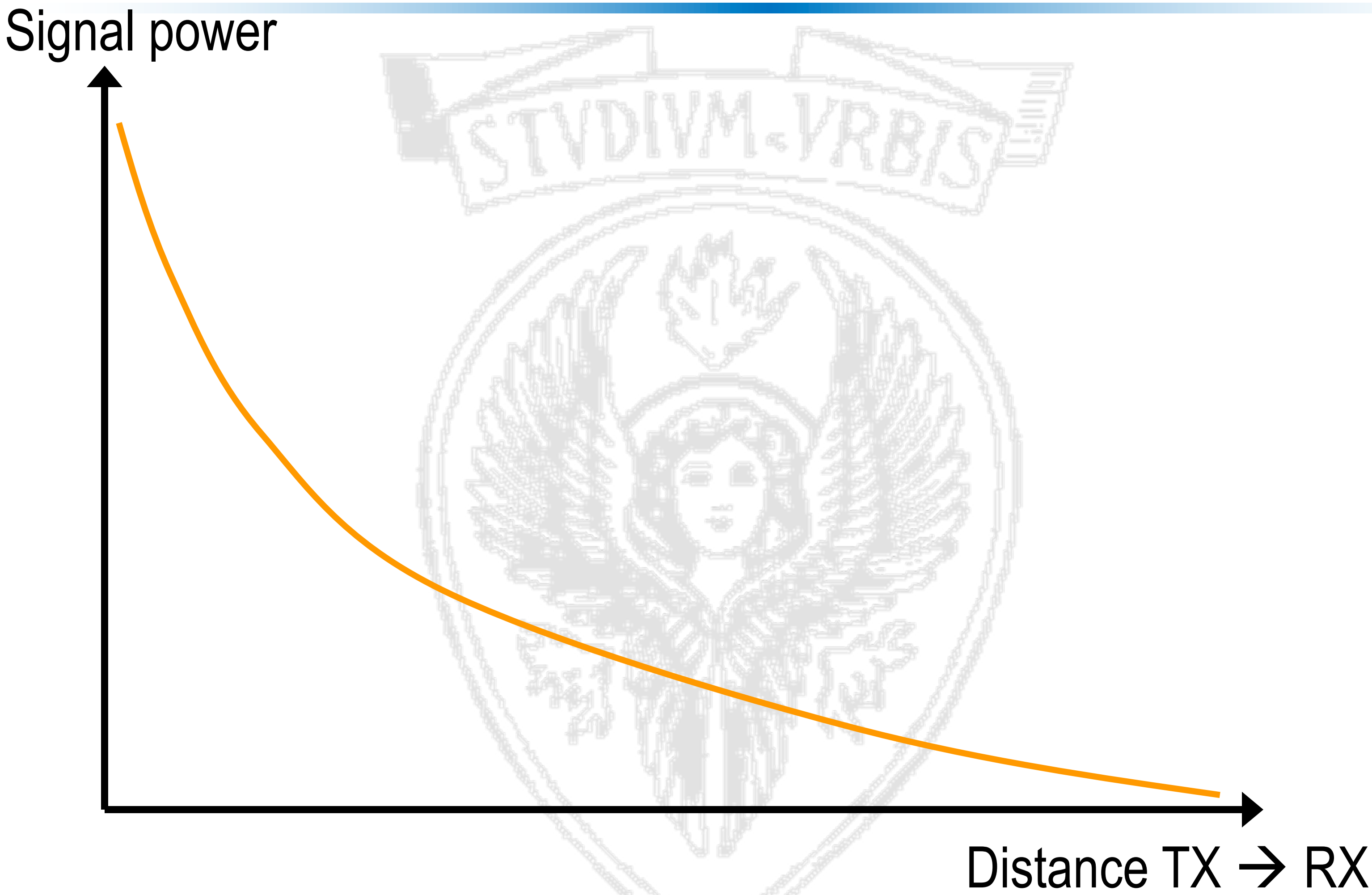
Radio signal propagation

LOS path non necessarily existing

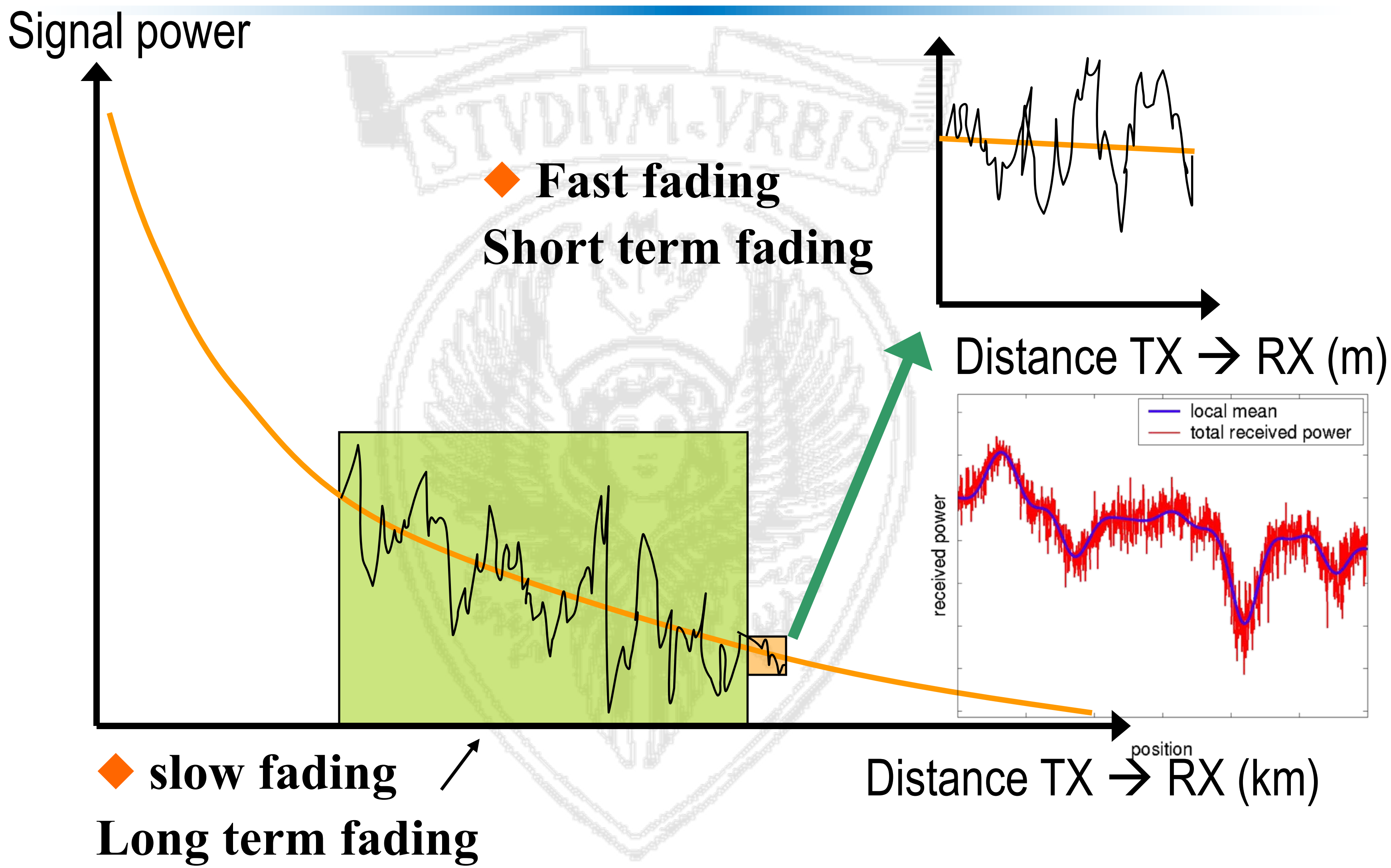
Example: city with large buildings;
No LINE OF SIGHT;
Diffraction; reflection



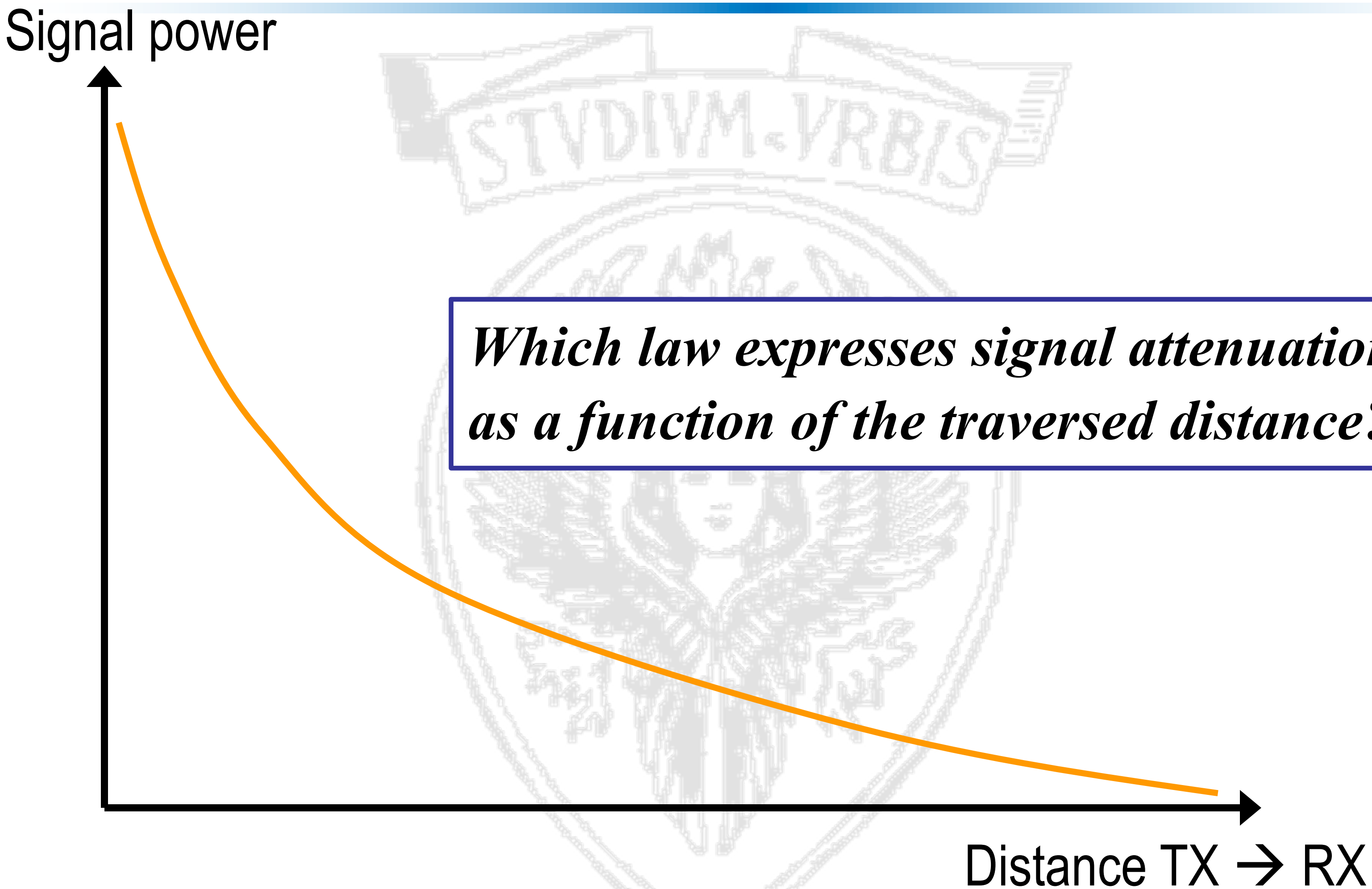
Radio signal attenuation



Slow fading – fast fading



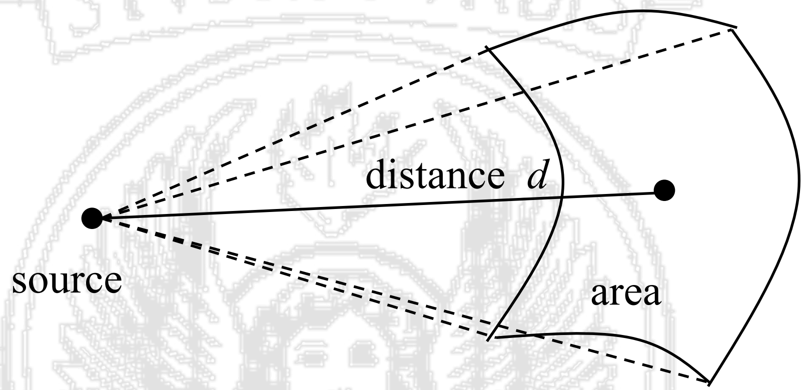
Radio signal attenuation



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

Radio signal attenuation geometrical spreading

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

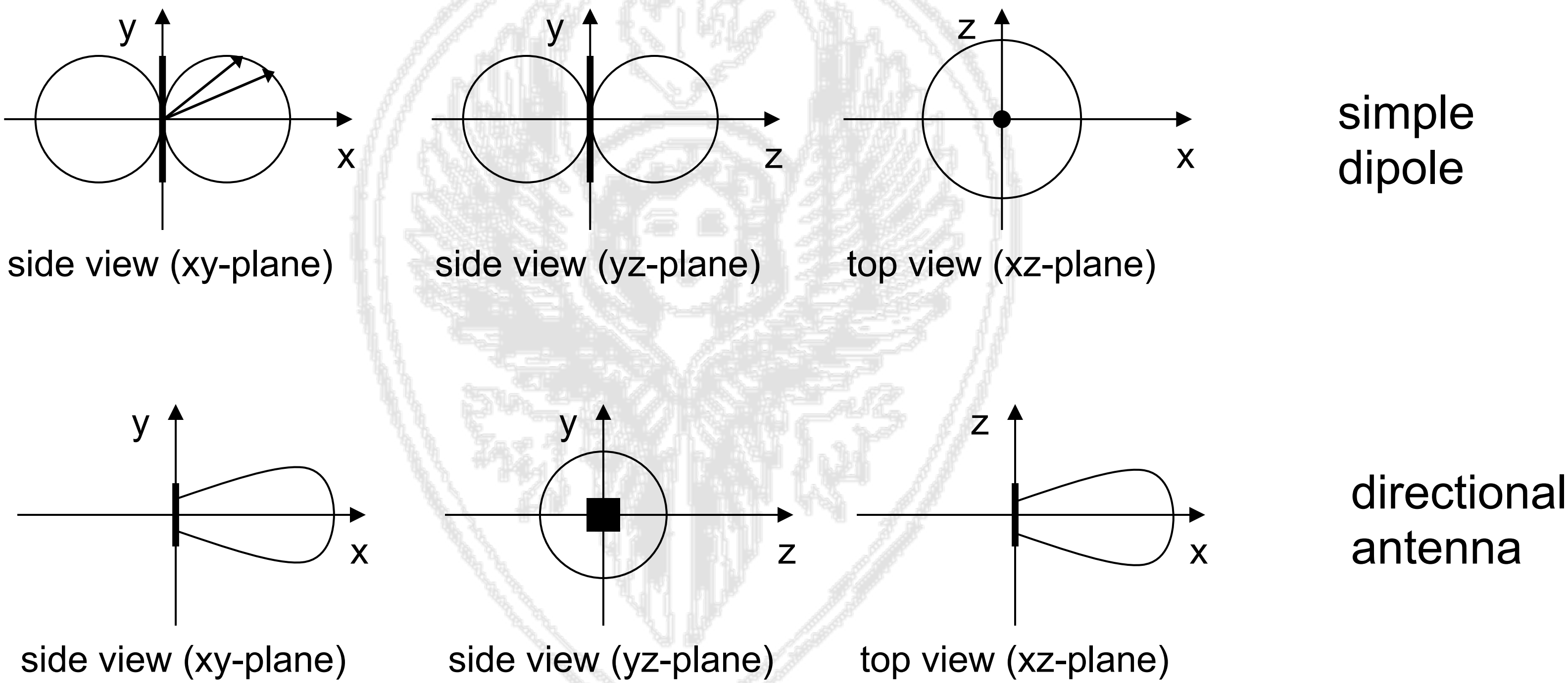


- The power density at distance d is equal to the ratio between the transmission power and the surface area of a sphere centered in the source and with radius d:

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

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)

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

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

- k antenna efficiency factor (<=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:

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

- 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

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

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

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

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

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

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 →P1 is twice P2, 10dB→P1 is one order of magnitude higher than P2

20dB→P1 is two orders of magnitude higher than P2

30dB→P1 is three orders of magnitude higher than P2

Decibels - dBm

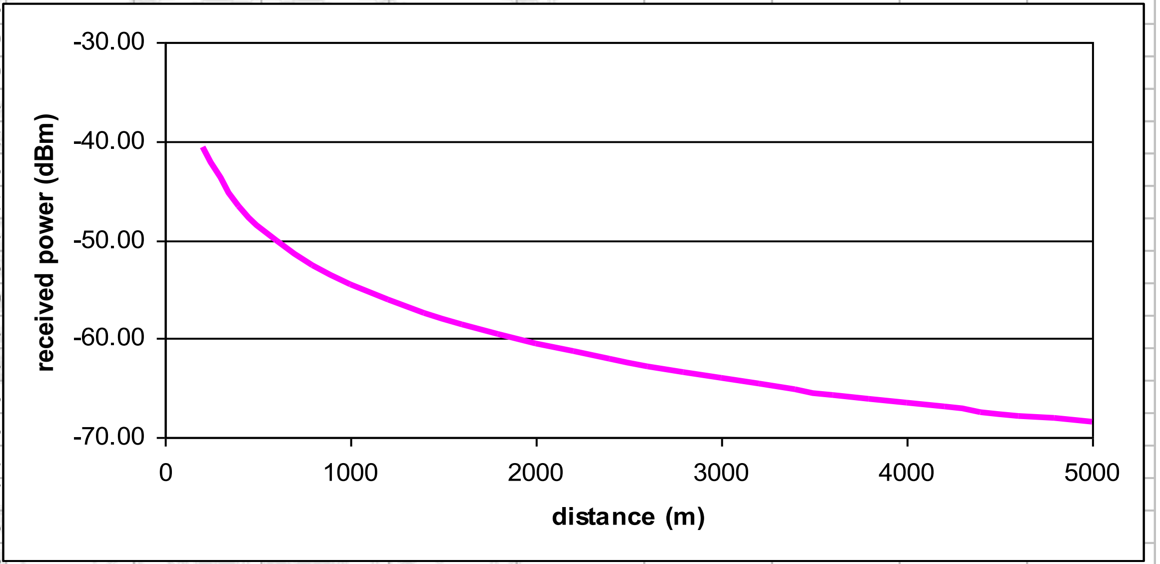
- dBm = ratio between the power and a nominal power of 1mW
  - Power in dBm = 10 log(power/1mW)
  - Power in dBW = 10 log(power/1W)

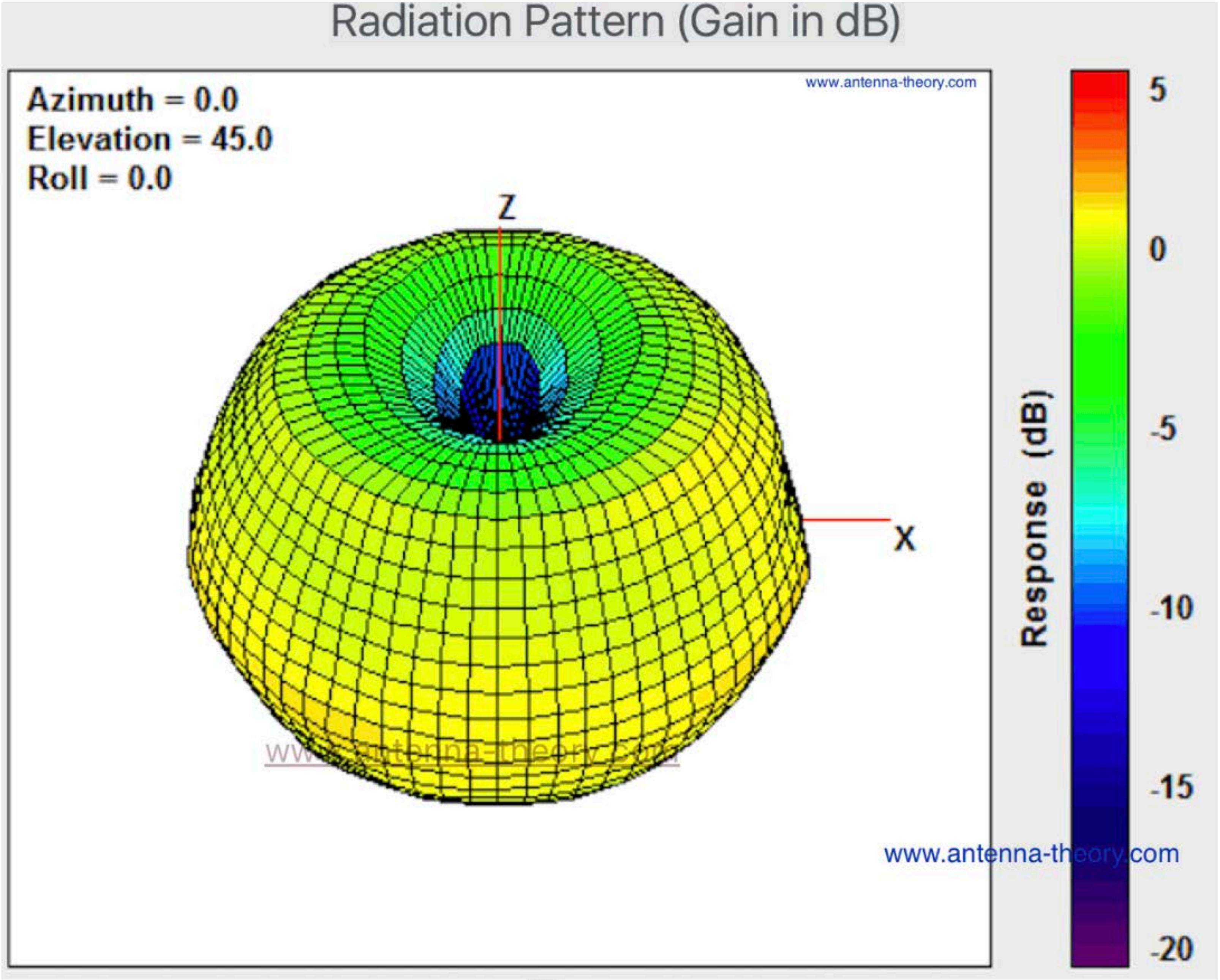
  Example
  - 10 mW = 10 $\log_{10}(0.01/0.001)$ = 10 dBm
  - 10 μW = 10 $\log_{10}(0.00001/0.001)$ = -20 dBm
  - S/N ratio = -3dB → S = 1/2 N
- Properties & conversions
  - P(dBm) = 10 $\log_{10}$(P (W) / 1 mW) = P (dBW) + 30 dBm
  - (P1 * P2) (dBm) = P1 (dBm) + P2 (dBW)

    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




Radiation Pattern (Gain in dB)
Azimuth = 0.0
Elevation = 45.0
Roll = 0.0
Z
X
www.antenna-theory.com
Response (dB)
5
0
-5
-10
-15
-20
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
  - 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

Wireless channel: path loss

- Path Loss

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

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

- 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

Denoted also as L_{free} in what follows

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

$= 20$

$= 20$ … $0\log_{10}\frac{c}{4\pi} =$

$= 20$ … 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)

Denoted also as L_{free} in what follows

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

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

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

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

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}…

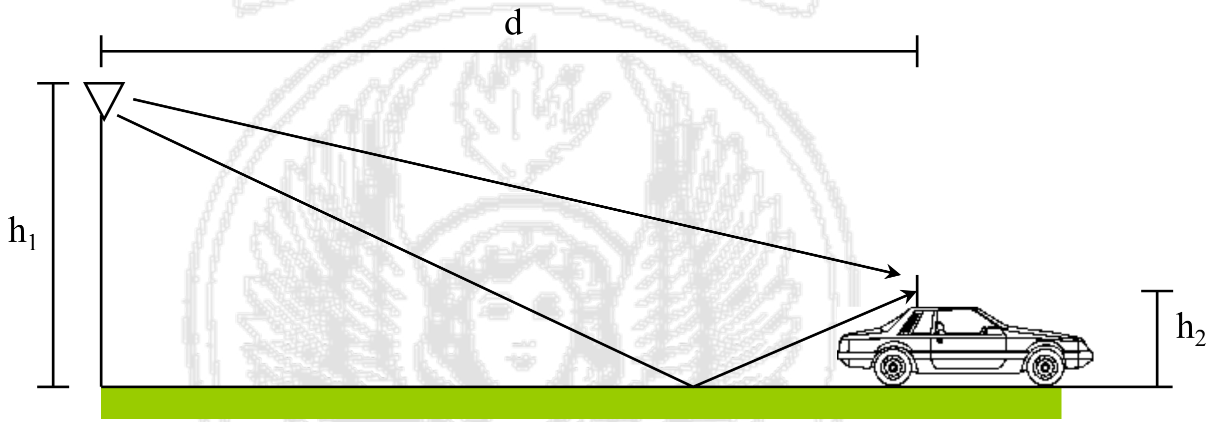
$$P_R(d) = P_R(d_{ref})\, (d_{ref}/d)^2$$

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

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

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

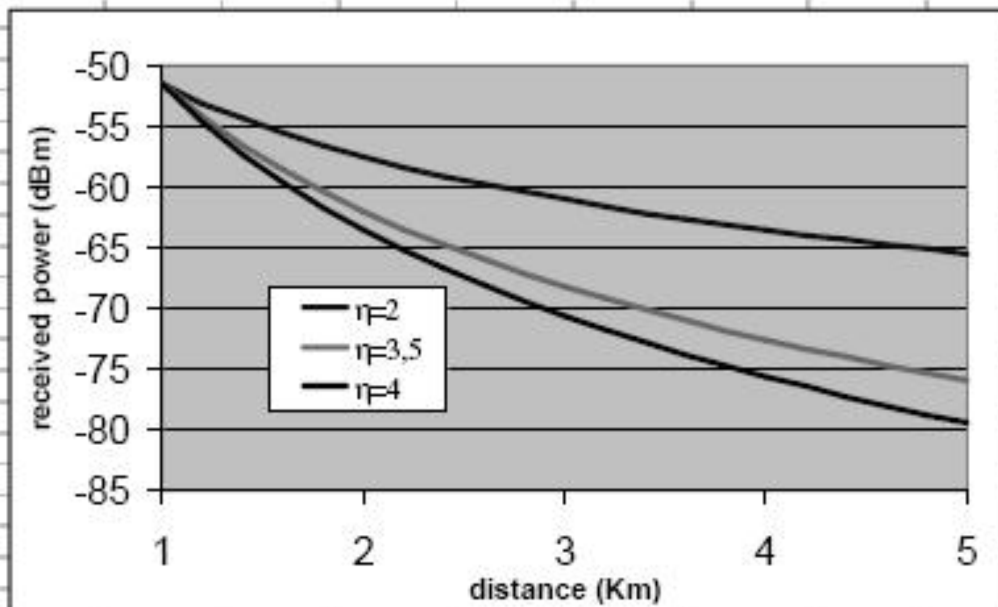
- In the two ray model the received power decreases much faster with distance (~$1/d^4$) than in the free space model (~$1/d^2$)
- Real life signal propagation is much more complex than what represented by the two models
- However, mean received power can be often expressed with a generalization of the 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)

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

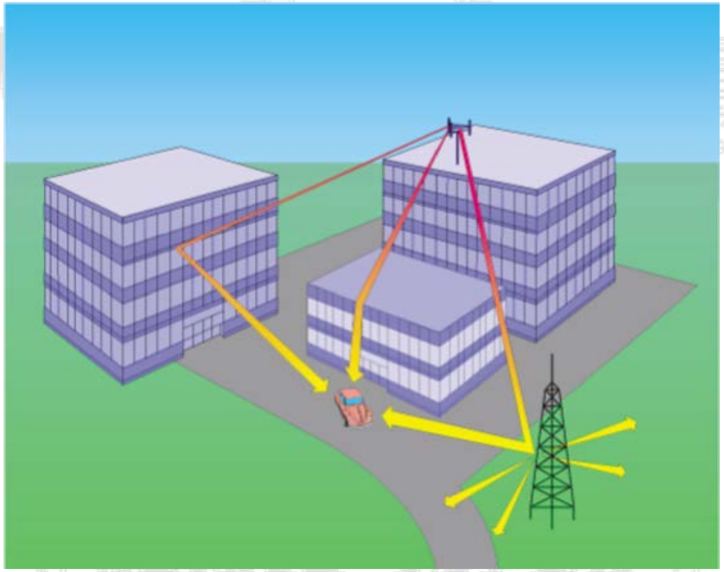
Extended formula

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

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

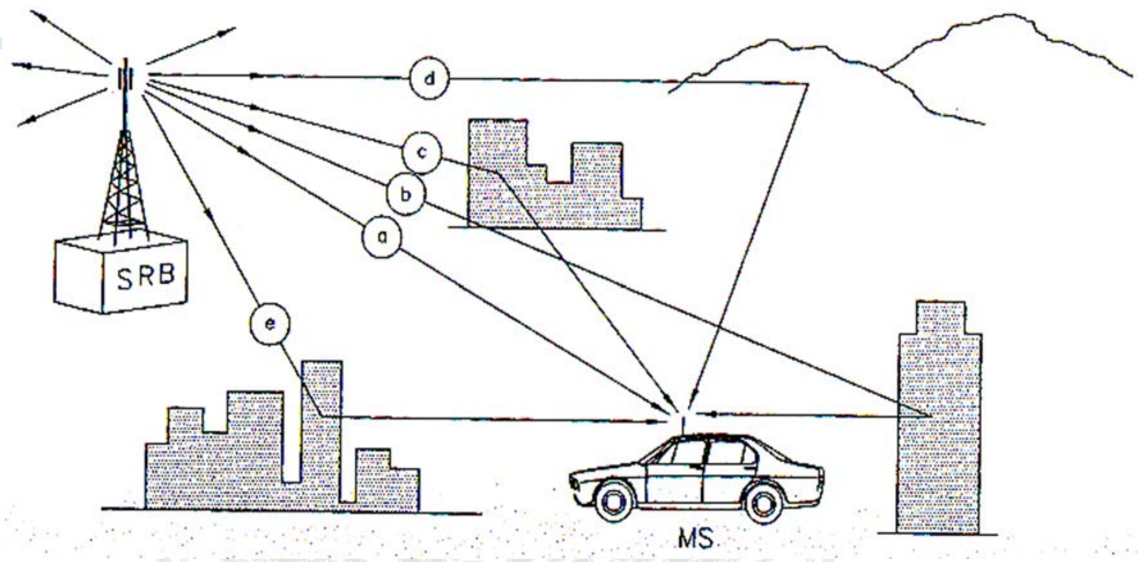


Wireless channel: multipath fading



- 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

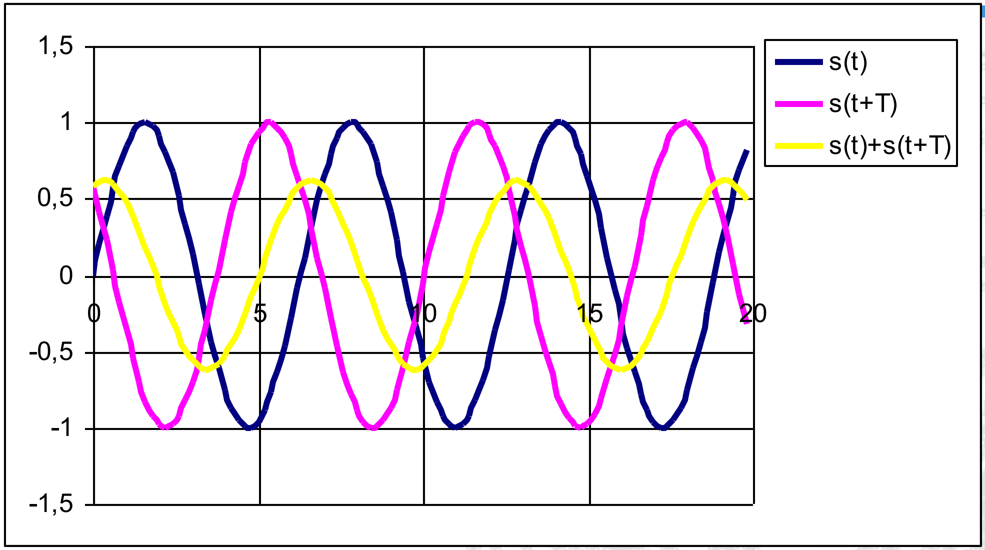


- Signal replicas received via different propagation paths are combined at the receiver
- The results depends on
  - The number of replicas
  - Their phases
  - Their amplitudes
  - Frequency

Received power differs, as a result

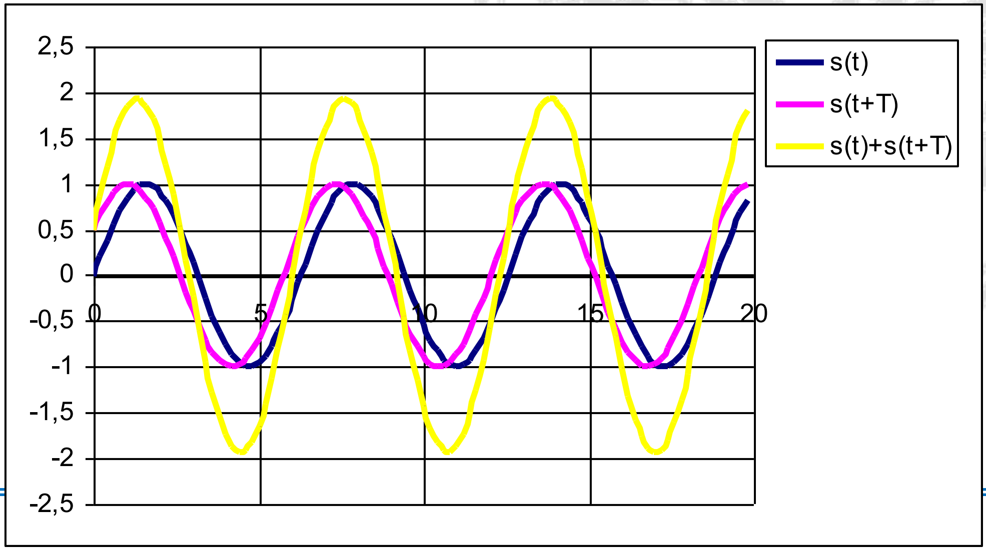
- from place to place, from time to time!

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

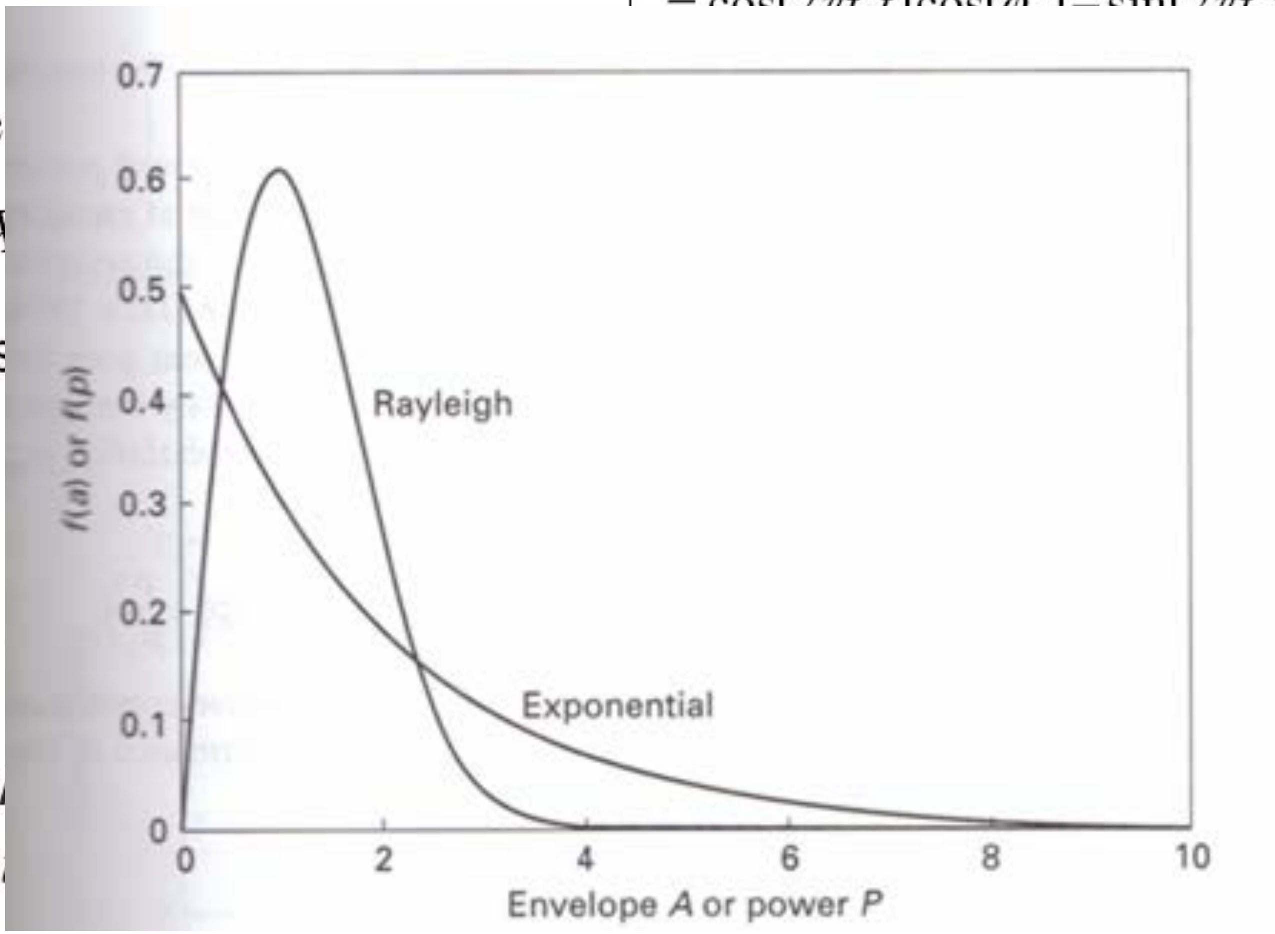
$$e_r(t) = \sum_{k=1}^{N} a_k \cos(2\pi f_0 t + \phi_k) =$$

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

$= c$

$= X$

In the as



X,Y are

s the
e of
variables

Rayleig
distribu

Rayleight fading

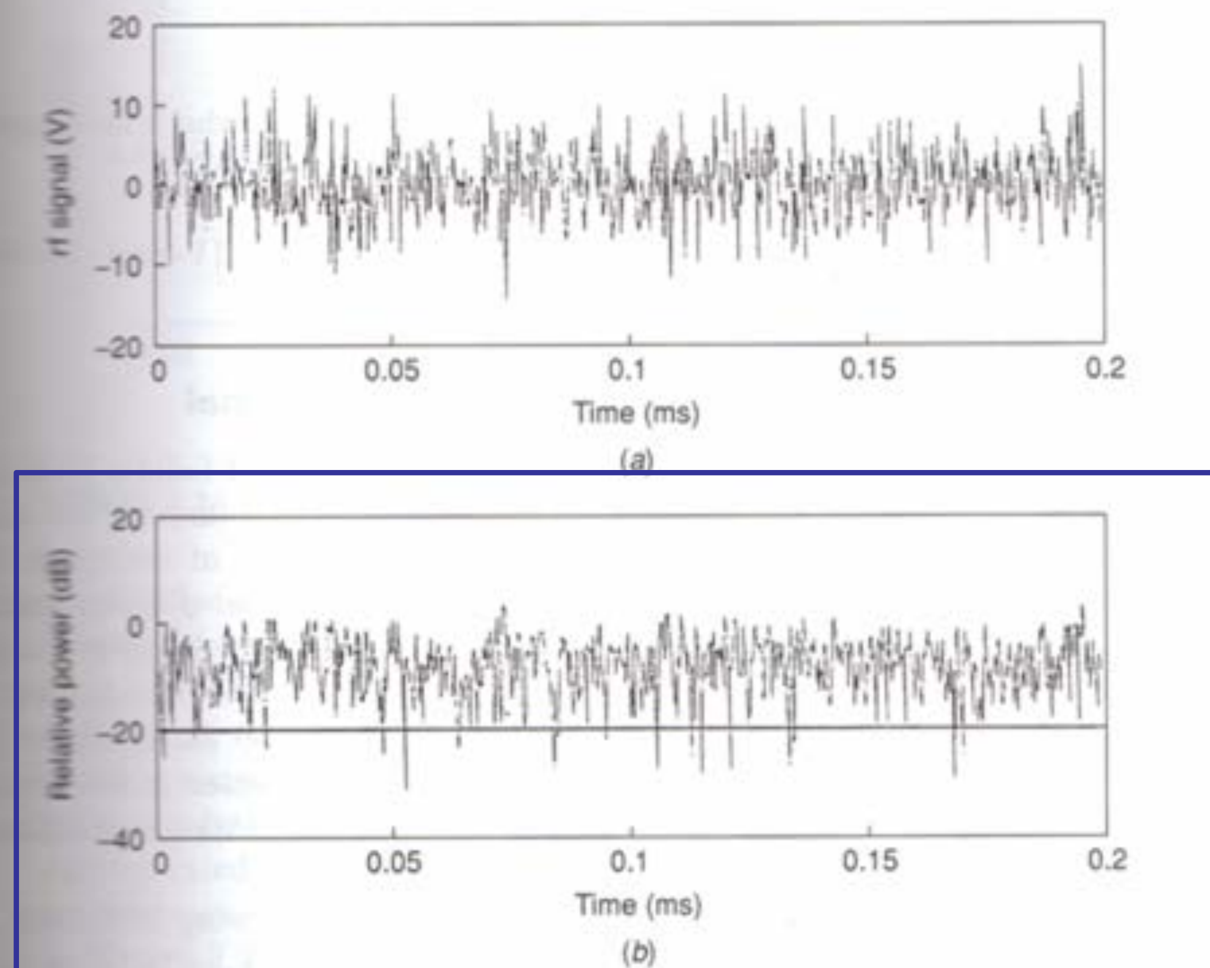


FIGURE 2.19 Rayleigh-faded rf signal (*a*) and its power (*b*). The plots were generated from 11 multiple paths. The envelope was obtained by demodulating the rf signal.

Fading-why is it important?

Answer1:

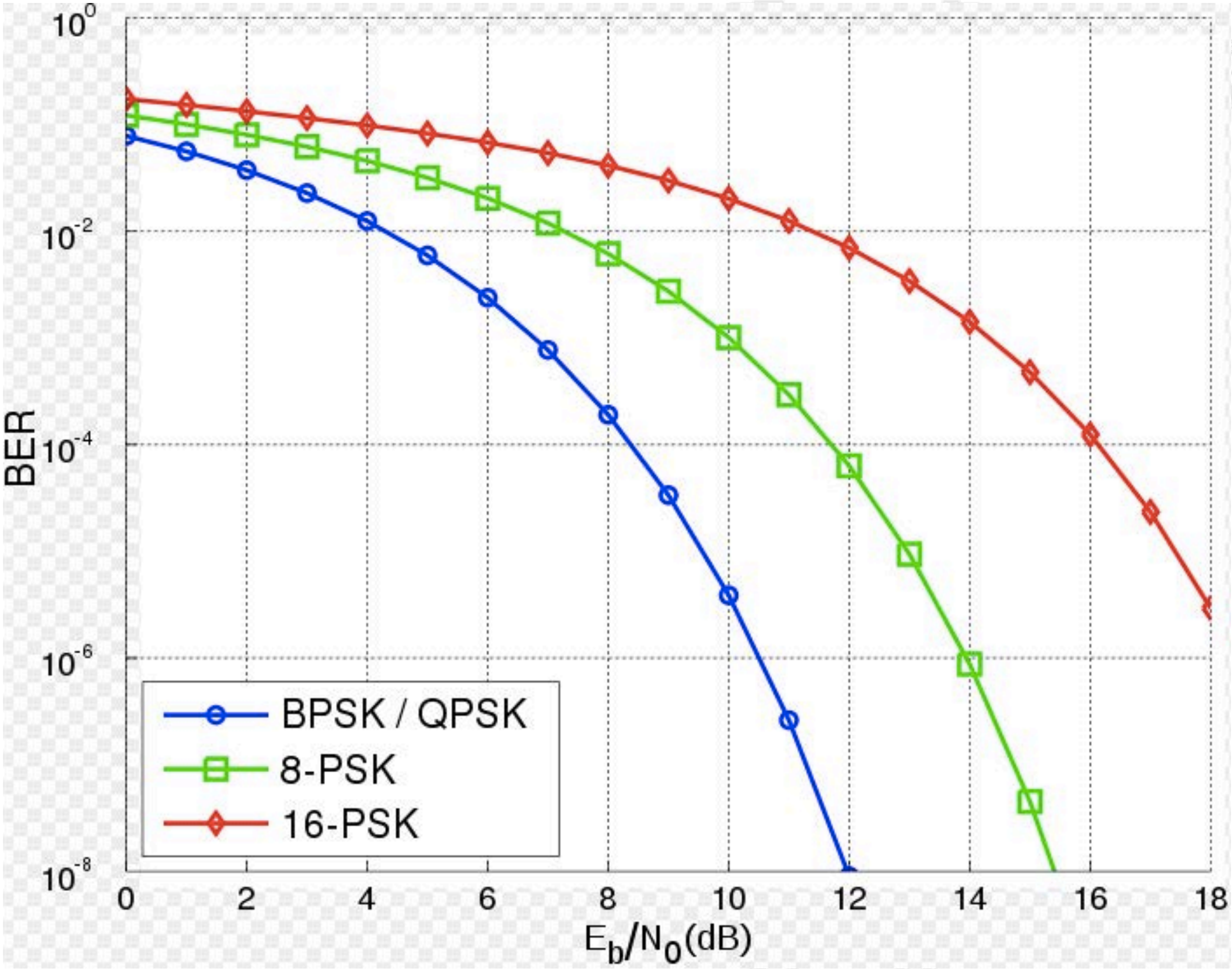
Outage Probability→Probability that received power is lower than a given threshold

⇨Below which signal cannot be correctly received

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

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→BER

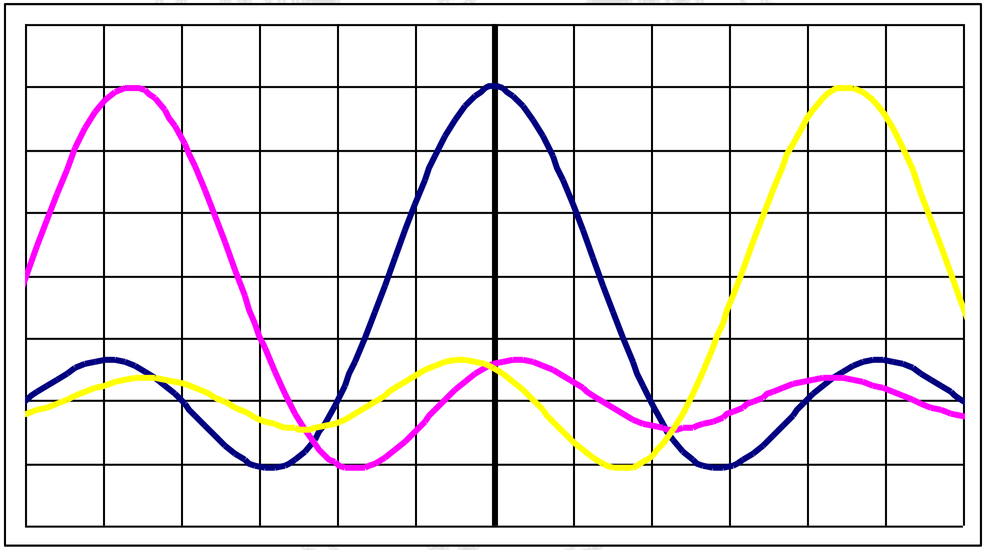
Using FEC BER

Performance can

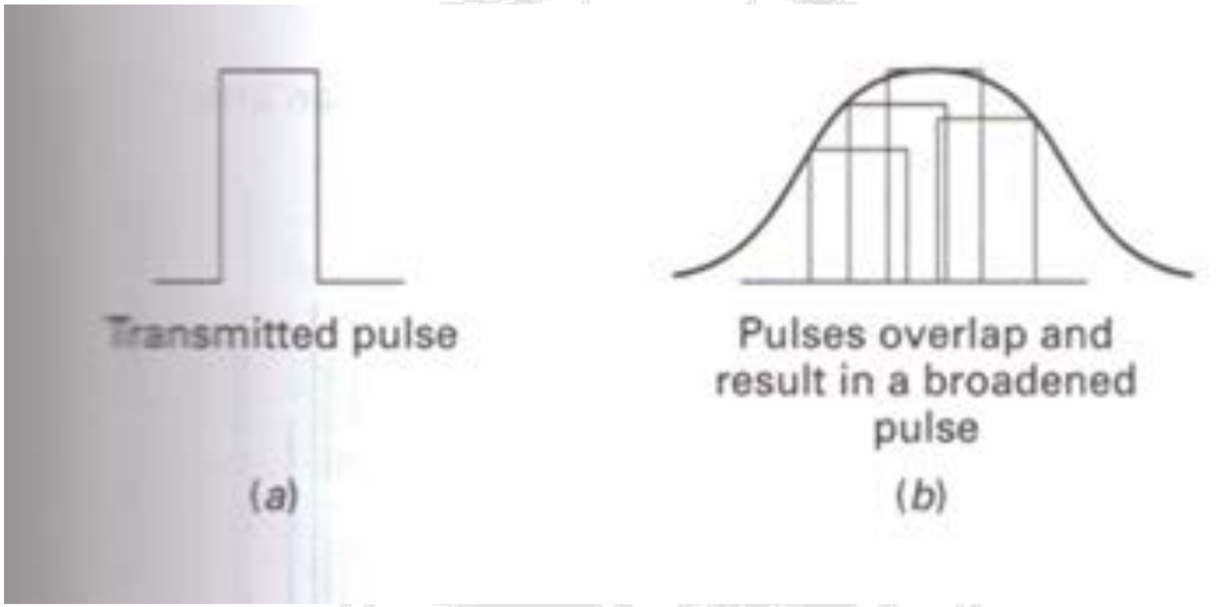
be improved

Multipath fading

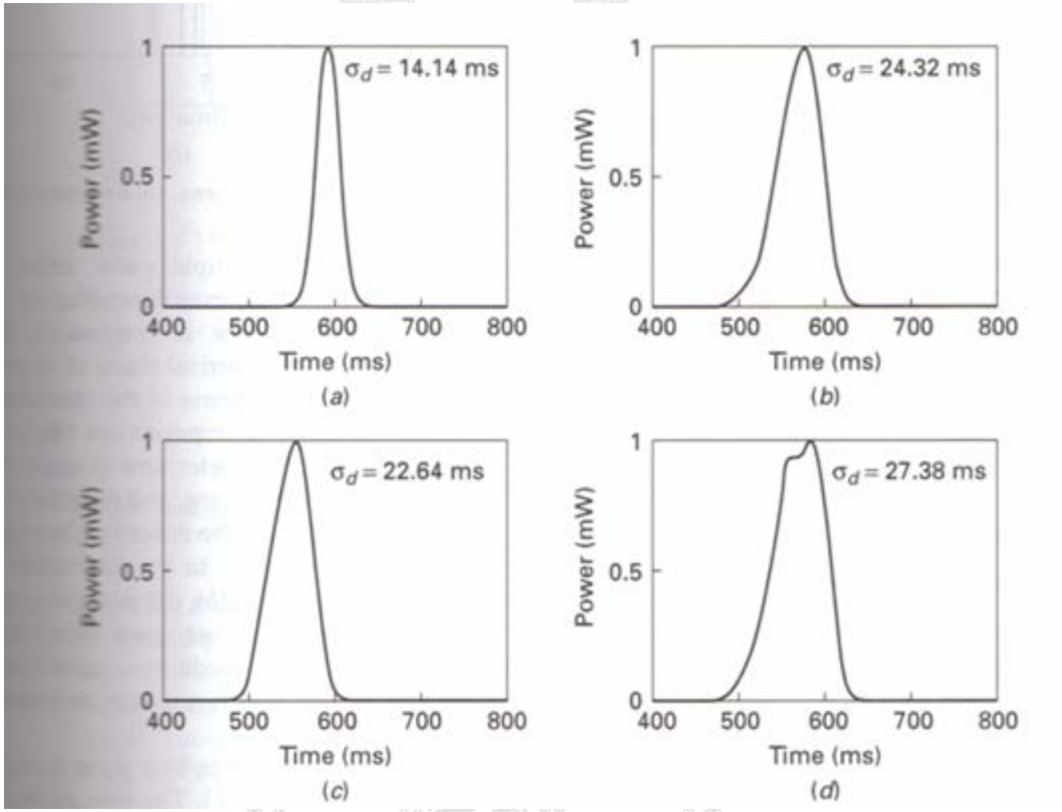
- Different delays experienced by the different signal replicas (*delay spread*) can widen the channel impulse response leading to intersymbol interference (ISI – Inter-Symbol Interference)



Examples

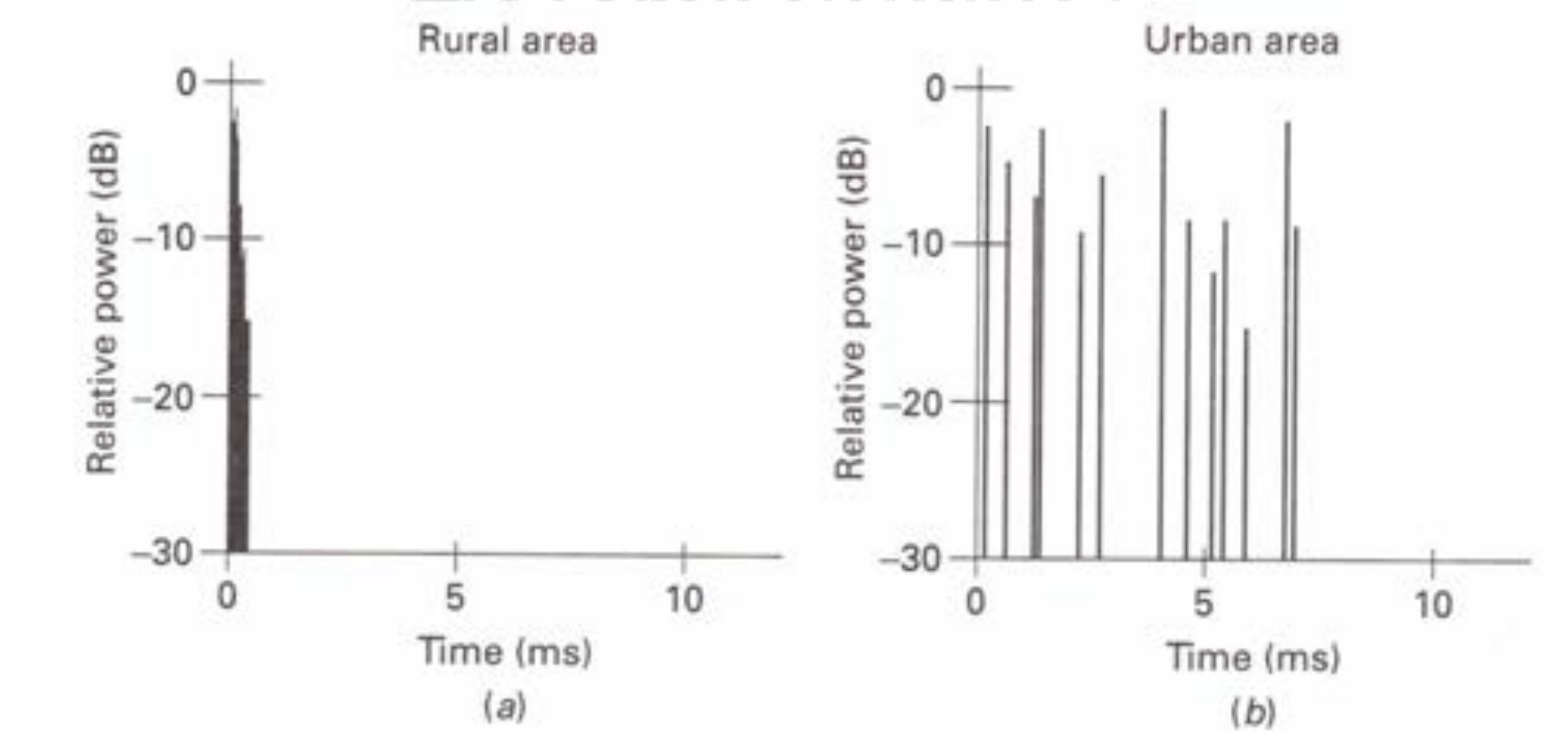

Transmitted pulse
(a)
Pulses overlap and
result in a broadened
pulse
(b)

Examples



σd = 14.14 ms
Power (mW)
Time (ms)
(a)
σd = 24.32 ms
Power (mW)
Time (ms)
(b)
σd = 22.64 ms
Power (mW)
Time (ms)
(c)
σd = 27.38 ms
Power (mW)
Time (ms)
(d)

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.