IoT, Course introduction

Internet of Things a.a. 2018/2019

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); Coordinator of the Cyber Physical System lab of "La Sapienza" center for Cyber Intelligence and Information Security.
  - 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 42, over 5700 citations).
  - International activities: Chair of the steering committee of **IEEE SECON**, general co-chair of **ACM MobiHoc,** 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, 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 an elected member of ACM Europe Council.

The instructor

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- 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.
  - 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) +
  - After the class

IoT Students

Career Aspirations

Background

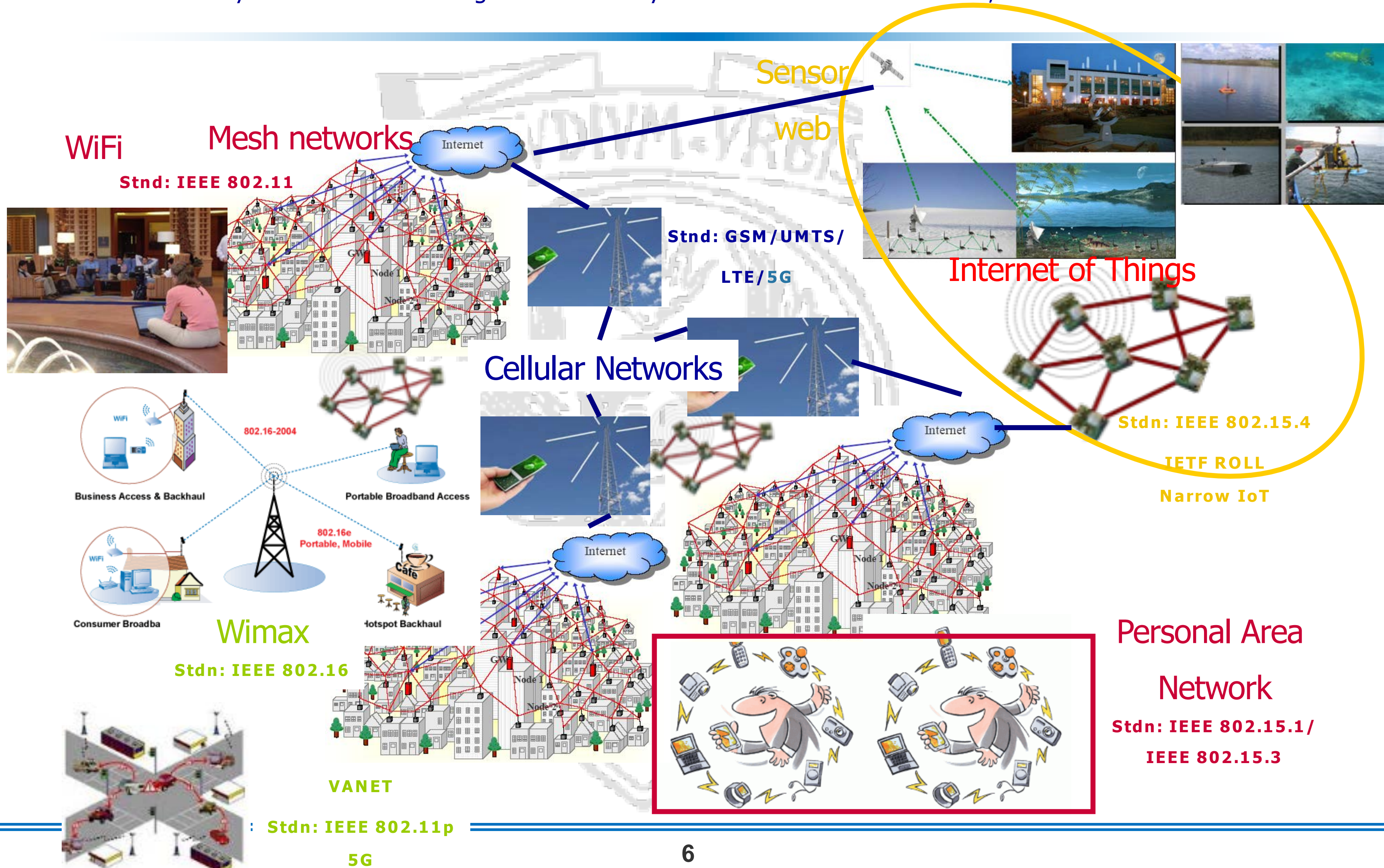
Status

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…



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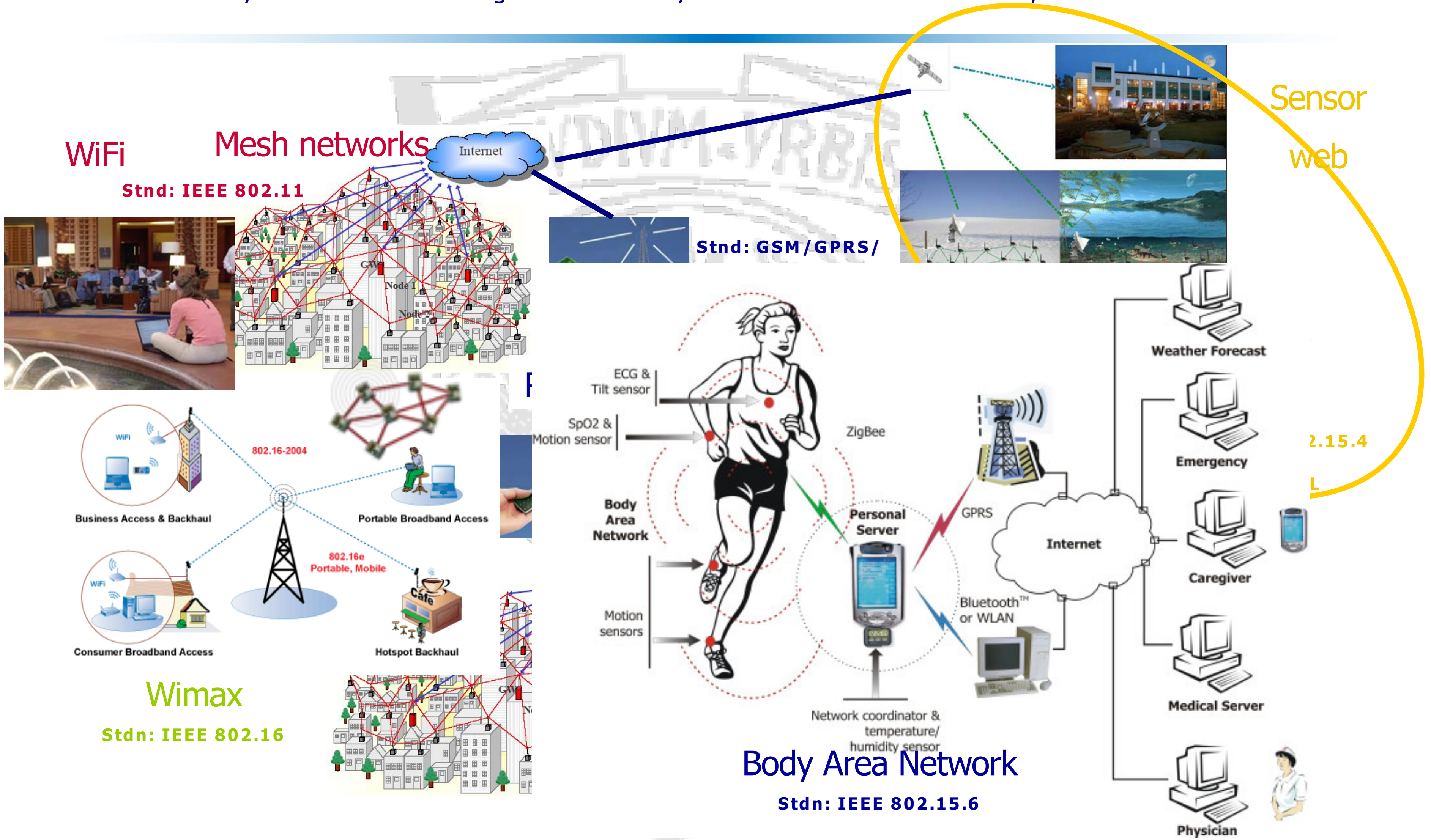
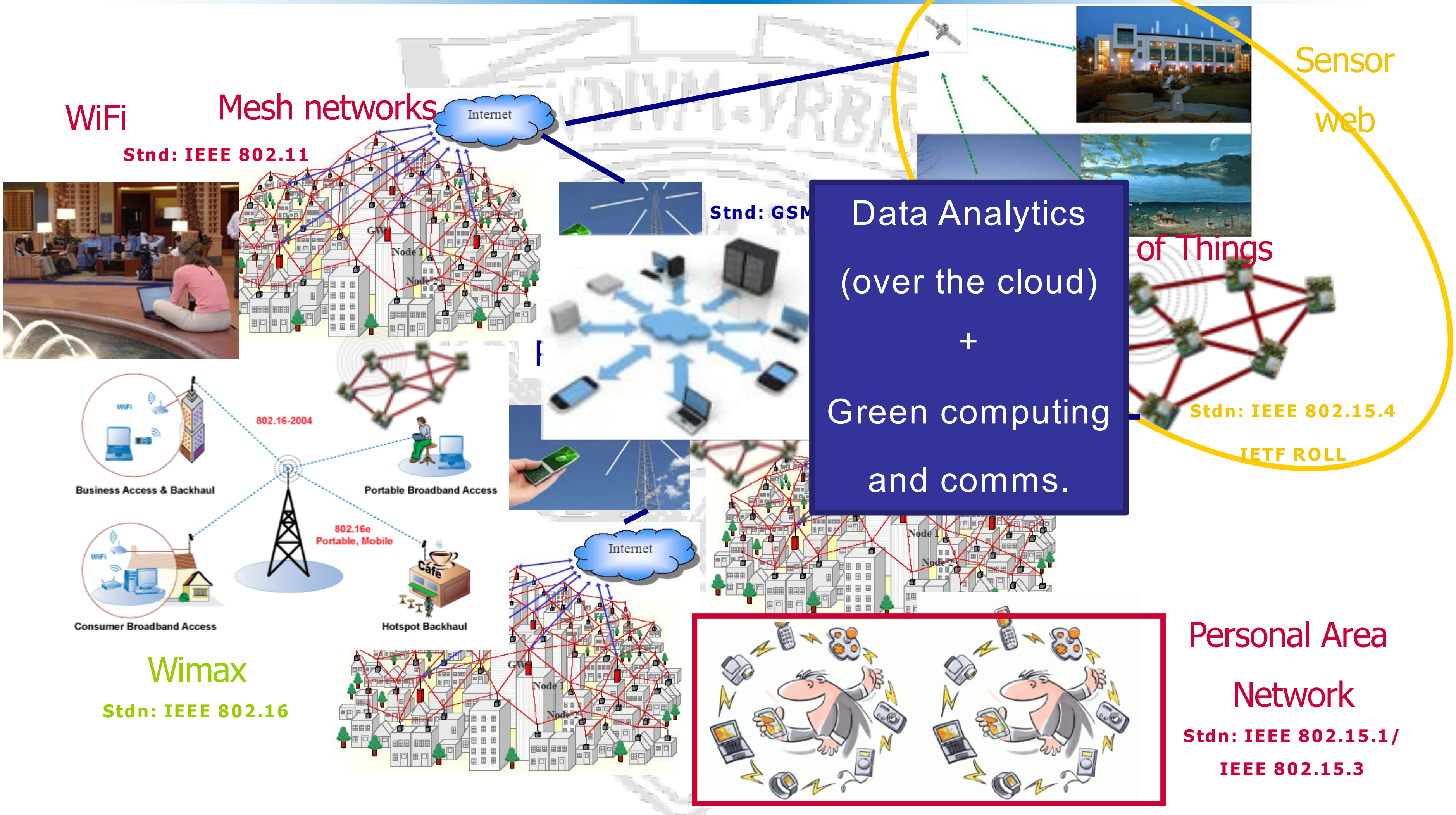


What we will do

Why a class on Internet of Things?

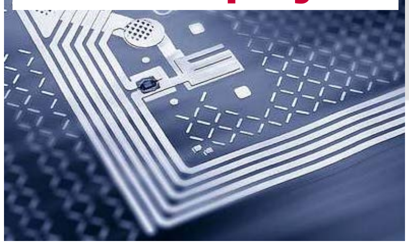
Wireless systems are becoming the usual way to connect to the Internet, and communicate…



SENSES lab

SEnsors NetworkS and Embedded Systems Laboratory

CHIRON project



RFID Anticollision Protocols

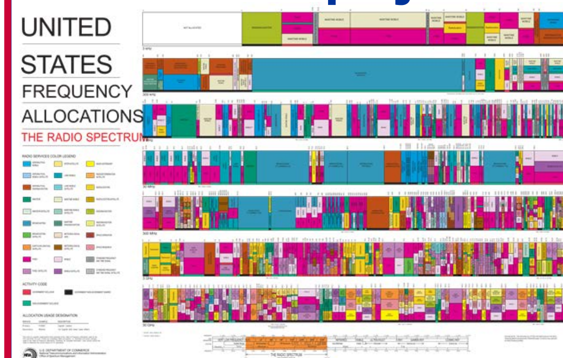
PENNSTATE

GENESI Project

Green sensing systems

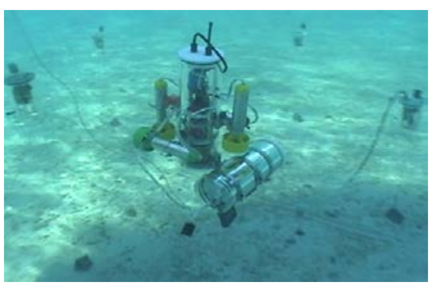
PENNSTATE

SENDORA project



Cognitive networks

CLAM Project; SUNRISE project



Underwater Monitoring systems

U.PORTO

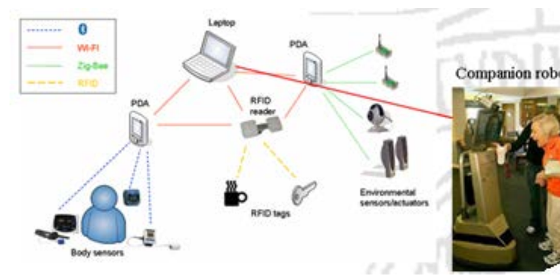
Sandia National Laboratories

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
Software platforms for Internet of Things systems: Amazon, Azure, Watson…

Cyber physical systems: aerial, surface and underwater drones

Syllabus

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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 systems

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: Green Castalia
How to move from an idea to a validated idea to a solution

Exam sessions

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

We will have a midterm on April 8th (on topics covered through April 1st) and a final written exam on May 30th (on the remaining topics, excluding the lab).

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.

Students attending the lab will have the opportunity (it will not be mandatory) to take an exam associated to it to get up to 3 extra points. The exam will be at the end of the lab.

Students attending the theory seminars will have the opportunity to do a modeling project for up to 3 extra points (maximum 4 extra points overall).

Extra points and associated lab/theory exam sessions will be granted only if students pass the exam in the June/July session, or through midterm and final.

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 programming (some classes provided here and within the associated AFC)
- Probability Theory

College experience

College experience

\+ Transversal Skills

Seminars of international experts

Large projects, EXPLOIT Labs

Internship

Spinoff

College experience

GRANTS “borsa di studio per attività di ricerca”

Contact me AT petrioliATdiDOTuniroma1DOTit

3 in the last year to top class students

http://senseslab.di.uniroma1.it

How To

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,

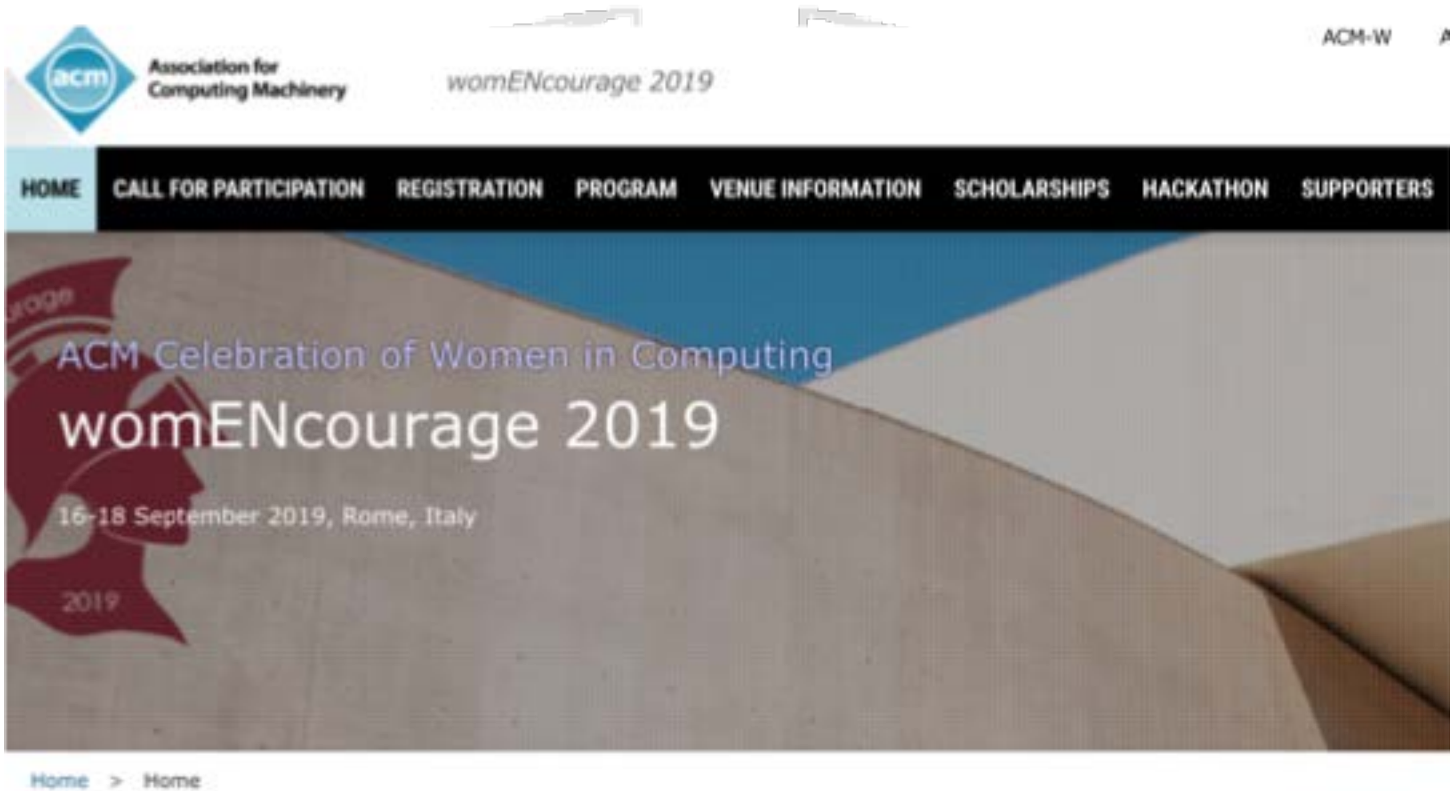
IEEE Infocom,

ACM MobiHoc,

ACM SenSys,

IEEE IPSN

Interesting opportunities



womENcourage 2019 – *"Diversity Drives Societal Change"*

ACM Celebration of Women in Computing: womENcourage 2019
Rome, Italy, September 16 – 18, 2019

Design and development of embedded systems for the Internet of Things

Altamente consigliato: Sfruttate le occasioni per fare laboratori e progetti

Fabio Angeletti

Michele Martinelli

SAPIENZA UNIVERSITÀ DI ROMA

W • SENSE INTEGRATED CABLELESS SOLUTIONS

From makers boards to IoT

Arduino Duemilanove
- 16 MHz ATmega328 MCU
- 32KB flash, 2KB RAM

Nucleo-F401
- 84 MHz ARM 32-bit + FPU
- 512KB flash, 96KB RAM

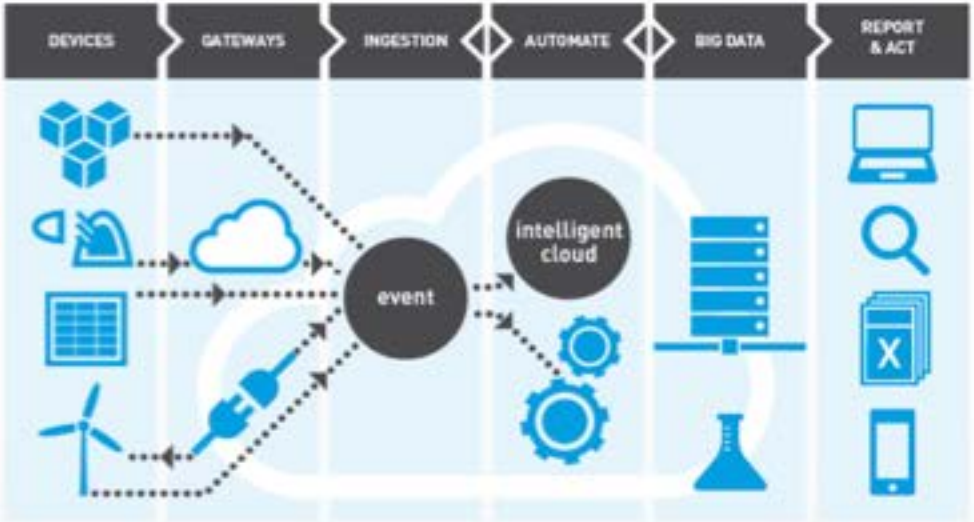
ALEXA,
Turn ON/OFF the
light

ALEXA ECHO DOT

ESP32 / ESP8266
- Dual-core CPU
- Wi-Fi: 802.11 b/g/n
- Bluetooth: v4.2 BR/EDR and BLE

Data visualization and remote control

In cloud services allow the users to visualize and interact with the IoT ecosystems in a comfortable and effective way.



Fundamental of wireless systems

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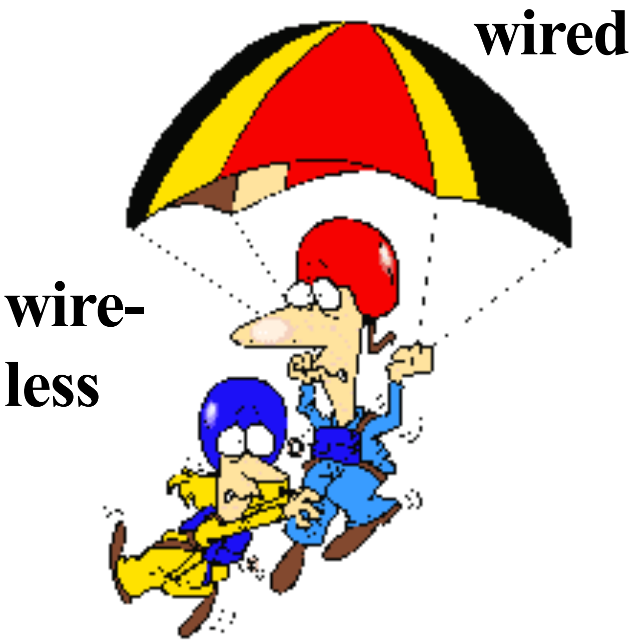
Background-
Wireless Systems

- 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

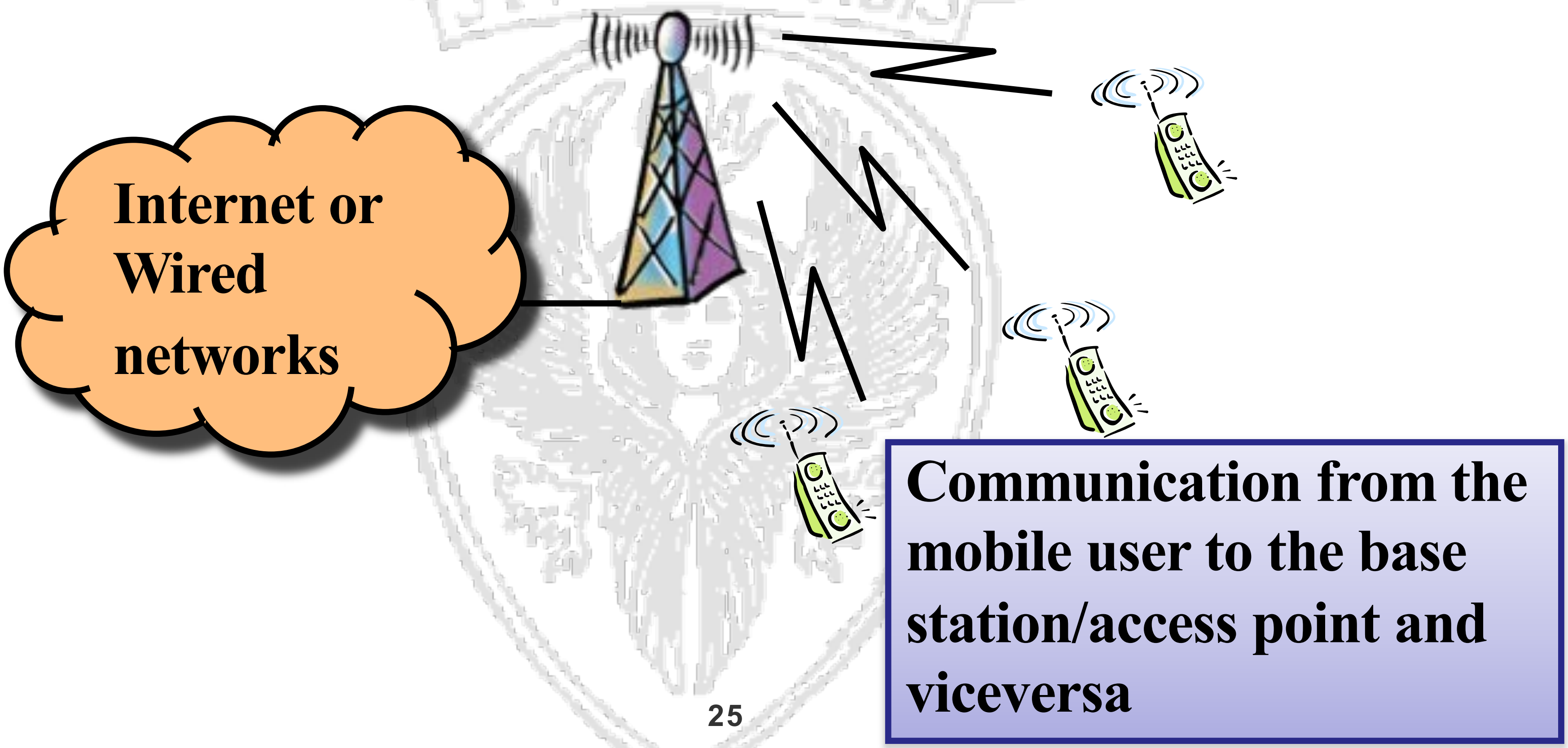
→Low power platforms and energy efficient protocols (green solutions)

→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)

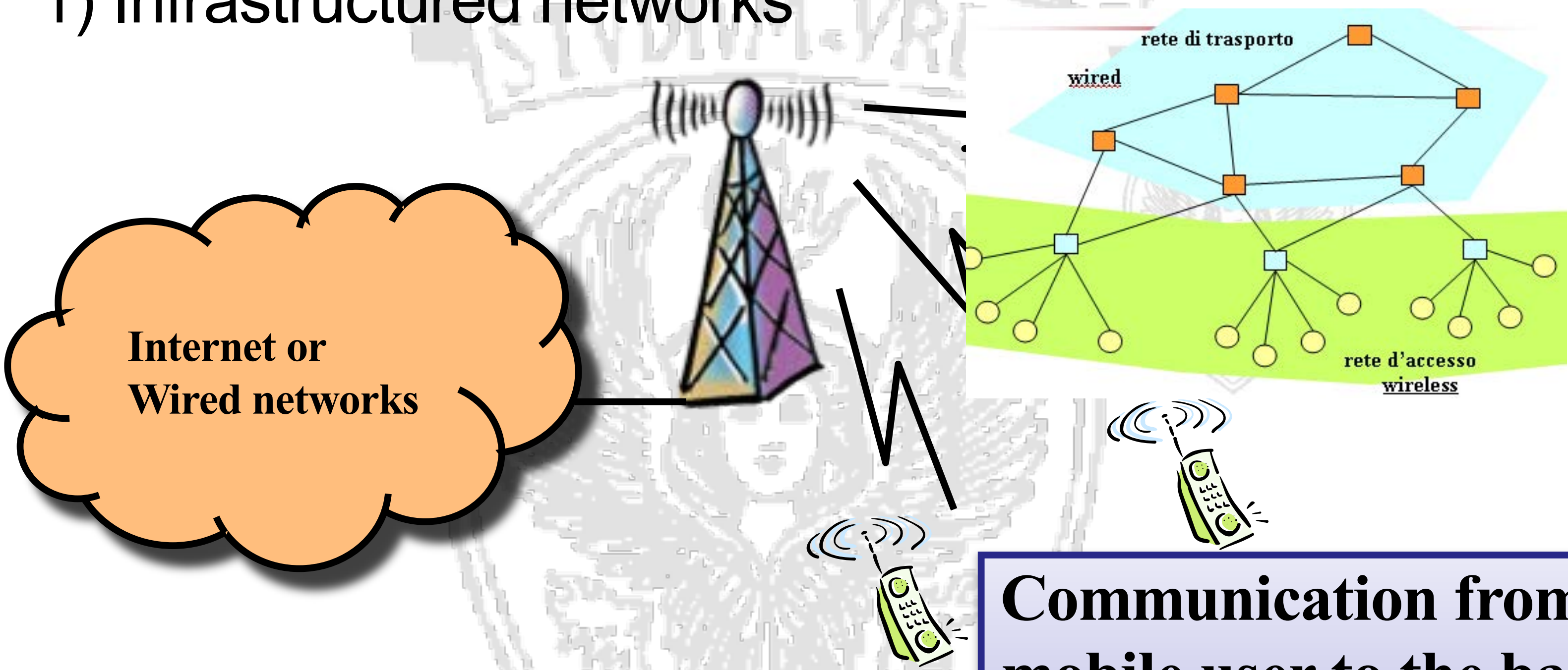
Wireless Systems Models

- Infrastructured networks



Wireless Systems Models

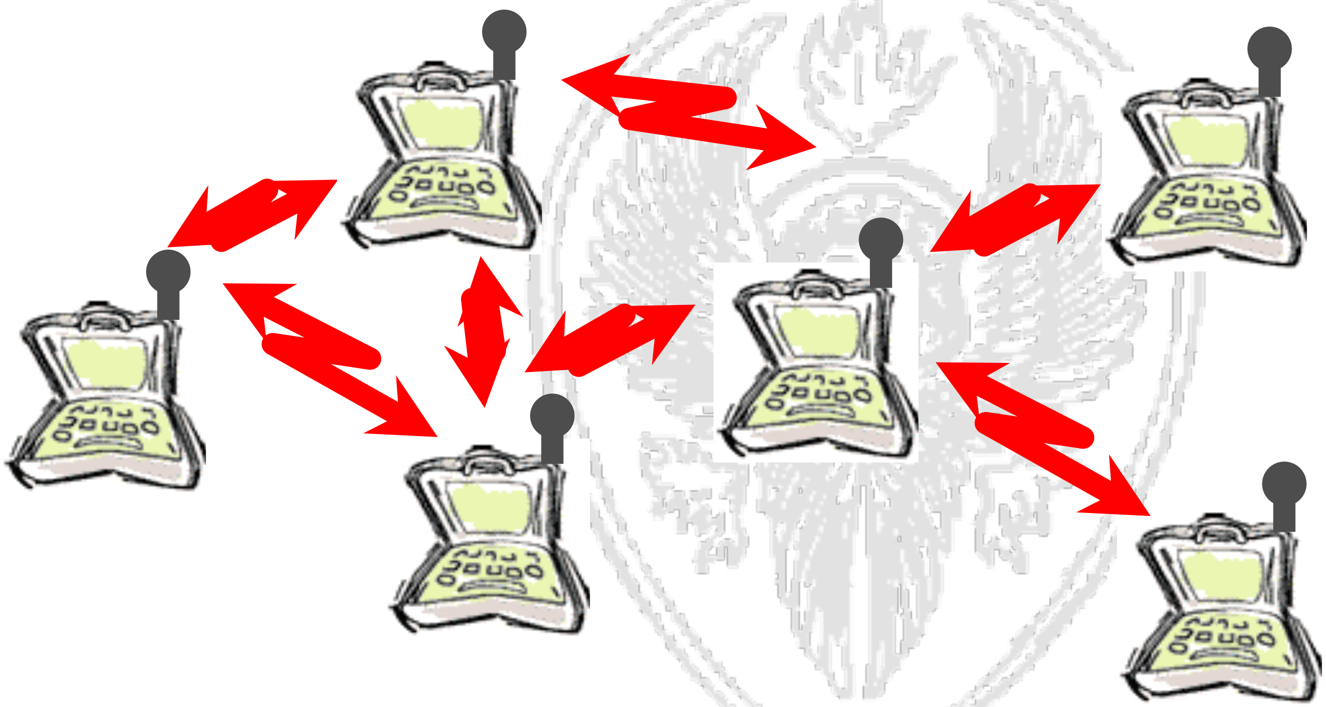
- 1) Infrastructured networks



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

Wireless Systems models

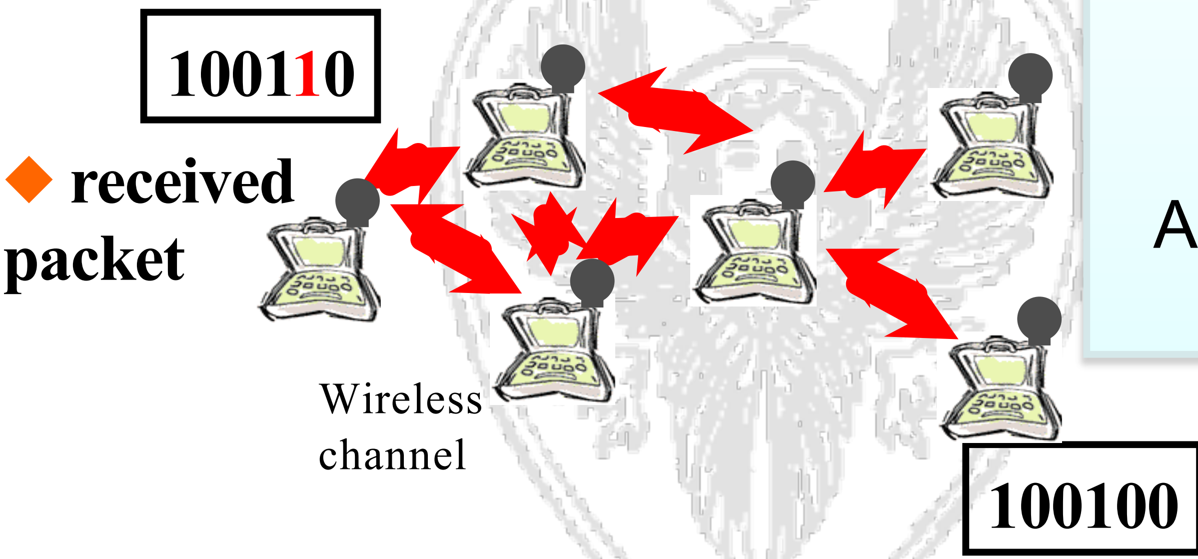
- 2) Ad Hoc Wireless Networks (wireless sensor networks, VANET, Mesh Networks,…)



- 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



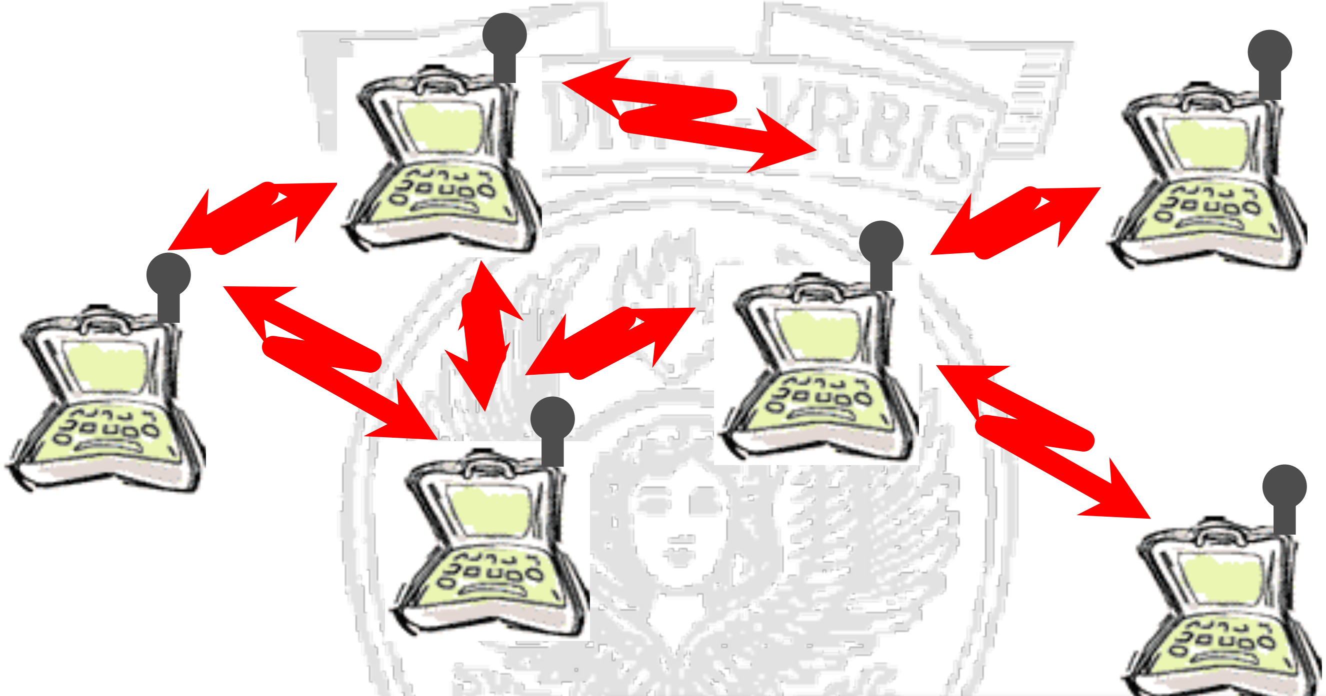
Forward Error Correction

Interleaving

Automatic Repeat Request

- transmitted packet

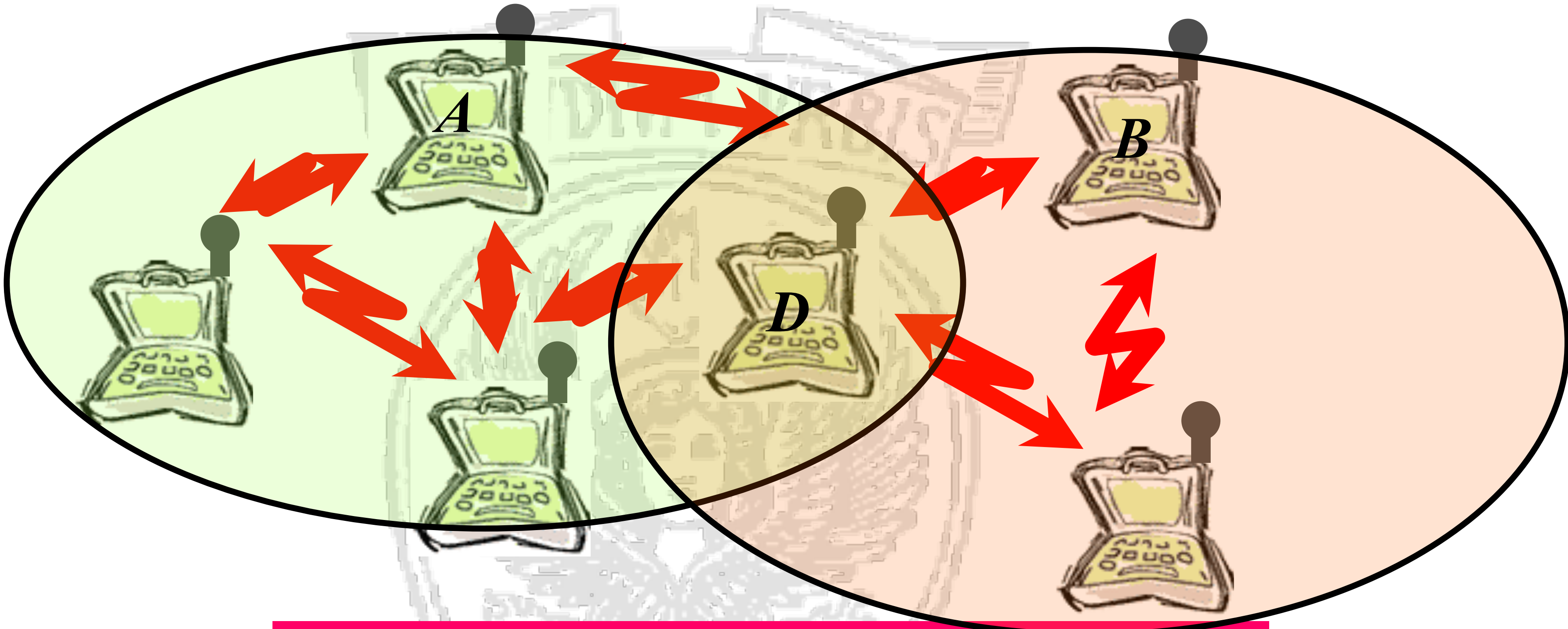
Medium Access Control



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

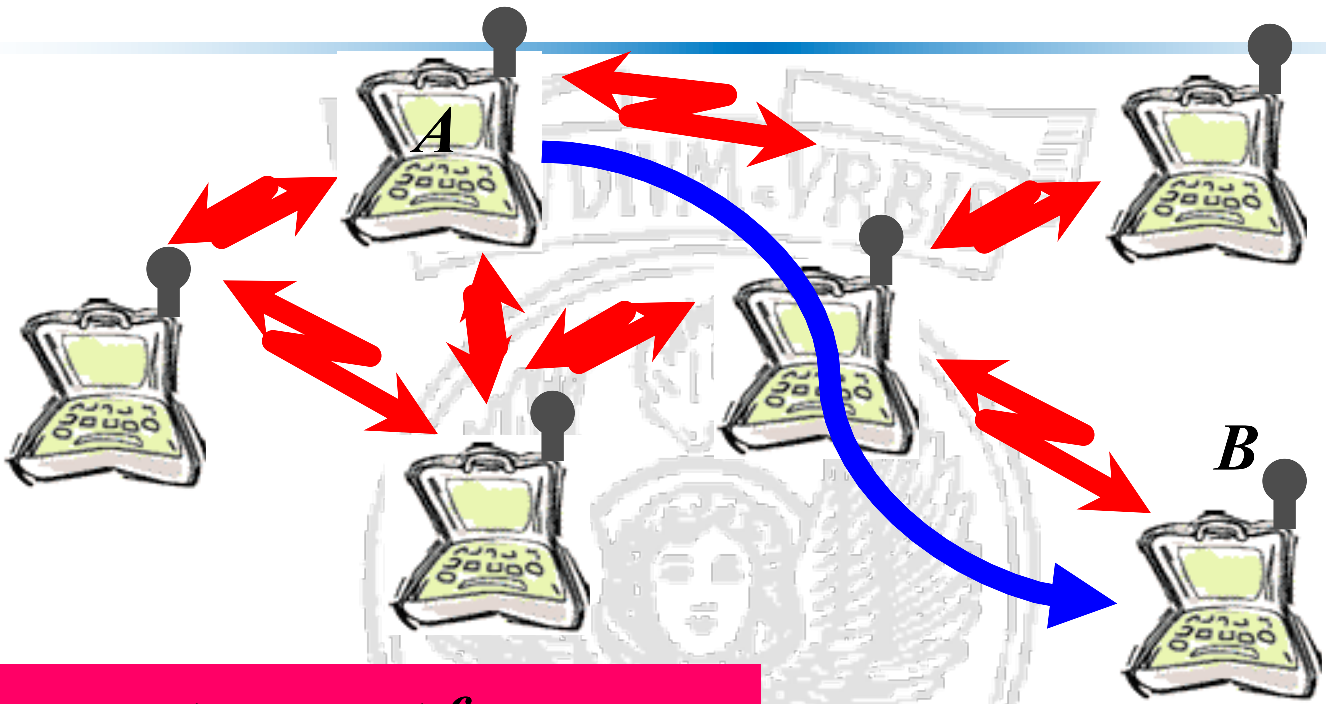
Medium Access Control



Hidden terminal

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

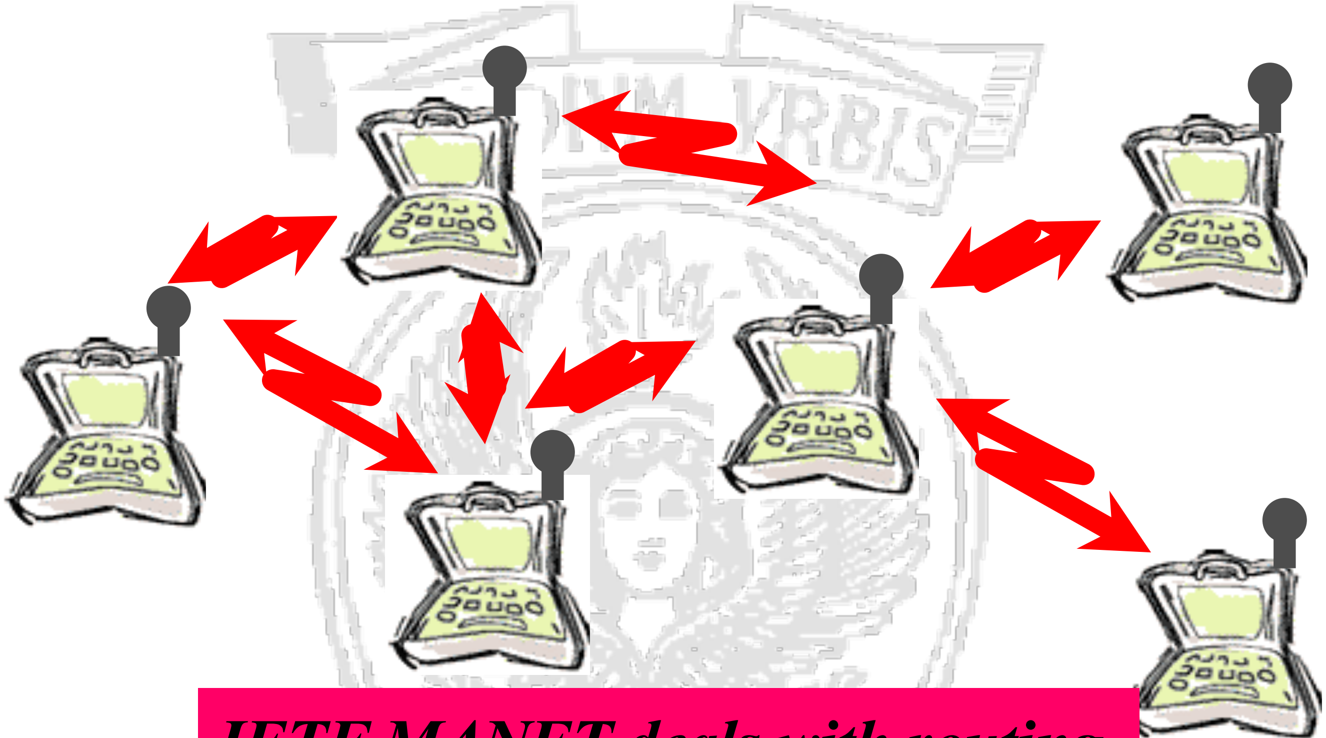
Routing



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)?

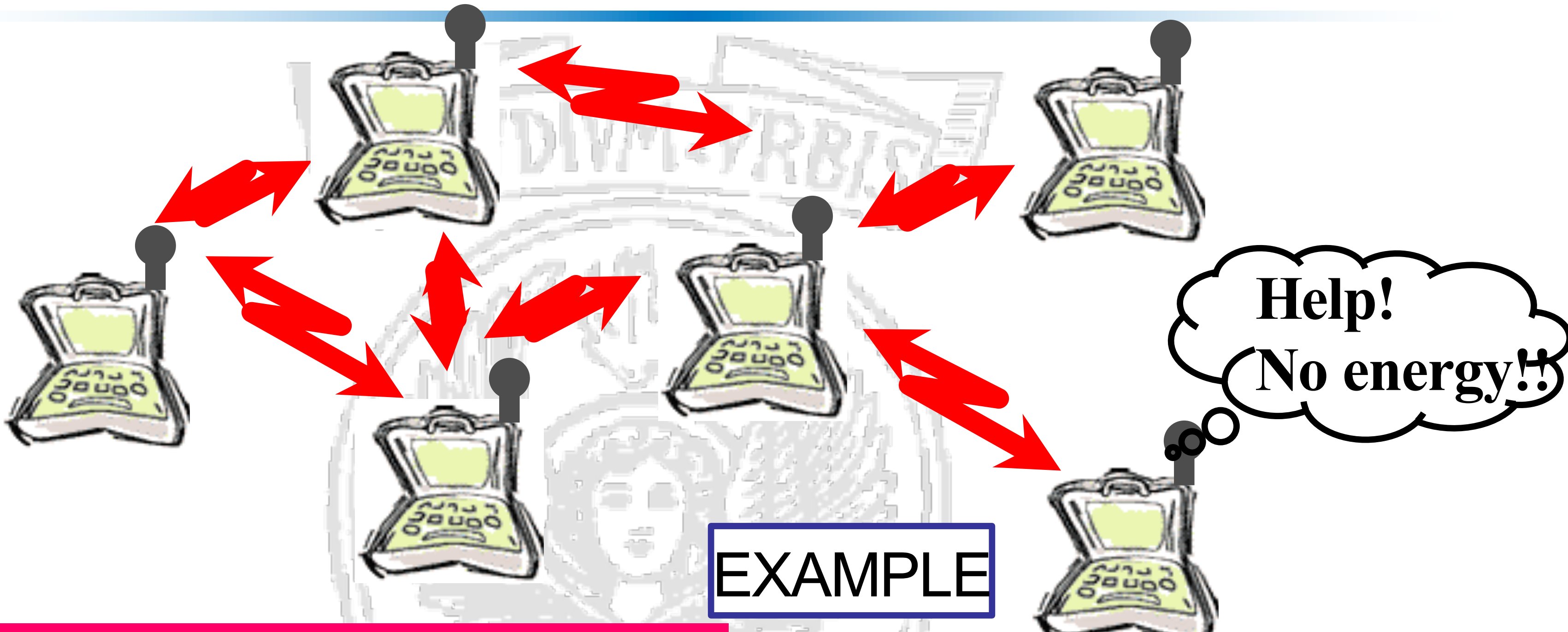
Ad Hoc Networks -Challenges



IETF MANET deals with routing

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

Ad Hoc Networks-Challenges



Energy efficient solutions at all different layers of the protocol stack: power control, MAC, data link, <u>routing,</u> 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

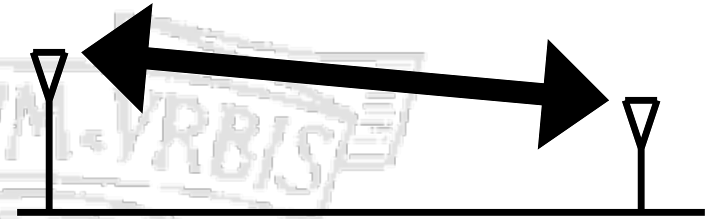
- Wireless Channel & Signal Propagation – Basic Concepts
- **Energy efficient comms. techniques**
- Channel Access problems
- Mobility management

Wireless channel

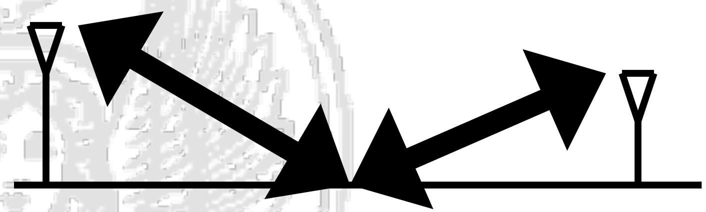
- Much less reliable than wired channels
- While propagating the signal can face
  - Attenuation as function of the distance from transmitter and receiver
  - Attenuation due to obstacles
  - Propagation over multiple paths (resulting in multipath fading)

Radio signal propagation

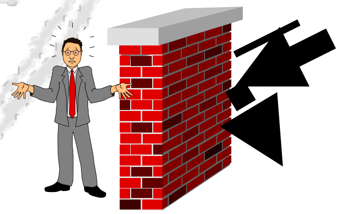
- Line of sight



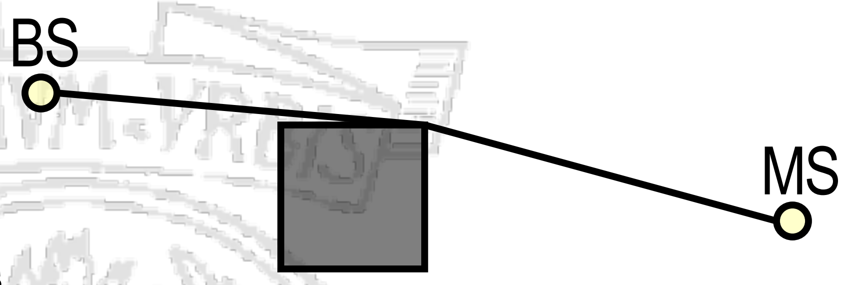
- Reflection



- Shadowing

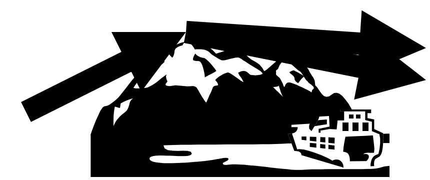


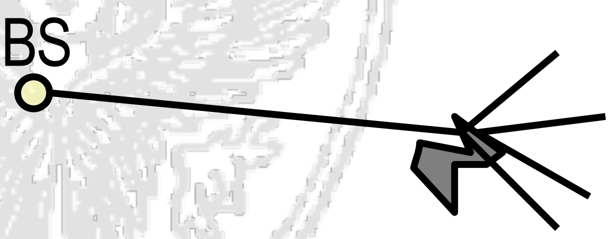
Radio signal propagation



➔Diffraction

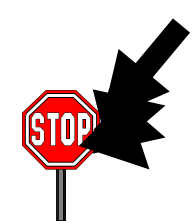
- ➔ When the surface encountered has sharp edges ➔ bending the wave





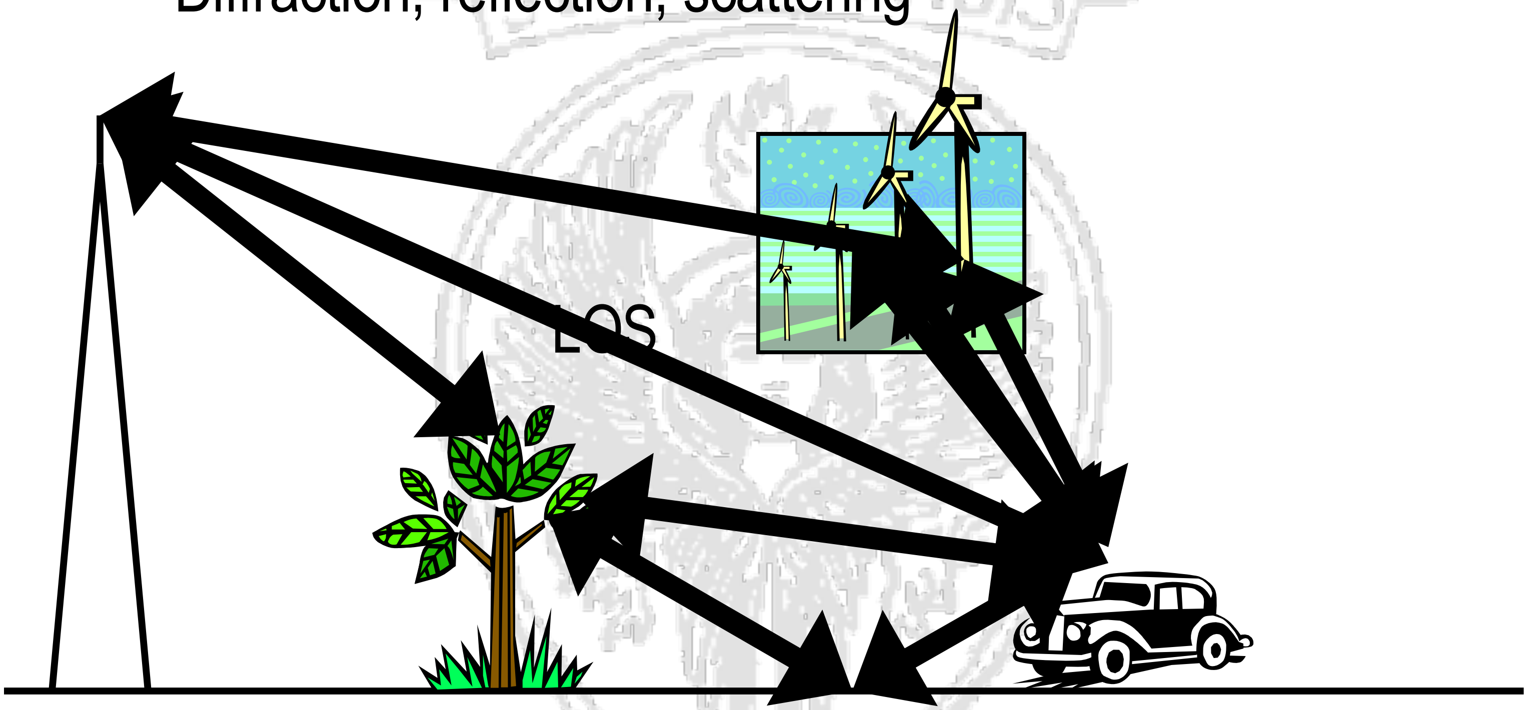
➔Scattering

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



Radio signal propagation

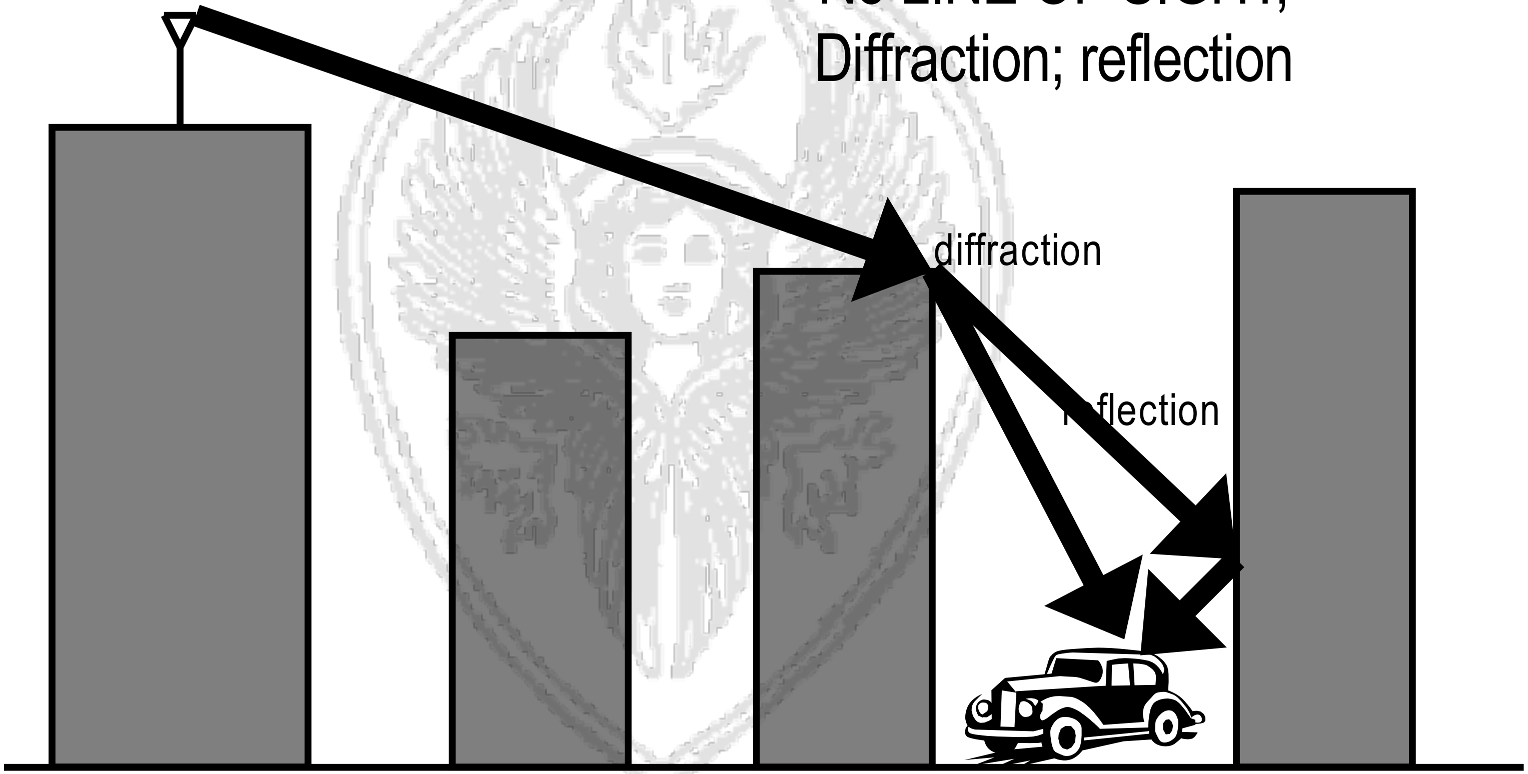
LINE OF SIGHT +
Diffraction, reflection, scattering



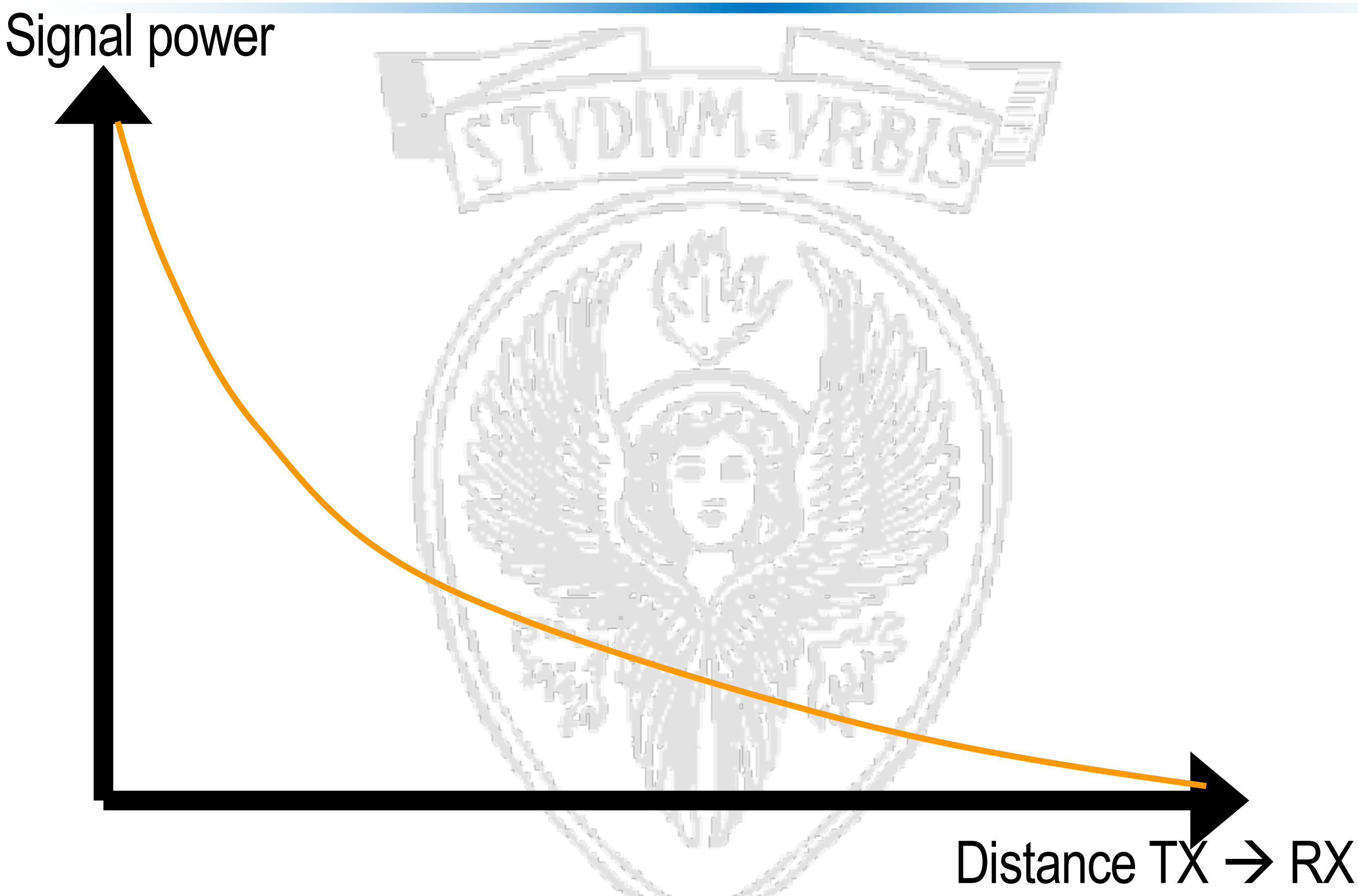
Radio signal propagation

LOS path non necessarily existing

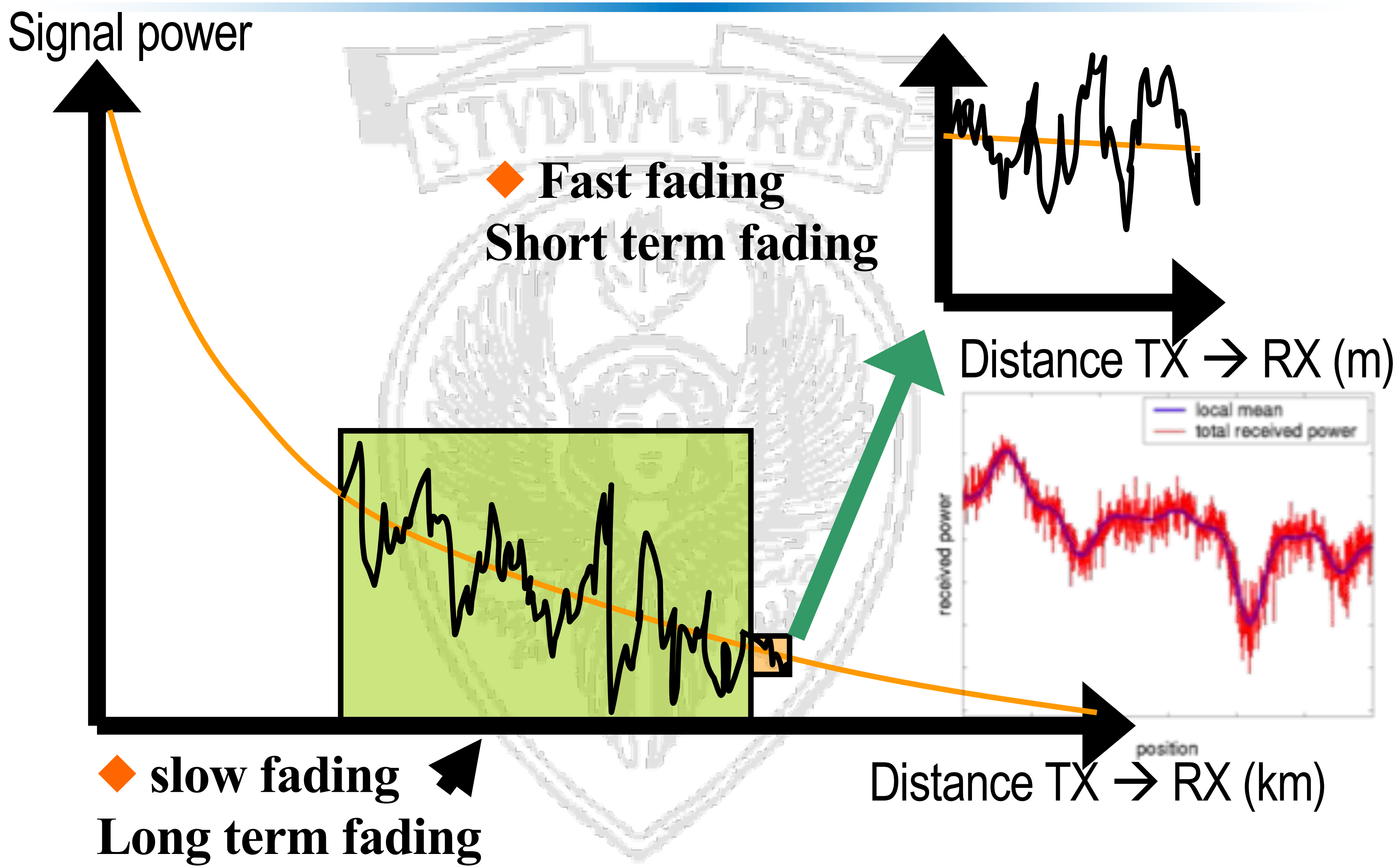
Example: city with large buildings;
No LINE OF SIGHT;
Diffraction; reflection



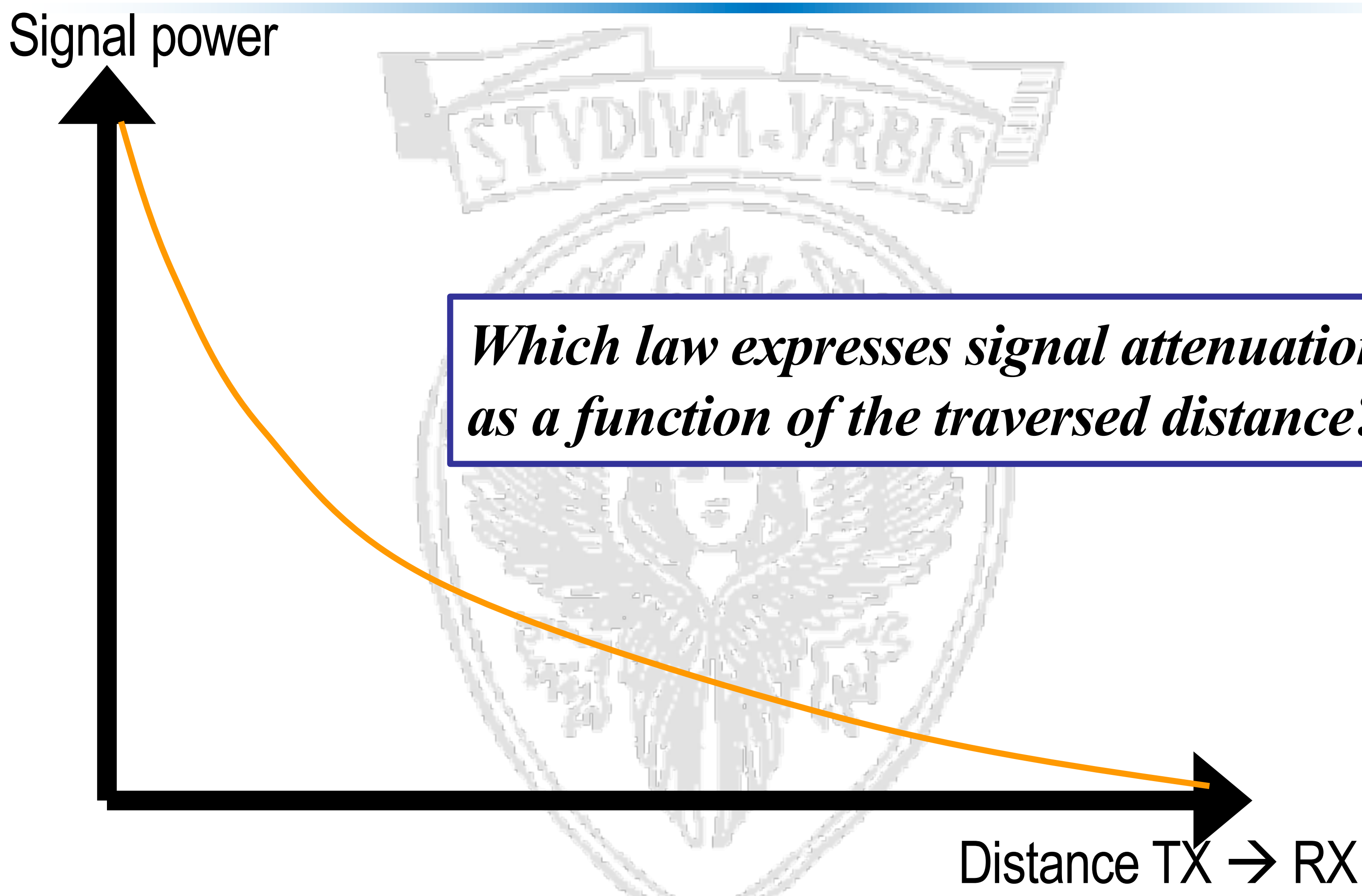
Radio signal attenuation



Slow fading – fast fading



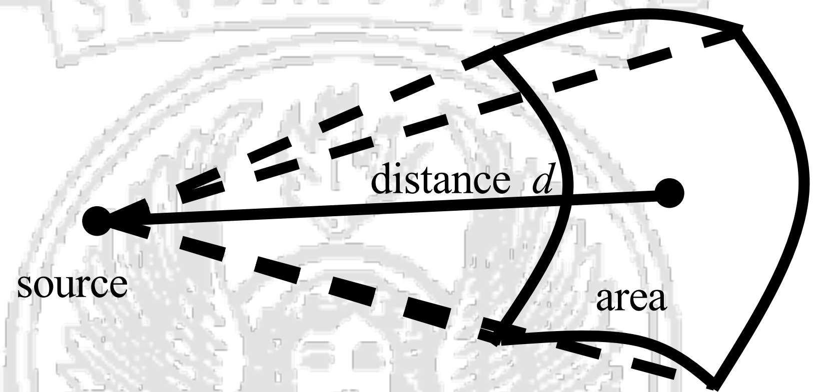
Radio signal attenuation



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

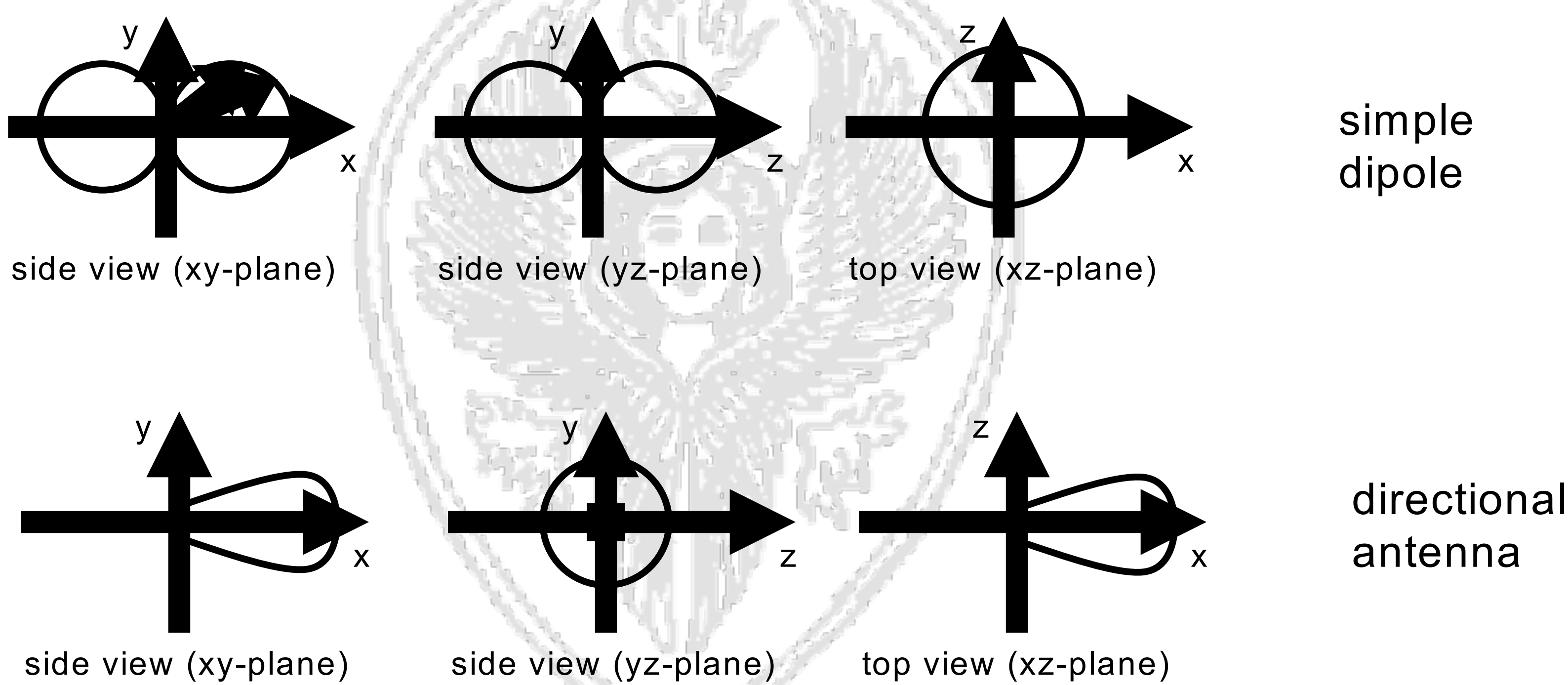


- The power density at distance d is equal to the ratio between the transmission power and the surface area of a sphere centered in the source and with radius d:

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

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)

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

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

- 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

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, 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 →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

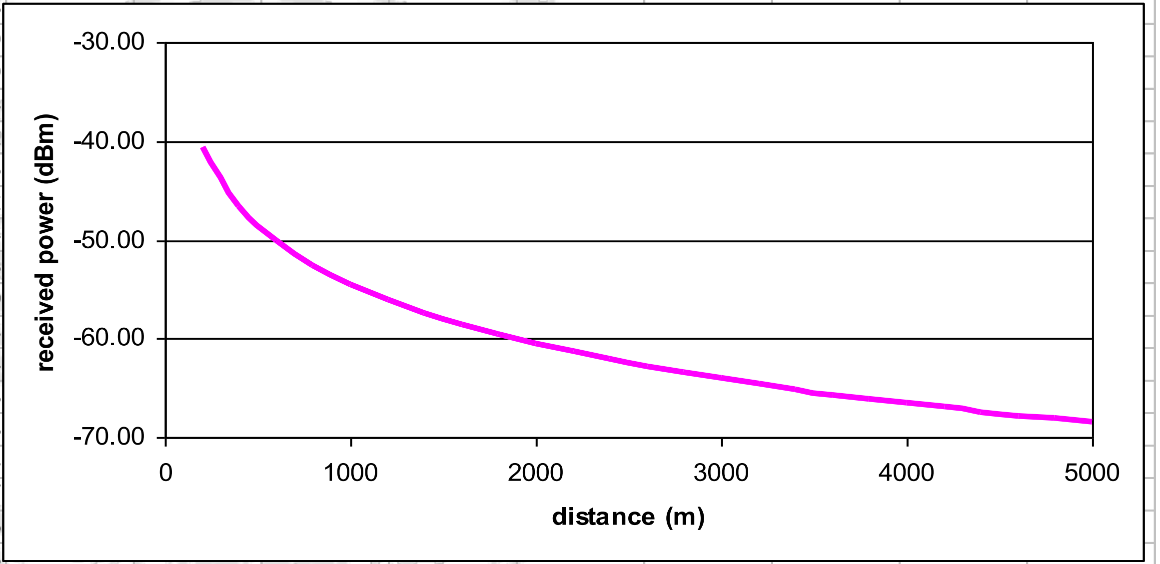
Decibels - dBm

- 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



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

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

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

- 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

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

$= 20$

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

$= 20$ … $0\log_{10}\frac{c}{4\pi} =$

$= 20$ … 7.56

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

Denoted also as L_{free} in what follows

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

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

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

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

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}…

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

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

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

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

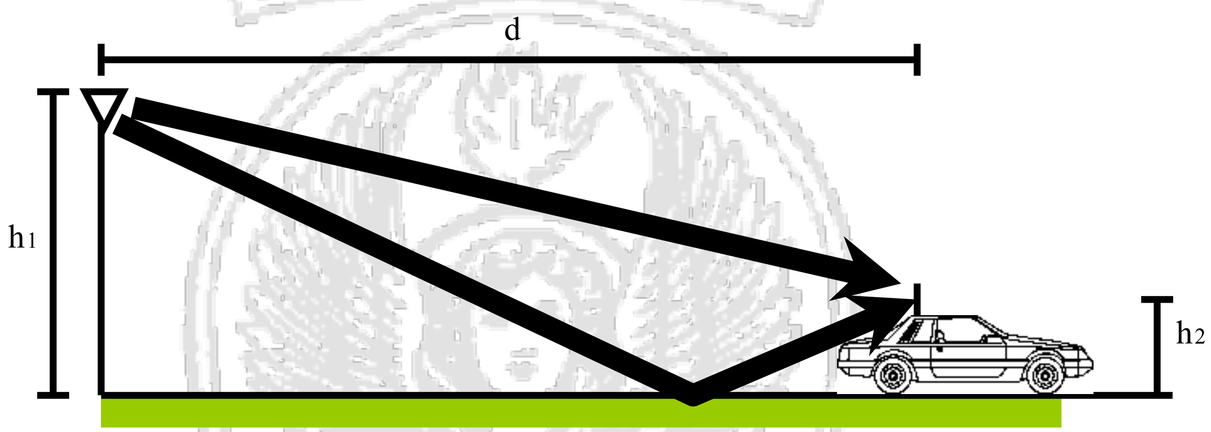
$$P_R(d) = P_R(d_{ref})\,(d_{ref}/d)^2$$

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

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

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

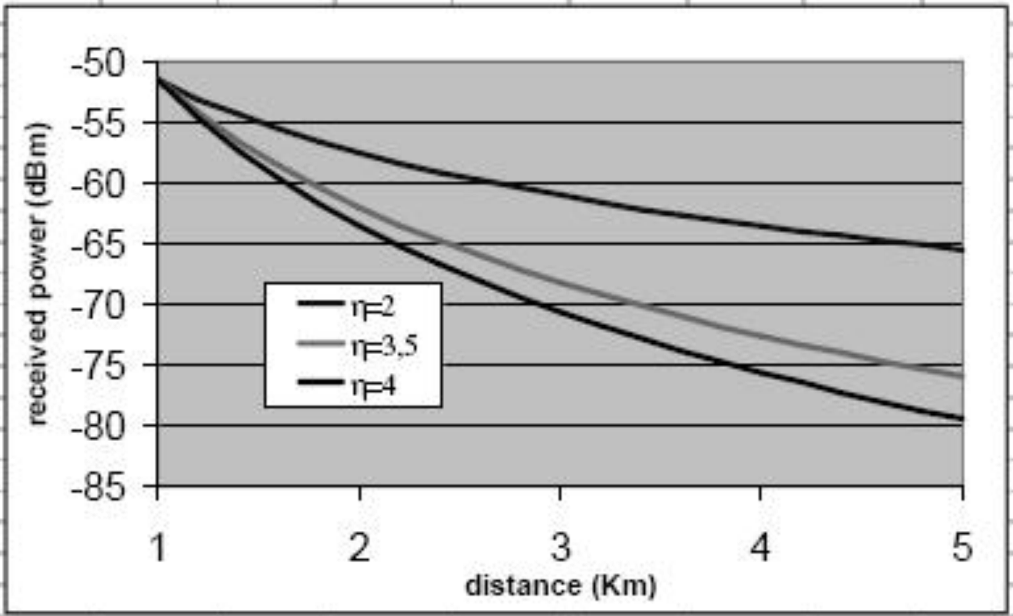
- In the two ray model the received power decreases much faster with distance (~$1/d^4$) than in the free space model (~$1/d^2$)
- Real life signal propagation is much more complex than what represented by the two models
- However, mean received power can be often expressed with a generalization of the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

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

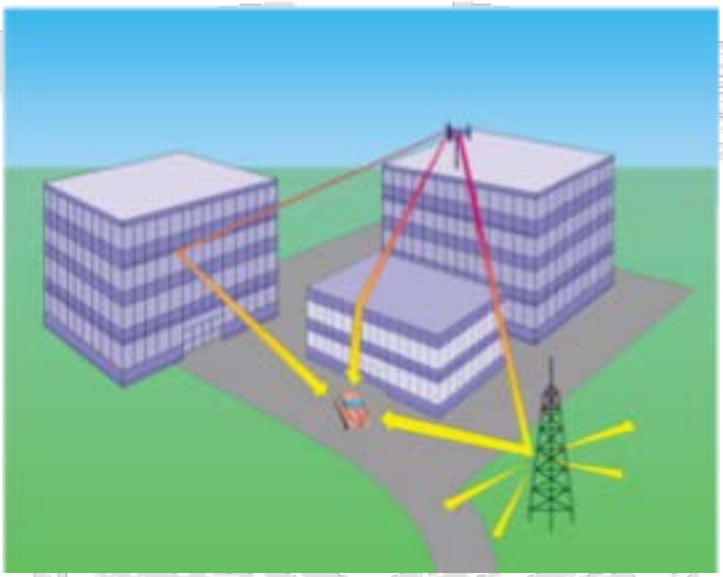
Extended formula

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

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

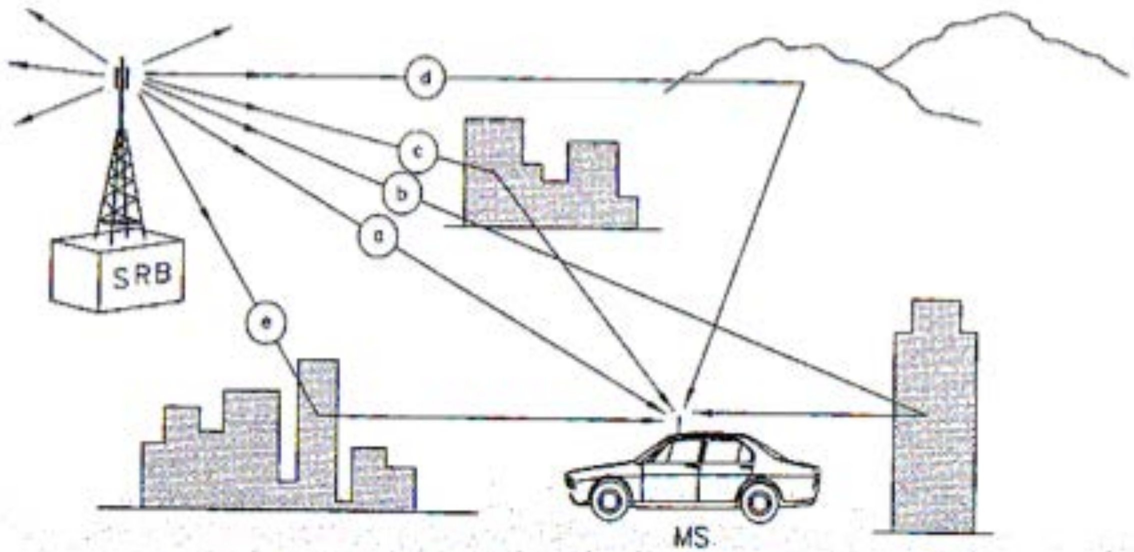


Wireless channel: multipath fading



- 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

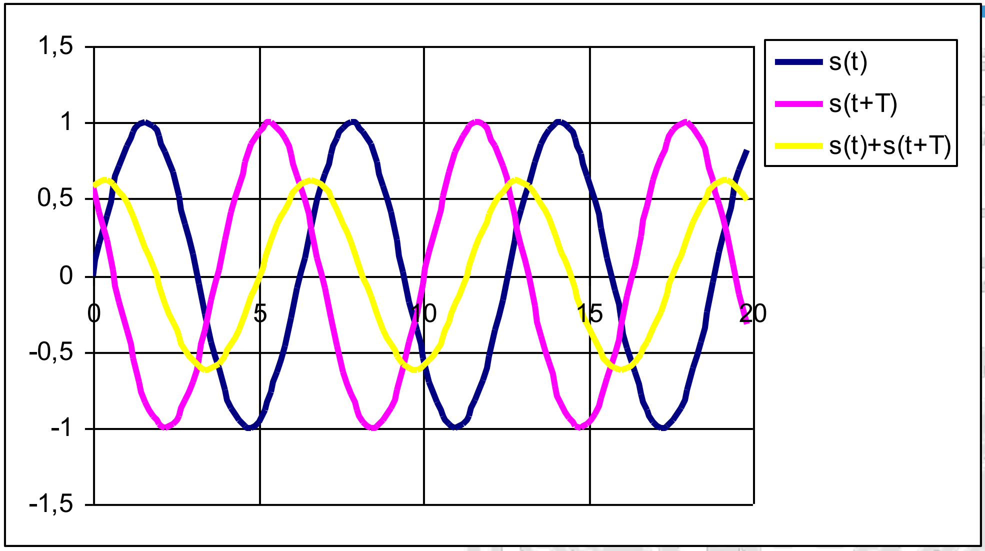


- Signal replicas received via different propagation paths are combined at the receiver
- The results depends on
  - The number of replicas
  - Their phases
  - Their amplitudes
  - Frequency

Received power differs, as a result

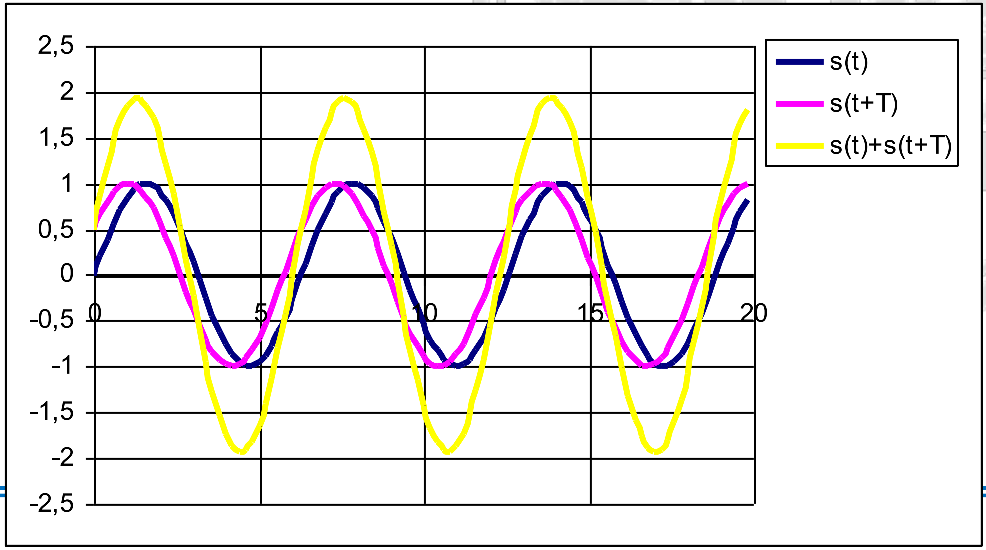
- from place to place, from time to time!

Multipath fading



- Resulting signal can be attenuated

T=4/5π



- Or amplified

T= π /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

Rayleigh fading power distribution

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

Sigma[2] is the Variance of The X,Y variables

Rayleight fading

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

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

$= c$

$= X$

In the as

X,Y are

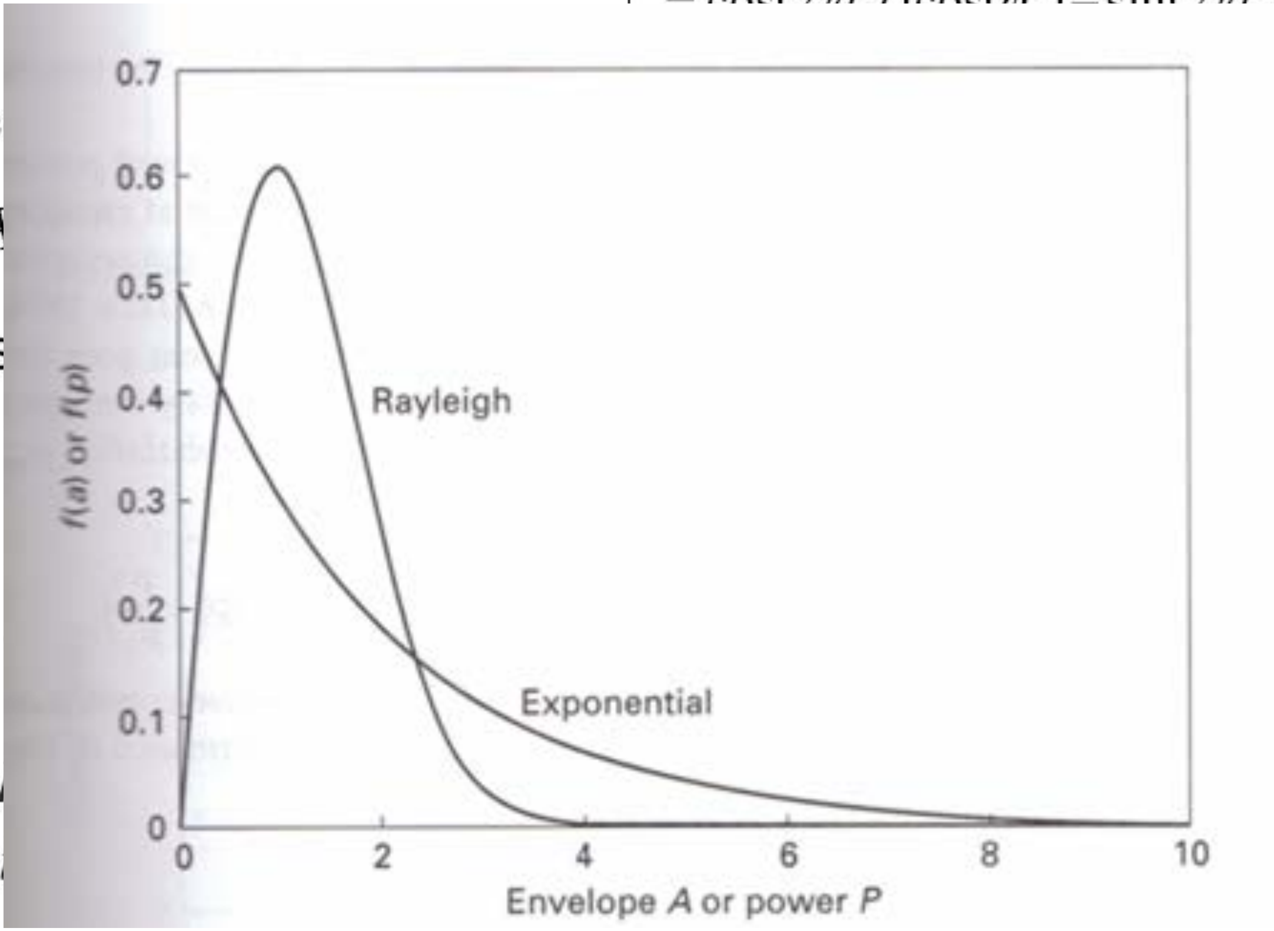
s the

e of

variables

Rayleig

distribu



Rayleight fading

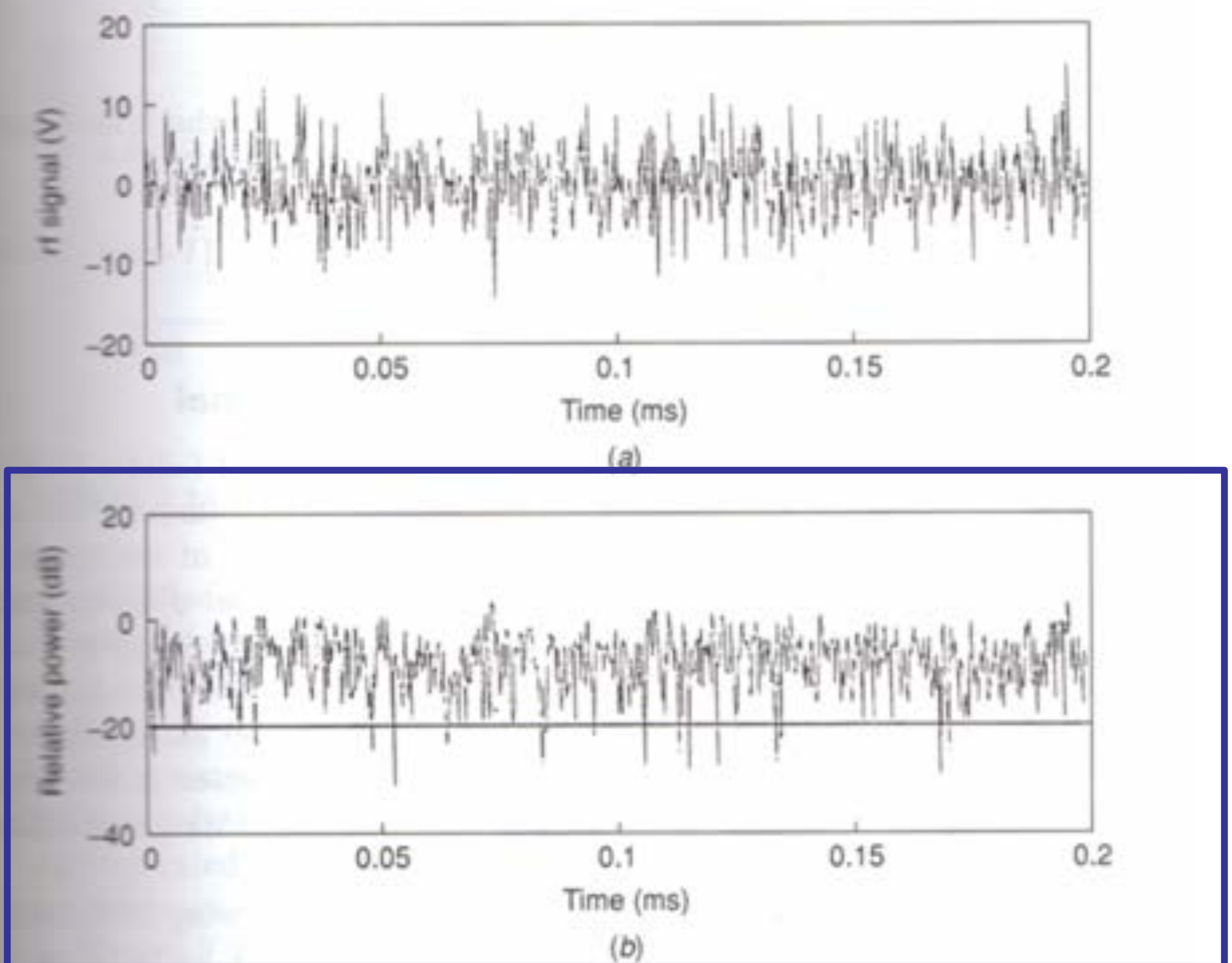


FIGURE 2.19 Rayleigh-faded rf signal (*a*) and its power (*b*). The plots were generated from 11 multiple paths. The envelope was obtained by demodulating the rf signal.

Fading-why is it important?

Answer1:

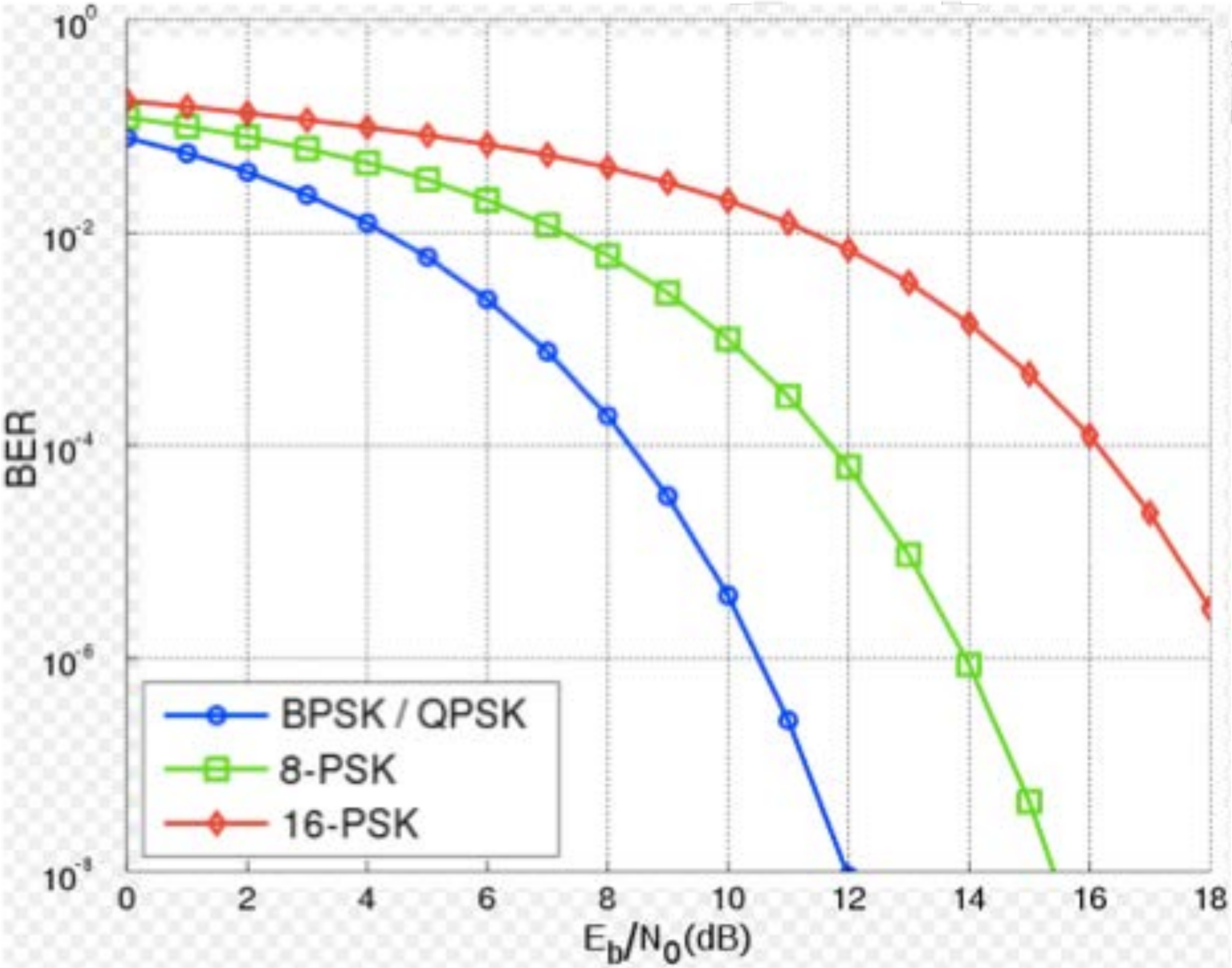
Outage Probability→Probability that received power is lower than a given threshold

⇨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

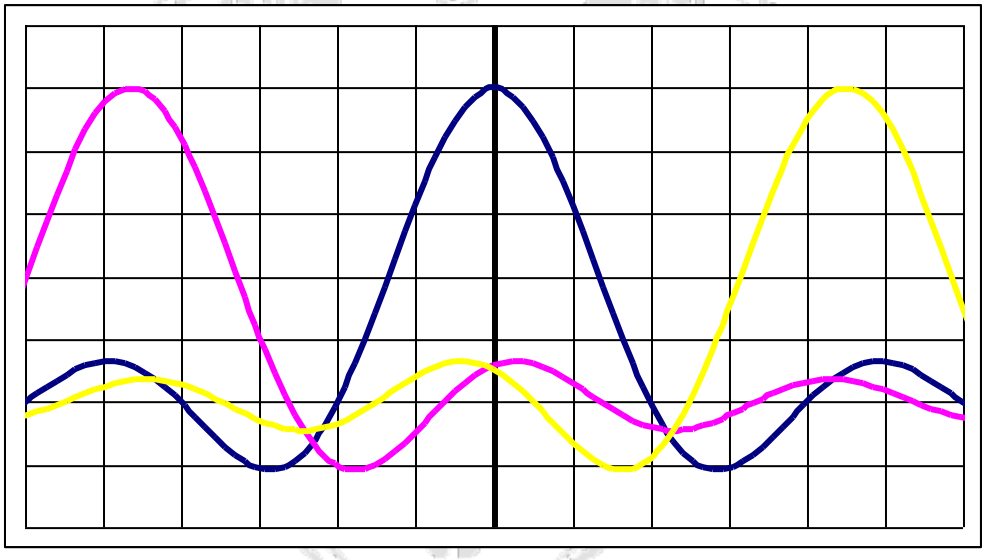
Using FEC BER

Performance can

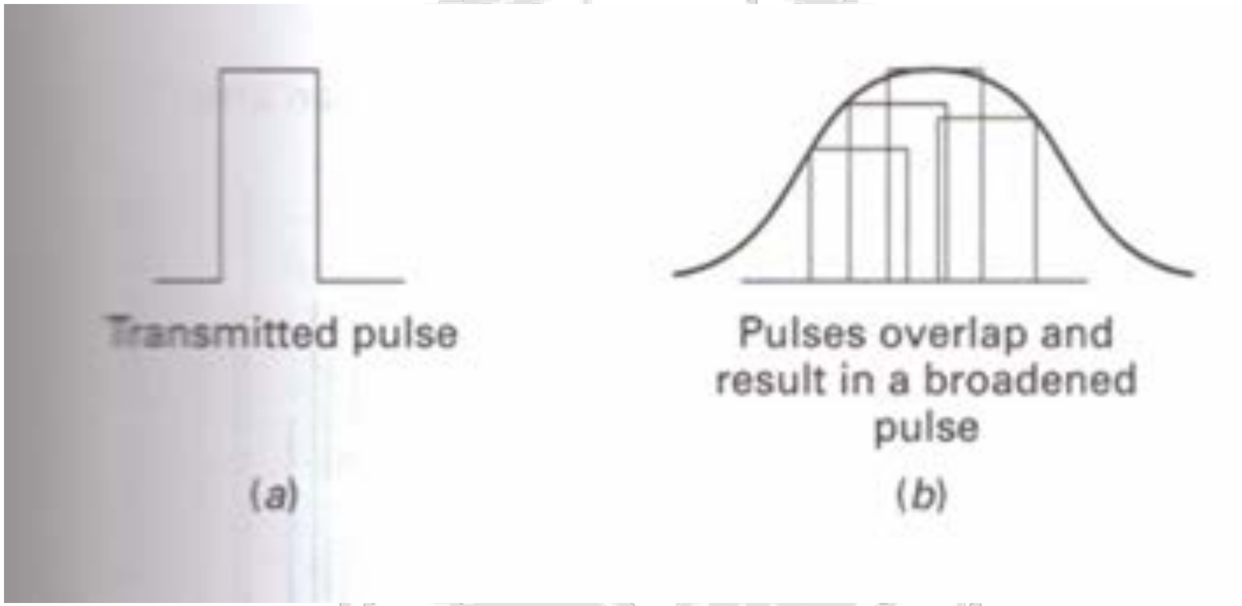
be improved

Multipath fading

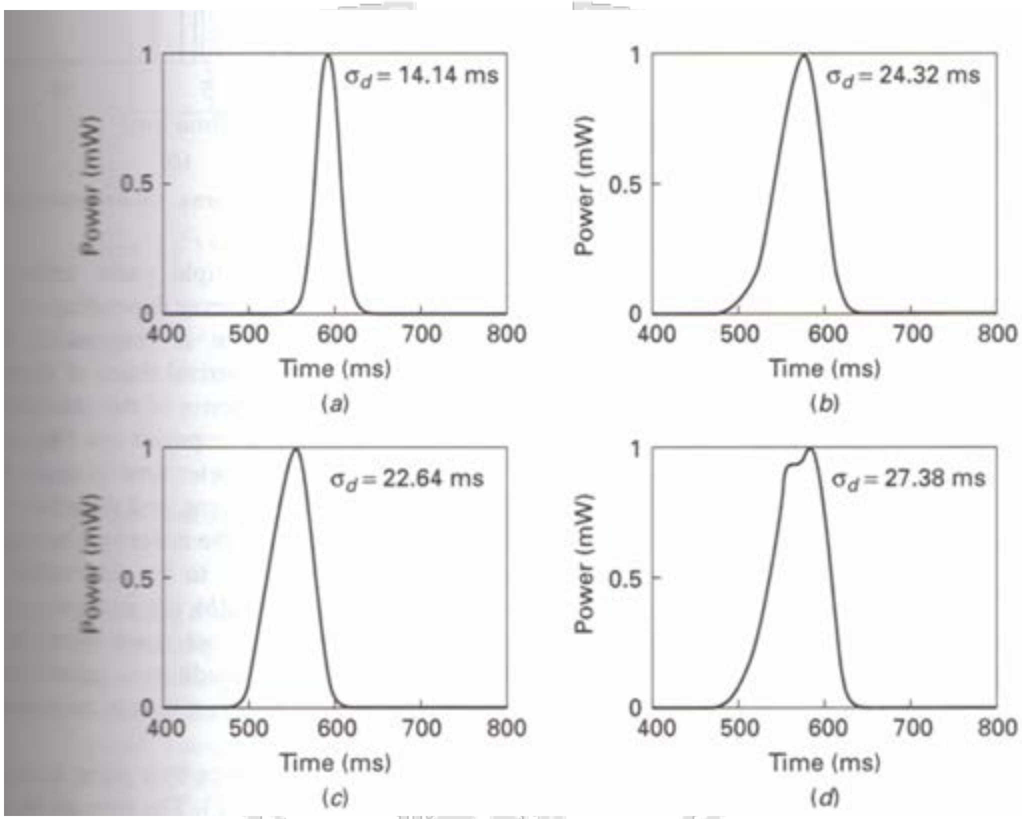
- Different delays experienced by the different signal replicas (*delay spread*) can widen the channel impulse response leading to intersymbol interference (ISI – Inter-Symbol Interference)



Examples

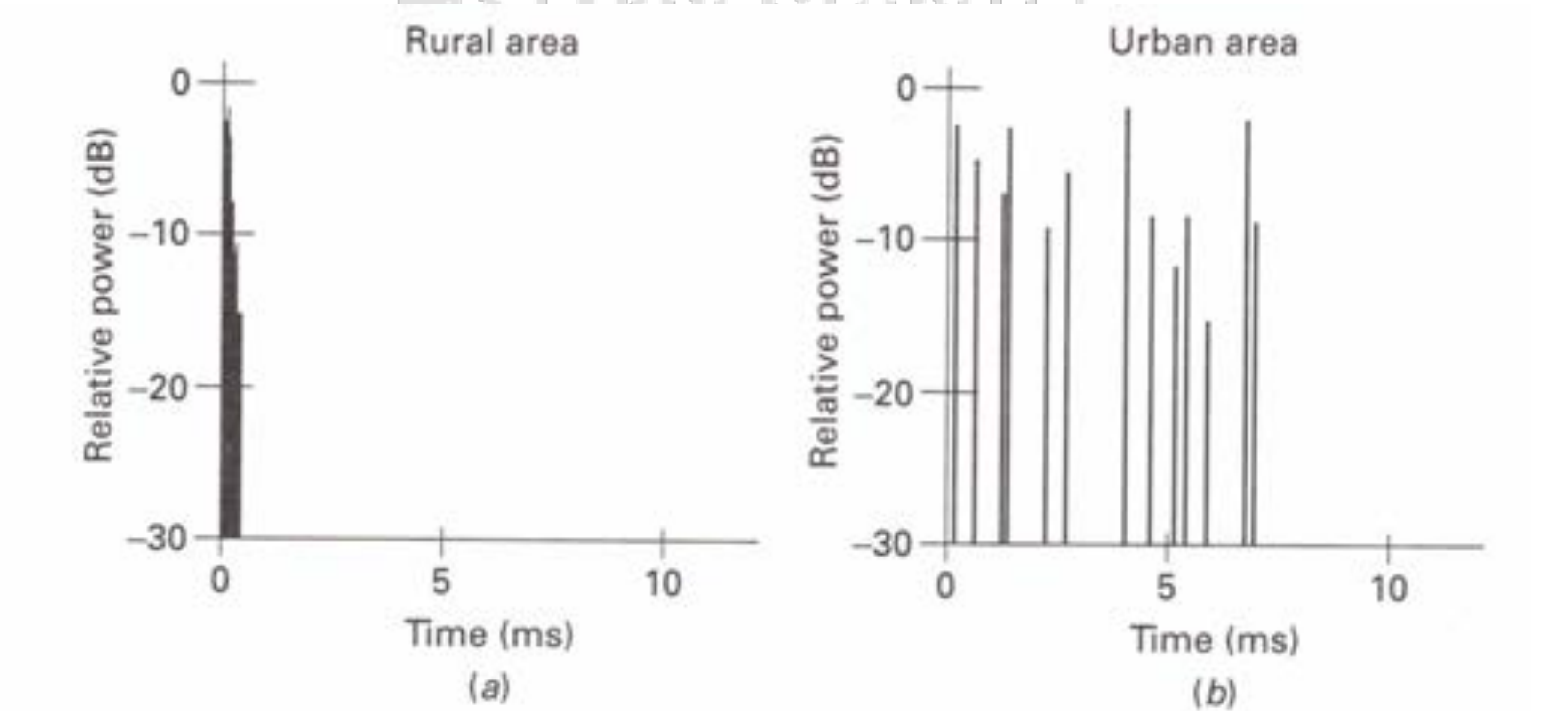

Transmitted pulse
(a)
Pulses overlap and result in a broadened pulse
(b)

Examples



σ_d = 14.14 ms
Power (mW)
Time (ms)
(a)
σ_d = 24.32 ms
Power (mW)
Time (ms)
(b)
σ_d = 22.64 ms
Power (mW)
Time (ms)
(c)
σ_d = 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.

Techniques for energy efficient communications

Energy efficient communication protocols

- Portable devices rely on external sources of energy (batteries, solar cells) to be able to communicate
- Battery lifetime is limited
  - Demanding to recharge battery operated devices after some time- for the device to remain operational;
- Despite improvements in battery technologies the problem has not been solved (and is not expected to be solved by better battery technology only):
  - energy demand is increasing;
  - users expectations in terms of device/network lifetime are increasing;

↓

  - Energy efficient techniques have been developed
  - Energy consumption is a critical metric driving wireless systems design

Energy efficient communication protocols

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Network lifetime:

- Time till the first node in the network dies having depleted its battery;
- Time before the network gets disconnected or fails to perform critical tasks (e.g., coverage of an Area of Interest)

Energy efficient communication protocols

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↓

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Energy efficient communication protocols

- Portable devices rely on external sources of energy (batteries, solar cells) to be able to communicate

Energy efficiency:

- Expresses how efficiently given tasks are performed.
  - Energy-efficient communication: energy spent by the network per bit correctly delivered to the final destination;
- To be considered in combination with other E2E metrics (throughput/latency)

  - Energy efficient techniques have been developed
  - Energy consumption is a critical metric driving wireless systems design

Energy consumption components

- Laptop most energy consuming components include CPU, liquid crystal display (LCD) and **wireless network interface card**
  - Toshiba 410 CDT (2001): 36% of energy consumption due to display, 21% due to CPU+memory, 18% due to wireless network interface card
- **Around mid nineties the area of energy efficient communication moved its first steps…**

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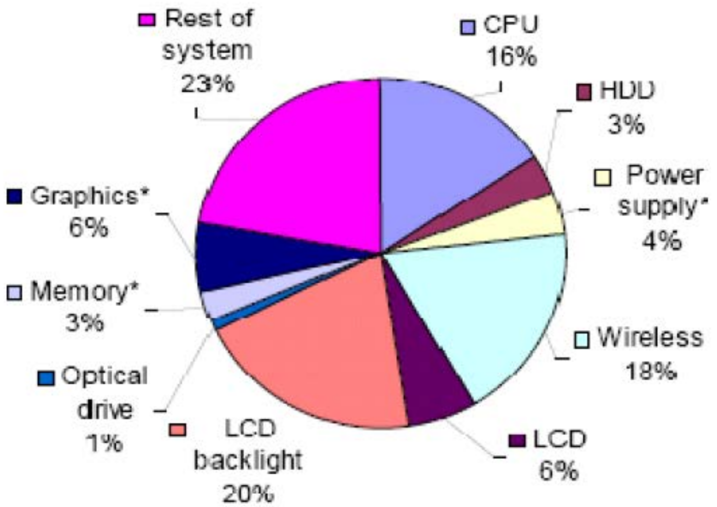

Somavat, Pavel, Shraddha Jadhav, and Vinod Namboodiri. "Accounting for the energy consumption of personal Computing including portable devices." in *Proceedings of the 1st ACM International Conference on Energy-Efficient Computing and Networking*, 2010.

Energy-efficient techniques

- Network-related energy consumption has two components
  - Computing: in network data processing, data fusion and aggregation, protocol operations;
  - Communications: Wireless transceiver consumes energy either to transmit/ receive data and control packets, or when it is idle, ready ro receive.

- Trade-off between computation and communication
  - Energy-efficient communication protocols can add overhead and computational complexity.
  - There is an inherent computing vs. communication trade-off:
    - ✓ Where should the 'intelligence' of the system be placed? Which data should be processed in network (→higher energy consumption due to computing in nodes which can be energy constrained, but →more compact data transmitted, thus lower energy consumption due to communication) and which data should instead be transmitted to "higher end" devices or computing systems for processing ?(e.g., to the base station, to the sink, or which tasks should be offloaded to the cloud)
    - ✓ Not a one fit all answer.

The objective of the energy efficient communication techniques is to optimized these trade-offs, and the trade-offs amongs different E2E performance metrics (not just energy consumption but also throughput, latency).

Energy-efficient techniques

- Network-related energy consumption has two components
  - Computing: in network data processing, data fusion and aggregation, protocol operations;
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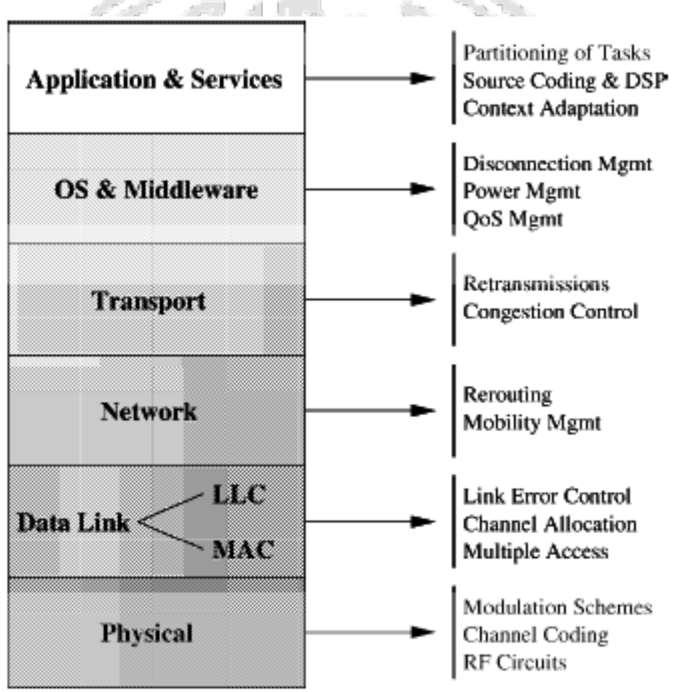
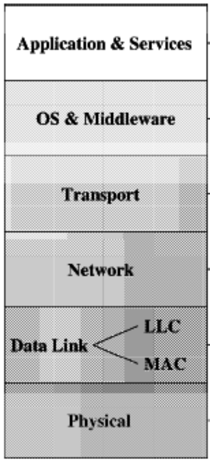


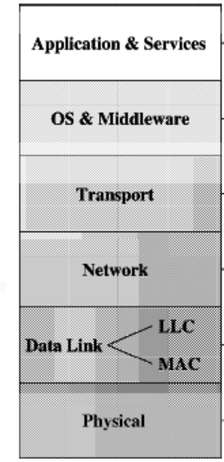
The objective of the en… …niques is to optimized these trade-offs, and the trade-offs amongs different E2E performance metrics (not just energy consumption but also throughput, latency).

Energy-efficient techniques



- General guidelines
  - PHY:
    - ✓ Power consumption is a function of the energy needed to activate the transceiver circuitry and of the emitted power → we can significantly decrease overall energy consumption in case of long range communication by applying power control (**Objective: minimizing transmission energy**)
    - ✓ Wireless technologies can dynamically change the modulation scheme used over time. Use of high data rate modulations reduce the time needed to transmit packets, thus the associated transmission energy consumption (**Objective: minimizing transmission energy**)
    - ✓ HW-dependent optimization and selection of HW: due to design choices standard compliant transceivers can have quite different performance in terms of energy consumption, BER and PER (Bit and Packet Error Rates). **HW selection can thus significantly impact the overall system energy consumption**.
    - ✓ Promiscous mode: several protocols proposed for ad hoc network routing exploit the idea of operating the wireless interface card in promiscous mode (→received packets are passed to higher layers and processed even if not addressed to the node) in order to gather information over the wireless broadcast channel which can be used to optimize the protocol operations.
    - ✓ Operating the wireless interface card in promiscous mode forces the interface card to stay in idle (instead of low power modes) for long periods of time, and leads to significant energy consumption due to processing of packets. Therefore, its use typically is a killer in terms of overall energy consumption.

Energy-efficient techniques



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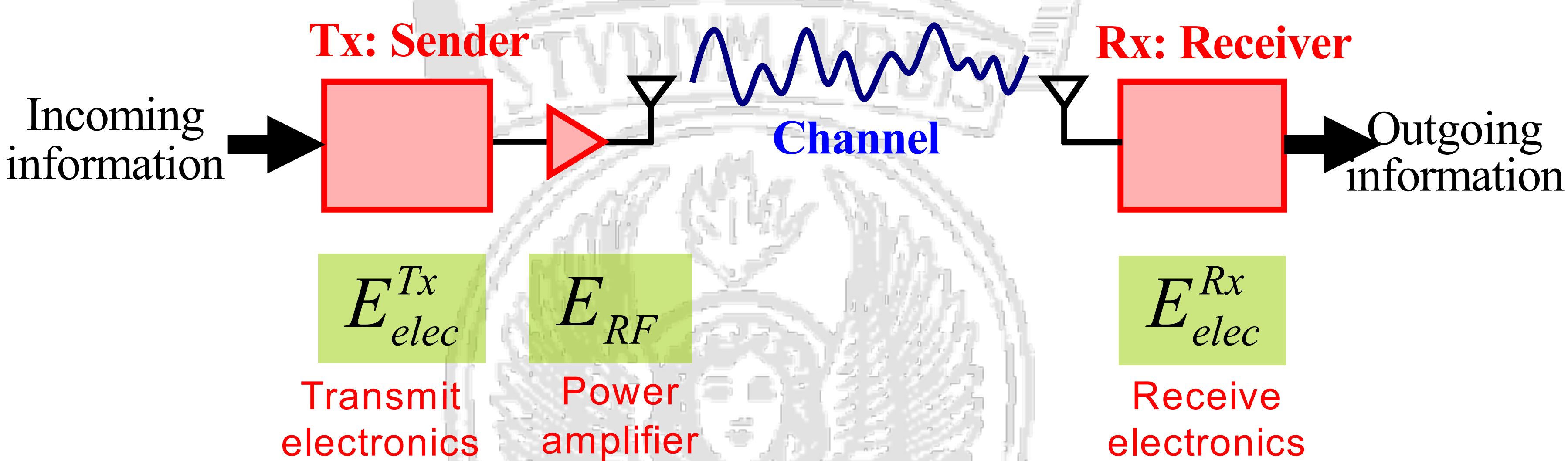
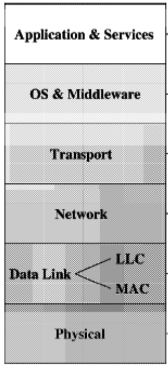
    - ✓ HW-dependent optimization and selection of HW: due to design choices standard compliant transceivers can have quite different performance in terms of energy consumption, BER and PER (Bit and Packet Error Rates). **HW selection can thus significantly impact the overall system energy consumption**.
    - ✓ Wireless transceiver should instead be switched to a low power 'sleep state' (where it cannot receive or transmit packets but the energy consumption is orders of magnitude lower) whenever a packet not addressed to the node or whenever information exchanged during a handshake make the node aware that the channel will be busy for the next future for transmitting packets not addressed to it
    - ✓ The transceiver should switch to low power mode for the whole time interval when it knows it will not be involved in communications.
      - This is also why destination address is the first field of the header
      - This is also why NAV field is part of RTS/CTS handshake in IEEE 802.11

Energy in Radio: the Deeper Story….



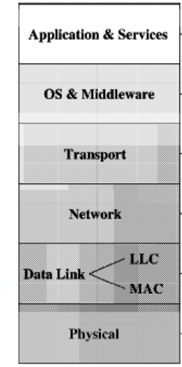
- Wireless communication subsystem consists of three components with substantially different characteristics
- Their relative importance depends on the **transmission range** of the radio

Energy-efficient techniques



- General guidelines
  - MAC
    - ✓ **Awake/asleep schedule:** Nodes alternate between
      - high energy consuming states (awake:transmit/receive/idle) in which the transceiver is ON and packets can be transmitted/received AND
      - states in which the transceiver is OFF, packets cannot be received or transmitted but the energy consumption is much lower.
      - Duty cycle=$T_{ON}/(T_{ON}+T_{OFF})$
      - Two possible classes of protocols:
        - » Synchronous:
        - nodes exchange information to coordinate on when to wake up;
        - periodic control message exchange ensures they know when their neighbors will wake up;
        - a packet is transmitted to a neighbor when it is ON.
        - » Asynchronous:
        - Awake/asleep schedule of neighbors is unknown;
        - No control overhead is needed to keep information updated;
        - To ensure reliable communications a sequence of packets must be sent until the destination node wakes up and answers (overhead when a packet has to be sent)
        - OR nodes must follow a cross-layering approach selecting one neighbors among the awake neighbors as relay.
    - ✓ Nodes not involved in communication should go to sleep till current information exchange completes (**Objective: avoid energy waste**).
    - ✓ Nodes should minimize collisions (**Objective: avoid energy waste**)
    - ✓ Header compression: By transmitting less bits the transceiver is ON for less time (**Objective: reducing transmission energy**)
    - ✓ Limit control information exchanged, aggregate redundant information (**Objective: reducing transmission energy**)

Tends to increase latency



Energy-efficient techniques

- General guidelines
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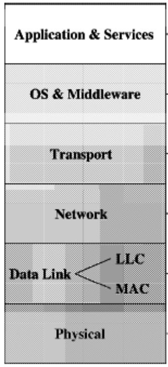
Energy-efficient techniques



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Tends to increase latency

Energy consumption due to reception is typically >> than that for transmission, as it is not possible to predict when a packet will have to be received: ← wake-up radio

Transceiver states

- Transceiver can be in one of the following states

There is a time and energy consumption associated to the switch whish should be accounted for when designing energy efficient protocols

tx — ***Awake and transmitting***

rx — ***Awake and receiving***

idle — ***Awake, neither transmitting nor receiving***

asleep — ***Asleep: the transceiver is not operational but energy consumption is low. There can be several asleep states with different subsets of the circuitery switched OFF → different time to switch to such states, but also different energy consumption.***

Transceiver energy consumption some examples

- Depend on technology, transmission range and phy layer solutions have an impact
- For the same type of device/technology significant changes in the energy consumption have occurred over time
  - As designers are striving to make technology more low power
  - Changes also occurred in the relative weight of different components of energy consumption (which has an impact on design of energy efficient protocols)
- Years: 90'-' 00
  - Message: transmitting costs >> receiving; idle cost costs significantly less, sleep mode 2-3 order of magnitudes lower
  - Examples:
    - ✓ Proxim RangeLAN2 2.4 GHz 1.6 Mbps PCMCIA card: 1.5 W in transmit, 0.75 W in receive, and 0.01 W in standby mode.
    - ✓ Lucent's 15 dBm 2.4 GHz 2 Mbps Wavelan PCMCIA card: 1.82 W in transmit mode, 1.80 W in receive mode, and 0.18 W in standby mode.

Transceiver energy consumption some examples

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  - Examples:
    - ✓ Proxim RangeLAN2 2.4 GHz 1.6 Mbps PCMCIA card: 1.5 W in transmit,

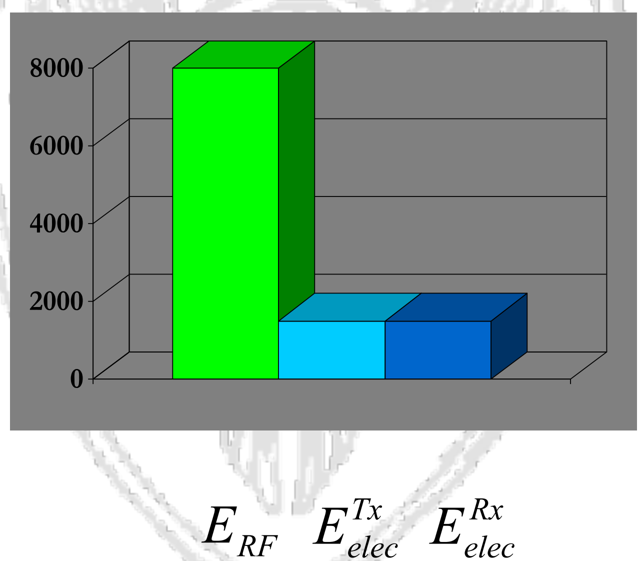
Nowadays for many low to medium range technologies transmission energy consumption is comparable to reception energy consumption and comparable to that of idle mode

Transceivers energy consumption-GSM

- When transmission range increases the percentage of transmitted energy due to emitted power increases

(data source: M. Srivastava, beginning of 2001)

GSM

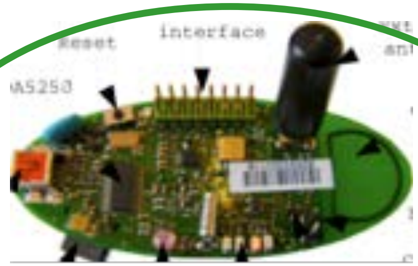


~ 1 km

Long range communications

Transceiver energy consumption-IoT technologies

- TmoteSky, EYES v2.0 platforms



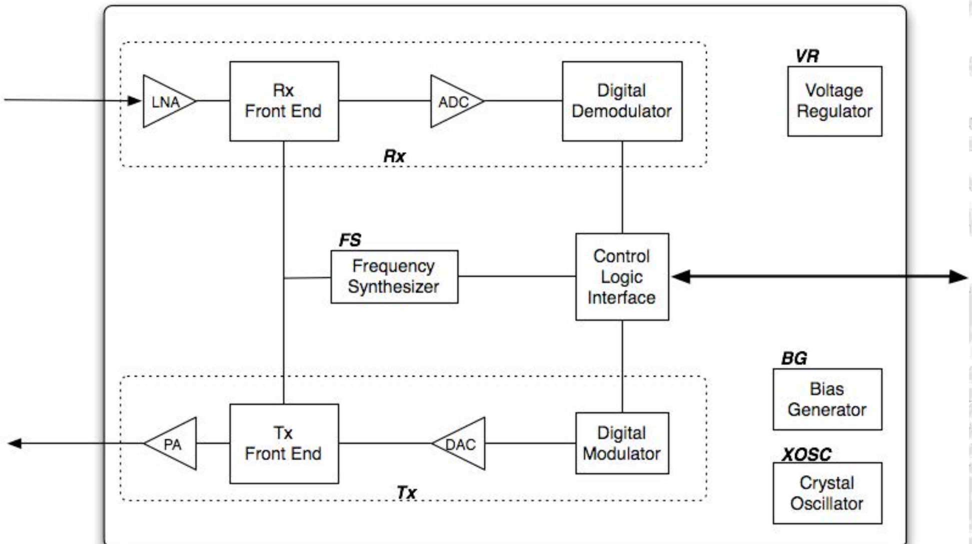
Texas Instruments Mps430 micro-controller,
16-b
fast
ADC
Ligh

TmoteSky:
radio chip CC2420 (Zigbee compliant), 2Ghz direct sequence spread spectrum (DSSS) modulation, datarate 250Kbps, on board 1 Mb serial EEPROM,

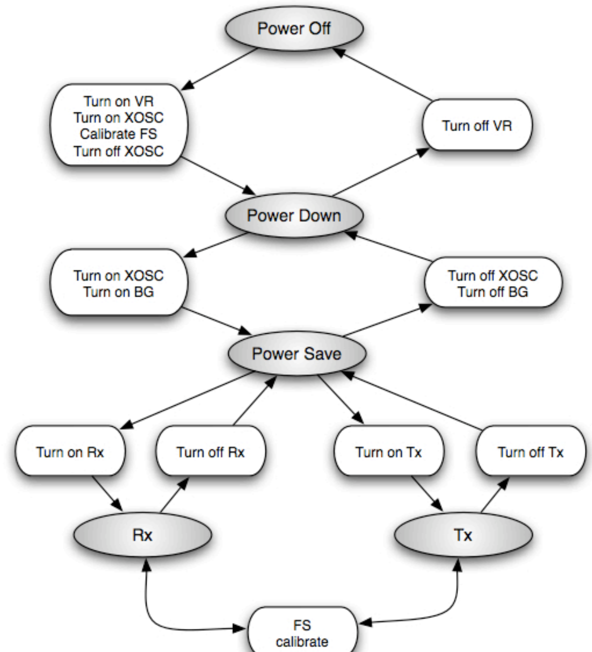
EyesIFXv2:
radio chip TDA5250, 868Mhz, FSK modulation, datarate 64Kbps, on board 512Kb serial EEPROM

TmoteSky Energy model

CC2420 Modules



Transceiver states



Energy model

State	Consumption (mA)
Rx	19.7
Tx	17.4
Save	0.45
Down	0.02
Off	0.001

Table 1: Consumption of CC2420 transceiver.

Switch Between (States)	Consumption (mA)	Duration (ms)
Rx/Tx	17.4	0.192
Tx/Rx	19.7	0.192
Tx/Save	17.4	0.192
Rx/Save	19.7	0.192
Save/Down	0.45	0.96
Down/Off	0.02	0.6

Table 2: Switch time of CC2420 transceiver.

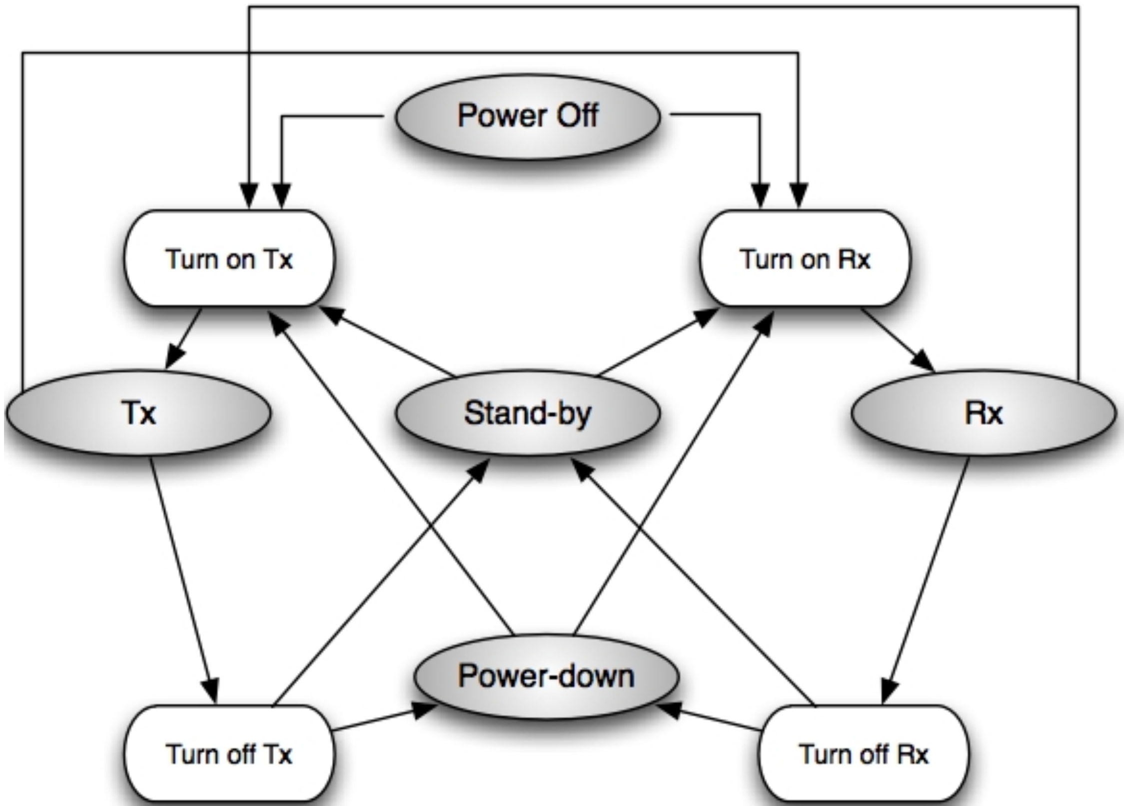
EYES IFXv2 Energy model

Energy model

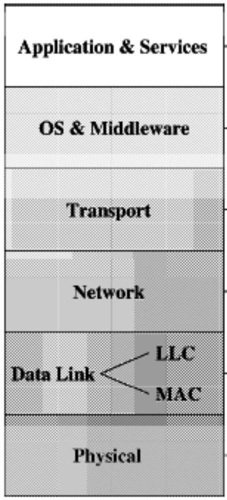
State	Consumption (mA)
Rx	8.6
Tx	11.2
$Stand-by$	0.75
$Power-down$	0.009
$Power-off$	0

State	Consumption (mA)	Duration (ms)
$Power-off/Tx$	0.3085	9.1
$Power-off/Rx$	0.2632	10.2
Tx/Rx	0.0739	2.2
Rx/Tx	0.0369	1.1
$Power-down/Tx$	0.0025	1.1
$Power-down/Rx$	0.0568	2.2
$Stand-by/Tx$	0.0025	1.1
$Stand-by/Rx$	0.0568	2.2

Transceiver states

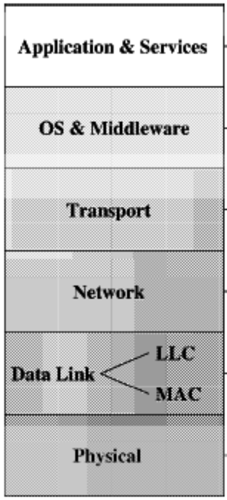


Energy efficient techniques



- General guidelines
  - Data Link
    - ✓ If channel is in a bad (deep fade) state it is convenient to delay transmissions as it is very unlikely packets will be correctly received (**Objective: avoid waste**)
    - ✓ Energy efficient ARQ and FEC schemes have been studied to optimize energy consumption while ensuring reliable and timely communication (overhead vs. number of retransmissions trade-off; adaptive solutions depending on load, channel, application requirements).

Energy efficient techniques



- General guidelines
  - Routing
    - ✓ Depending on the scenario it can be more energy efficient to transmit over a higher number of shorter links or minimize the number of hops (**can you tell me when one option is better than the other? Suggestion: Long range vs. short range communication**)
    - ✓ Minimize the overhead associated to route discovery and maintenance
    - ✓ Load balancing of the energy consumption among nodes to increase the network lifetime;
    - ✓ Energy aware routing solutions which account for residual energy (and expected future availability of energy in case harvesting is an option) when selecting the best next hop relay.
    - ✓ Link quality aware relay selection to avoid retransmissions.
    - ✓ Relay selection which favors data fusion/aggregation.
    - ✓ All the above combined ← cross layer solutions.

Tecniche di risparmio energetico

- In the last few years there has been a change of devices used to access the Internet
  - From PC to smartphone
  - Novel Phy layer and more advanced transceiver features
  - How has the energy model been affected by changes in the device technology?
  - Can we still make the same assumptions or are there additional components to account for?

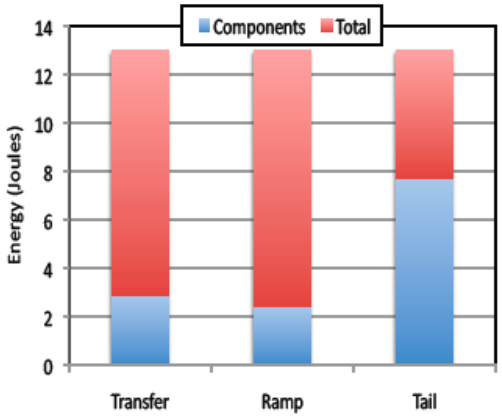
In the following the outcomes of:

N. Balasubramanian, A. Balasubramanian, A. Venkataramani “Energy consumption in mobile phones: A Measurement Study and Implications for Network Applications”, ACM IMC 2009. Observation: Workload impacts energy consumption of typical devices (cellular-GSM/3G; WiFi)

A. Garcia Saavedra, P. Serrano, A. Banchs, G. Bianchi “Energy Consumption Anatomy of 802.11 Devices and Its Implication on Modeling and Design” in Proceedings of Co-NEXT 2012 (on WiFi)

Device and standard-dependent optimizations

- Implementations and choices made for implementing standards make the difference:
  - N. Balasubramanian, A. Balasubramanian, A. Venkataramani "Energy consumption in mobile phones: A Measurement Study and Implications for Network Applications", ACM IMC 2009. Observation: Workload impacts energy consumption of typical devices (cellular-GSM/3G; WiFi)
    - ✓ In 3G, a large fraction (nearly 60%) of the energy, referred to as the *tail energy,* is wasted in high-power states after the completion of a typical transfer.



Typical 3G transfer

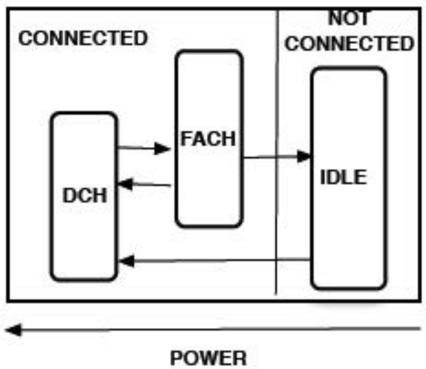
HTTP request issued to a remote server

50KB download

Nokia N95

Device and standard-dependent optimizations

- Implementations and choices made for implementing standards
  – N. Balas… …nkataramani "Energy… …rement Study and Imp… …IMC 2009. Observa… …ion of typical devices



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    – Switching back from an active state is handled by means of inactivity timers often set to a few seconds.
  - ✓ Tail and ramp energies (more limited) are constants that amortize over larger transfer sizes or frequent successive transfers.

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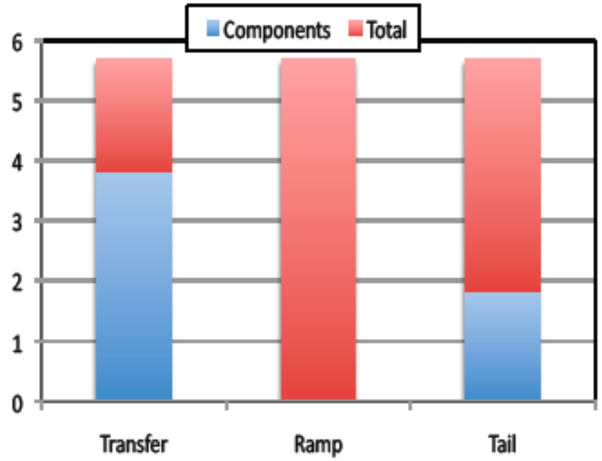
Device and standard-dependent optimizations

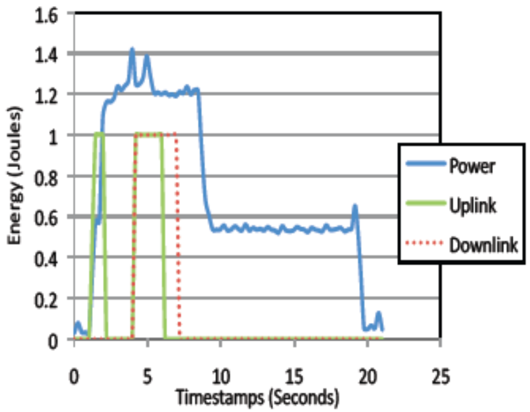


GSM shows a different trend

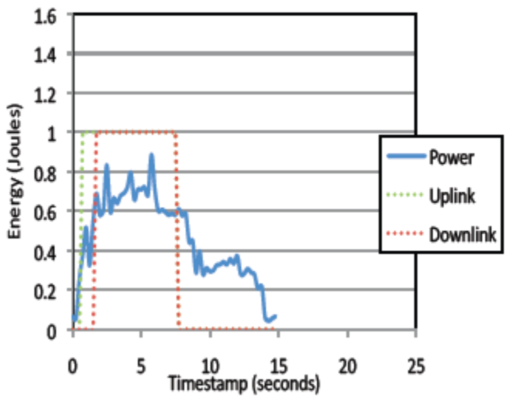
Lower power

More significant transmission energy

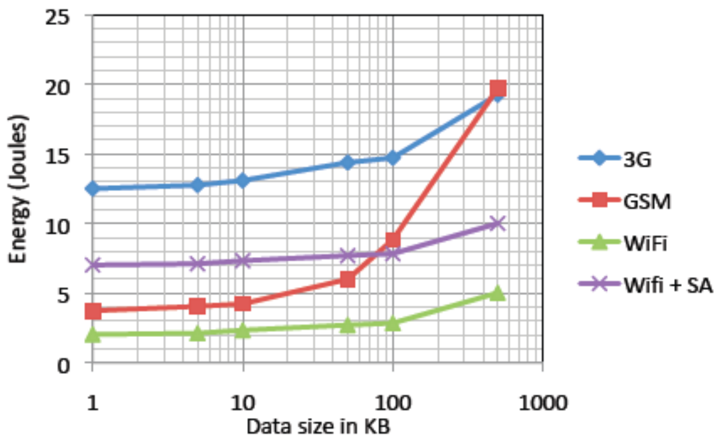
Less significant (even if present) tail energy effect



(a) 3G: Power Profile - 50K



(b) GSM: Power Profile - 50K



Solution:TailEnder

- Three ideas:
  - Combine use of 3G and WiFi (with prediction of WiFi availability)
  - For delay tolerant applications (news, emails) delay transfer if tolerable delay so to transfer batches
  - For web surfing applications design of energy-optimized prefetching techniques

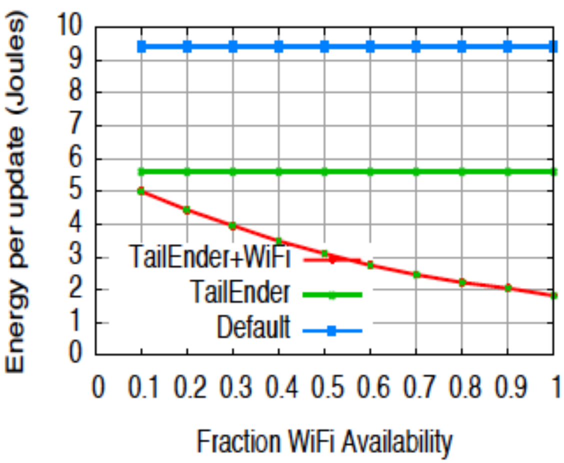


Figure 22: News feed. Average energy improvement when switching between WiFi and 3G networks.

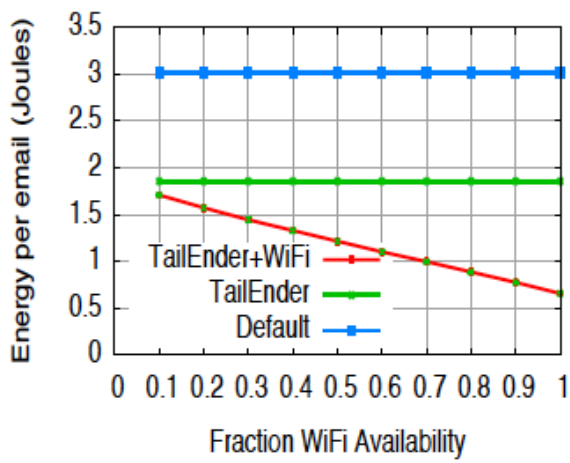


Figure 23: E-mail. Average energy improvement when switching between WiFi and 3G networks.

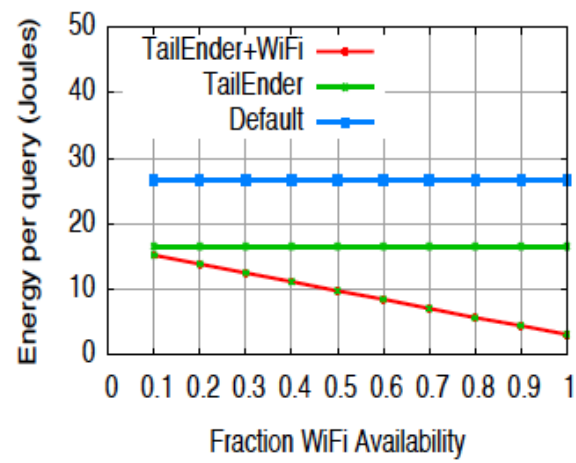


Figure 24: Web Search. Average energy improvement when switching between WiFi and 3G networks.

Energy Consumption Anatomy- IEEE 802.11

- Experiments and measurements on multiple commercial devices
  - Soekris net 4826-48 + Atheros 802.11a/b/g Mini-PCI card, configured to use the 802.11a PHY
  - Alix2d2 + Broadcom BCM4319 802.11b/g Mini-PCI card
  - Linksys WRT54GL + Broadcom BCM4320 802.11b/g Mini-PCI card
- Checking no interference (sniffers)
- Measuring energy consumption with high accuracy power meters
- Controlled traffic generation (mgen generates UDP packets)

A. Garcia Saavedra, P. Serrano, A. Banchs, G. Bianchi "Energy Consumption Anatomy of 802.11 Devices and Its Implication on Modeling and Design" in Proceedings of Co-NEXT 2012

Energy Consumption Anatomy IEEE 802.11

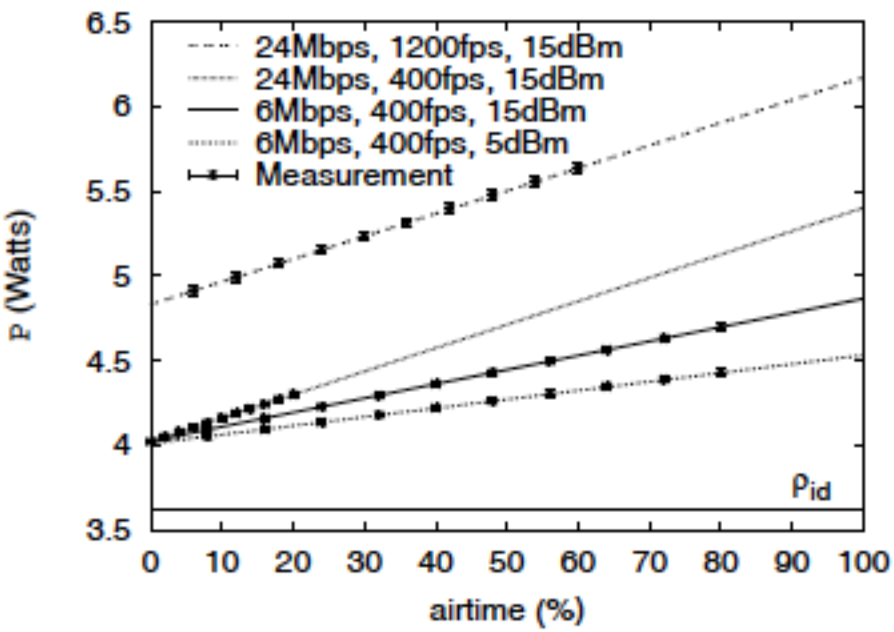
- Baseline energy consumption has been measured

Table 2: Soekris Baseline consumption profile

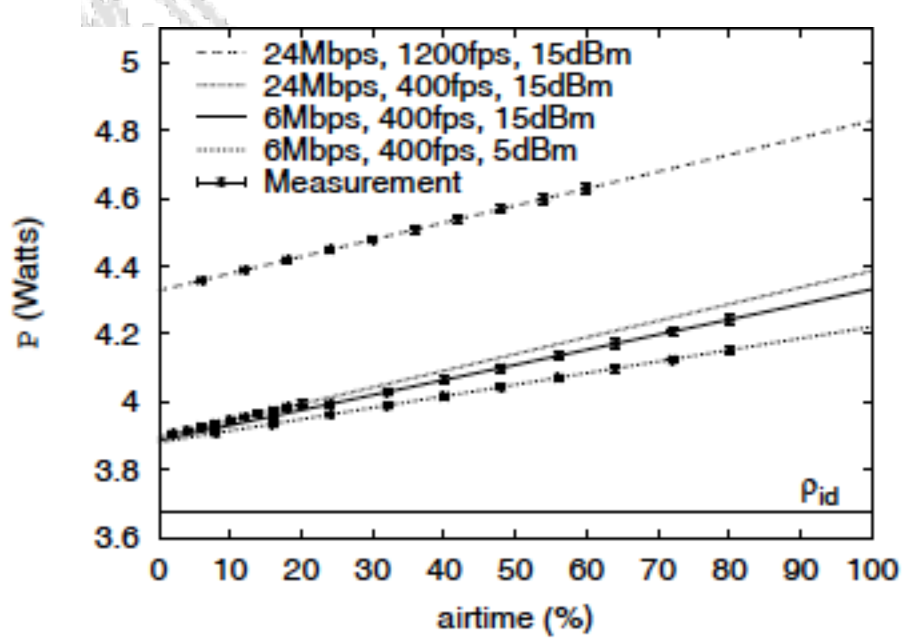
Config.	Description	Cons. (W)
w/o card	no NIC connected	$2.29 \pm 2.2\%$
WiFi off	NIC connected driver not loaded	$2.58 \pm 2.0\%$ (+0.29)
Idle (ρ_{id})	NIC activated+associated to AP no RX/TX besides beacons	$3.56 \pm 1.7\%$ (+0.98)

- Eenergy consumption of transmitting one packect without ACKs has been studied
- Impact on energy consumption of varying transmission power, packet length, type of modulation has been quantitatively studied

- Experimental results: Total power consumed by (unacknowledged) transmissions vs. airtime percentage



(a) Soekris



(b) Alix

Energy Consumption IEEE 802.11

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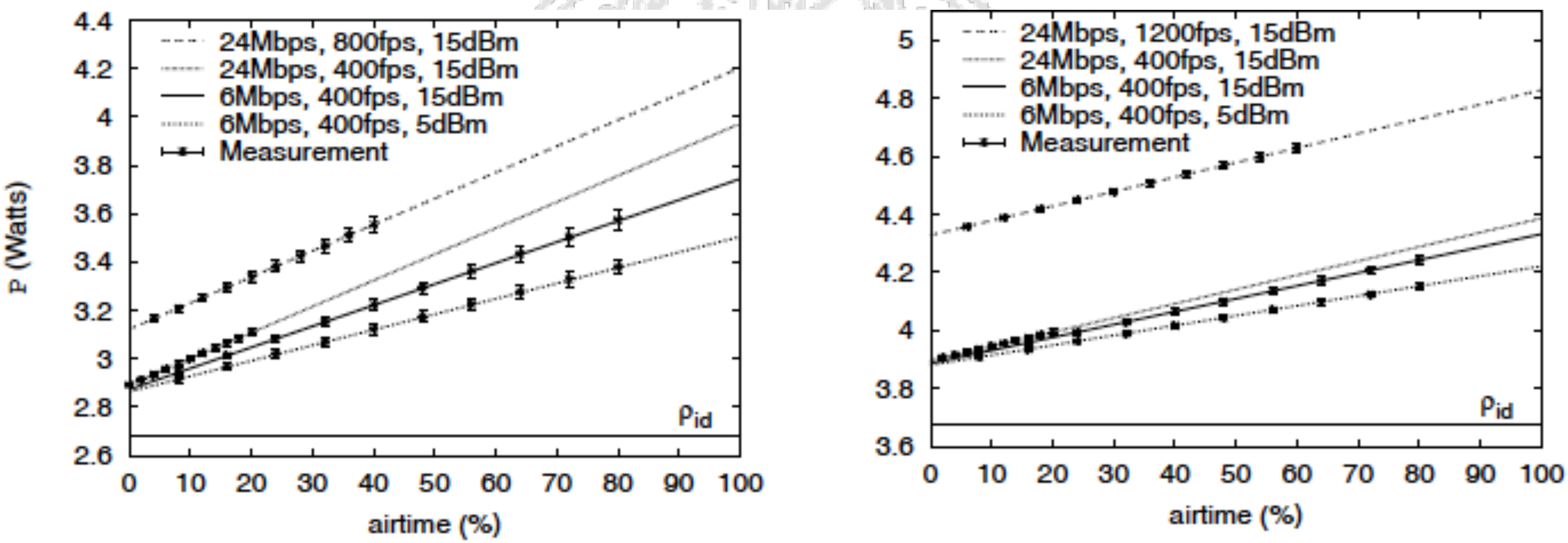


(c) Linksys (b) Alix

Energy Consumption IEEE 802.11

- Experimental results: Relationship between cross factor and traffic intensity

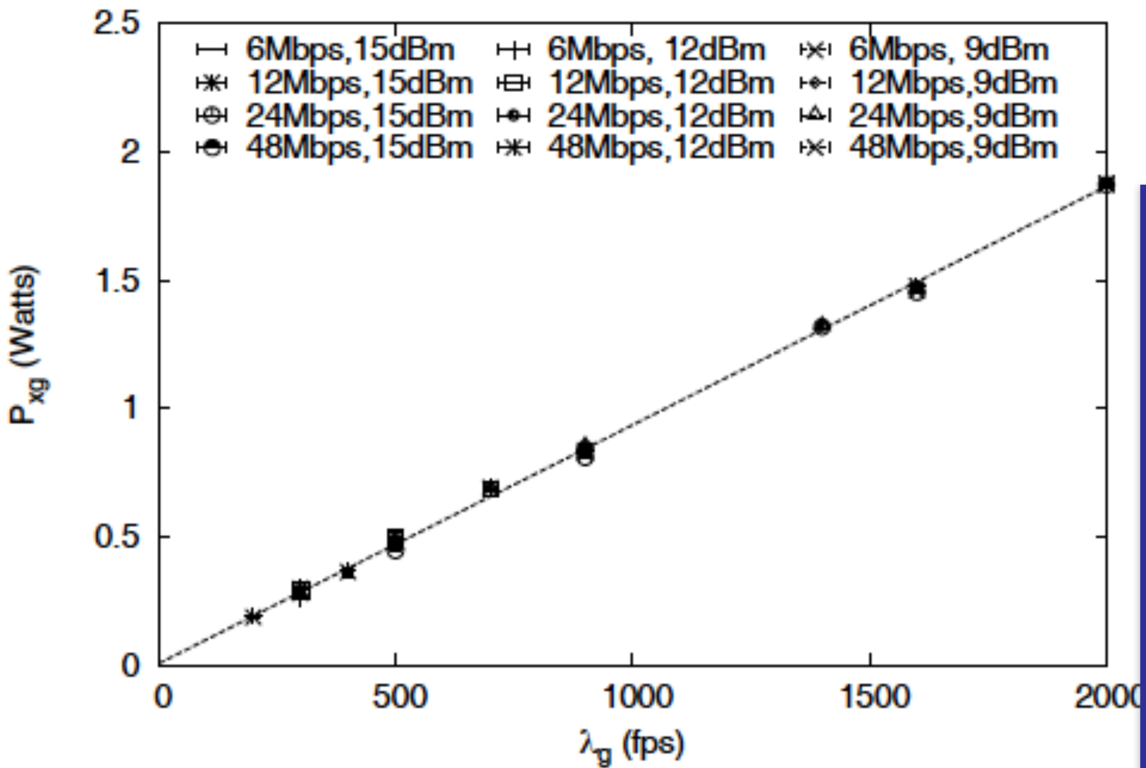


Figure 2: Relation between $P_{xg}(\lambda_g)$ and λ_g.

New energy model

$$\mathbf{P} = \rho_{id} + P_{tx} + P_{xg}(\lambda_g)$$

ρ_{id} is the platform specific baseline power consumption

P_{tx} is the power consumption Associated to transmission (depends on airtime, tx power Modulation)

$P_{xg}(\lambda g)$ is the new cross factor

Cross factor analysis

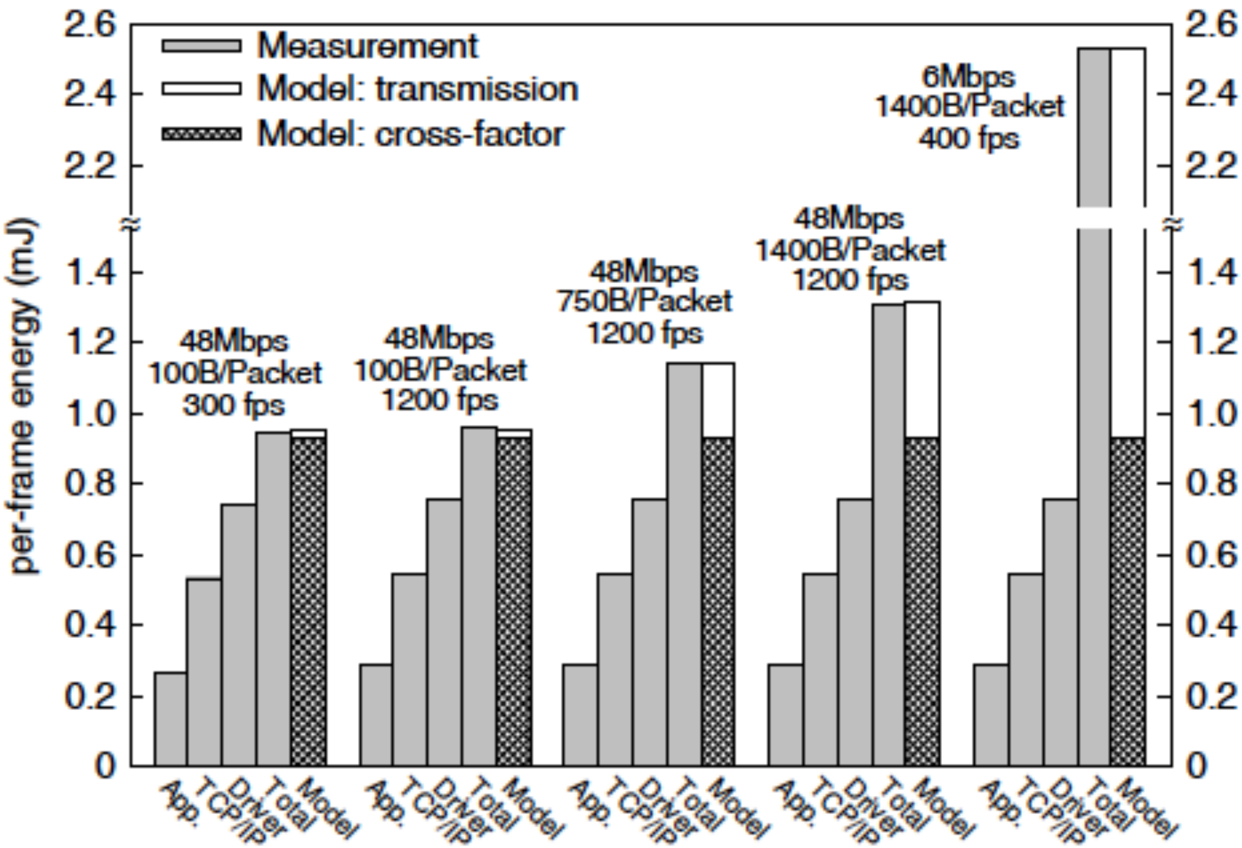


Figure 4: Per-frame energy cost in transmission.

New approaches are proposed for

- Packet relay selection
- Data compression
- Data transmission (back to back)
- Stack implementation

To offload or not to offload?

Number, type & OS	CPU	RAM
7×Samsung Galaxy S Plus (Android 2.3)	1.4 GHz Scorpion	512 MB
2×Samsung Galaxy S (Android 2.3)	1 GHz Cortex-A8	512 MB
1×Samsung Galaxy Note (Android 2.3)	1.4 GHz dual-core Cortex-A9	1 GB
1×Samsung Galaxy Nexus (Android 4.1)	1.2 GHz dual-core Cortex-A9	1 GB

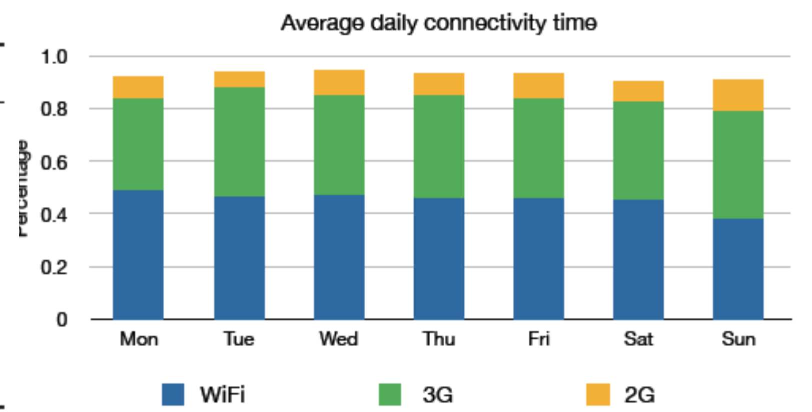
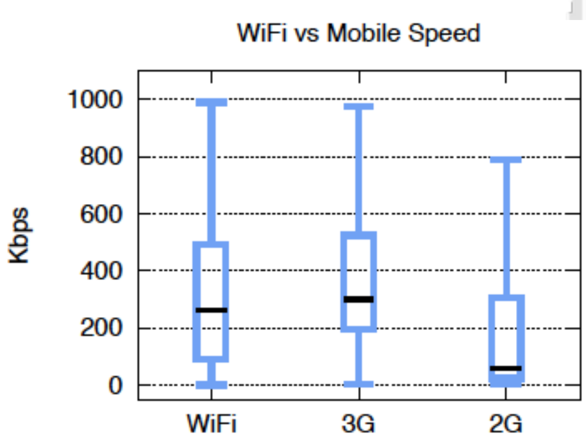
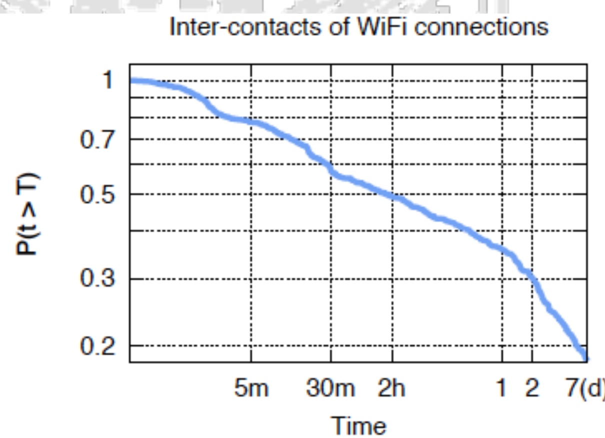


Fig. 1. Average daily connectivity percentage for various technologies.



Average (per user) daily upload speed. The graphics lude the minimum and maximum speed value as well he 25^{th}, 50^{th} and 75^{th} quartile.



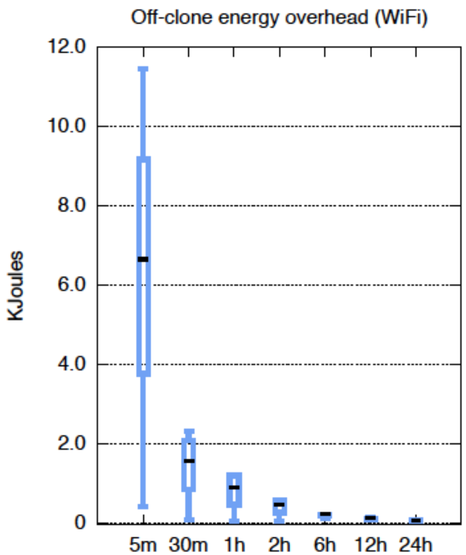
(b) Cumulative distribution of WiFi connection inter-contact times.

M.V. Barbera, S. Kosta, A. Mei, J. Stefa

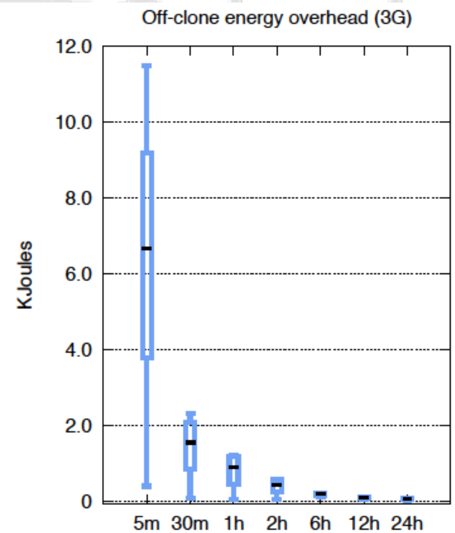
To offload or not to offload? The bandwidth and Energy costs of mobile cloud computing

IEEE INFOCOM 2013

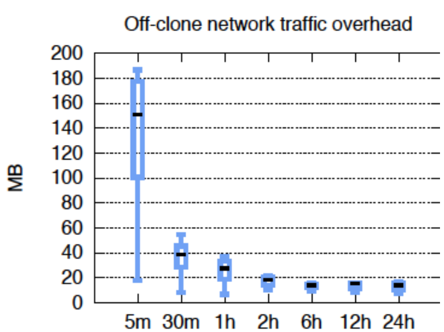
To offload or not to offload



(a) Off-clone energy overhead (WiFi) per day.



(c) Off-clone energy overhead (3G) per day.



(a) Average (per user) off-clone traffic overhead.

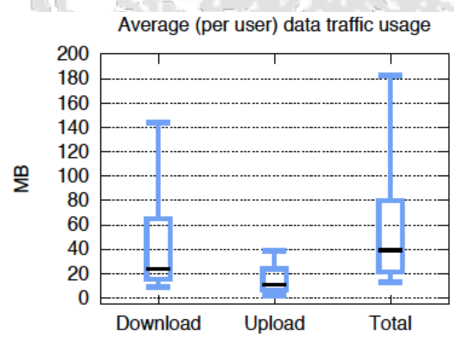


Fig. 4. Average (per user) data traffic sent/received per day.

Comparable energy performance when using WiFi or 3G (file diff computation dominates)

A high overhead is needed to maintain the clone over the cloud synch with the mobile application

Demos

Demos focusing on energy efficient solutions in different environments

- Energy harvesting demo
- Underwater sensor network demo