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Pervasive Sensing by Passive UHF Technology

the Electromagnetic Way to the Internet of Things

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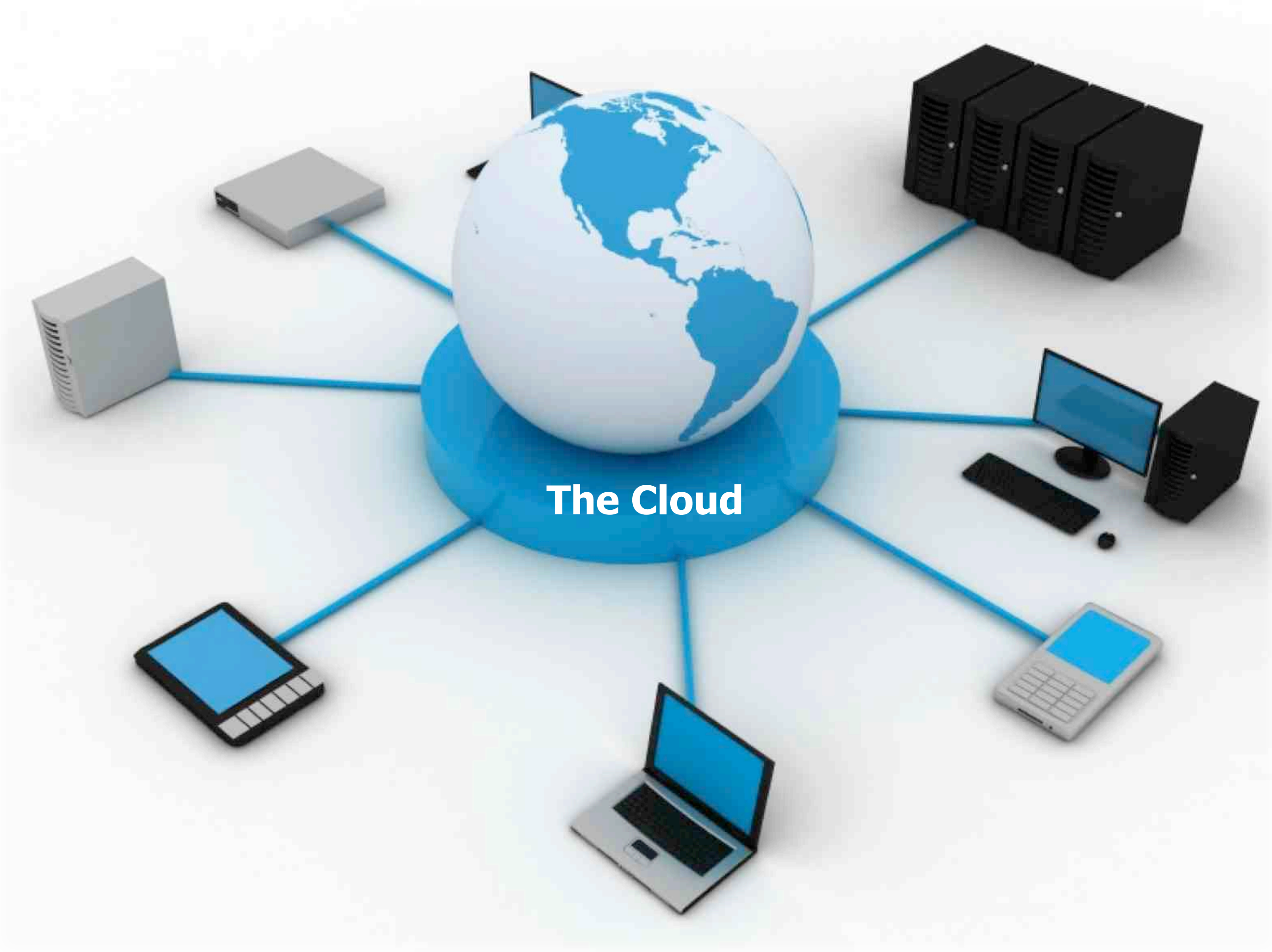
Internet Today



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Internet …. Tomorrow

Internet …. Tomorrow

Embodied Virtuality (Pervasive Computing)

The most profound technologies are those that disappear.
They weave themselves into the fabric of everyday life until they are indistinguishable from it.


(Siemens)

Uniquitous, Invisible Computing:
The process of drawing computers out of electronics shells

The virtuality of computer-readable data is **brought into the physical world.**

When almost every object contains a computer [..], obtaining information will be trivial

(M. Weiser (PARC), The Computer for the 21st Century, 1991)

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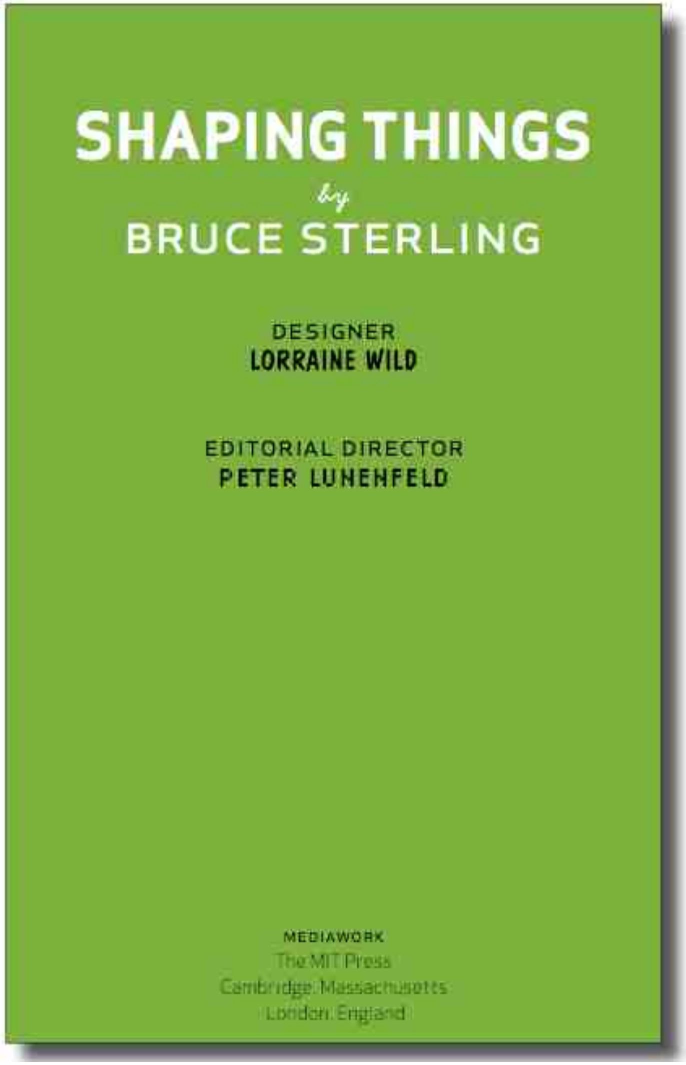
Spimes



SPIME=SPace + tiME

"Manufactured objects whose informational support is so extensive and rich that they are regarded as material instantiations of an immaterial system.

After the purchase, manufacture, and delivery, the **Spime continuously generates information through interactions** with the surrounding environment".

(B. Sterling, 2005)

Internet …. Tomorrow

Planetary Skin

A global "**nervous system**" that will integrate

- land-sensors
- sea-sensors
- air-sensors
- Space sensors

helping the public and private sectors make decisions to prevent and adapt to **climate change**.

(CISCO- NASA, 2009)

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Internet …. Tomorrow
A "Smarter Planet"

Measuring the World to change the paradigm from react to anticipate "

Computation and decision-support tools handling huge amount of data
- smarter Banking
- smarter Communications
- smarter Electronics
- smarter Government
- smarter Healthcare
- **…**

(IBM, 2011)

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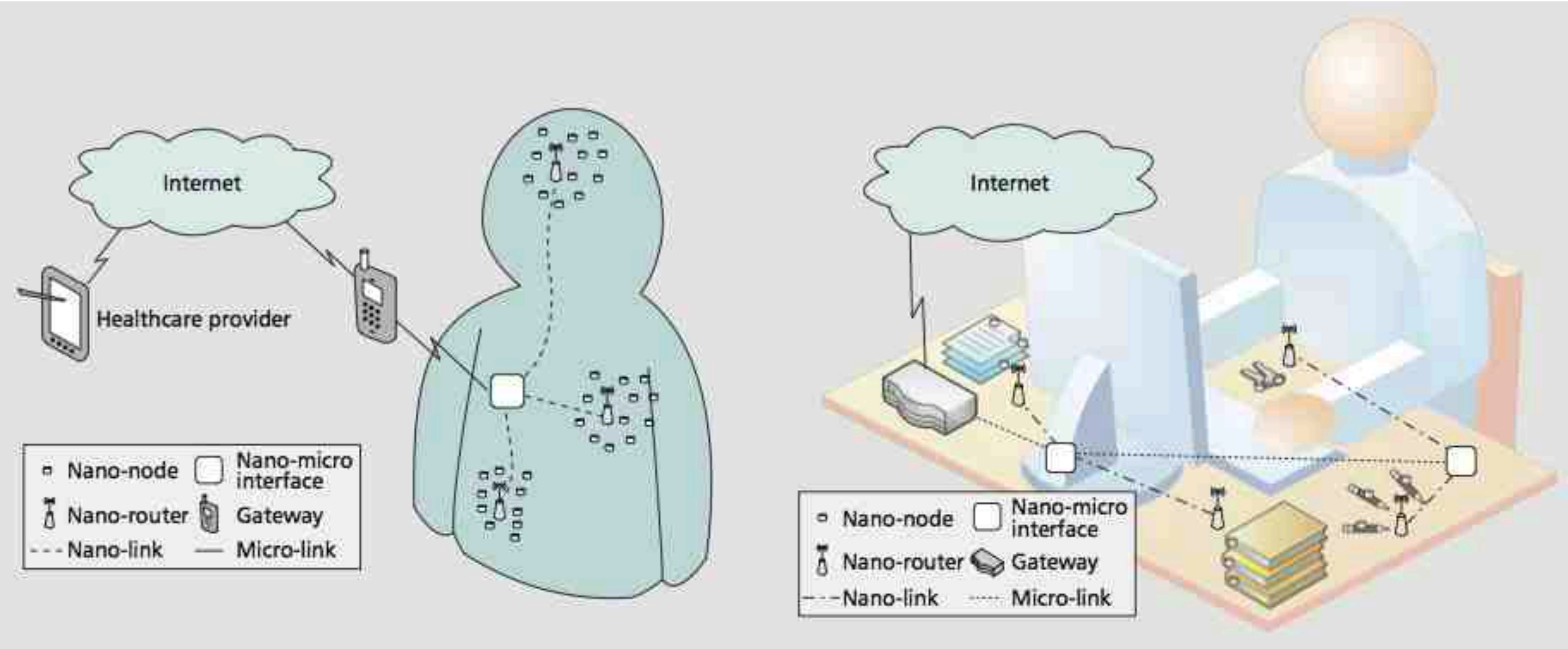
Internet .... Tomorrow

Interconnected NanoThings



Nanonetworks for healthcare **The interconnected office**

(Akyildiz, Jornet, 2010)

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Internet …. Tomorrow
the Swarm

Fig. 1: The swarm at the edge of the cloud [1].

(J. Rabaey. 2011)

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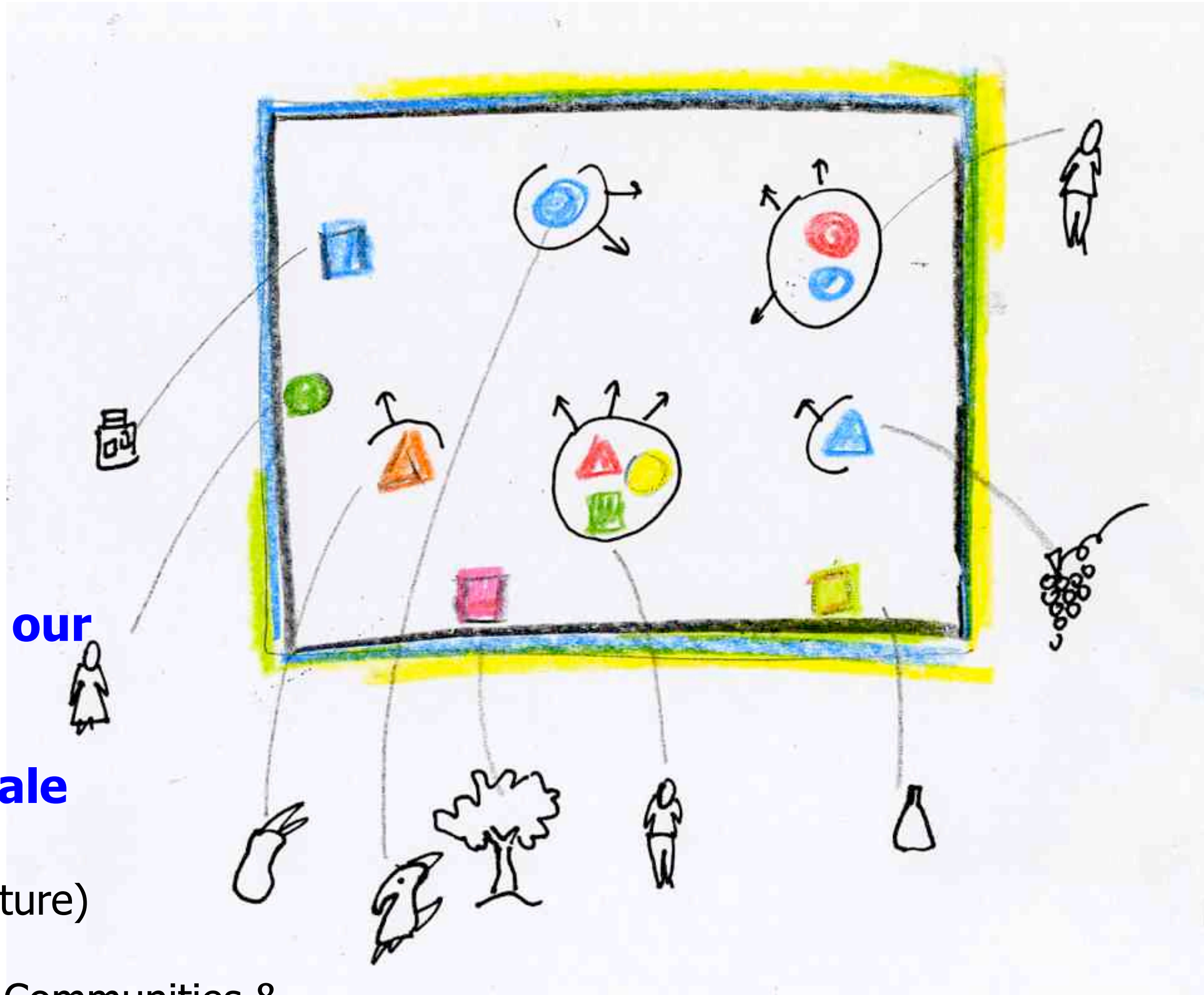
Internet of Things

Labelling,
Measuring,
Timing,

of made Things and Humans and their **mapping** into virtual environments



Augmented perception of our day life

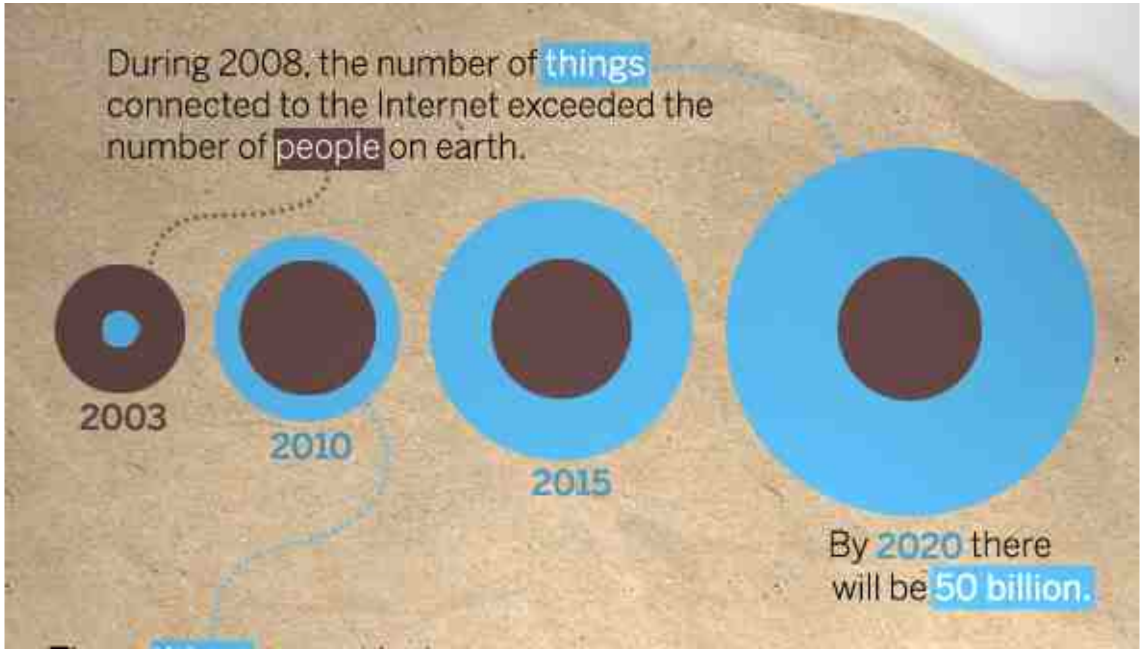
Data-support for large-scale decisions

- Environment (Precise Agriculture)
- E-Health
- Sustainable progress (Smart Communities & Smart-Cities)

Interconnected Smart Objects

2011: **3,9 Millions** in Italy

43% (automotive)
32% (logistics)
10% (webcams)
15% (others)



(CISCO)

Interconnected Smart Objects

One or more of the following features

- **Identification**
- **Localization**
- **Self-diagnostic**
- **Sensing**
- **Actuation (of remotely-given commands)**
- **Local Computing**

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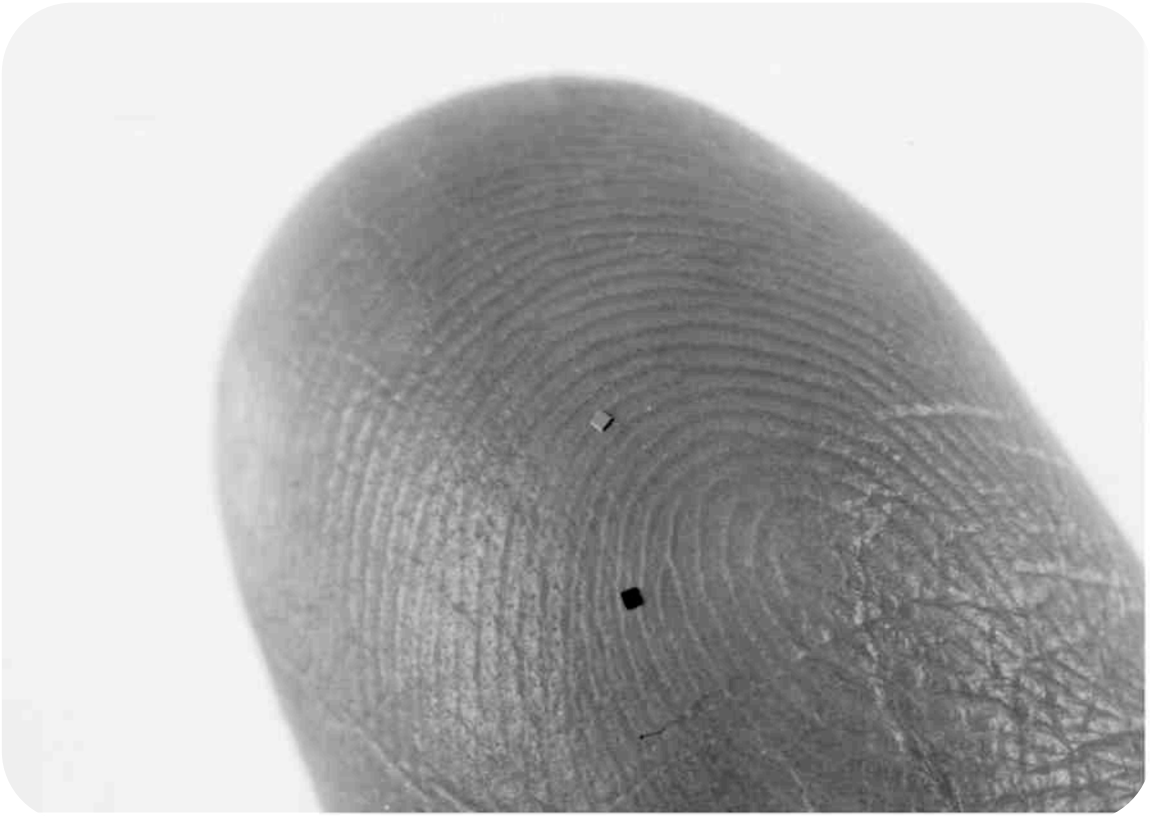
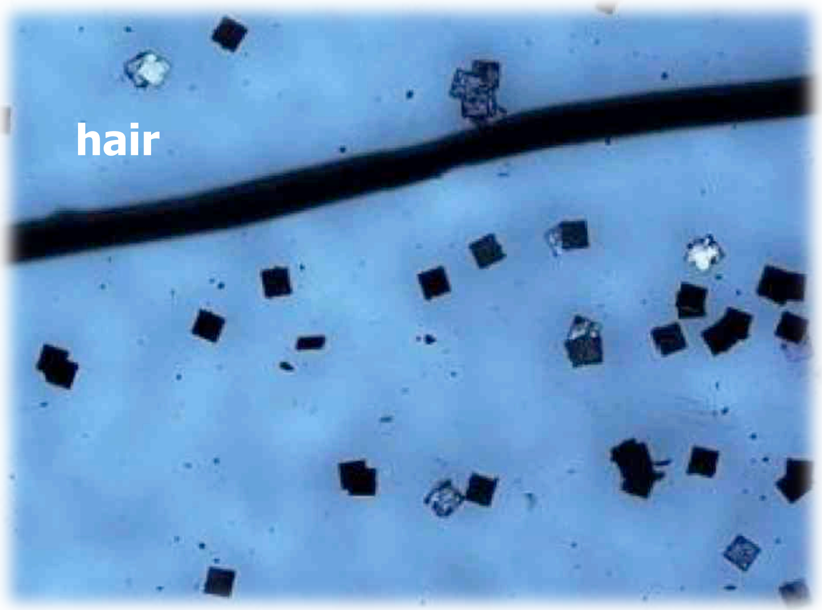
How Interconnecting Things ?

Microchip

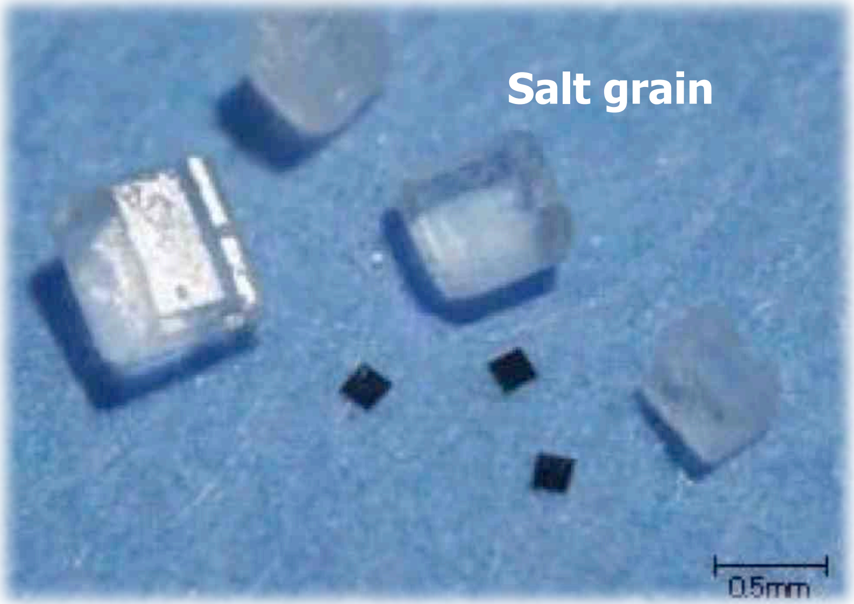


Memory + Radio



(Hitachi 2004)

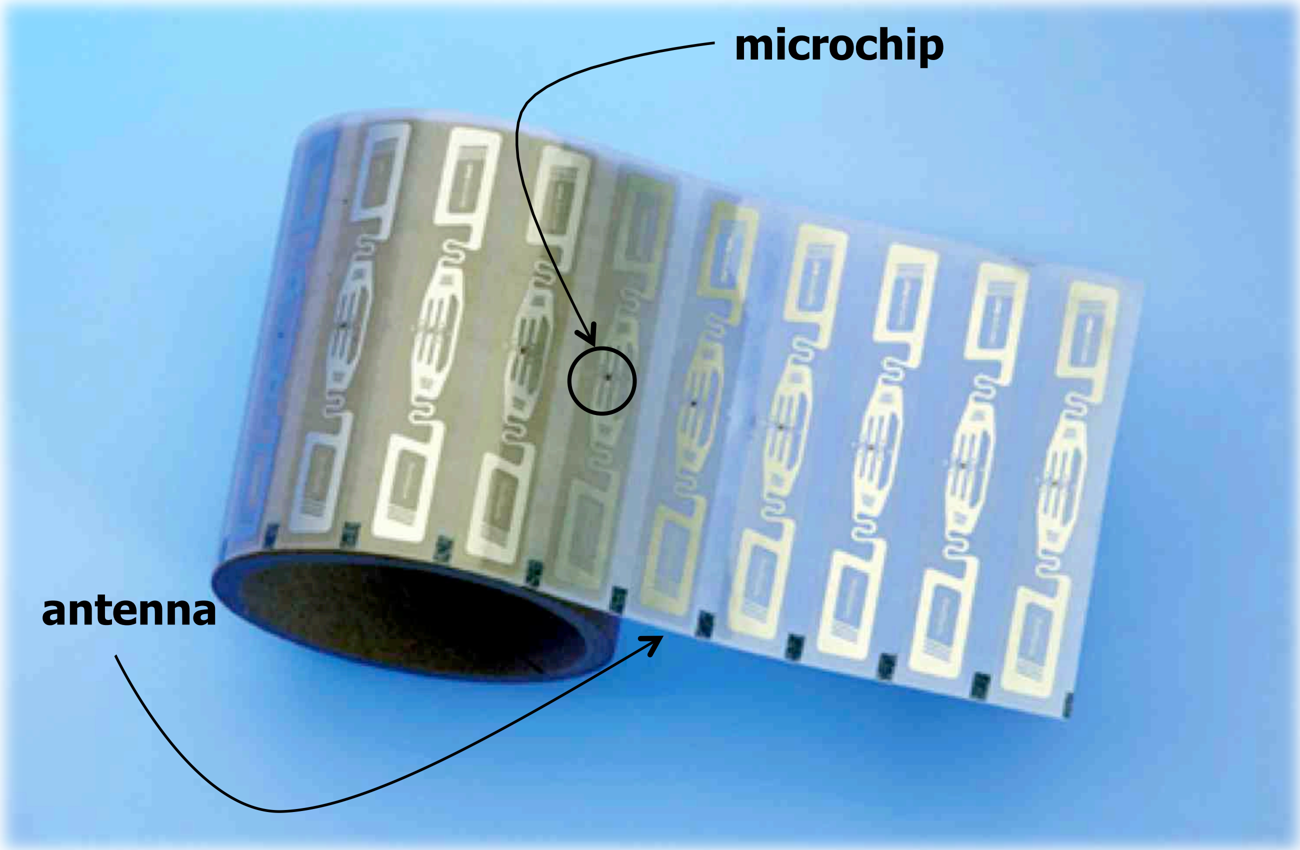
0,4 x 0,4 mm



(Hitachi 2012)

0,16 x 0,16 mm

The Radiofrequency Identification (RFID) Label



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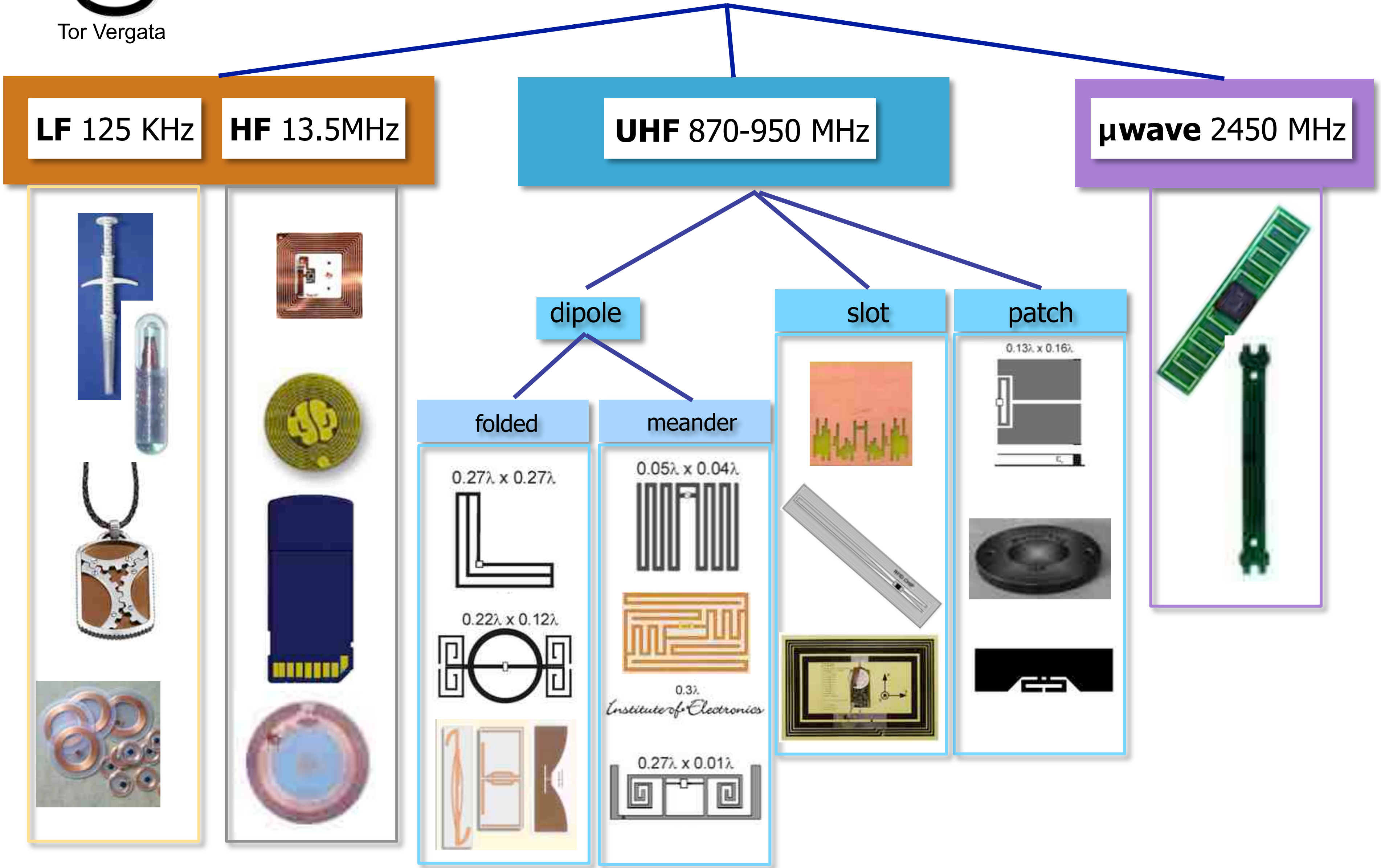
RFID Species



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.. Back to Waves ..

Sensitive Antennas !

RFID:

From visual to Electromagnetic labeling

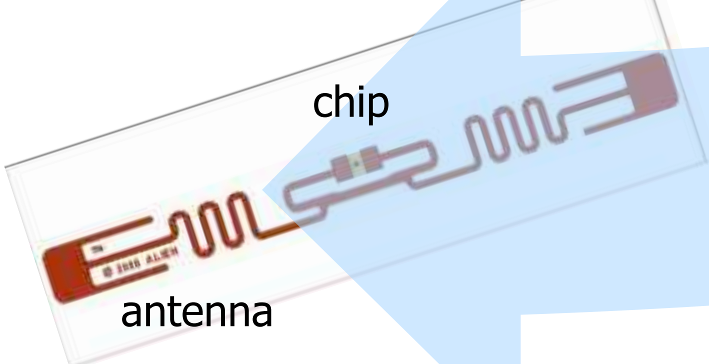
Printed Label

Direct and Visual access to data

Barcode

- Indirect access to data
- Binary coding
- Optical reading by laser scanner
- Reading range: a few cm

Electromagnetic tag
(Radio Frequency Identification RFId)



Electromagentic access to data

Electronic tag (Magnetic & Smart Cards)

- Data reading by electrical contact or magnetic induction
- Battery-less devices
- Binary coding

RadioFrequency Identification (RFID)

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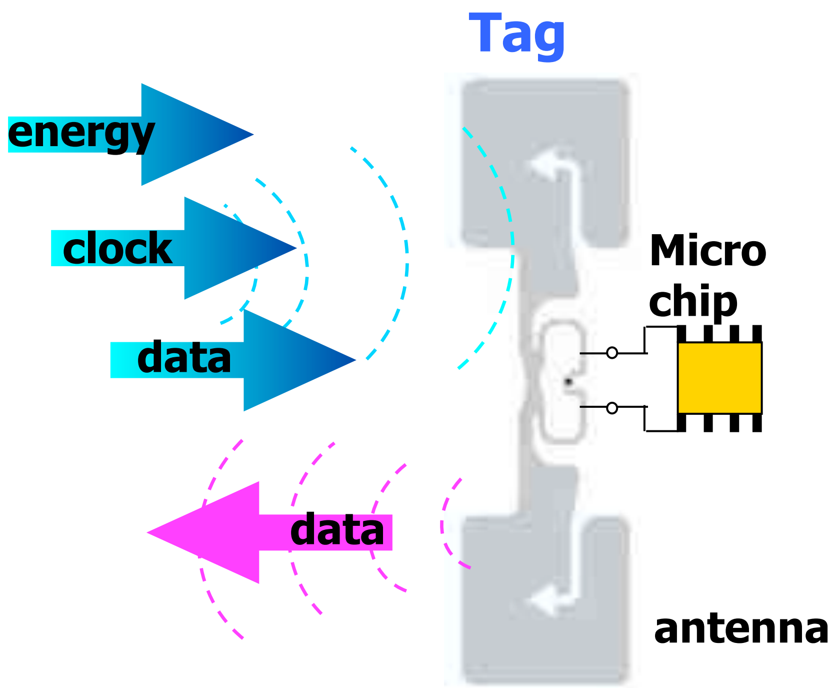
Reader



- PASSIVE devices: Tags do not contain a battery; the power is supplied by the reader.
- BACKSCATTERING: Tags reflect the reader's signal right back, modulating the query signal to transmit data.

- Back-scattered data modulation

- **Complex impedance matching**

$$Z_A = Z_C^*$$

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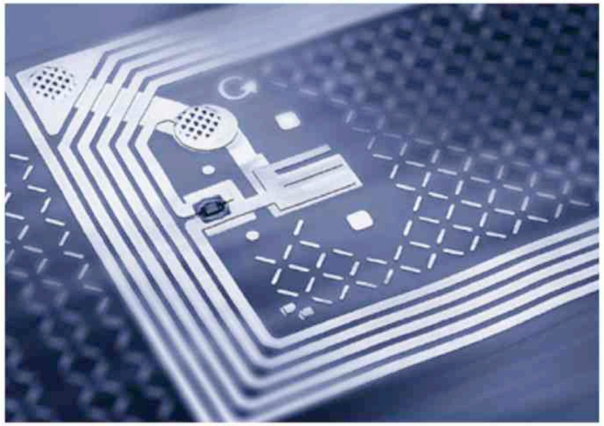

Labeling:
giving an ID to an object

Sensing:
giving a "state" to an object

Can we use a sensor-less tag (a bare antenna) to achieve physical information about the tagged object ?

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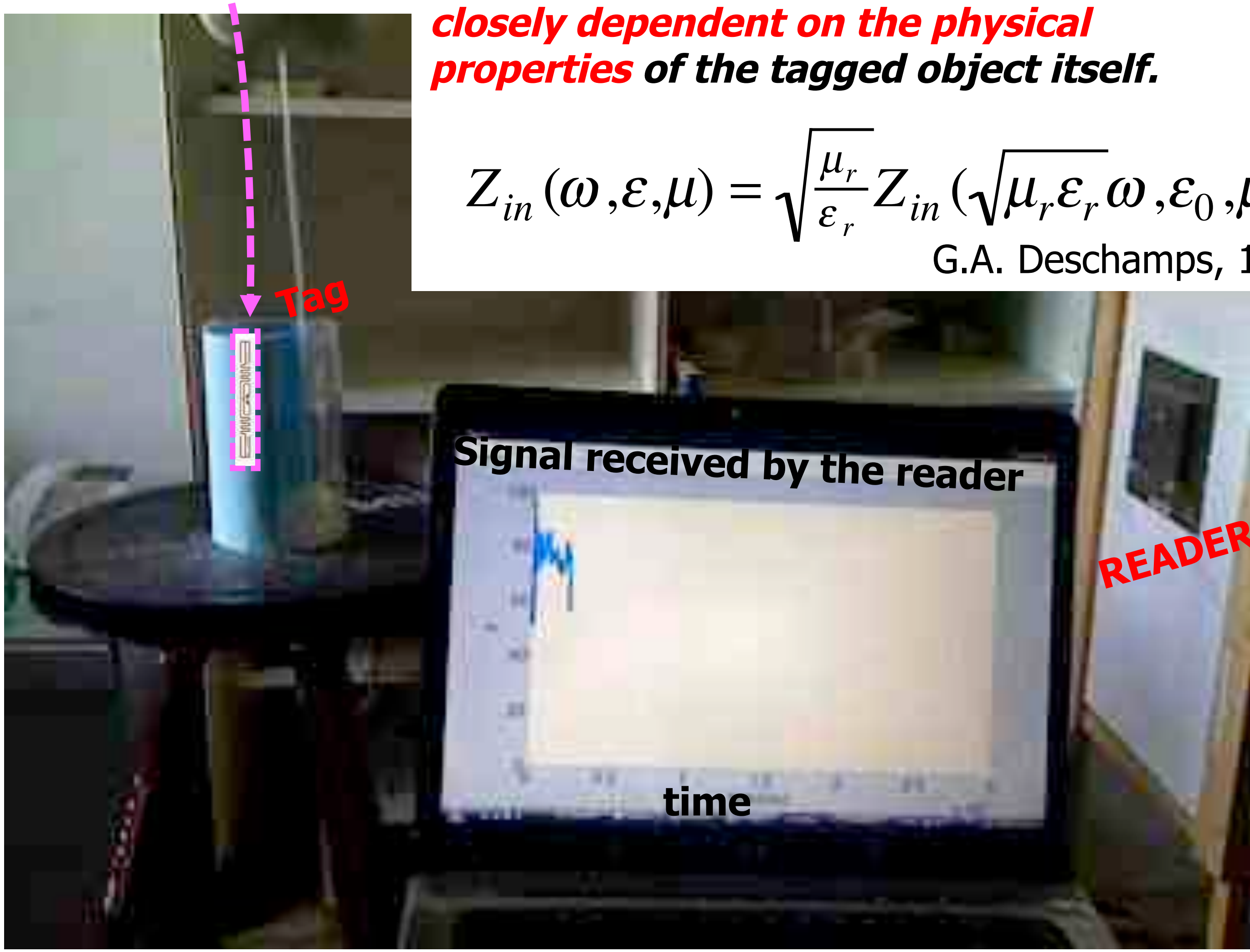
Sensing-Antenna Rationale

The electrical features of a passive RFID transponder placed on a target are closely dependent on the physical properties of the tagged object itself.

$$Z_{in}(\omega,\varepsilon,\mu) = \sqrt{\frac{\mu_r}{\varepsilon_r}}\, Z_{in}(\sqrt{\mu_r\varepsilon_r}\,\omega,\varepsilon_0,\mu_0)$$

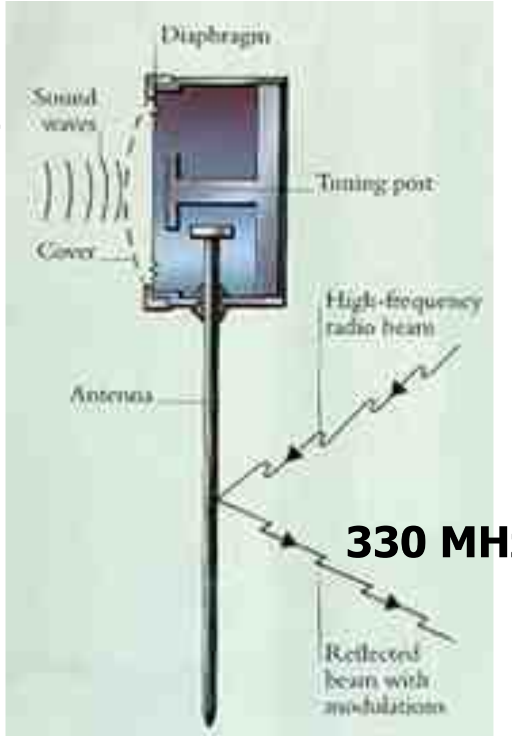
G.A. Deschamps, 1962



Wireless passive sensing devices ?
definitely not a new Idea

Лев Сергеевич Термен
(**Leon Theremin**)
1896, Saint Petersburg
1993, Moscov

The Thing, also known as the Great Seal bug, was one of the **first convert listen device** (or "bugs") to use passive electromagnetic induction to transmit an audio signal.



Issued: 1945
Discovered (CIA): 1952
Understood: some years later

Hidden in a **replica of the Great Seal of the United States** carved in wood, in 1945 Soviet school children presented the concealed bug to **U.S. Ambassador** as a "gesture of friendship" to the USSR's World War II ally. **It hung in the ambassador's residential office in Moscow**, and **intercepted confidential conversations** there during the first seven years of the **Cold War**, until **it was accidentally discovered in 1952**

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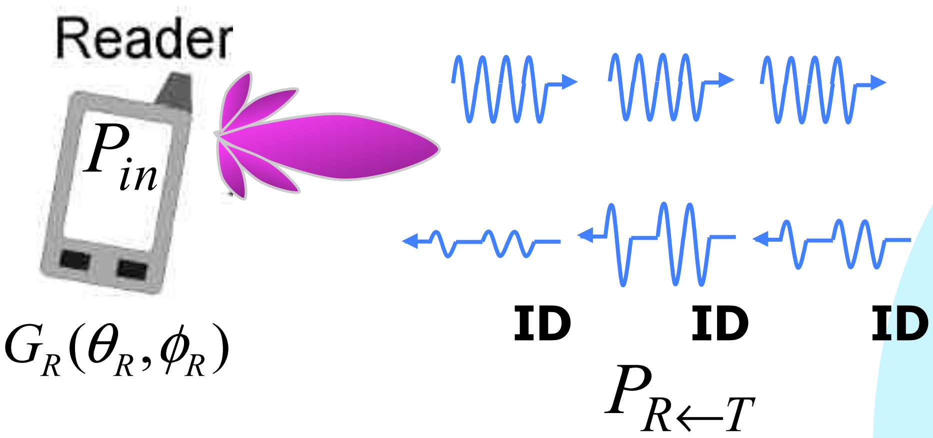
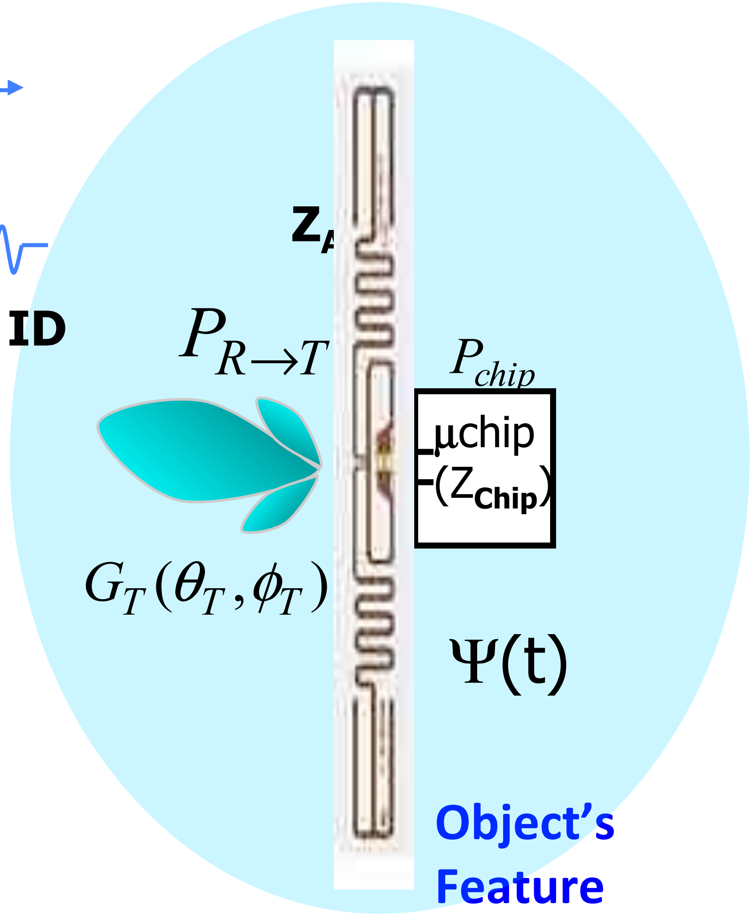
What the Reader may measure

- accessible data





Object's Feature
-Geometrical
-Chemical
-physical

1. Turn-on power:

$$P_{in}^{to}[\Psi]$$

The minimum input power through the reader's antenna, forcing the tag to respond

2. Backscattered power

$$P_{R\leftarrow T}[\Psi]$$

(RSSI - received signal strength indication)

Basic Sensing Equations
- free space

1. Turn-on (to) power: $P_{in}^{to} = P_{in} \quad when \quad P_{R\to T} = P_{chip}$

$$P_{in}^{to}[\Psi] = \left(\frac{\lambda_0}{4\pi d}\right)^{-2} \frac{P_{chip}}{G_R(\theta_R,\phi_R)\,\eta_p\,G_T(\theta_T,\phi_T)[\Psi(t)]\,\tau[\Psi(t)]}$$

Friis Eq.

$$\tau_T[\Psi] = \frac{4R_{chip}R_A[\Psi]}{|Z_{chip}+Z_A[\Psi]|^2}$$

Power transfer coefficient

2. Backscattered Power (←RSSI)

$$\frac{P_{R\leftarrow T}[\Psi]}{P_{in}} = \frac{1}{(4\pi)}\left(\frac{\lambda_0}{4\pi d^2}\right)^2 G_R^2(\theta_R,\phi_R)\,\eta_p^2\,\sigma_T(\theta_T,\phi_T)[\Psi(t)]$$

Radar Eq.

$$\sigma_T[\Psi] = \frac{\lambda_0^2}{4\pi} G_T^2[\Psi] \frac{R_A[\Psi]}{R_{chip}} \tau[\Psi]$$

RCS:
Radar Cross-section

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The RFID- Sensing Problem

$$P_{in}^{to}(\Psi, d, \theta_{R,T}, \phi_{R,T}, environment)$$

$$P_{R\leftarrow T}(\Psi, d, \theta_{R,T}, \phi_{R,T}, environment)$$

measurement ↑ $P_{R\leftarrow T}$

Reader-tag position ↑ d

?

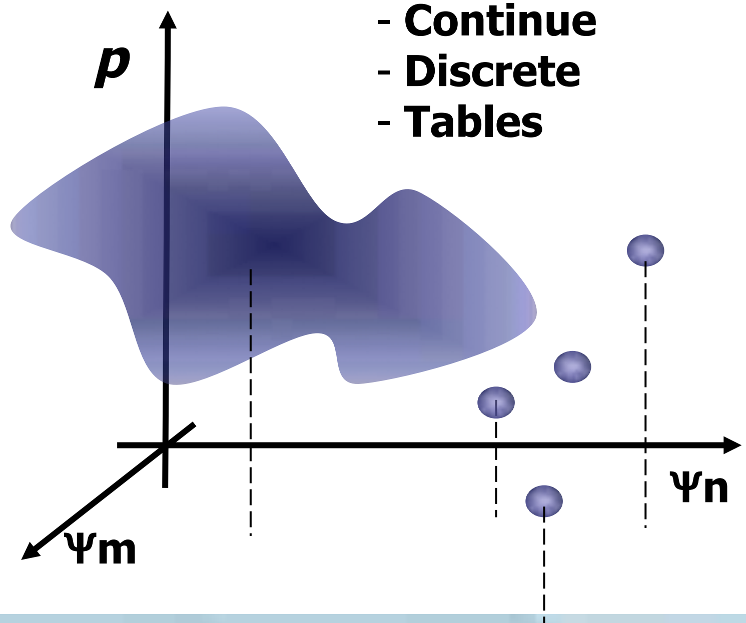
$$\Delta\Psi(t)$$

Unknown

Definition and Shaping of
Data Inversion (Calibration) Curves

$$p(P_{R\leftarrow T}, P_{in}^{to}) \leftrightarrow \Psi$$

- **Multidimensional**
- **Continue**
- **Discrete**
- **Tables**



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S-Tags: Electromagnetics Challenges

Sensing has to be mastered, not only discovered and verified as side effect

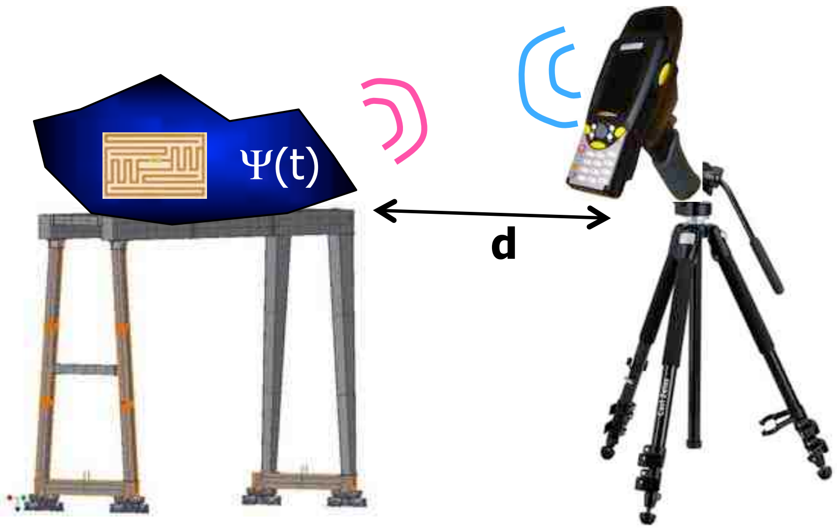
- The antenna boundary conditions have to be intended as **time-dependent**.
- The geometrical design requires to predict the **antenna response for any state of the process** under observation
- This is similar to the **design of broad-band antennas** wherein frequency is replaced by the state of the process
- The antenna's **geometry** itself my by subjected to **changes** during the process' evolution
- Optimization may be hence time-consuming and involving **multiphysics background**

On the Ways Things are sensed

Sensing Modes

Stationary sensing

the reader-tag mutual position remains fixed during the continuous interrogation



Inversion curve (backscattering)

$$p_S(\Psi) \equiv \frac{P_{R\leftarrow T}(\Psi)}{P_{R\leftarrow T}(\Psi_0)} \Leftrightarrow \Psi$$

$$= \frac{G_T(\theta',\phi')[\Psi]}{G_T(\theta',\phi')[\Psi_0]} \left(\frac{R_A[\Psi]}{R_A[\Psi_0]} \right)^2 \frac{|Z_{chip} + Z_A[\Psi_0]|^2}{|Z_{chip} + Z_A[\Psi]|^2}$$

Inversion curve (turn-on power)

$$p_{to} = \frac{P^{to}(\Psi)}{P^{to}(\Psi_0)} = \frac{G_T(\theta',\phi')[\Psi_0] \cdot \tau(\Psi_0)}{G_T(\theta',\phi')[\Psi] \cdot \tau(\Psi)}$$

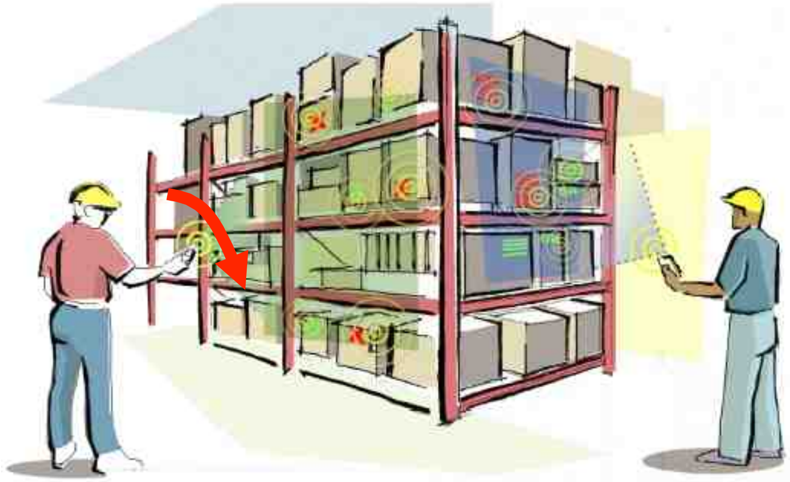
Variation of the Object ⟺

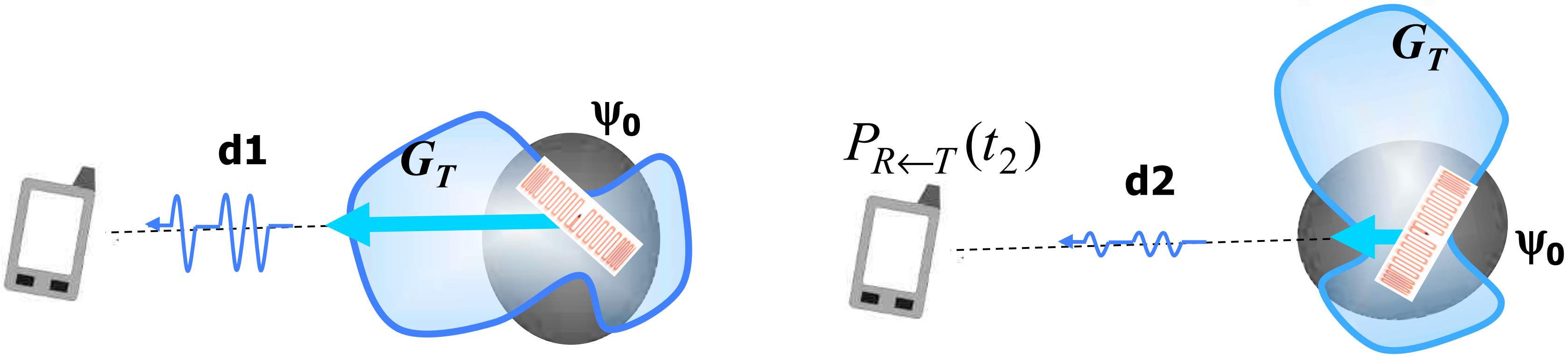
- Variation of gain
- Variation of impedance

Sensing Modes

Non-Stationary sensing

- the position and orientation of reader and tag is unknown or may be changed in successive measurements (manual sweep);
- the surrounding environment has been somehow modified;



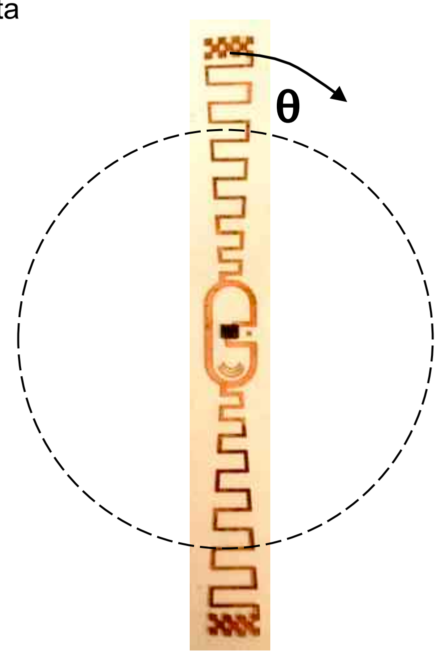


First interrogation ($t=t_1$)

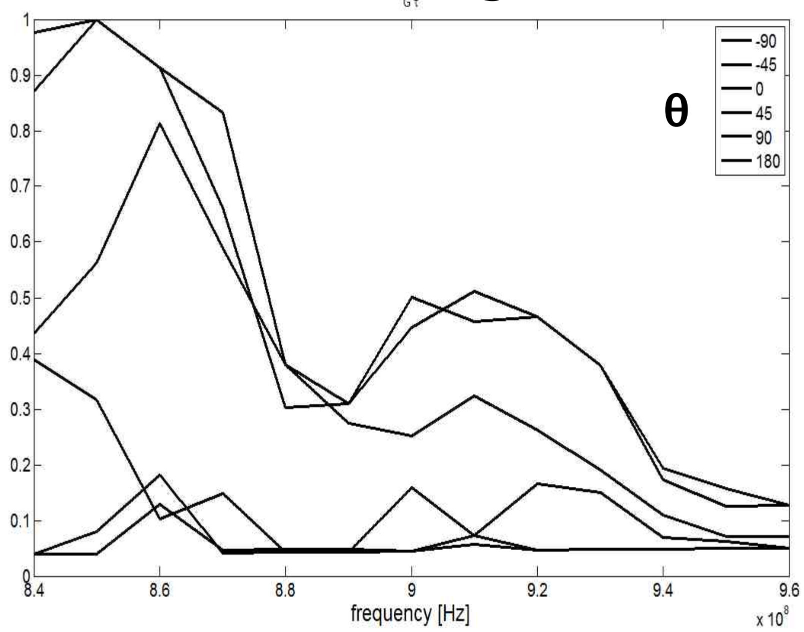
Second interrogation ($t=t_2$)

Sensing Modes

Non-Stationary sensing



Realized gain



Vertical SCAN ⇨ High Indetermination over θ

<u>Additional data</u> are required to overcome uncertainty and achieve a unique inversion curve ➔ need of an invariant

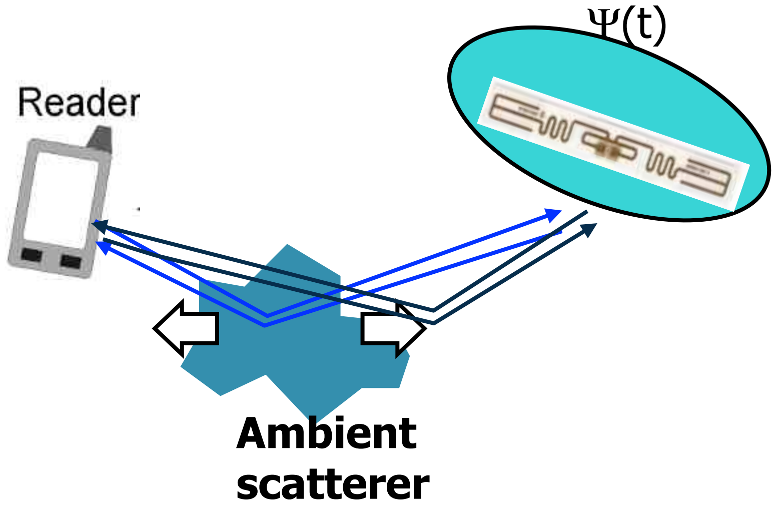
- ➔ **single chip (port) tag, two measures**
- ➔ **multi-chip (port) tags**

Non-Stationary sensing

Analog Identifier

Measurement of the tag backscattering at turn-on $(P_{R \to T} = P_{chip})$

$$F[\Psi] = \frac{P_{chip}}{\sqrt{P_{R \leftarrow T} \cdot P_{in}^{to}}} = \frac{2R_C}{|Z_{chip} + Z_A[\Psi]|}$$



Analog identifier

- **No dependence on orientation**
- **No dependence on distance**
- **No dependence on the environment** (the even complex link attenuation is the same for direct and reverse path)

Variation of the Object ⟷ **Variation of impedance**

G. Marrocco, F. Amato, "**Self-sensing passive RFID: From theory to tag design and experimentation**", European Microwave Conference EUMC 2009, pp.1 -4, Sept. 29 2009-Oct. 1 2009

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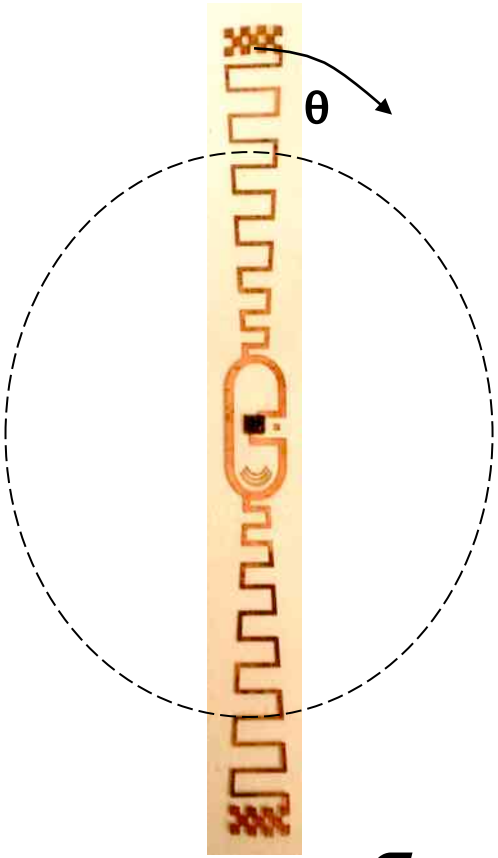
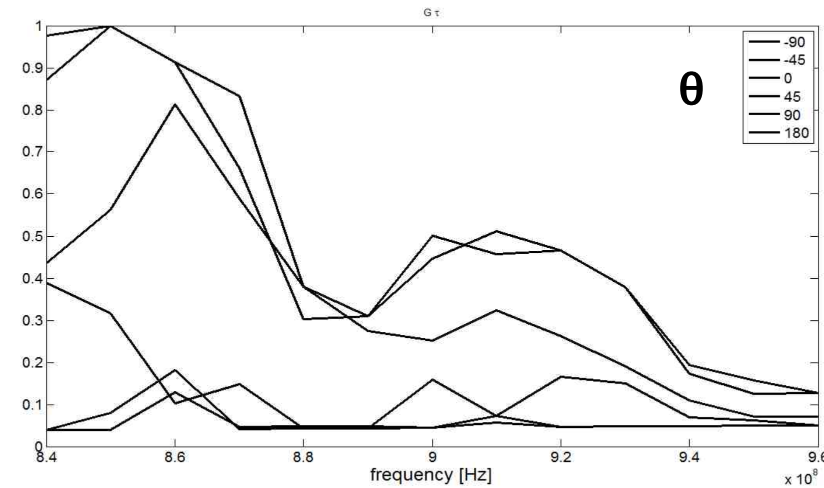
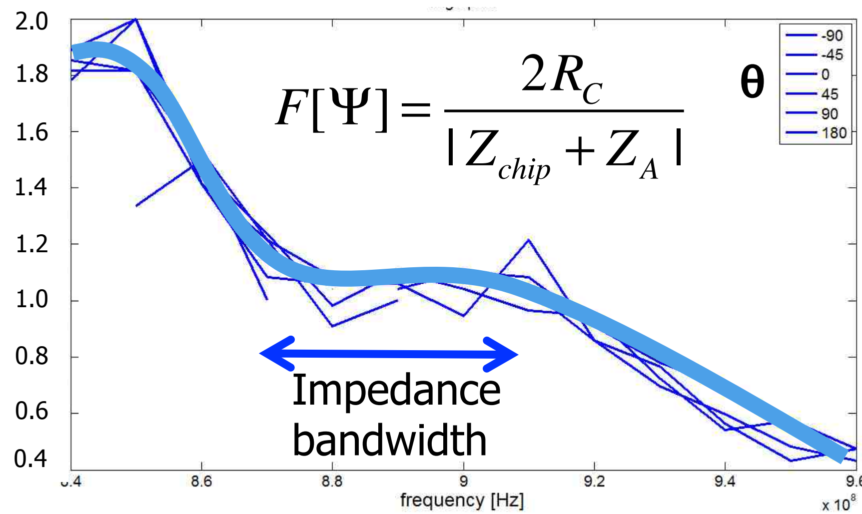
Analog Identifier



Realized gain



Analog Identifier



$$F[\Psi] = \frac{2R_C}{|Z_{chip} + Z_A|}$$

$$\tau = \frac{R_A}{R_C} AID^2$$

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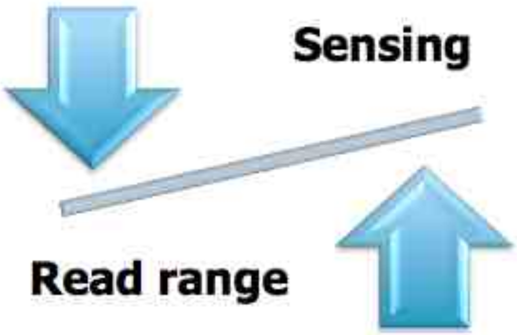
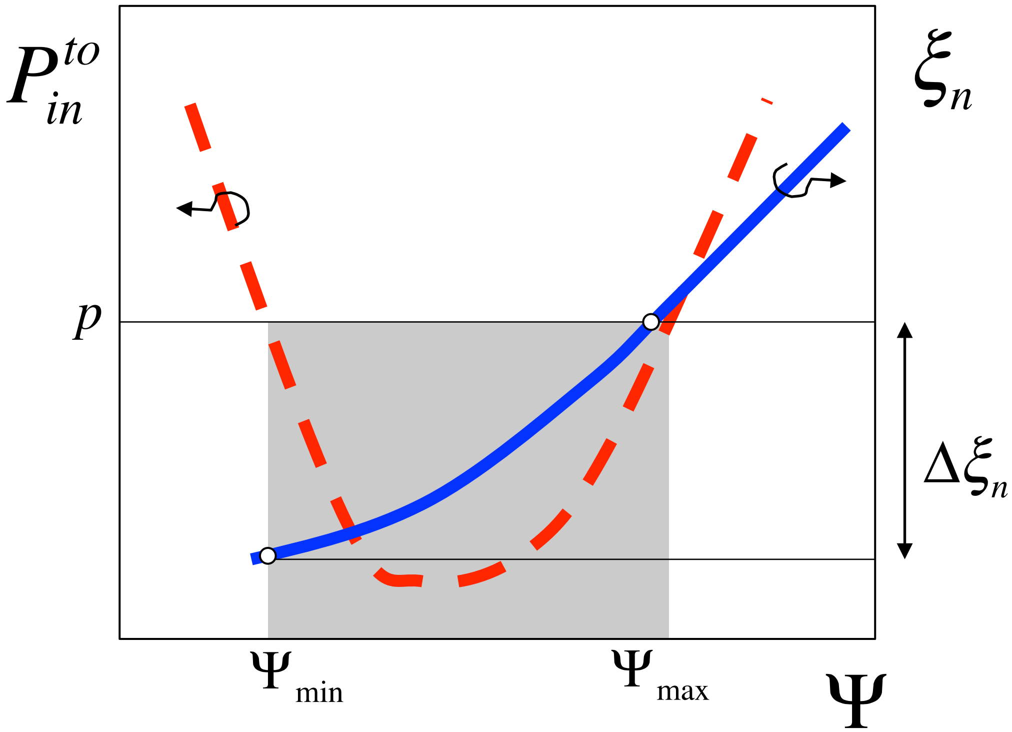
Sensing vs.Communication

Sensing is often obtained at the expenses of read-distance degradation





1. Communication with the allowed power

$$P_{in}^{to}[\Psi] \le p \qquad \Psi \in R$$

2. Dynamic range of the sensing indicator

$$\Delta\xi = |\xi[\Psi_{max}] - \xi[\Psi_{min}]|_{dB} > R$$

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Sensing and Communication

A Chart

A possible parametrization:

read distance ←→ τ

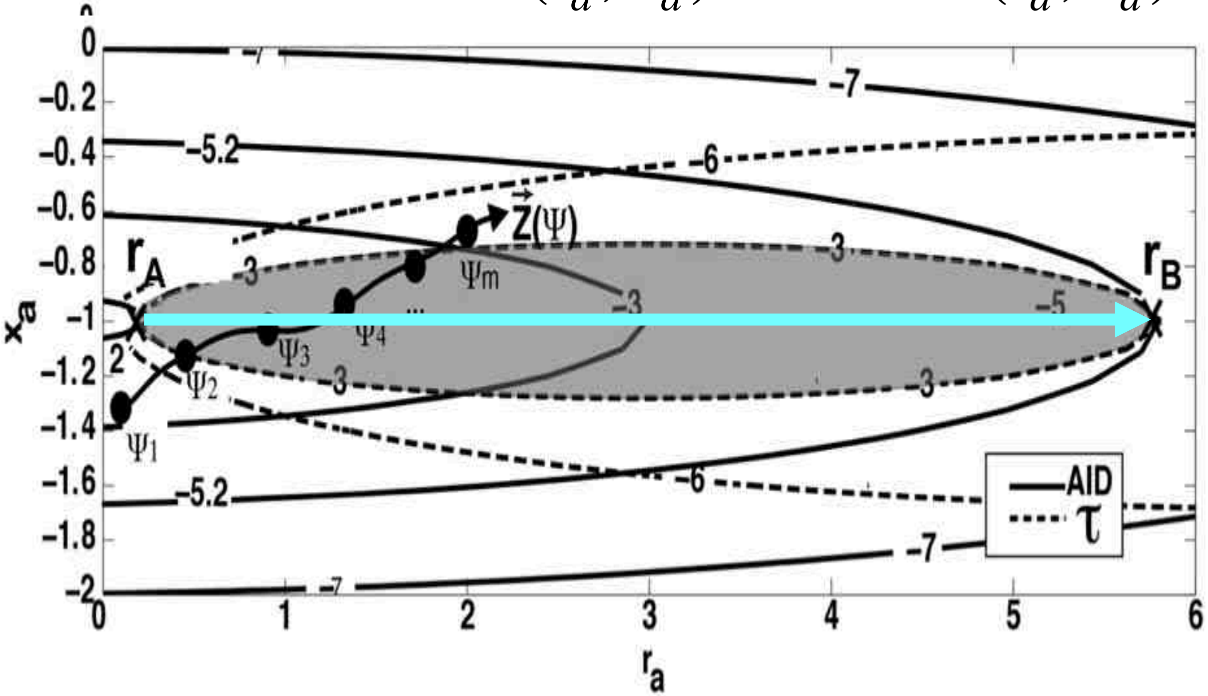
sensing ←→ **AID**

Any process in evolution involving a change of the Antenna impedance can be **traced** onto the chart

$$r_a = \frac{R_a}{R_{chip}} \quad x_a = \frac{X_a}{X_{chip}}$$

$$Q = \frac{|X_{chip}|}{R_{chip}}$$

$\tau(r_a, x_a) \qquad AID(r_a, x_a)$



$$\vec{Z}(\Psi) = r_a(\Psi)\hat{i} + x_a(\Psi)\hat{j} \quad \in R^2$$

$f \leftrightarrow \Psi$

"Sensing" Smith Chart

C. Occhiuzzi, G. Marrocco, **"Constrained-Design of Passive UHF RFID Sensor Antennas",** IEEE TAP, under review

Optimization by the **Alternate Projection Method**

Human Body
- Motion
- Breath
- Neuropathologies
- Stress
- Edema
- Stenosis

Environment & Things
- Humidity
- Temperature
- Ammonia
- Deformations
- Cracks

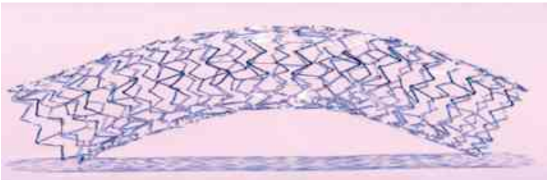
Technology
- Shape Memory Alloys
- Carbon Nanotubes
- Hygroscopic Polymer
- Textile & Elastic Substrates
- Inertial Switches

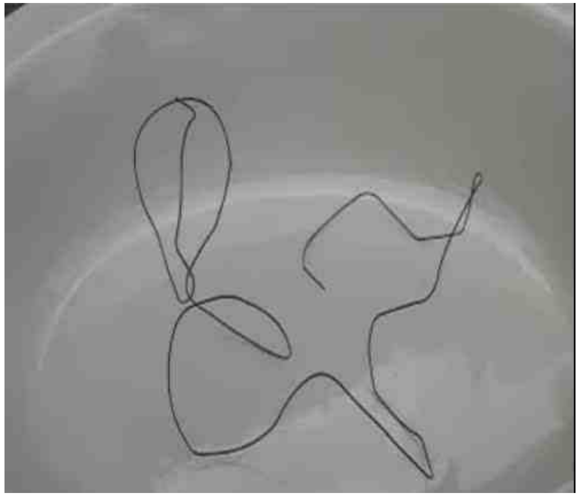
- Antenna Design
- Data Processing

Sensing Temperature thresholds

Shape Memory Alloy

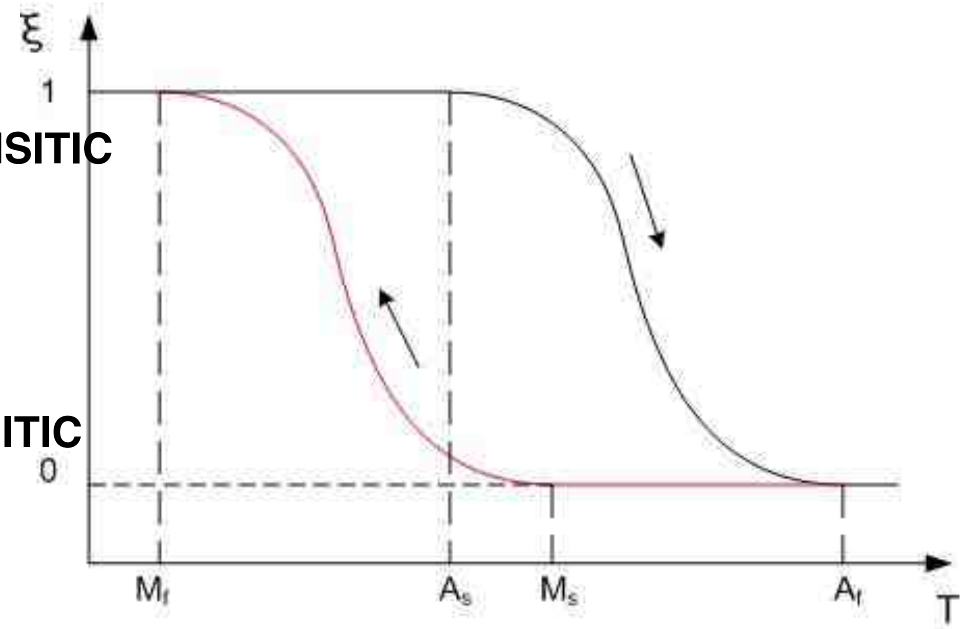
A Shape memory alloy is an alloy that "**remembers**" its original forged shape: after being deformed, it returns to that shape, if it is put in a hot environment





MARTENSITIC PHASE

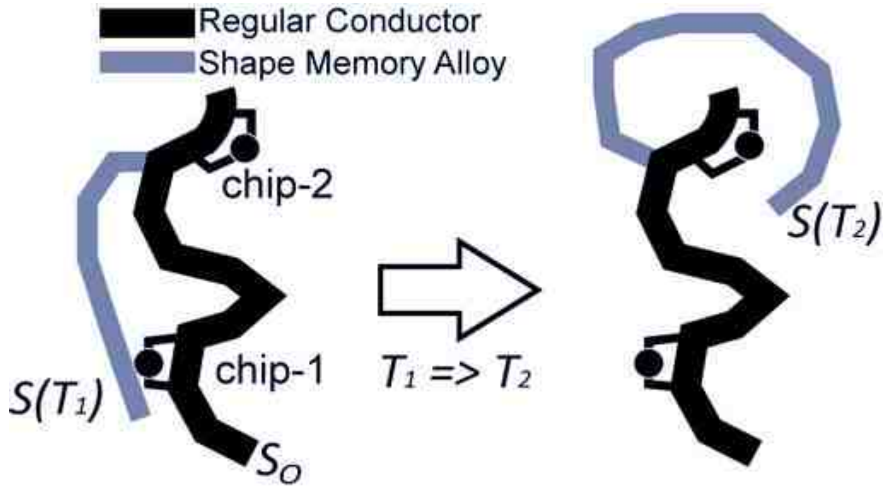
AUSTENITIC PHASE



Dynamic Antennas

*Antenna which senses the change of the object (or of the environment) through the variation of its **shape***

- *temperature*
- *strain*



S_0: parameter-independent Shape

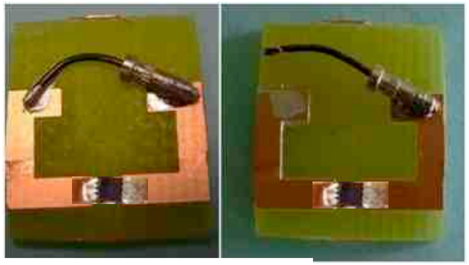
S(T): parameter-dependent Shape

S. Caizzone, C. Occhiuzzi, G. Marrocco, "**Temperature Sensing by Multi-Chip RFID Antenna Integrating Shape-Memory Alloys**", *IEEE Trans. Antennas. Propagat.*, 2011

Temperature threshold

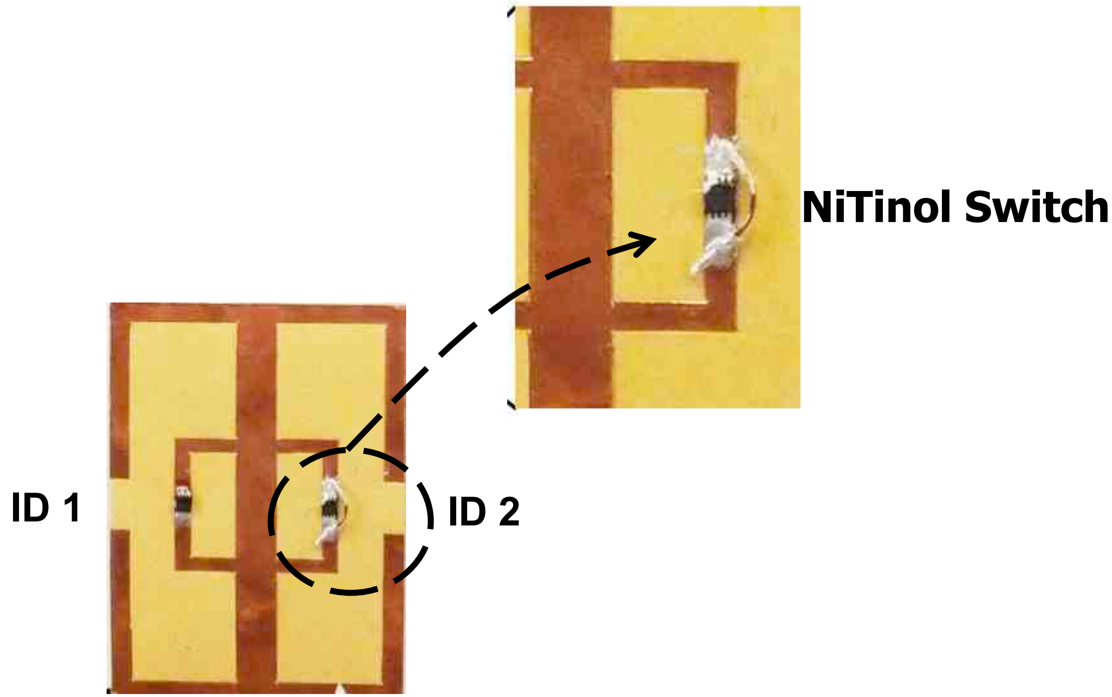
Nitinol Thermal Switches

Short c. **Open .c.**



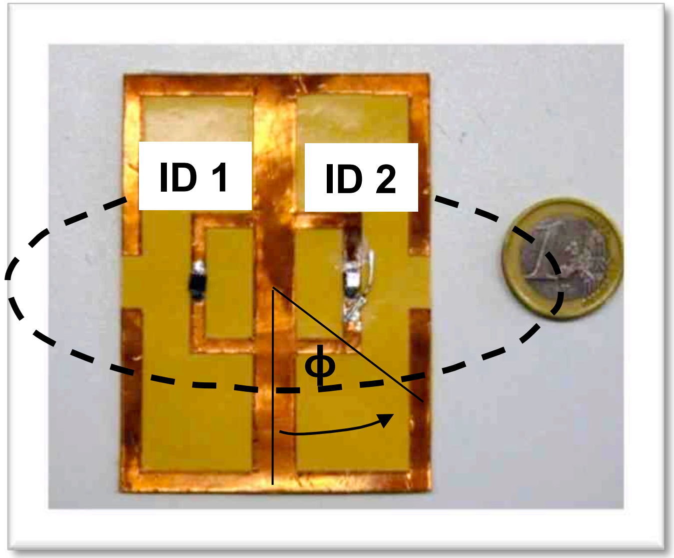
T<Ta ➔ ID.1

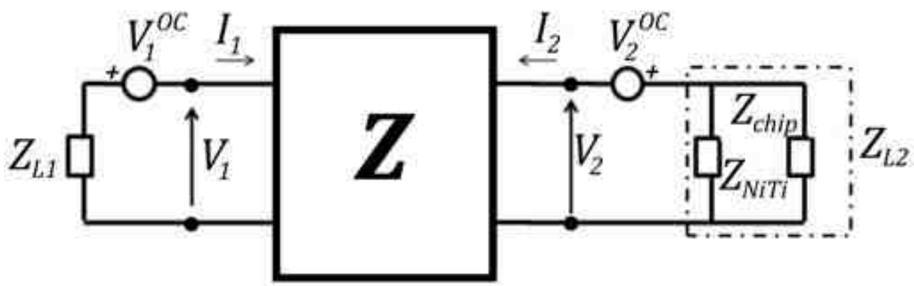
T>Ta ➔ ID.1 + ID.2

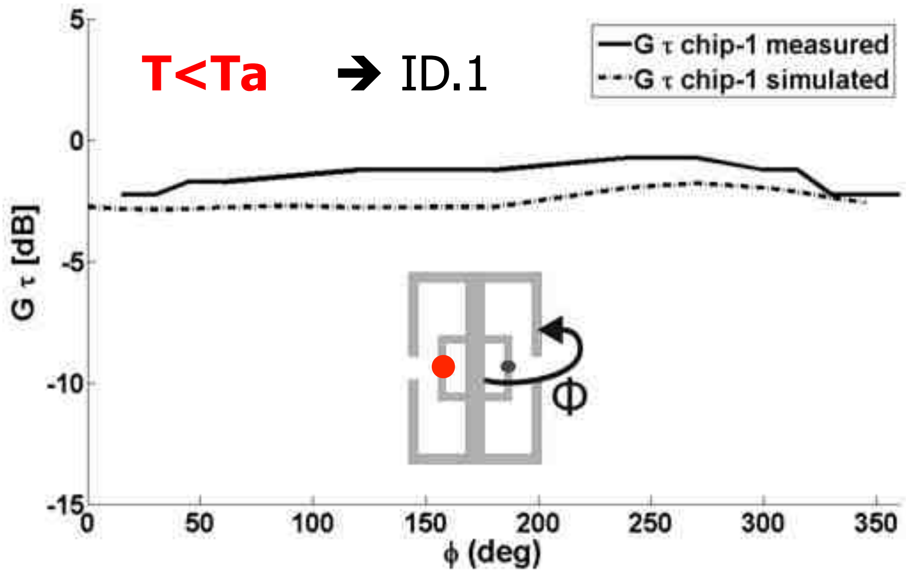


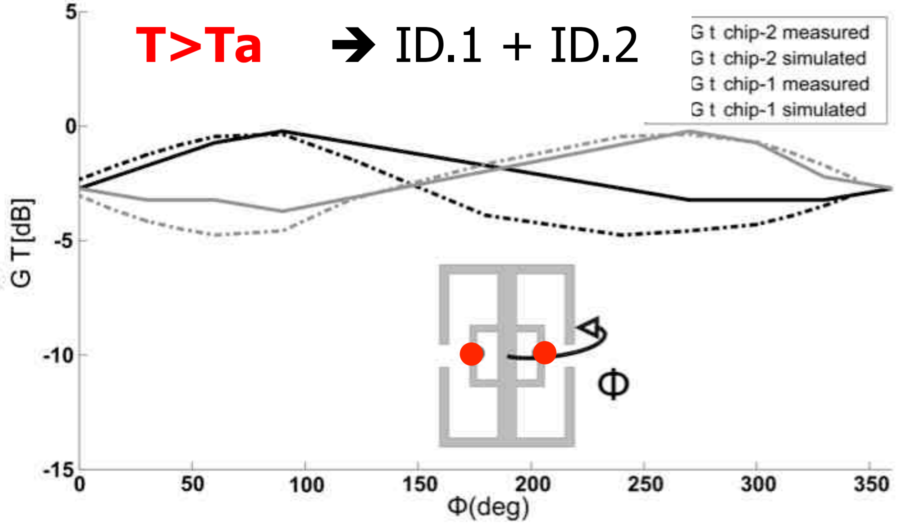
When T>Ta the sensor reacts changing **permanently** its state.

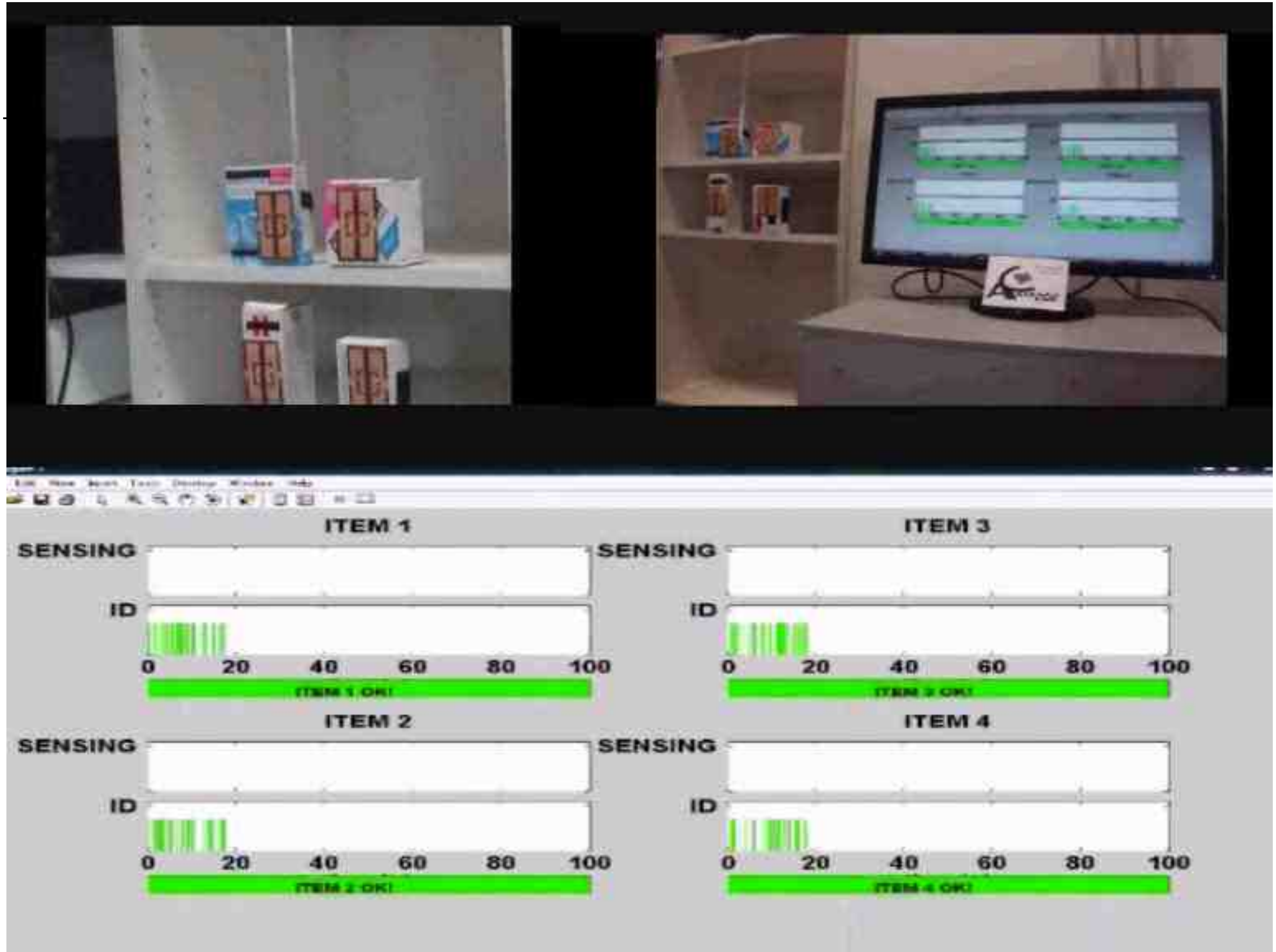
Temperature threshold



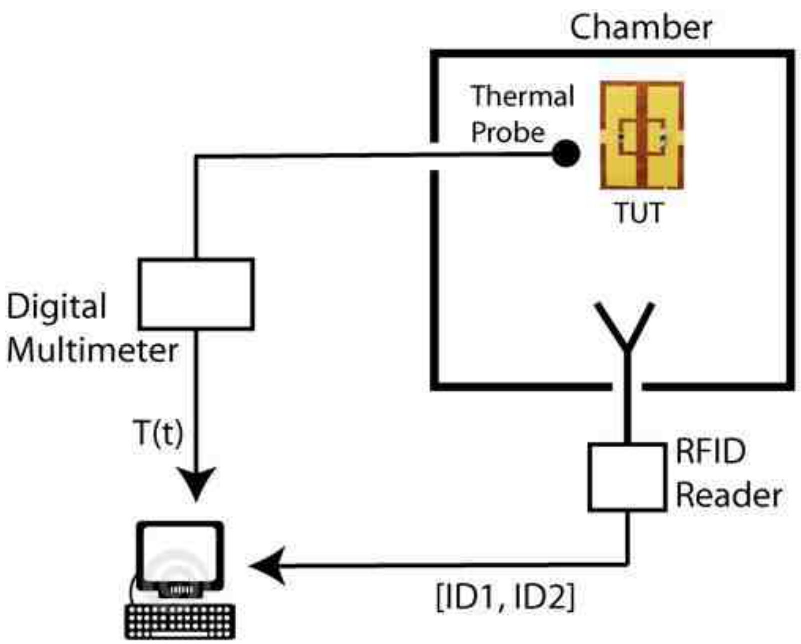






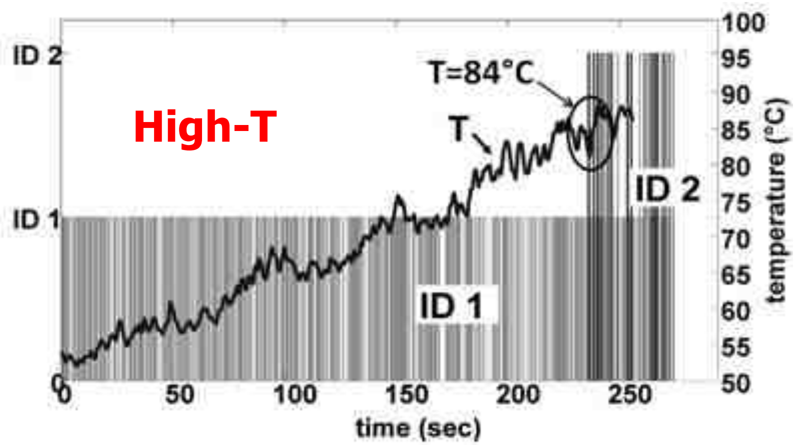

ITEM 1
SENSING
ID
0 20 40 60 80 100
ITEM 3
SENSING
ID
0 20 40 60 80 100
ITEM 2
SENSING
ID
0 20 40 60 80 100
ITEM 4
SENSING
ID
0 20 40 60 80 100

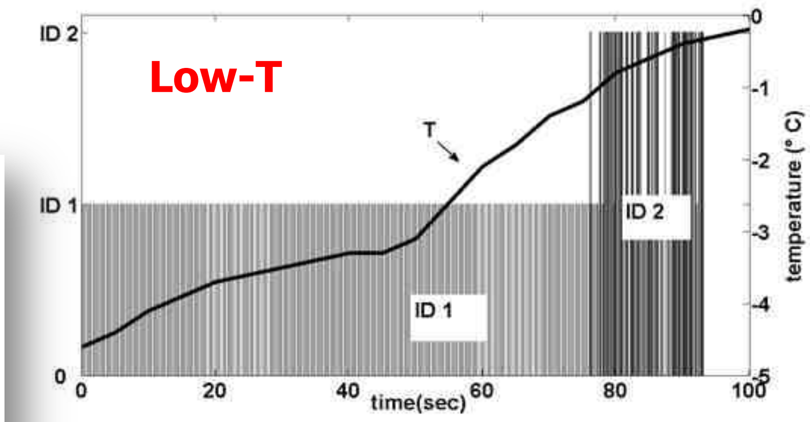
Hot and Cold Thresholds



SWITCH-OFF TEMPERATURES OF THE SENSING TAGS

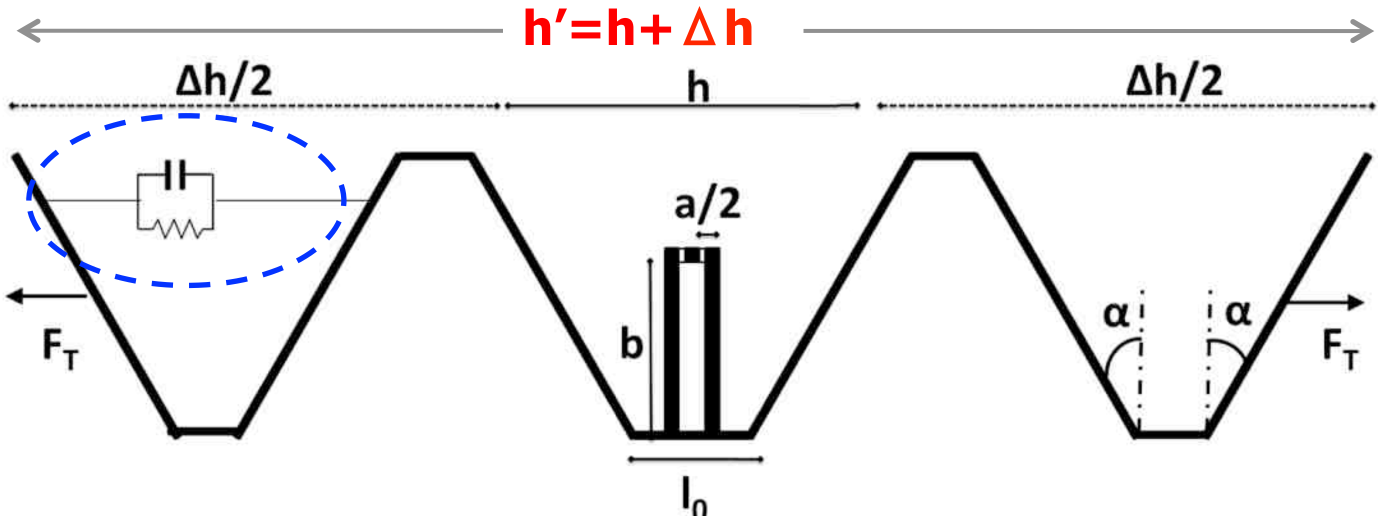
nominal $A_S(°C)$	$T_{SW}(°C)$	$\sigma_T(°C)$
80	84.7	3.1
0.0	-4.1	3.0





Sensing Deformations

Deformable Meanderline Tag



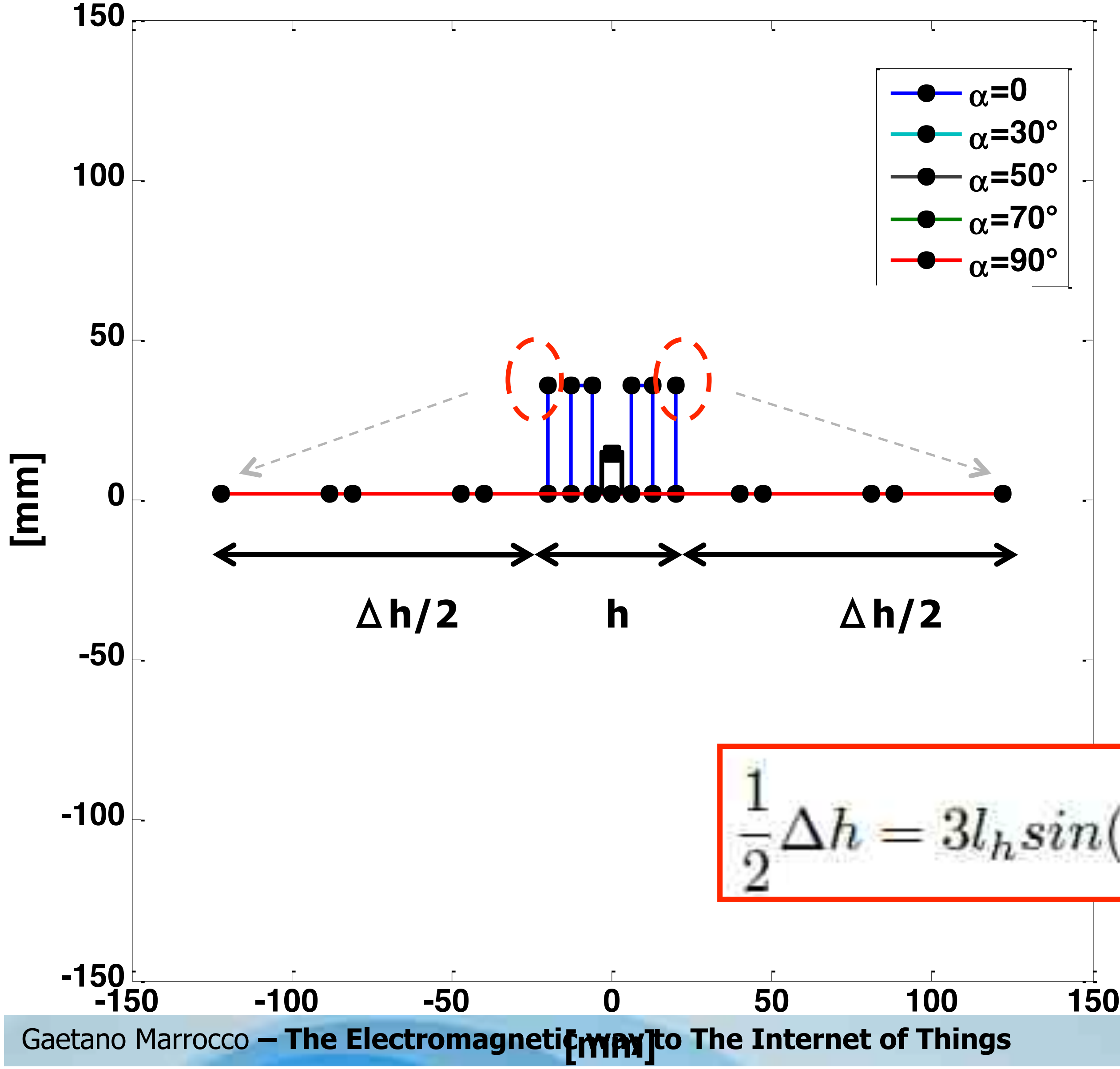
The antenna's **shape factor** changes as well as the **distributed loading**, and hence both the input impedance and the antenna gain will be accordingly modified.

Strain

Δ Zin **Δ G**

C. Occhiuzzi, C. Paggi, G. Marrocco, "**Passive Strain-Sensor based on Meander-line Antennas**", *IEEE Trans. Antennas and Propagat. 2011*

Strain Model



Hypothesis: inextensible wires (rigid structure)

- the external forces act only at the joints,
- rotation of the folding elements
- translation (horizontal and vertical) of the moving nodes of the structure

$$\frac{1}{2}\Delta h = 3l_h sin(\alpha) + 4r_s[1 - cos(\alpha)]$$

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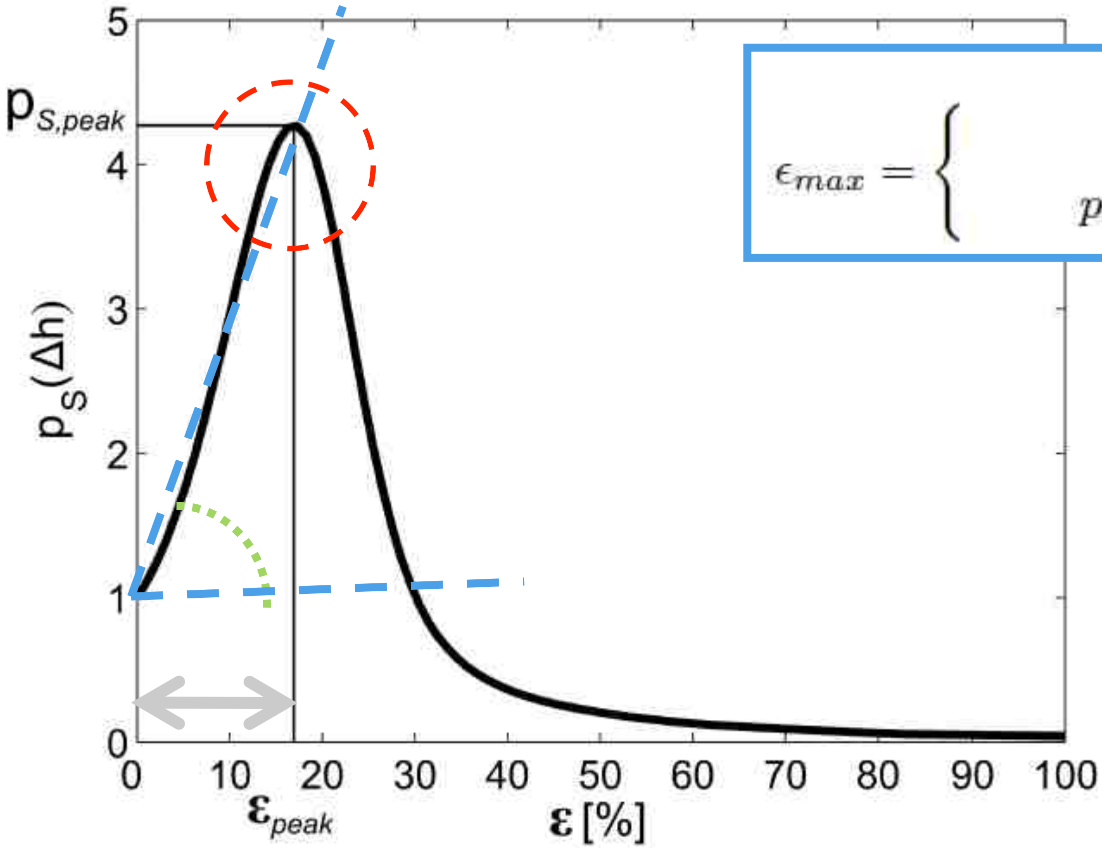
Master the Sensing



Dynamic Range

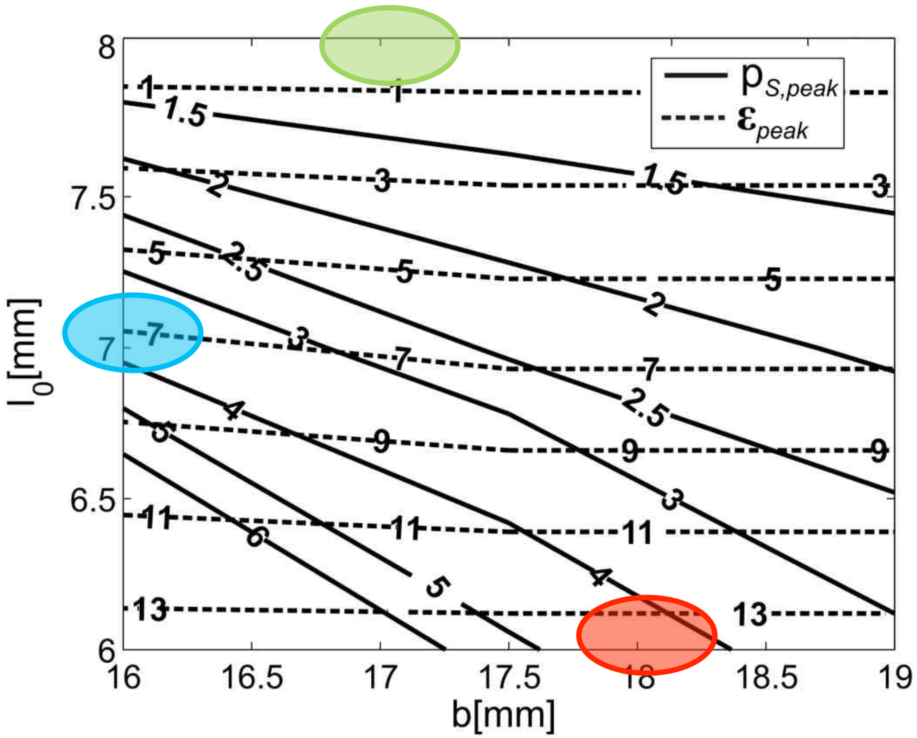
$$\epsilon_{max} = \begin{cases} \epsilon_{peak} & \text{positive slope} \\ p_s(\epsilon_{max}) = 0.1 p_s(\epsilon_{peak}) & \text{negative slope} \end{cases}$$

$$s\,[\%] = \frac{p_s\left[\epsilon_{max}\right] - 1}{\epsilon_{max}}$$

Sensitivity

The response of the tag in the DESIGN PROCESS is controlled by a proper choice of the geometrical size of the MLA layout

Sensing chart



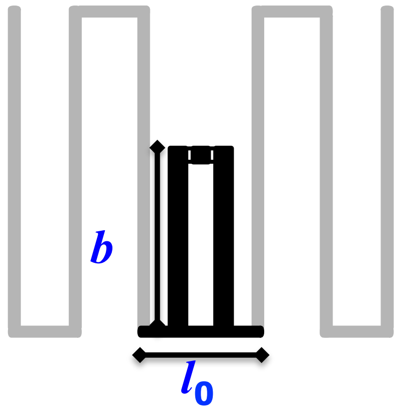
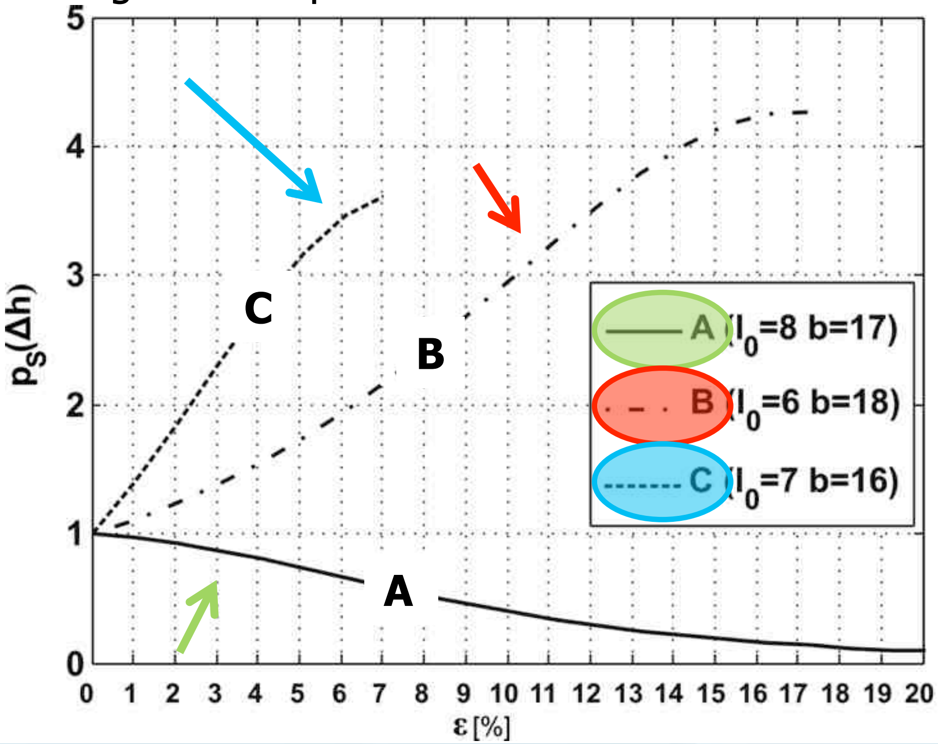


Table I
DYNAMIC RANGE RANGE AND SENSITIVITY CORRESPONDING TO MLAS IN FIG.4

MLA	ϵ_{max} [%]	$p_s(\epsilon_{max})$	s [%]
A	20	0.1	-4.5
B	17	4.3	19
C	7	3.7	39

BS Power response vs. strain and geometric parameters



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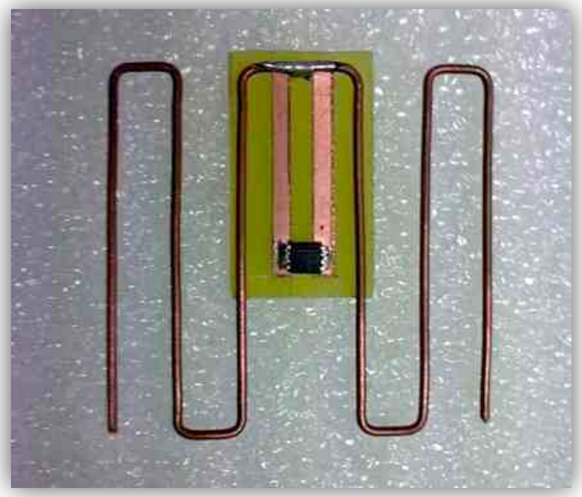
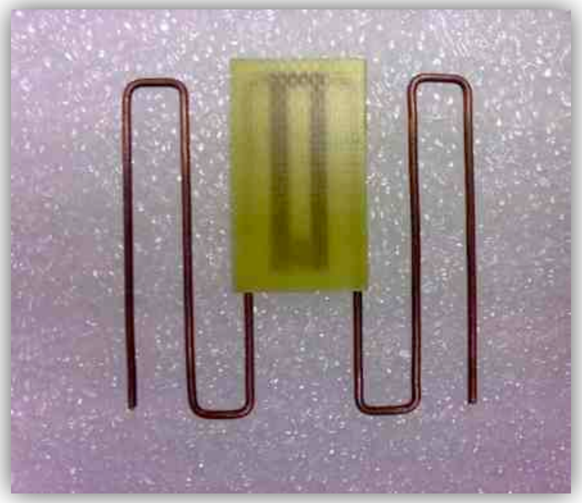
Prototype

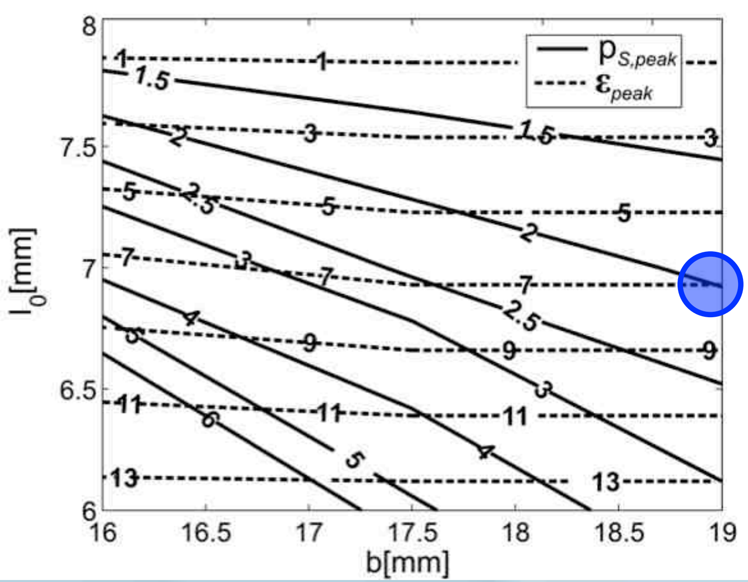




T-match section is printed over a 15x25x0.96 mm FR4 substrate

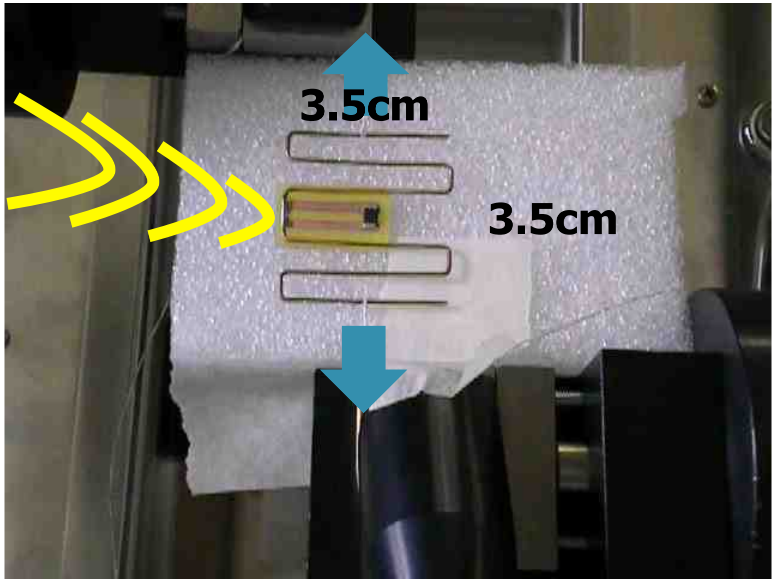
Parameter	Value [mm]
l_0	7
l_v	7
a	4
b	19
h	36
r_s	0.5
l_h	36

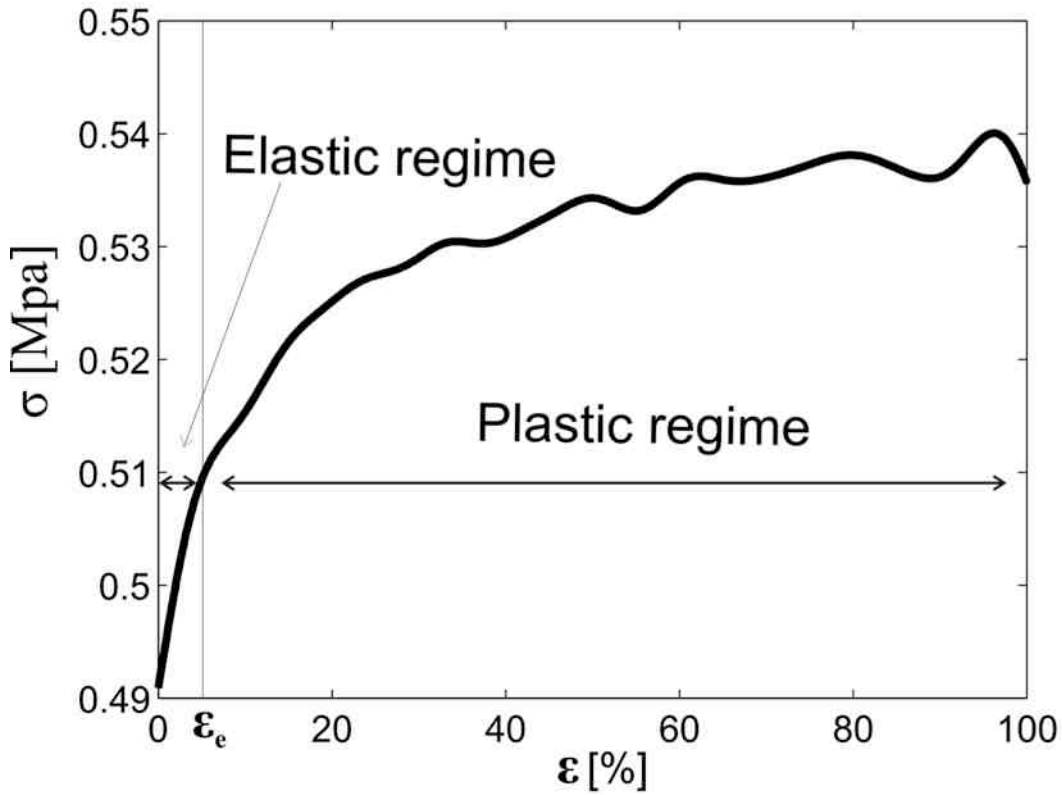
emphasize small deformations



Measurements

Prototype subjected to controlled **0-3 Newton axial tractive** force for a period of 80s

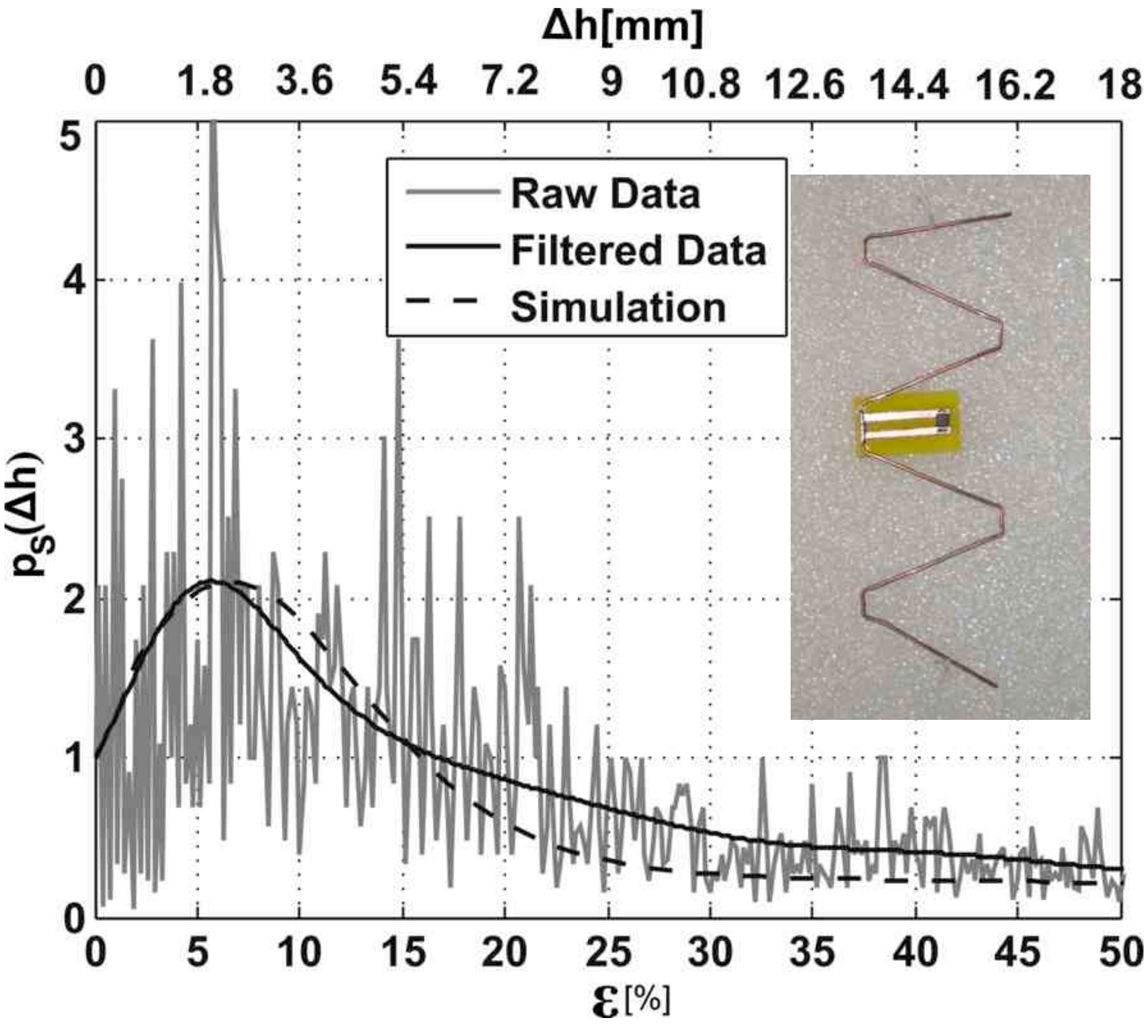




Strain

Measurements

backscattered power



ε_{max}=7% s=20%

Δp_s=10%

ε =0.7%
Δh=250μm @870MHz
Δh=85μm @2450MHz

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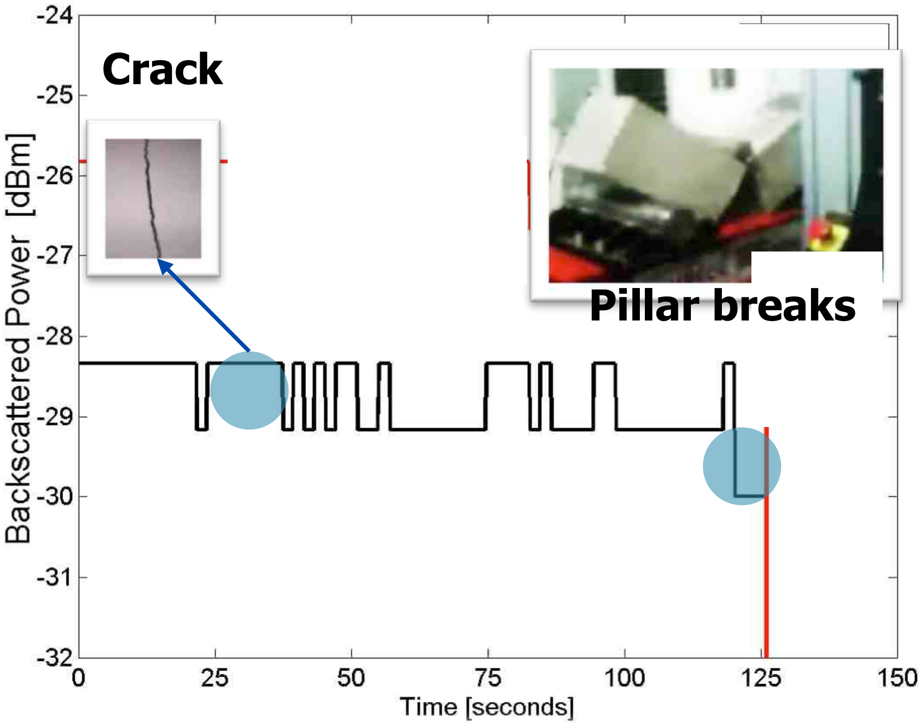
Structural Healthcare Monitoring (SHM)

Planar MLA over elastic substrate



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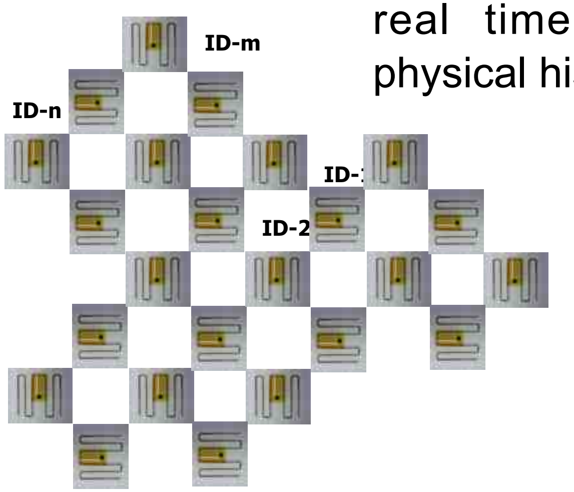
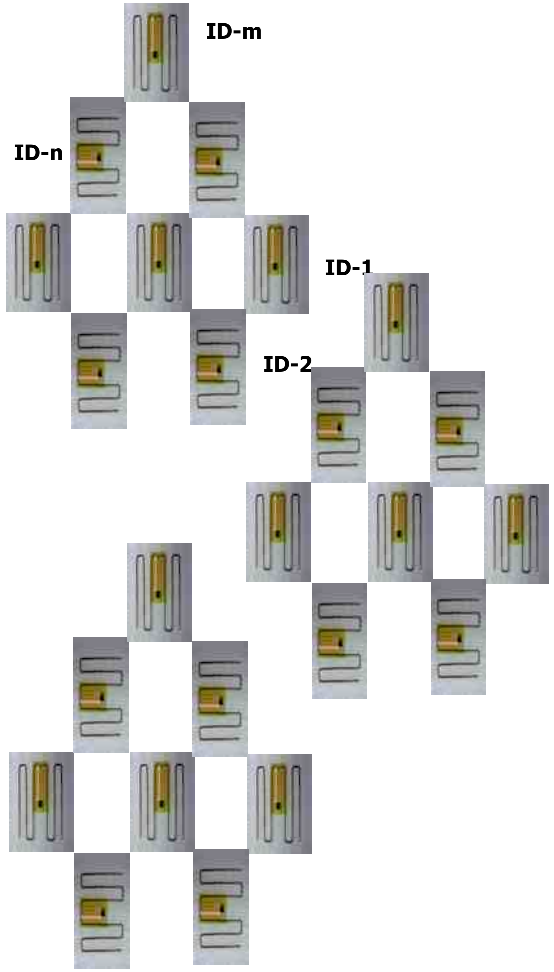
Structural Healthcare Monitoring

It is conceivable to develop smart self-sensing skins suited to envelope things, plants and even body regions, which may communicate in real time their multidimensional physical history



Deformation =>

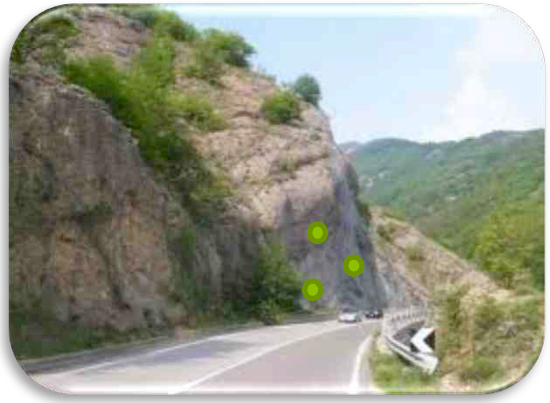


Sensing:

➔ Deformation of the single tag

➔ Variation of mutual position (coupling)

E- Environment



Fixed reader

Hand-held

Mobile

Sensing Chemical Species

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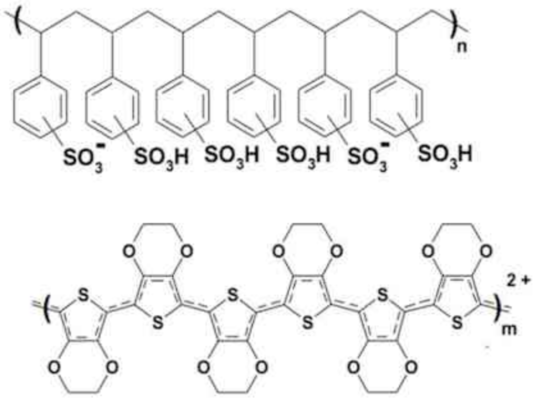
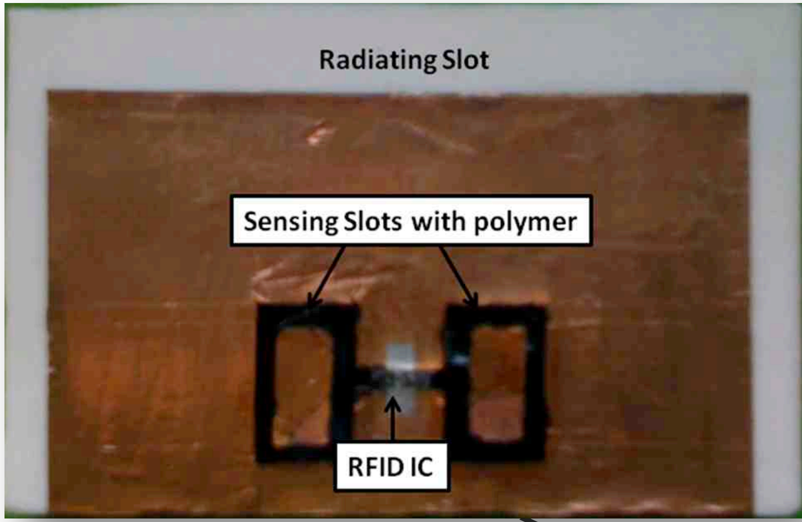
Conductive Polymer-doped tag

Chemical Receptors for Humidity Sensing





poly (3,4-ethylenedioxythiophene):poly (styrene-sulfonic acid) – **PEDOT:PSS**

- **Hygroscopic polymer** dispersion which is used to paint the antennas' slots.
- Change of permittivity/conductivity along with vapor absorption
- Possibility of integration into plaster or **bandages to remotely monitor the healing grade of wounds**

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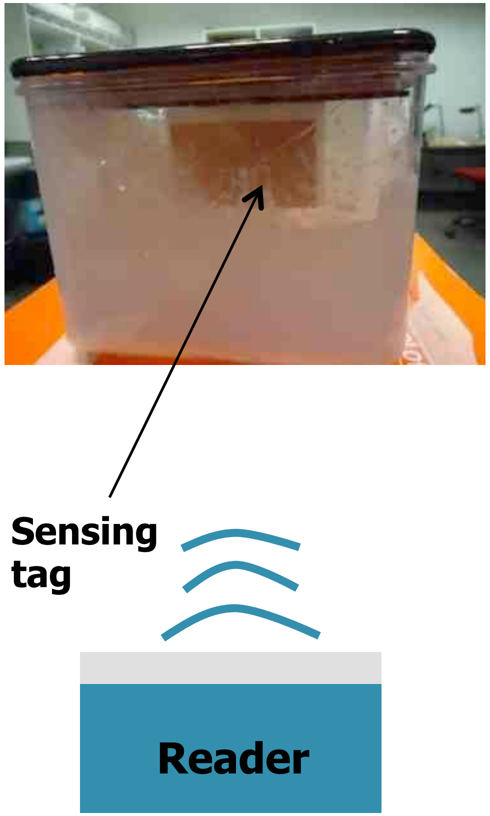
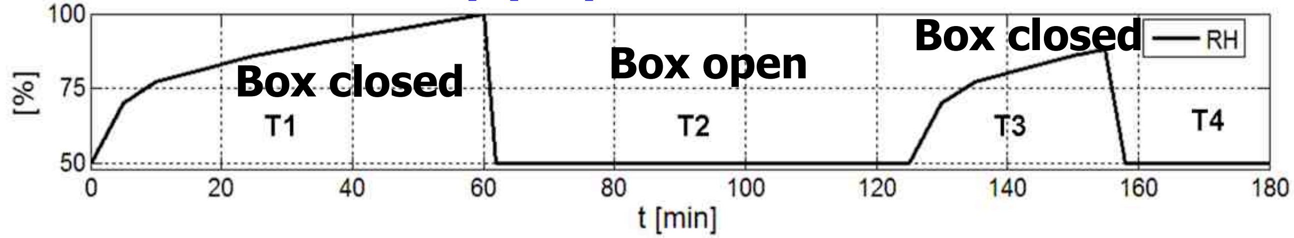
Measurements

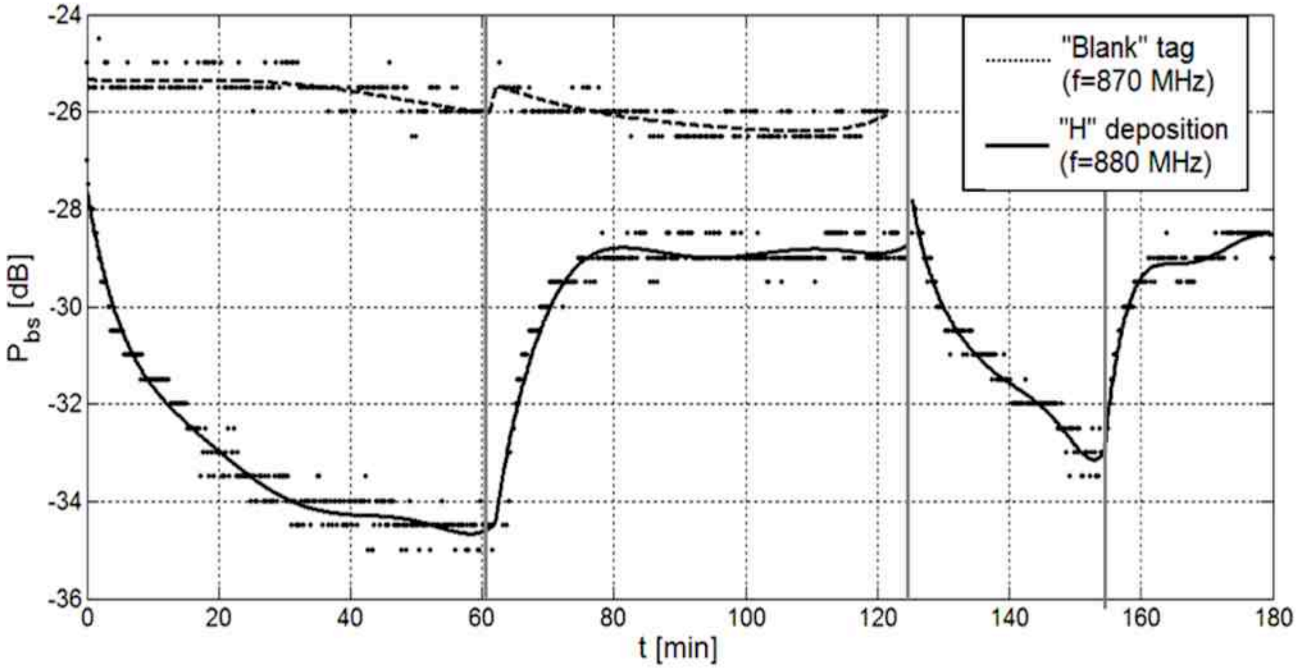
Exposure to H_2O vapor



Relative humidity (RH)



Measured Backscattered Power



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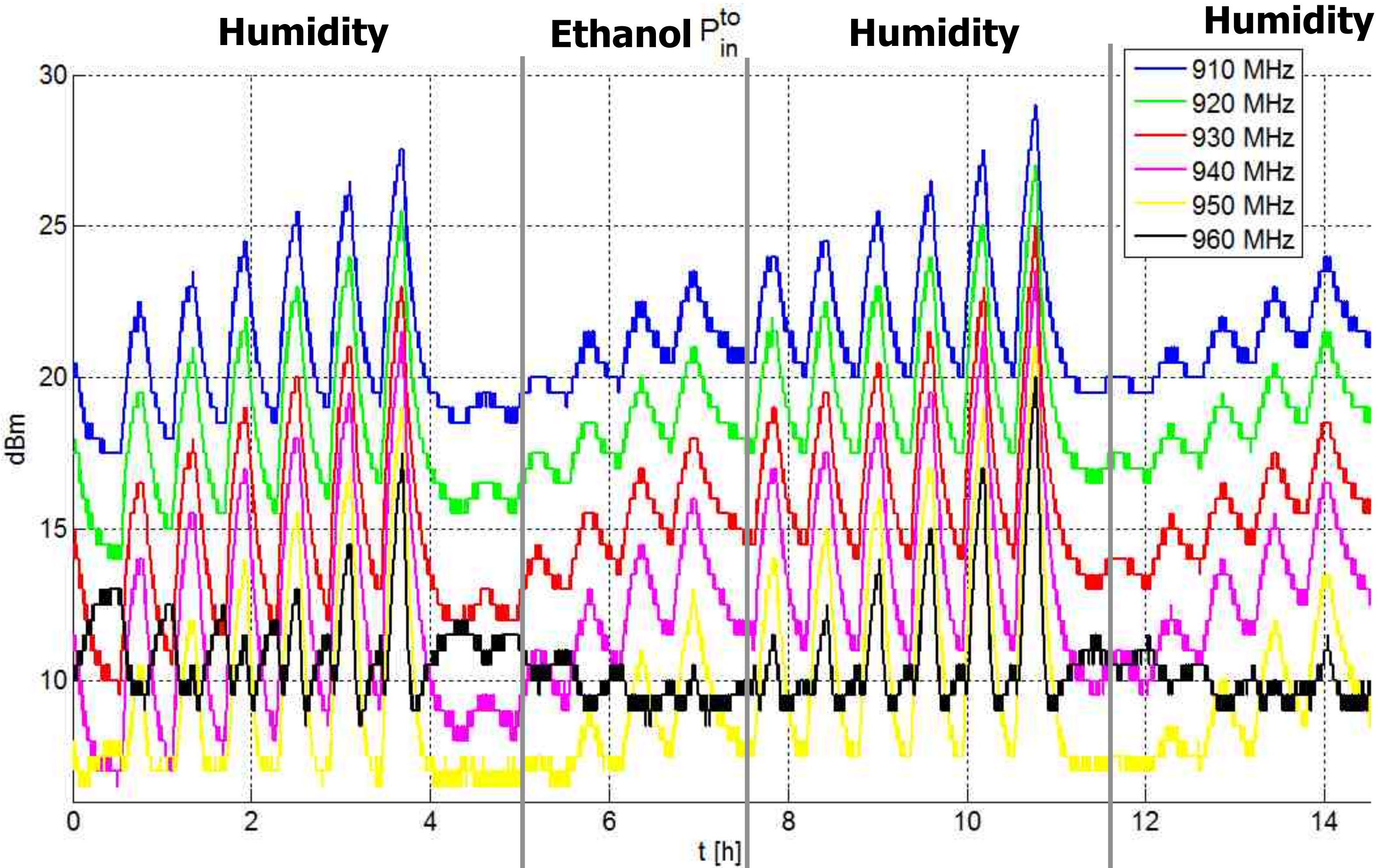
Lab On-Antenna !!

Humidity: 0%-50%-0%-60-0%-70%-0-80%-0%-90%-0%-100%

Ethanol: 0%-10%-0%-20-0%-30%-0-40%-0%-50%-0%



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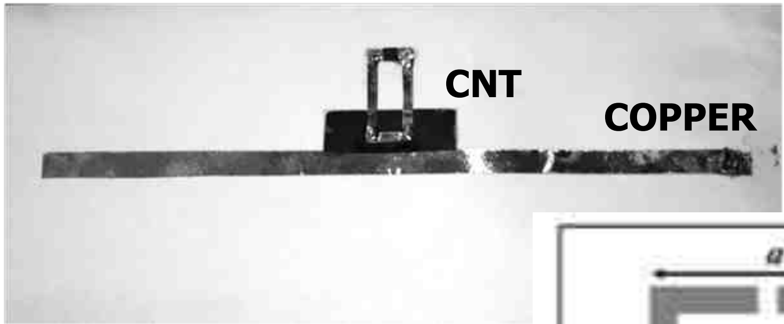
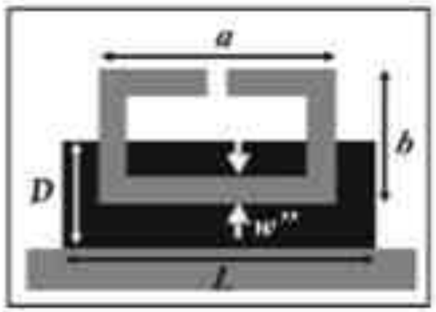
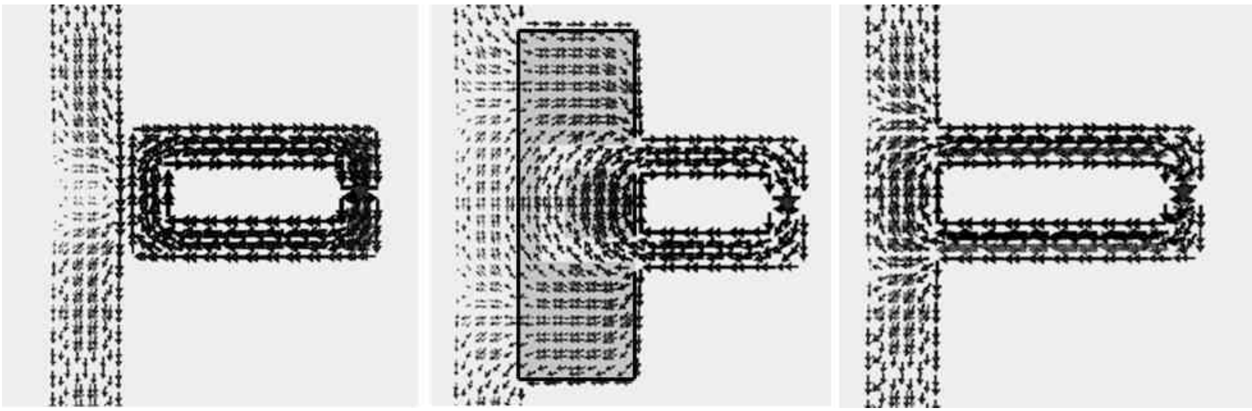
RFIDs & Carbon NanoTubes

Ammonia radio-sensor





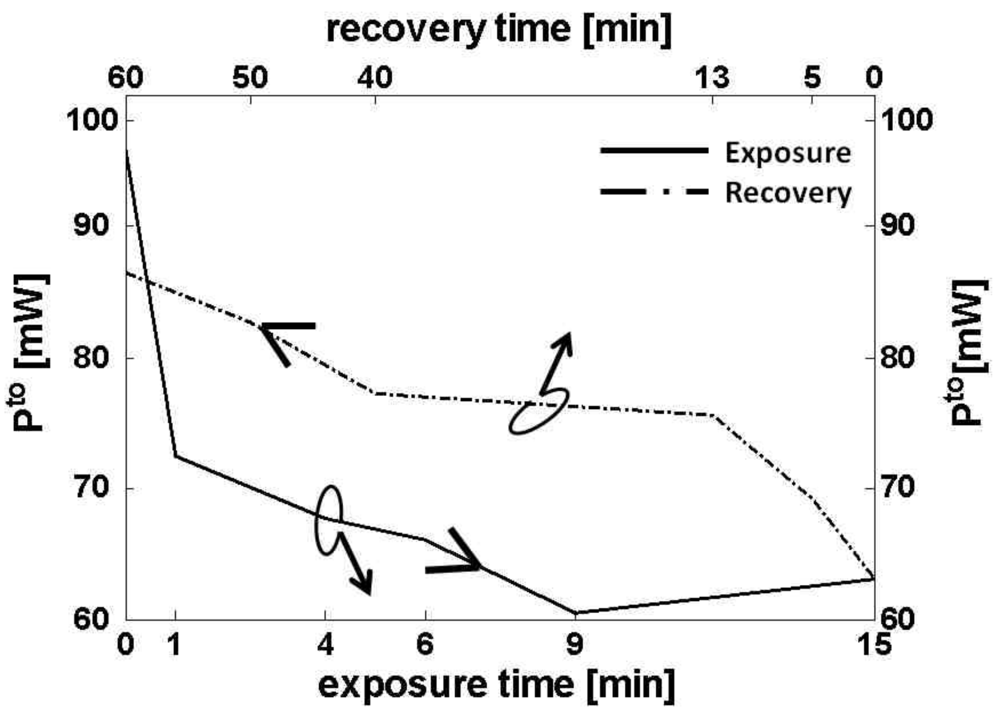
CNT is a partially conductive material, whose conductivity decreases due to the ammonia absorption.
This **gas** plays as a reducing agent that **injects electrons to the nanotubes** (p-type) reducing the number of holes and hence the conductivity.



Loop-feed **CNT** **T-match**

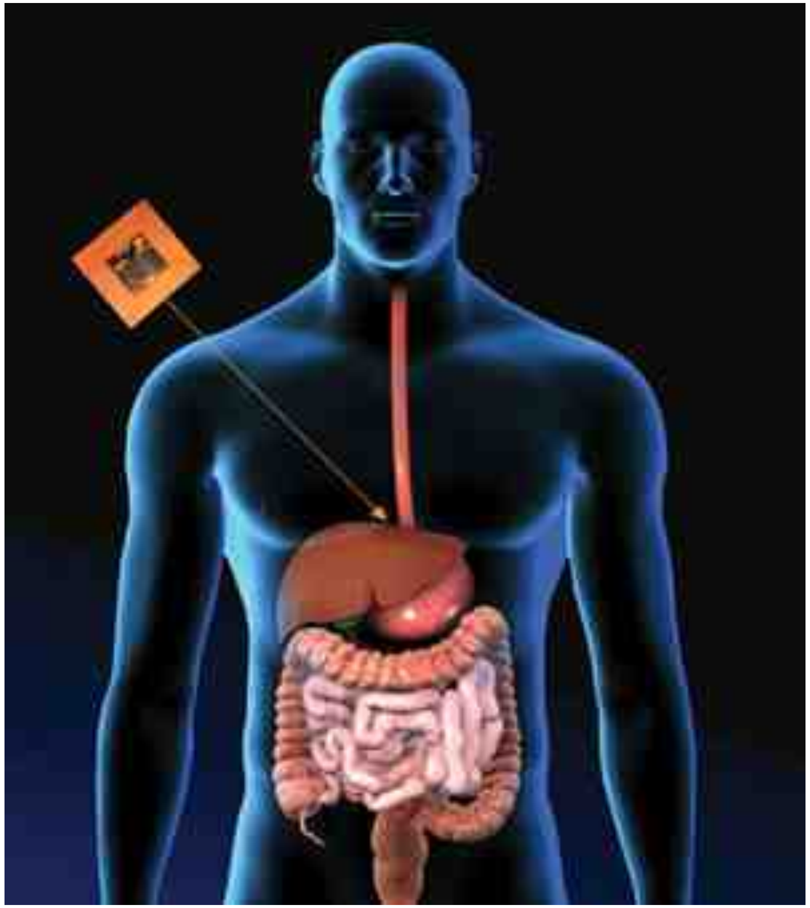
RFIDs & Carbon NanoTubes

Turn-on power



Gas-detection tags for food and environmental monitoring

C. Occhiuzzi, A. Rida, G. Marrocco, M. Tentzeris, "**RFID Passive Gas Sensor Integrating Carbon Nanotubes**", *IEEE Microwave Theory Tech*, 2011



Sensing Humans

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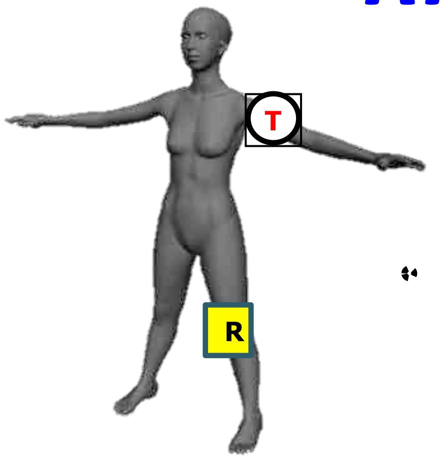
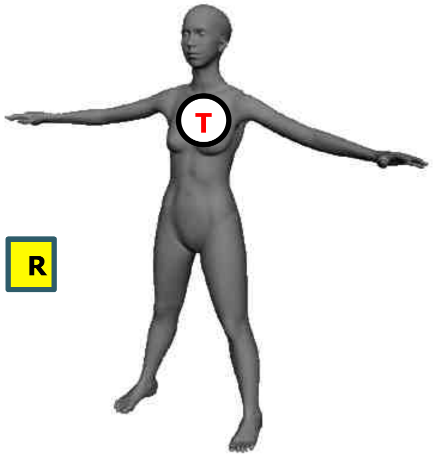
RFID-Bodycentric Systems



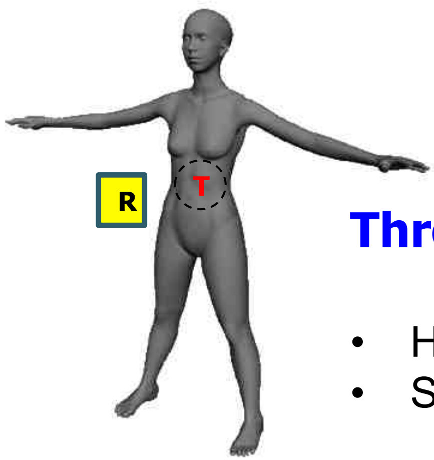
On-Body link: The reader's antenna over the body

- Activity and shadowing effect
- Exposure limit



Off-Body link: The reader placed far from the body

- Reading range in real scenario
- Environmental influence
- Position



Through-the-Body link: The tag is implanted

- High loss
- Small read ranges

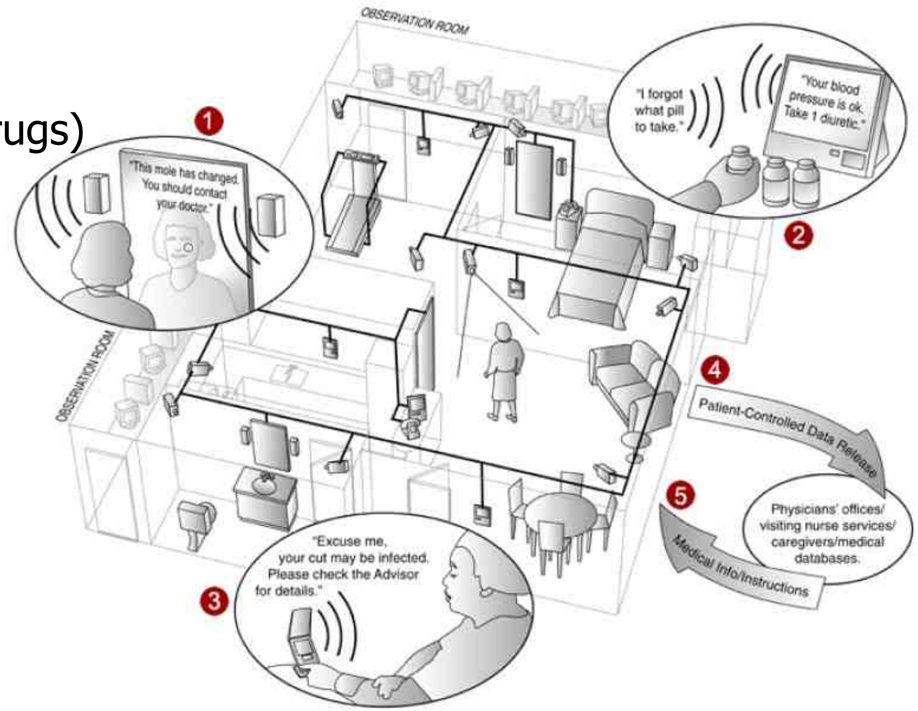
Pervasive Healthcare systems

Context-aware systems

Body sensors
- motion
- ECG
- Evolution of pathologies

Smart Objects
- Localization
- Quality (food, drugs)

Smart House
- temperature
- Gas
- Structural safety
- localization systems



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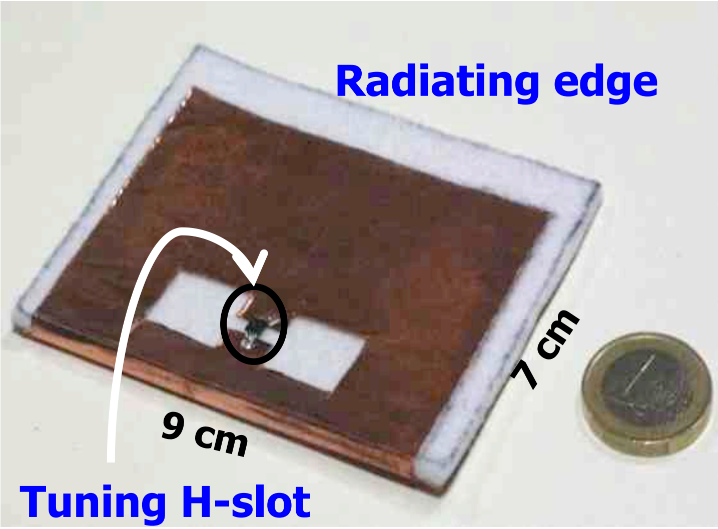
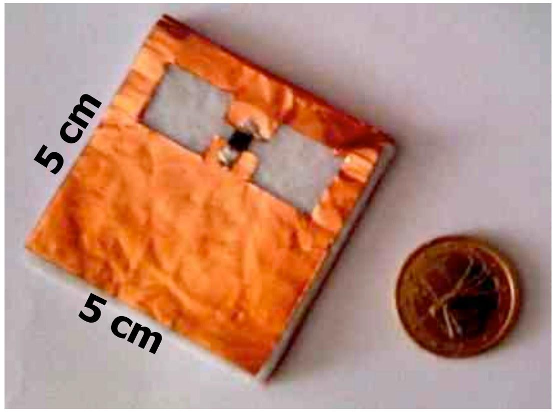
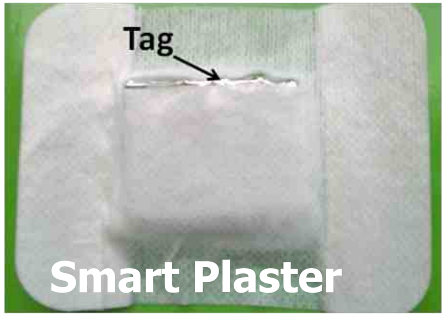
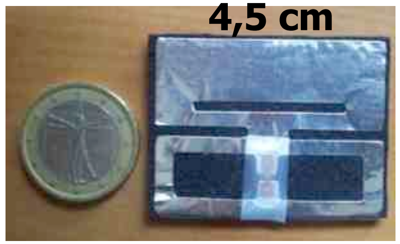
Wearable textile RFID Tags





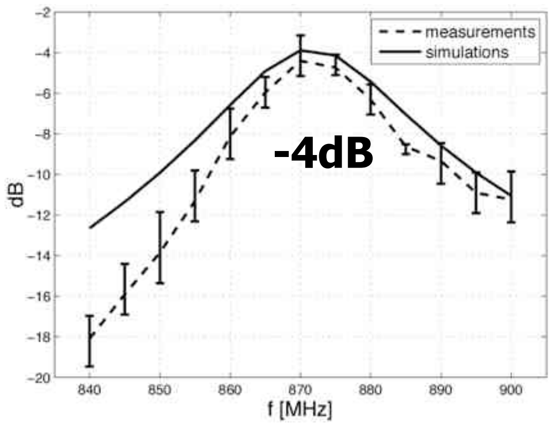


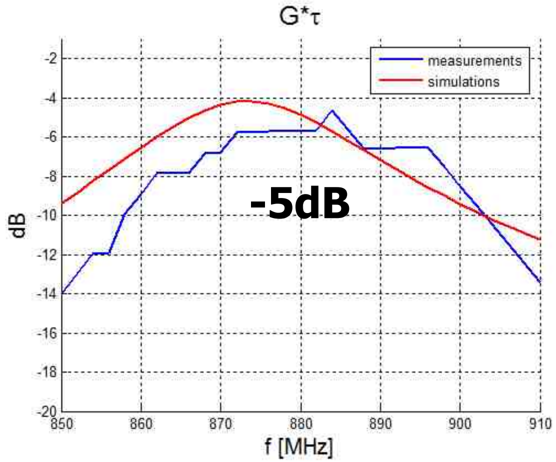


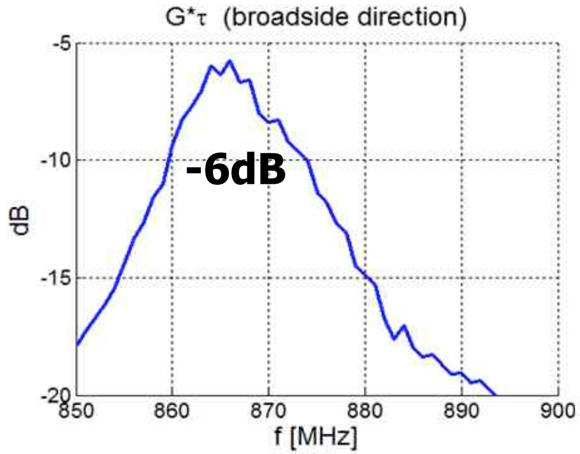
3,5 cm

Felt substrate

EPDM (Ethylene-Propylene Diene Monomer)







Observation: Normal incidence

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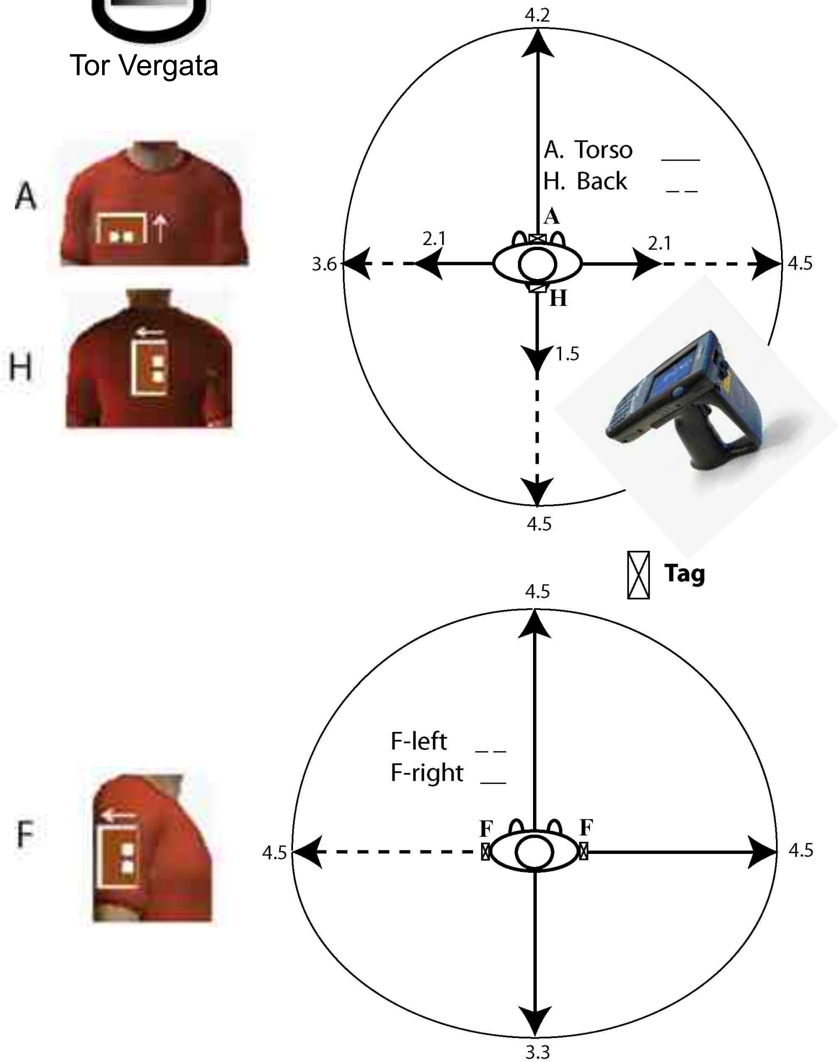
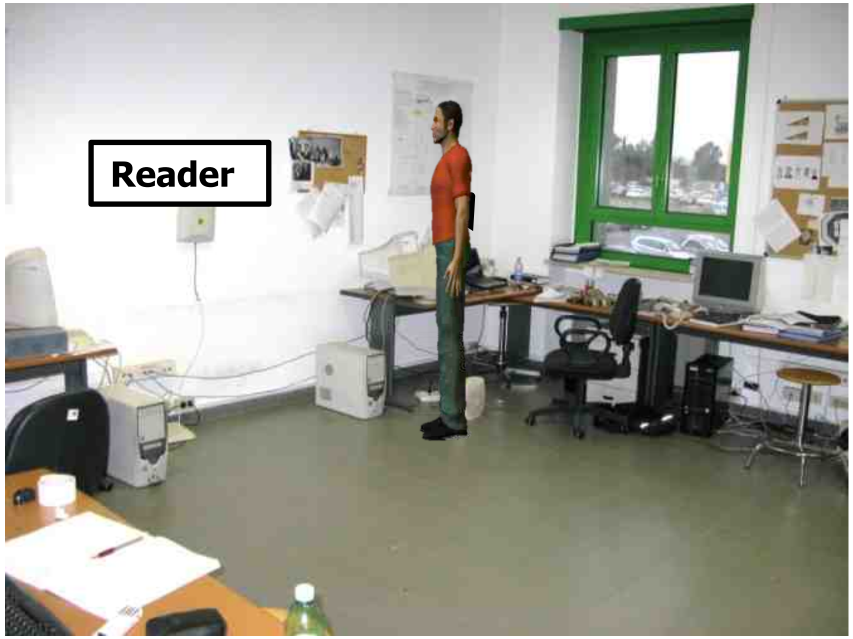
Off-body RFID link

- Real scenario



5.5m x 5.5m x 3m



- Two tags properly placed enable a robust monitoring in a 4x3 m room
- **Chip Sensitivity -15dBm**
- No shadowing effects during normal activity

S. Manzari, C. Occhiuzzi, G. Marrocco, "**Feasibility of Bodycentric Passive RFID Systems by Using Textile Tags**" to appear on IEEE Antennas Propagat. Magazine Aug. 2012

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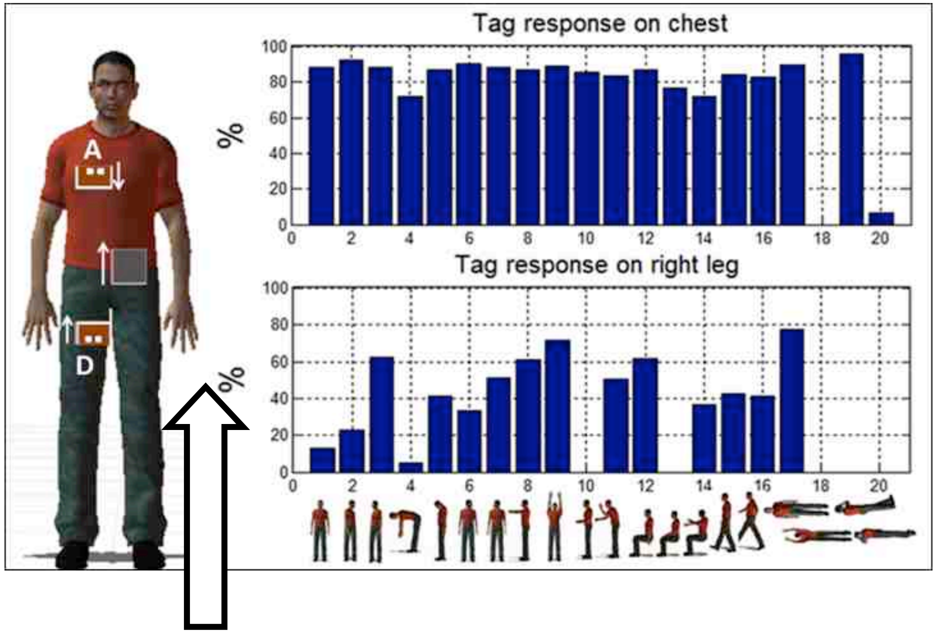
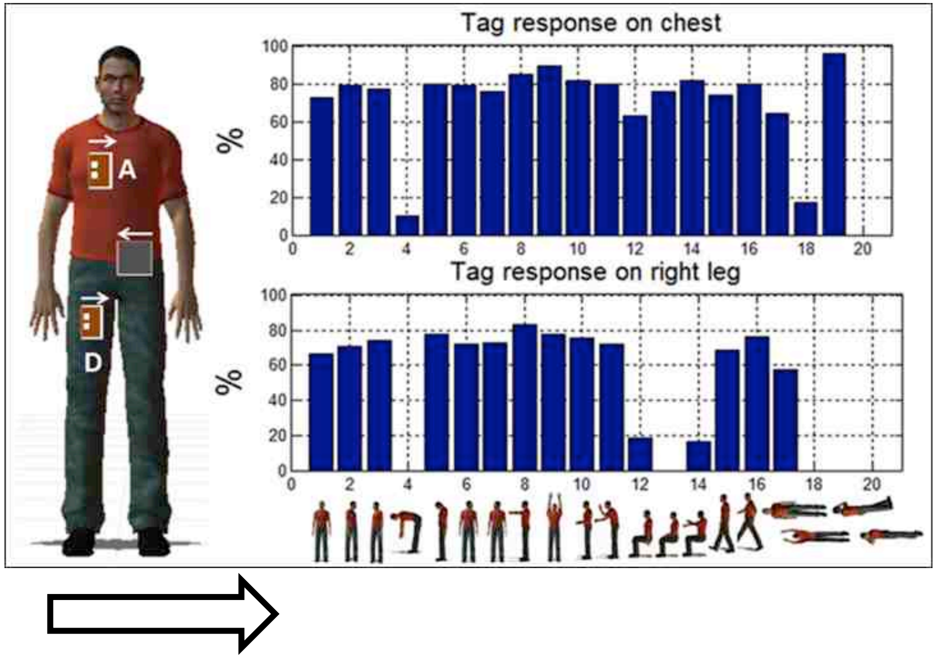
On-body RFID link

Pin=200 dBm/10

Vertical Polarization

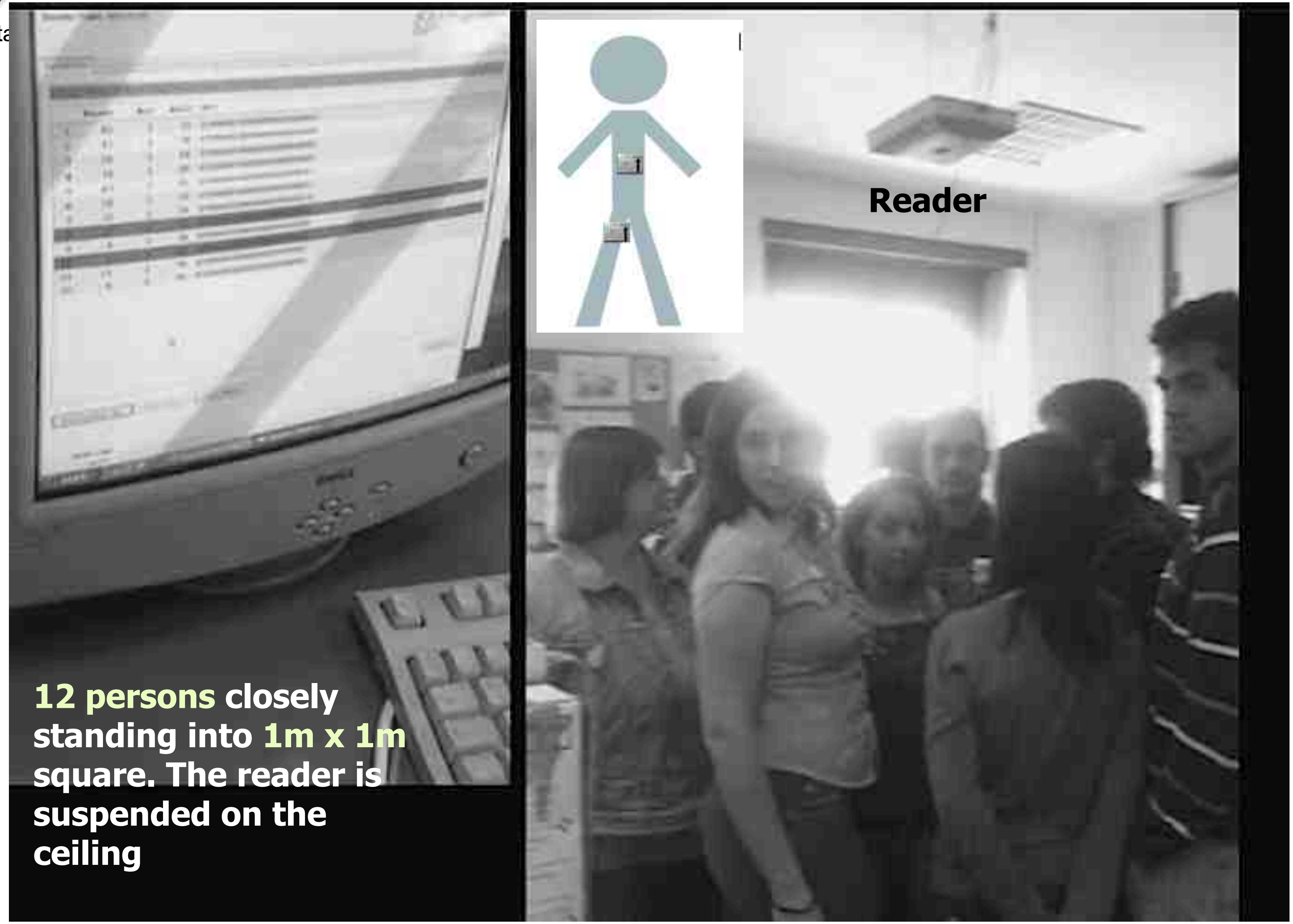


Horizontal Polarization



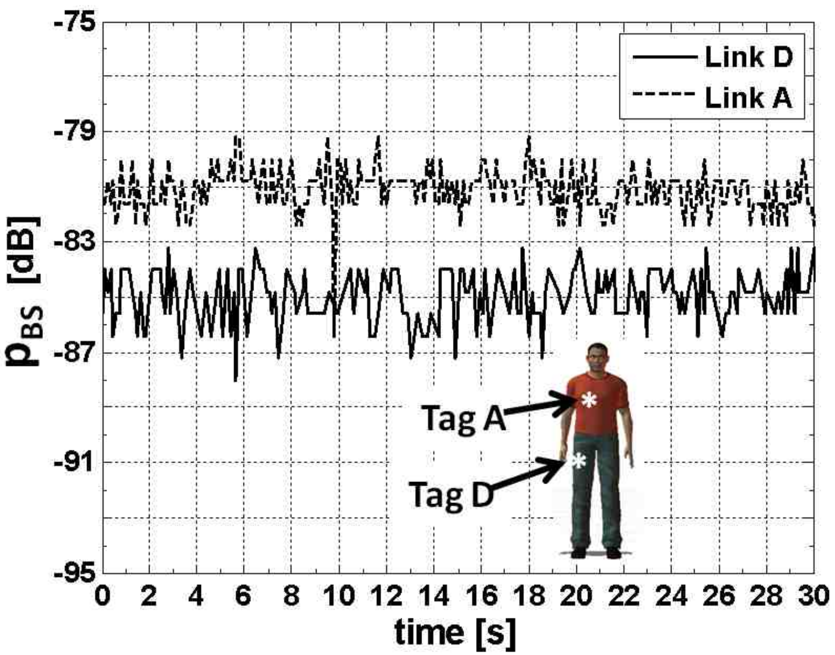
The tag on the chest is almost always visible except for one lying position

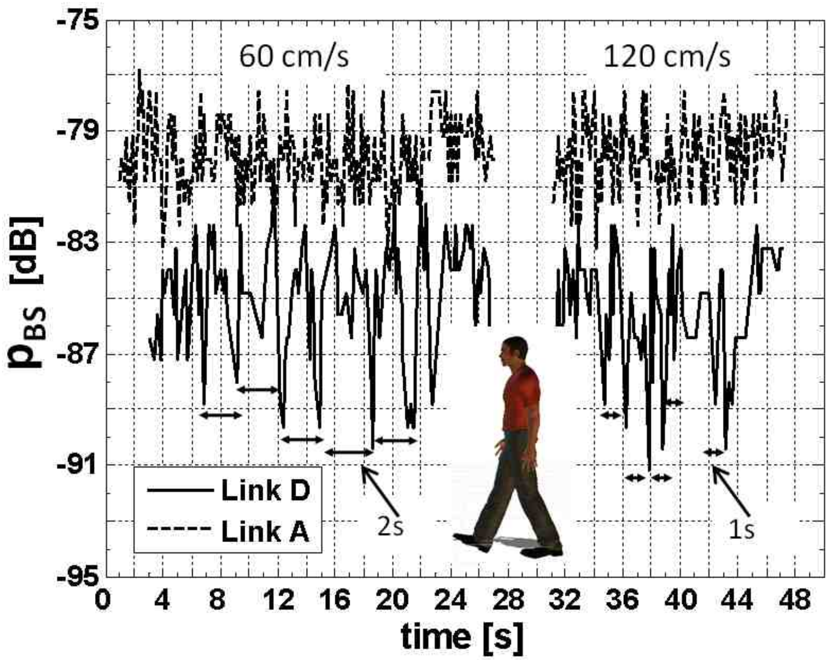
On-body RFID link



On-body RFID link
- RSSI processing

Processing backscattered RSSI-power could permit detecting standing or moving subjects

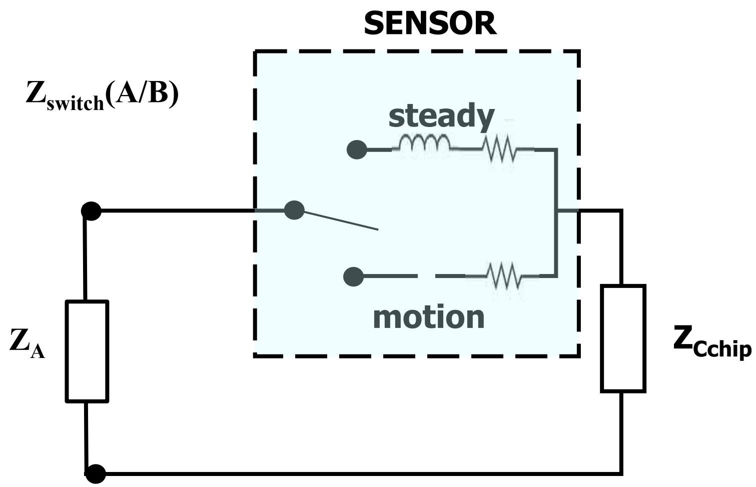


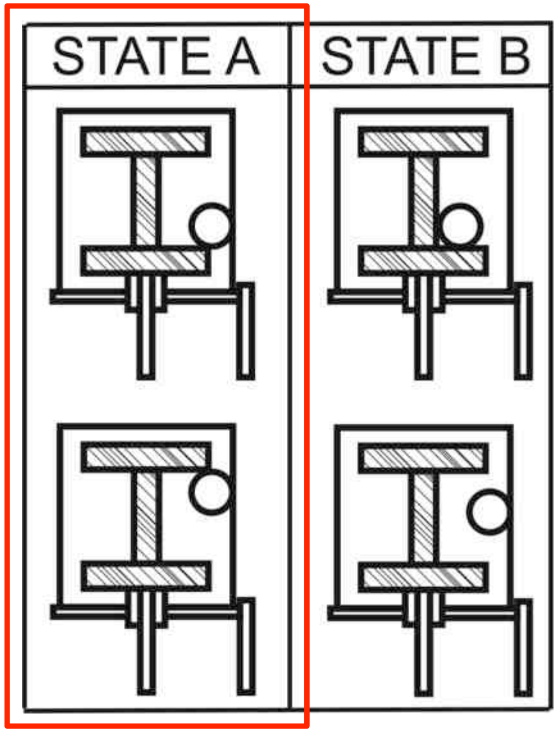


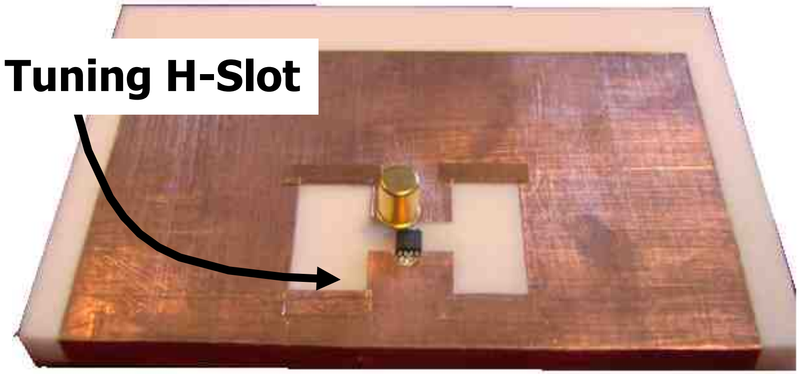
Sensor–powered Wearable Tag

Omni-directional Motion Sensor

the reader will receive the tag ID when the tag is at rest and does not receive anything if the tag is subjected to motion.







C. Occhiuzzi, S. Cippitelli, G. Marrocco, "**Modeling design and experimentation of wearable UHF RFID sensor tag antennas**", *IEEE Trans. Antenna Propagat.*, Vol.58 N.8, pp. 2490 - 2498, 2010

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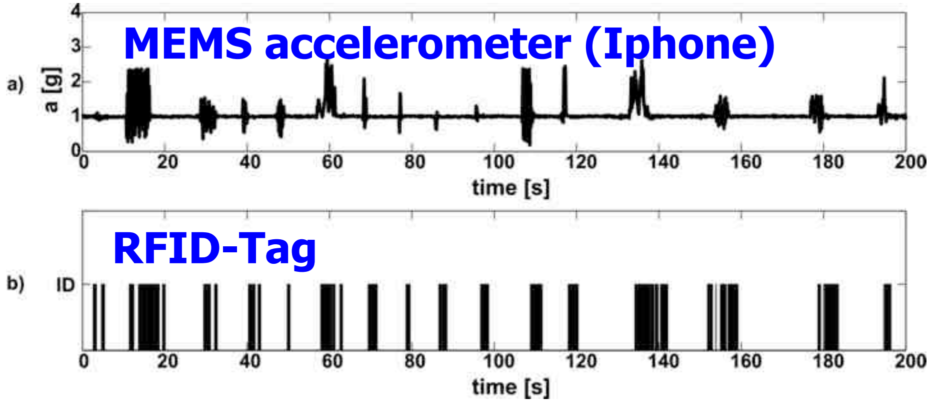
Sensor–powered Wearable Tag

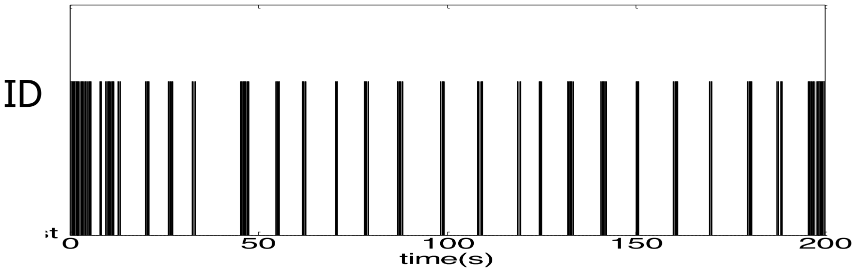
Omni-directional Motion Sensor

Movements of arms



- Human behavior statistics
- Neuroscience
- Man-at-work safety

Deep Breath



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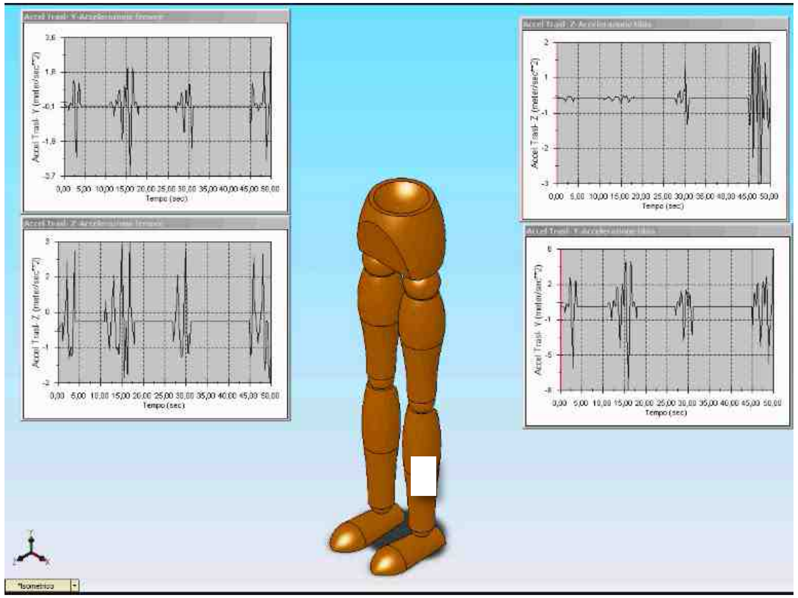
Omni-directional Motion Sensing

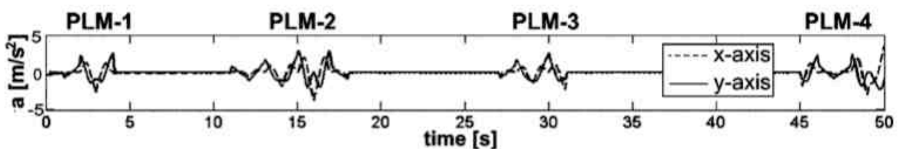
Ex. Motion in sleep disease



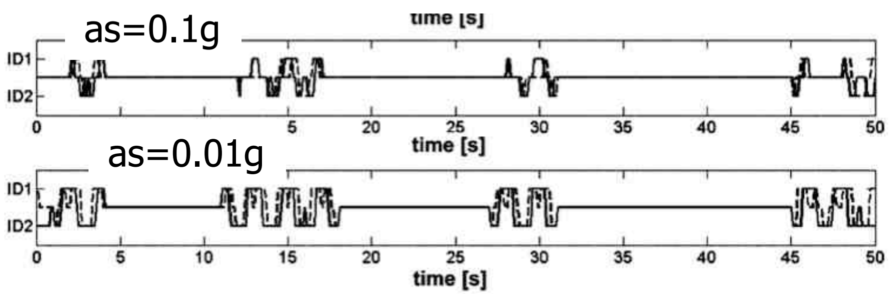
Electromechanical model

- Restless sleep
- Periodic Limb Movements

Analog Acceleration



RFID

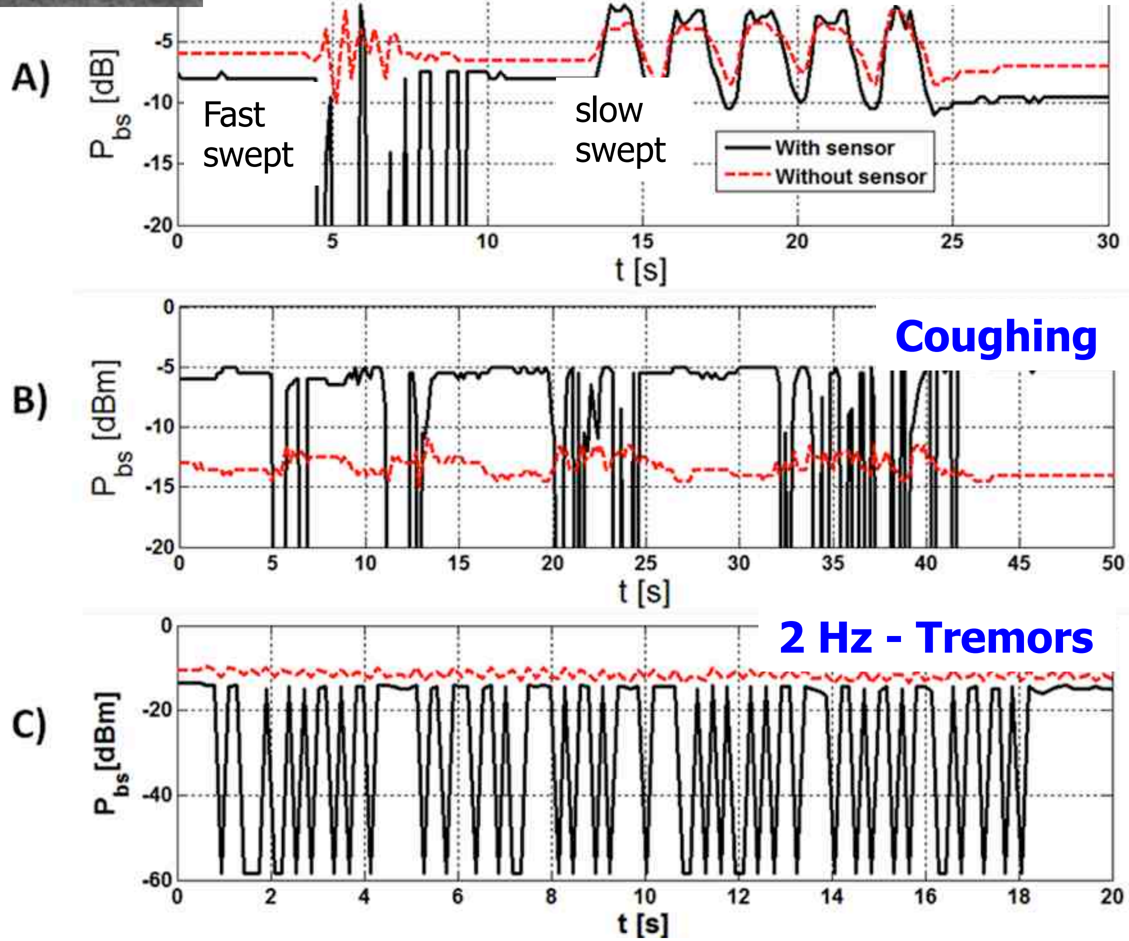


C. Occhiuzzi, G. Marrocco, "**The RFID Technology for Neuroscience: feasibility of Limbs' Monitoring in Sleep Diseases**". IEEE Trans. Information technology in Biomedicine, Vol.14, N.1, pp. 37-43, Jan. 2010.

Omni-directional Motion Sensing

Various movements

Cushier hand motion



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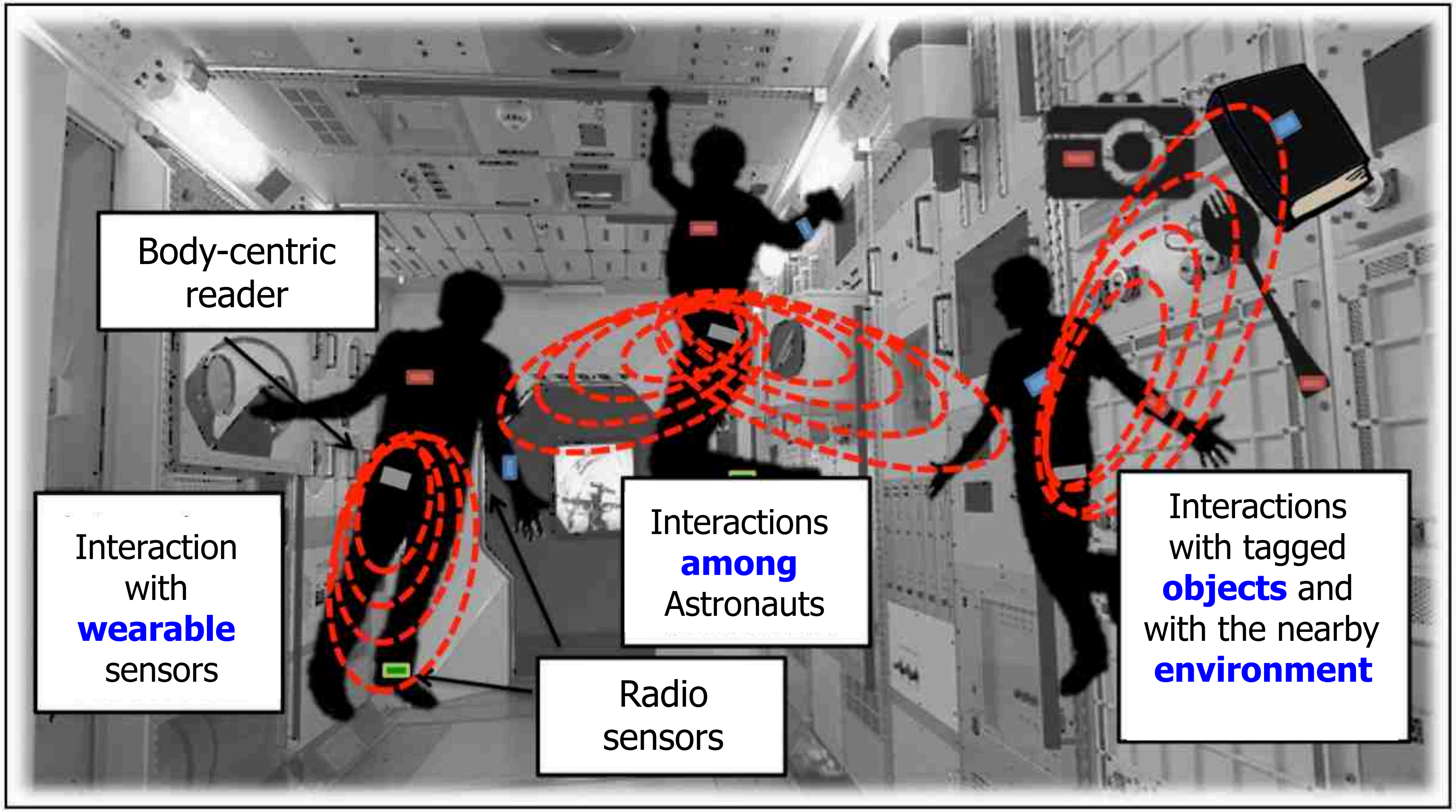
Stress- Monitoring in Hursh Environments



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Sensing from the "inside"
- rationale

Table I
HEALTHY AND UNHEALTHY HUMAN TISSUES: DIELECTRIC PROPERTY AT 870MHz

Tissue	Healthy	Unhealthy
Brain White Matter	$\overline{\epsilon} = 38.9 - j12$	$\overline{\epsilon} = 50.2 - j20.78$ Brain Edema [9], [10]
Liver	$\overline{\epsilon} = 46.9 - j17.4$	$\overline{\epsilon} = 64.1 + j27.85$ Cancer [11] $\overline{\epsilon} = 61.7 + j28.68$ Cirrhotic Tissue [11]
Treated Vessels	$\overline{\epsilon} = 61.4 - j31.5$	$\overline{\epsilon} = 55 - j19.2$ Neointimal Proliferation[12] $\overline{\epsilon} = 5.46 - j1.04$ Atherosclerotic plaque [13]

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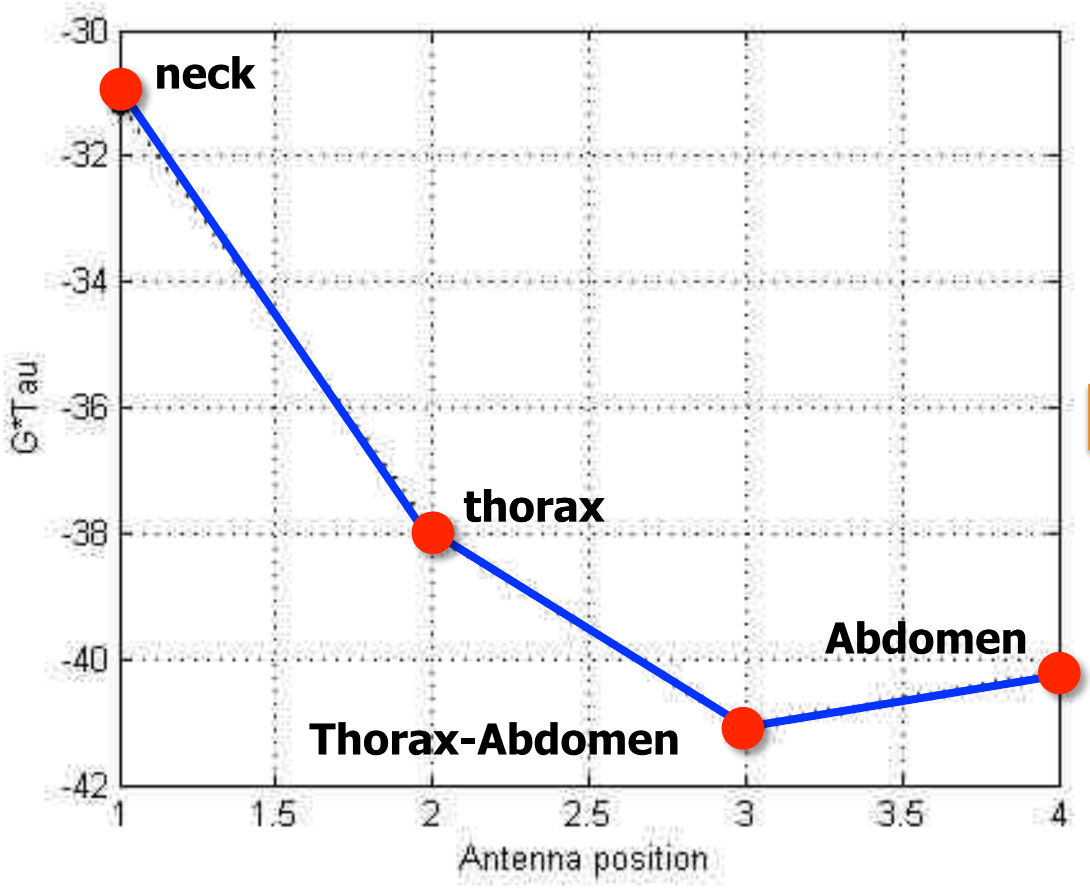
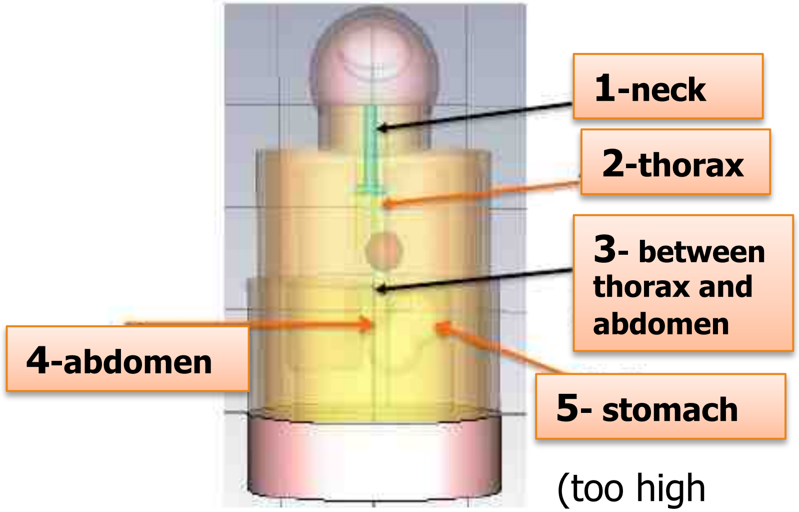
Through-the-body UHF-RFID link

FDTD simulations

Realized gain

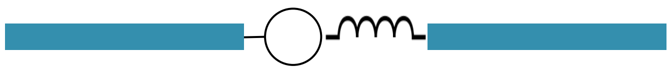




(too high reactance)

Reference tag:

- 2cm flat dipole
- Inductor-tuning



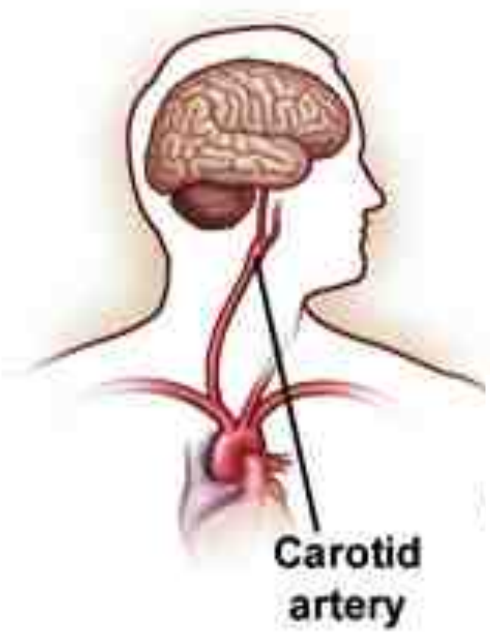
3cm

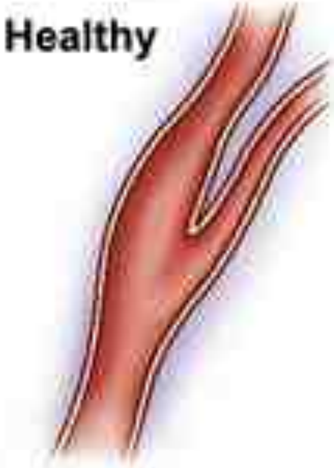
Through-the-body UHF-RFID link

Realistic body-phantom

Under development …

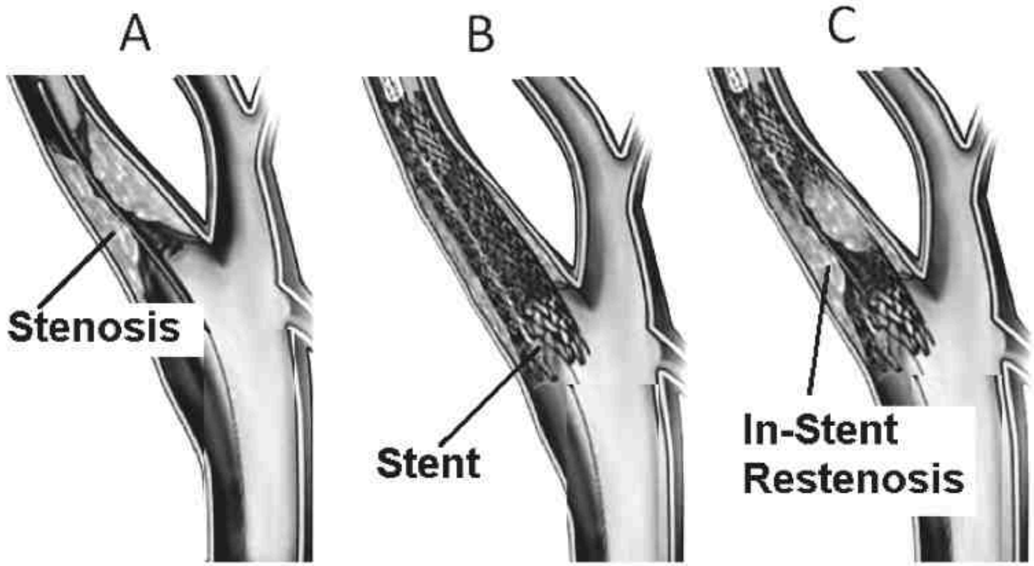
Vascular Stenosis and Restenosis





Stenosis: is a narrowing or constriction of the inner surface of the vessel mainly due to plaque formation.

Stenting is a procedure in which the vascular surgeon inserts a slender, <u>metal-mesh tube</u>, called “stent”, which expands to increase blood flow in areas blocked by plaque.



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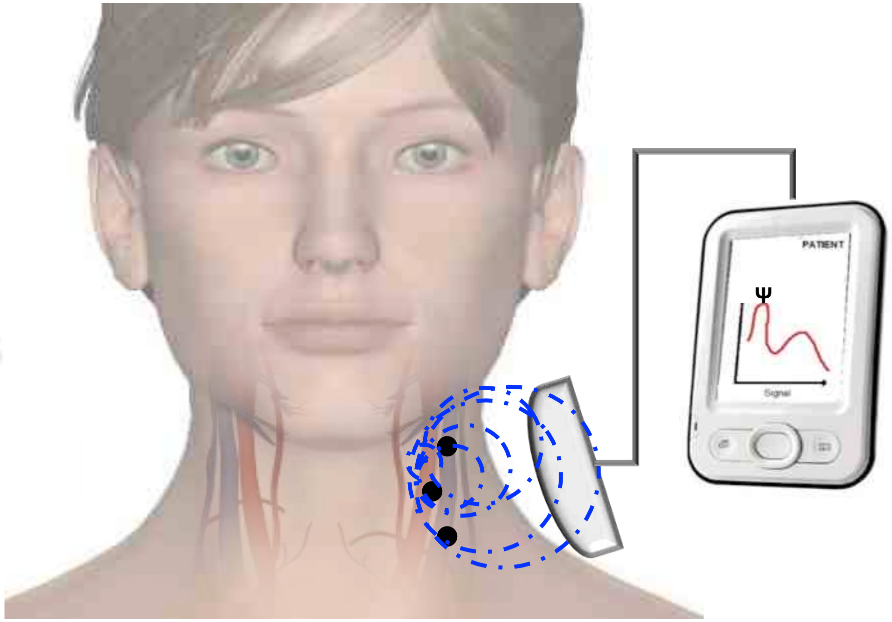
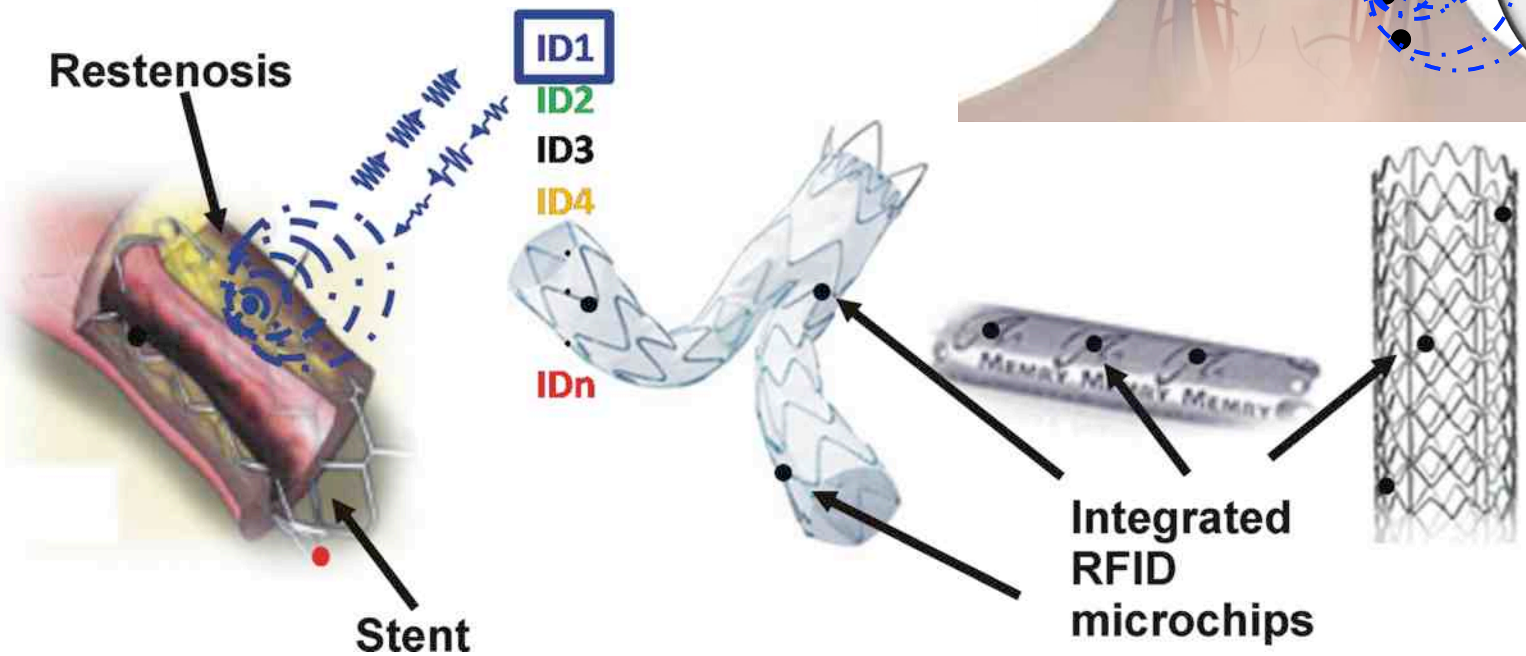
The STENTag

- Hacking a stent to achieve sensing

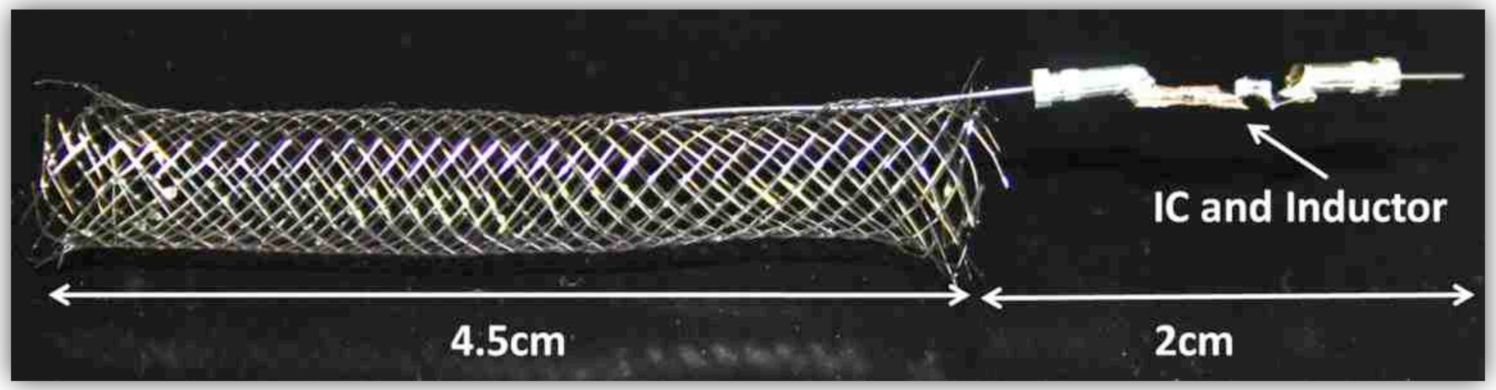
- Identify& evaluate restenosis
- Store data (USB-key)



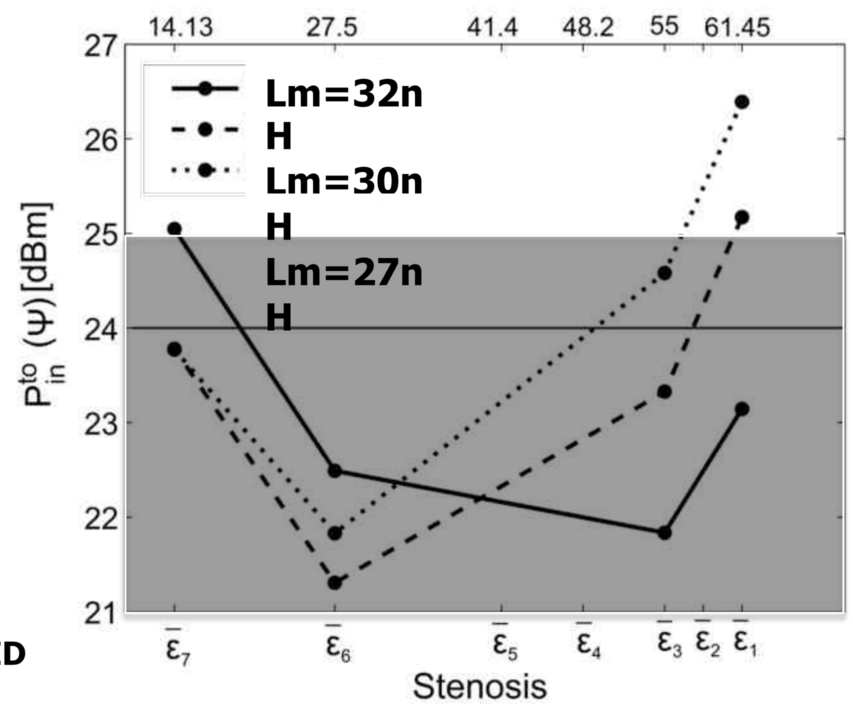


The STENTag

Prototype



The **inductor** Lm permits to shape the response curve of the STENtag with the purpose to emphasize the early grade of the restenosis



G. Marrocco, C. Occhiuzzi, "**Device Implantable in Biological Ducts**",
Patent Pending, 2011

C. Occhiuzzi, G. Contri, G. Marrocco, "**Design of Implanted RFID Tags for Passive Sensing of Human Body**", IEEE TAP 2012

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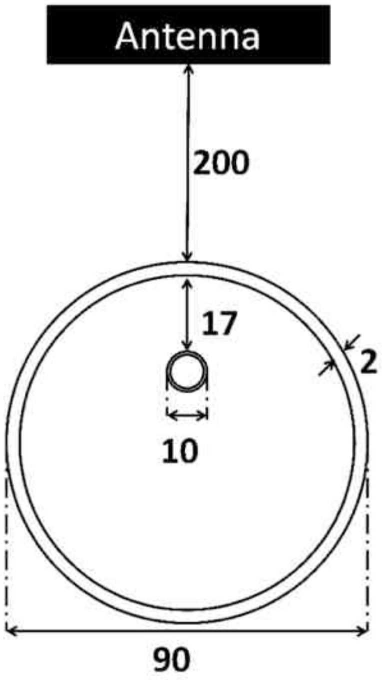
The STENTag
Experimental Setup



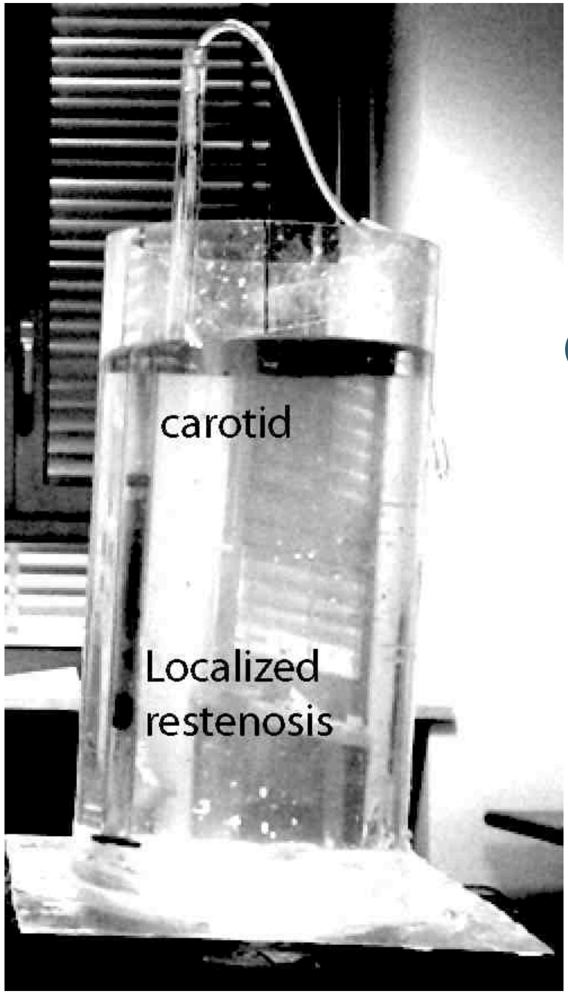


Table I
RE-STENOSIS: PROPERTIES AT 870MHZ OF THE VESSEL'S DIELECTRIC

Vessel's filler	**Theoretical Complex Permittivity**	**Measured Complex Permittivity**
1- Healthy vessel $ISR = 0\%$	$\bar{\epsilon}_1 = 61.45 - j31.5$	$\bar{\epsilon}_{1m} = 57.8 - j33.0$
2-Neointimal proliferation $ISR = 50\%$	$\bar{\epsilon}_2 = 58.22 - j25.3$	$\bar{\epsilon}_{2m} = 56.17 - j27.6$
3-Neointimal proliferation $ISR = 100\%$	$\bar{\epsilon}_3 = 55 - j19.2$	$\bar{\epsilon}_{3m} = 51.65 - j22.7$
4-Plaque proliferation *grade 1*	$\bar{\epsilon}_4 = 48.2 - j17.0$	$\bar{\epsilon}_{4m} = 46.7 - j20.19$
5-Plaque proliferation *grade 2*	$\bar{\epsilon}_5 = 41.4 - j14.8$	$\bar{\epsilon}_{5m} = 41.8 - j17.6$
6-Plaque proliferation *grade 3*	$\bar{\epsilon}_6 = 27.5 - j10.95$	$\bar{\epsilon}_{6m} = 27.5 - j10.95$
7-Plaque proliferation $ISR = 100\%$	$\bar{\epsilon}_7 = 14.13 - j12.15$	$\bar{\epsilon}_{7m} = 14.13 - j12.15$

- UHF Thing-Magic M5e reader
- 6dB gain circular polarized patch antenna
- D=20cm

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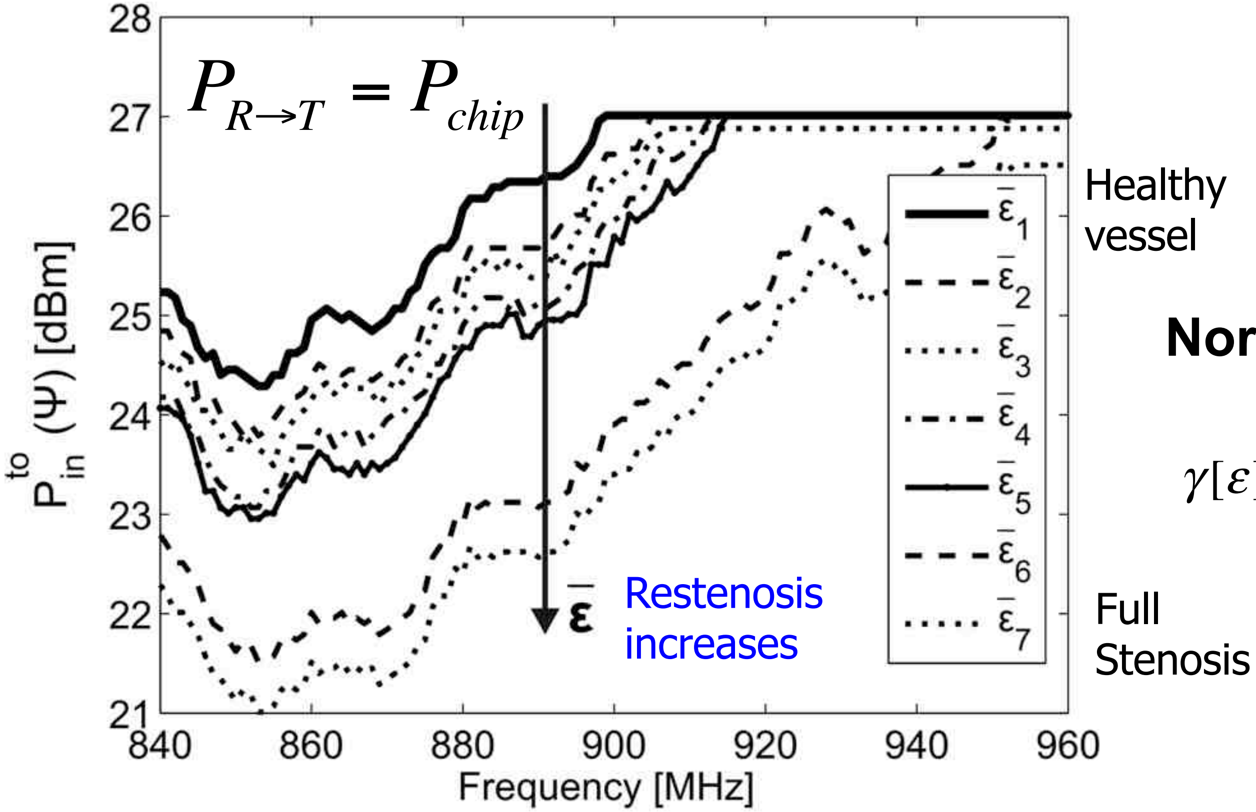
The STENTag
Measured data

The uncertainty in the measured data may be reduced by using all the frequency domain-data and introducing an averaging operator over frequency.

Turn on power



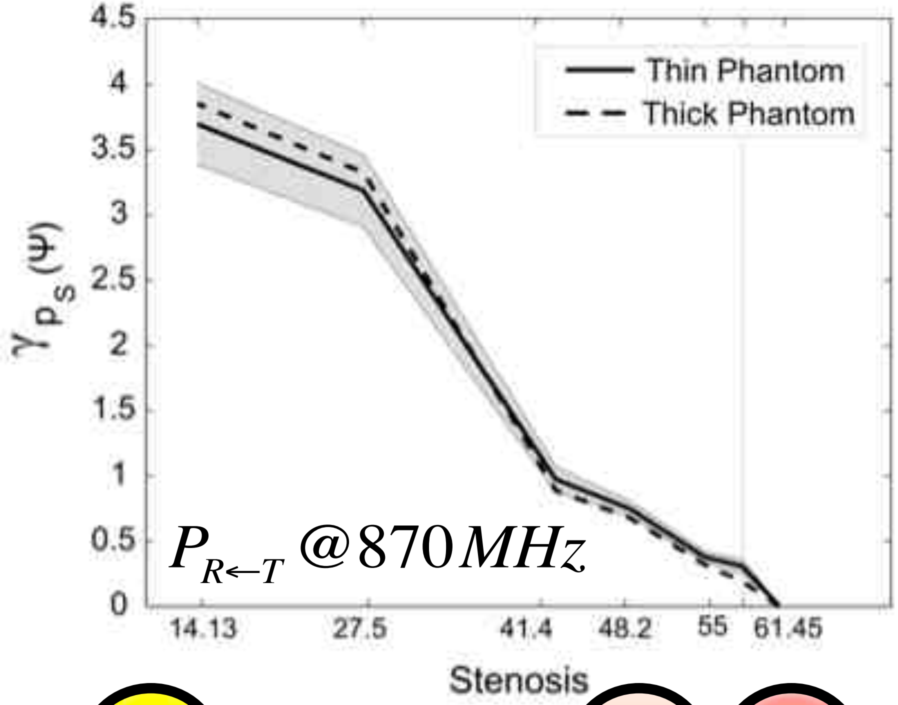
Dynamic Range 5dB

Normalized scale factor

$$\gamma[\varepsilon] = \frac{\int |p(f,\varepsilon) - p(f,\varepsilon_1)|\, df}{\int |p(f,\varepsilon_1)|\, df}$$

The STENTag

Measured data



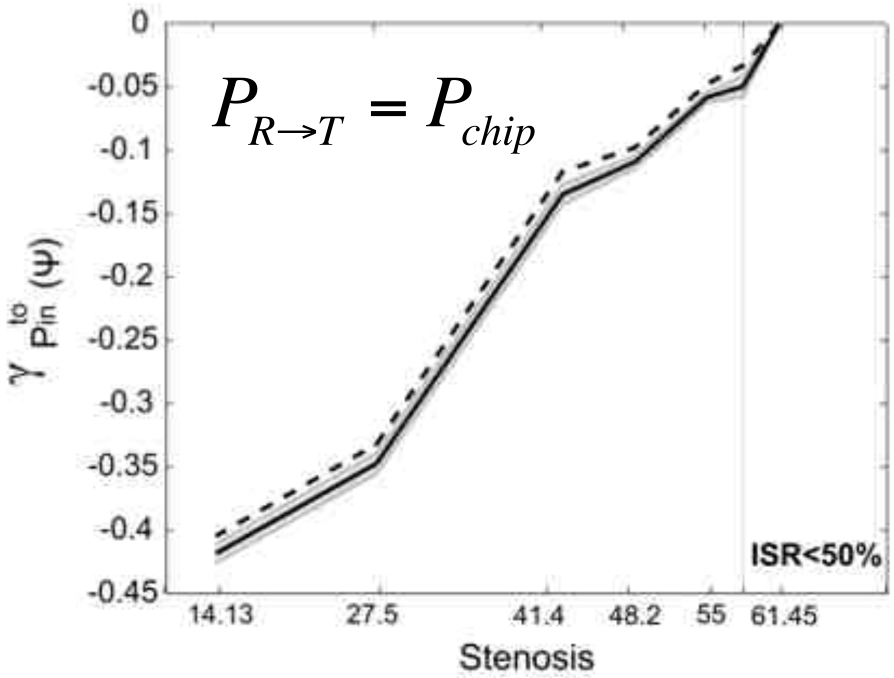


Table II
MEASURED RELATIVE CHANGES IN THE STENTAG RESPONSES

	$\Delta P_{to}^{in}(\%)$	$\Delta P_{R\leftarrow T}(\%)$	$\Delta\gamma_{P_{to}^{in}}(\%)$	$\Delta\gamma_{P_S}(\%)$
$\bar{\epsilon}_1 \rightarrow \bar{\epsilon}_2$	11%	33%	6%	38%
$\bar{\epsilon}_1 \rightarrow \bar{\epsilon}_7$	56%	400%	42%	370%

- **Statistically robust**
- **Independent on the size of the body**

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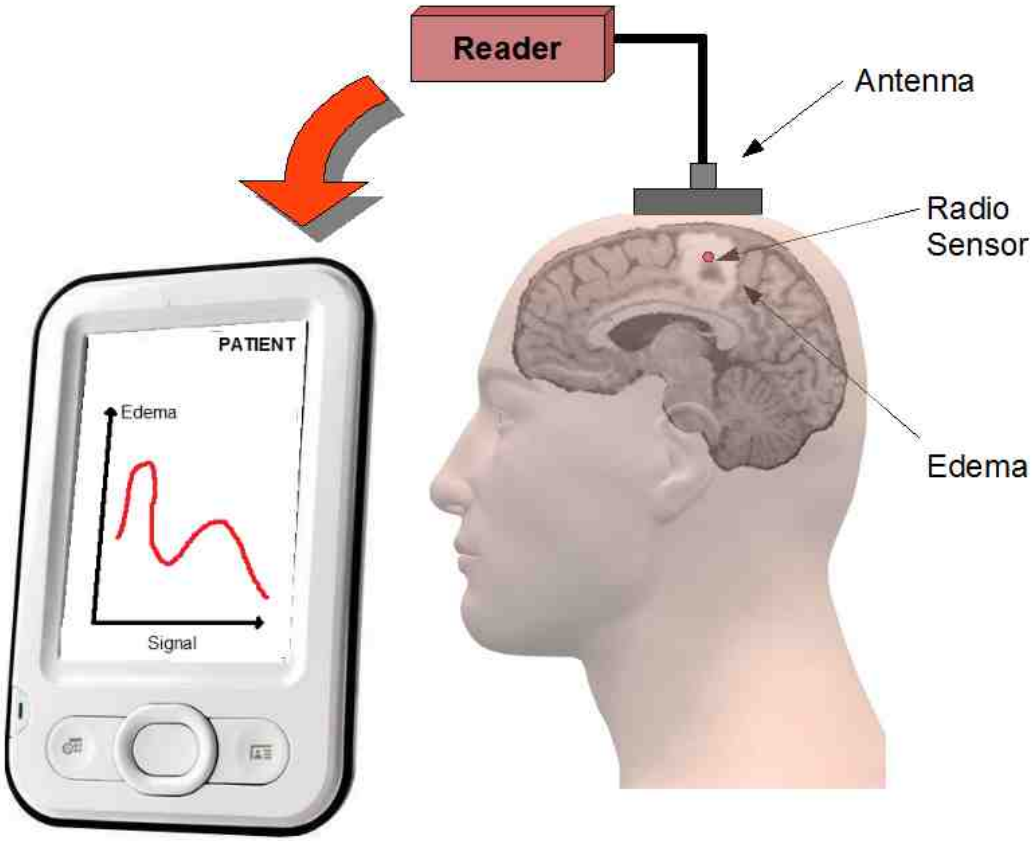
Brain Edema Growth

IDEA: A batteryless radio-sensor, comprising an antenna and a RFID microchip is implanted inside the brain into the removed tumor region. The radio-sensor is interrogated by an external reader and the signal reflected back by the sensor may be related to the edema arising and advance.



C. Occhiuzzi, G. Marrocco, "**Sensing the human body by implanted RFID tags**", EUCAP-2010, Barcelona, Spain

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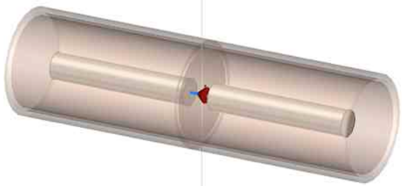
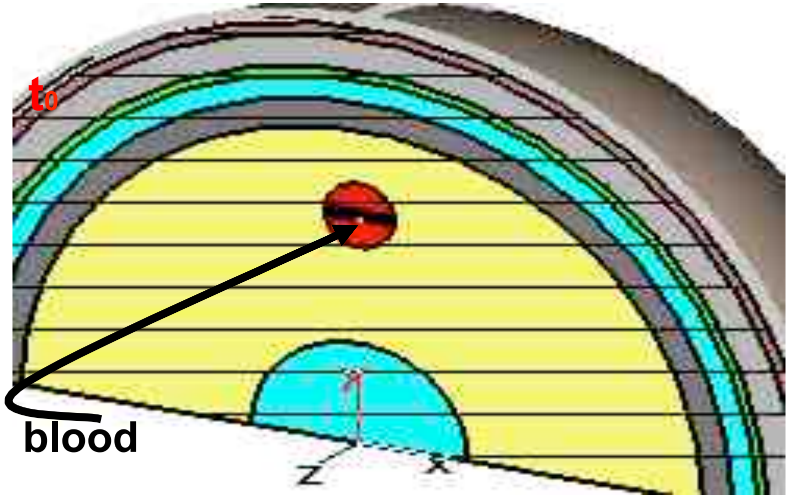
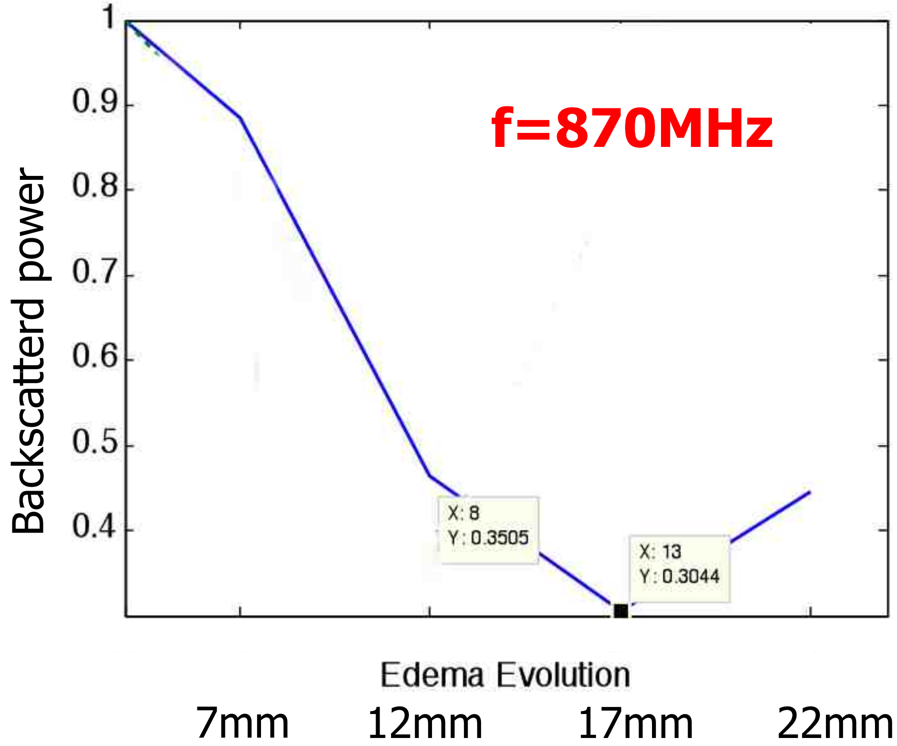
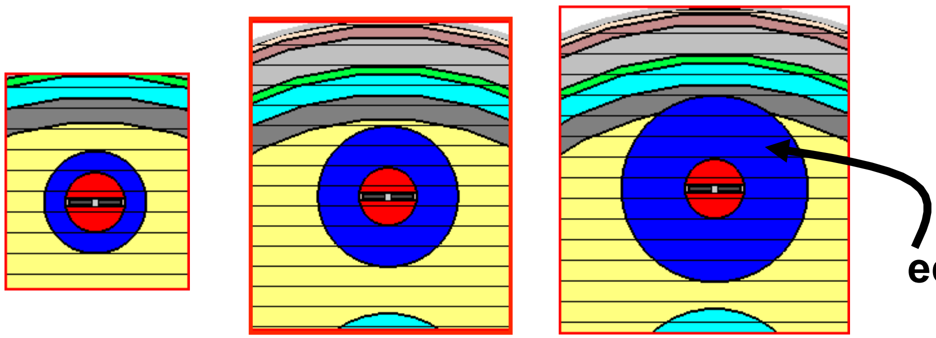
Brain Edema Growth
- numerical experiments







12mm 17mm 22mm



edema

A 1cm-dipole antenna covered by a silicon capsule and fully implanted in the center of the edema

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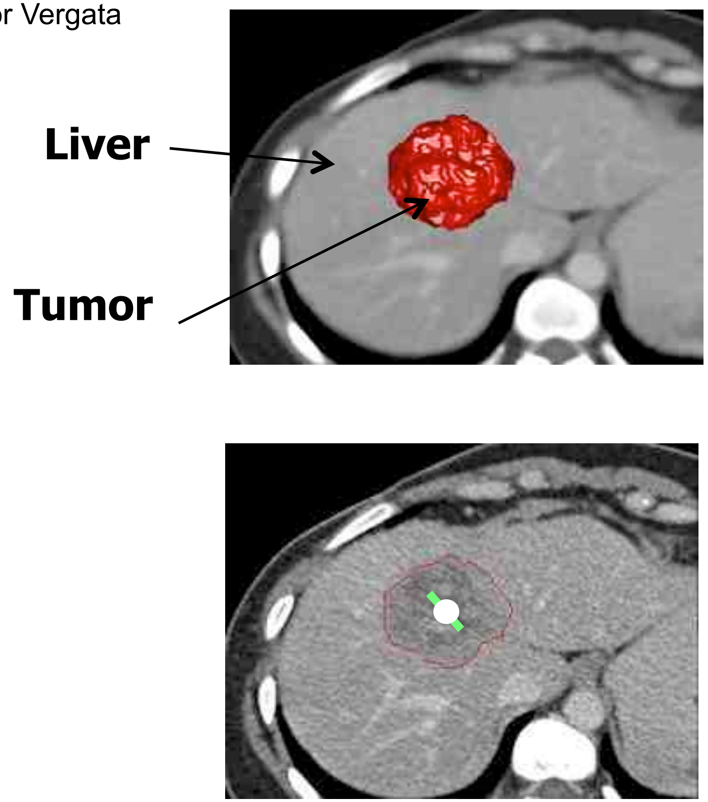
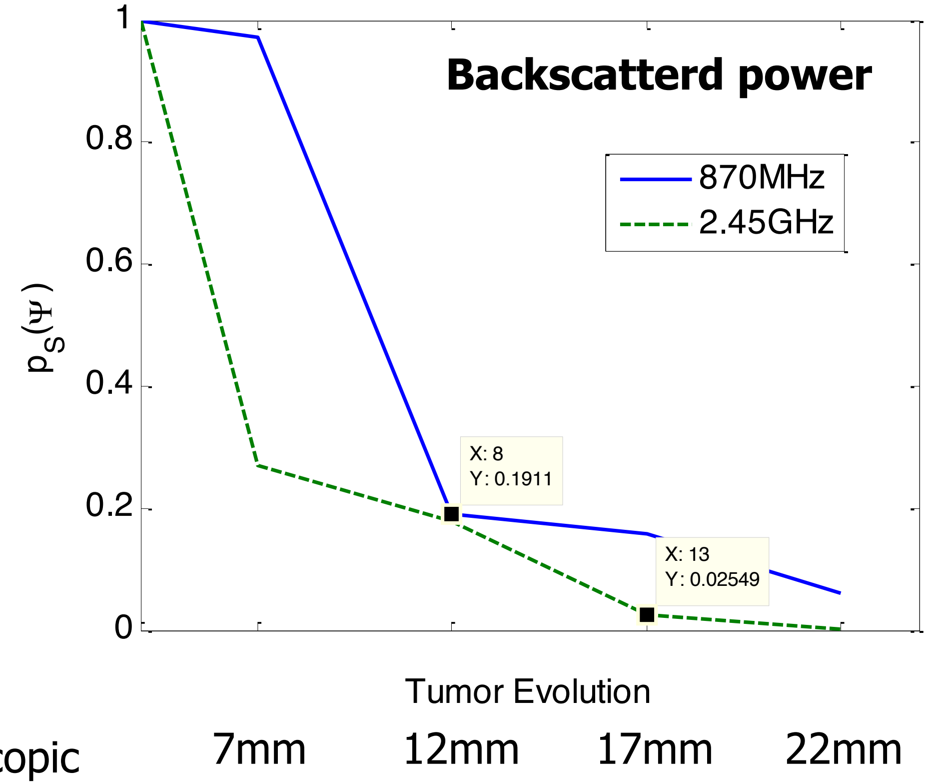
Tumor monitor





- Tag may be implanted by the same endoscopic probe used to deliver drugs.
- Increase or decrease of the tumor size produces a modification of the effective permittivity **sensed** by the tag

The tool could be useful to test the effectiveness of a specific drug

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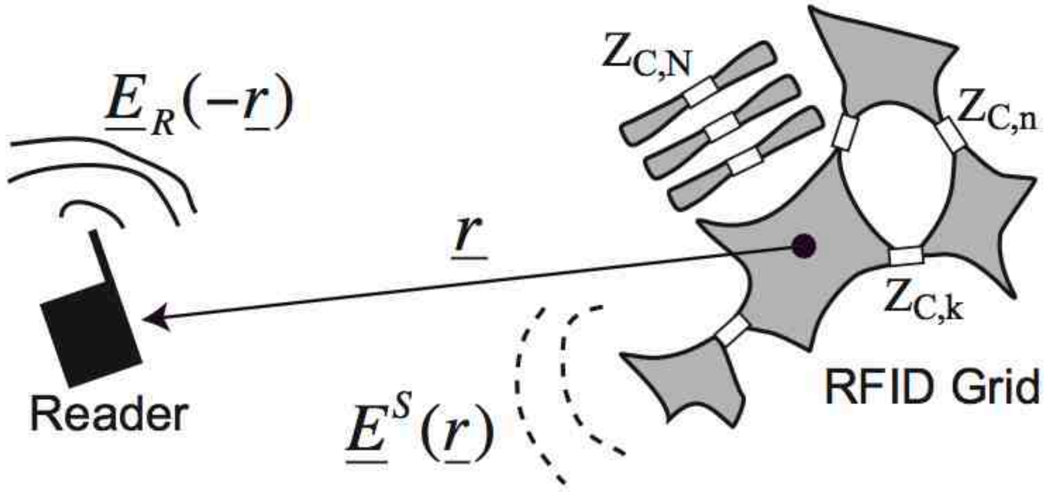
RFID Grids

RFID Grids (multi-chip systems)

The close displacement of UHF RFID tags can be considered as an electromagnetic interconnected system having specific properties



- **Cluster of single-chip tags**

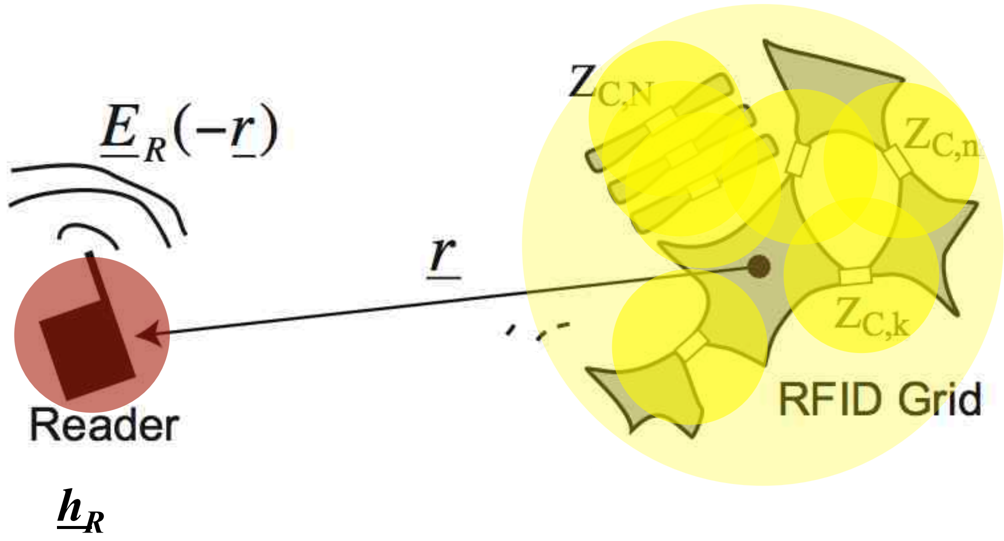
- **Multi-chip tags**

- **Both**

RFID equations ?
- **optimum matching**
- **observable invariants**
- **cooperative use**

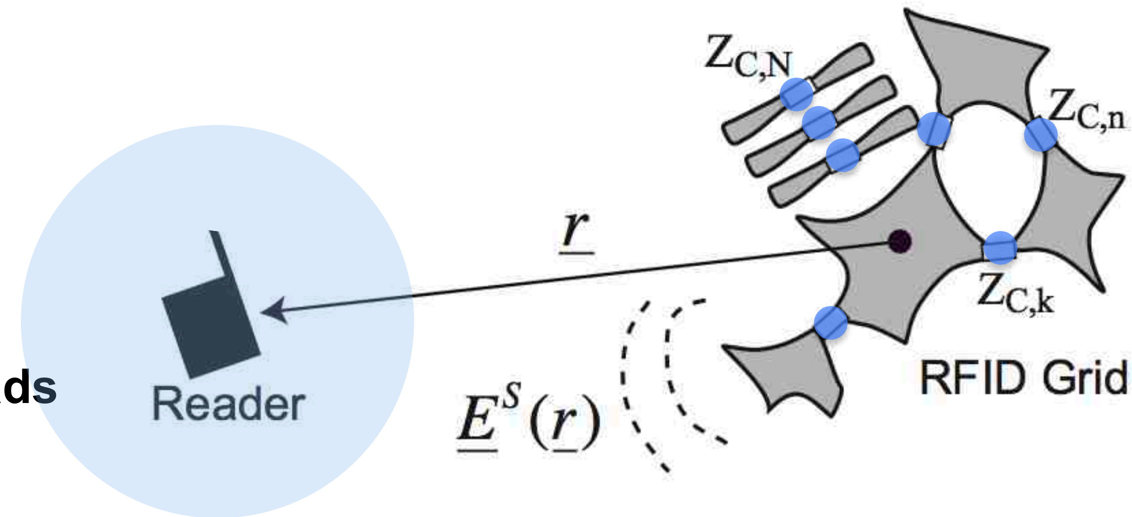
Keyword: inter-port coupling

RFID Grids: *links*



Direct Link (scavenging)

- A highly-coupled coherent system
- not an Array since there is no summation of received signals



Inverse Link (backscattering)

- Anti-collision protocol
- Multi-port scatterer with incoherent modulating loads

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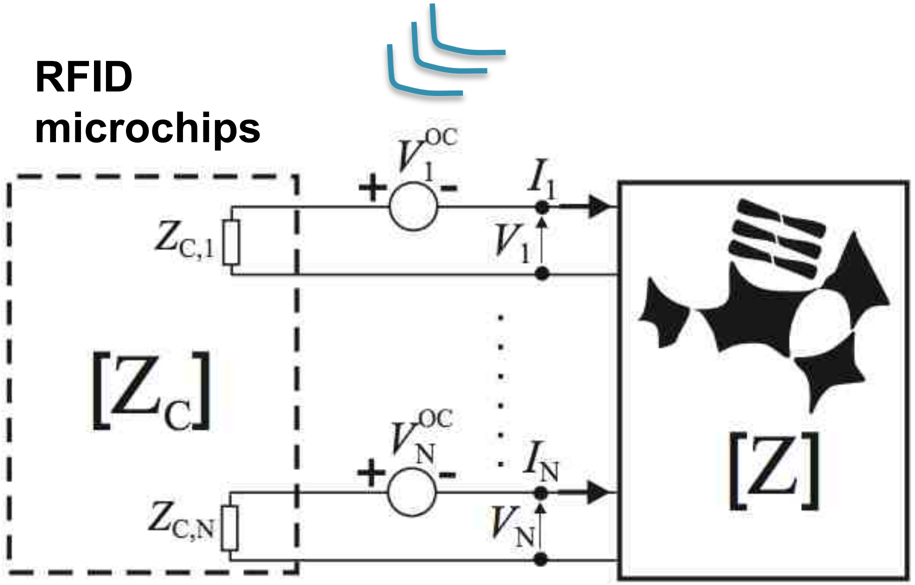
Model: Multi-port scatterer



Radiation / scattering

Embedded effective length & Gain

$$\left\{\underline{h}_n(\hat{\underline{r}}), G_n(\hat{\underline{r}})\right\}, \quad n = 1..N$$

Impedances

Network representation

$$\mathbf{I} = -\mathbf{Y}_G \cdot \mathbf{V}^{OC}$$

$$\mathbf{Z}_C = \begin{bmatrix} Z_{C,1}(t) & 0 & 0 & 0 \\ 0 & Z_{C,2}(t) & & 0 \\ 0 & & & 0 \\ 0 & & 0 & Z_{C,N}(t) \end{bmatrix}$$

$$Y_G = [Z + Z_C]^{-1} = [Z_G]^{-1}$$

Admittance Matrix of the Grid

J. R. Mautz, R. Harrington, "Modal Analysis of Loaded N-Port Scatterers". *IEEE Trans. Antennas Propagat.*, Vol.21, N.2, pp. 188-199, March, 1973

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Invariants

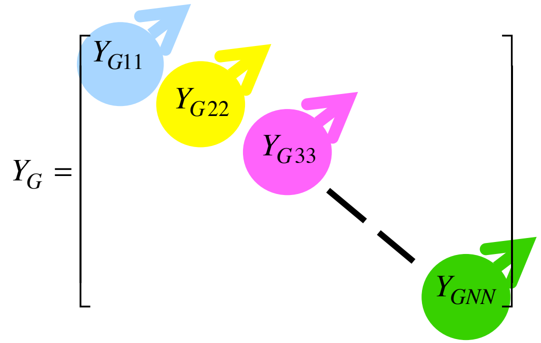
For RFID Grids it is possible to derive (distance, angle)-independent measured data

$$\frac{1}{s_n^{max}\sqrt{P_n^{to}}} \propto R_{C,n}\,|Y_{G,nn}| \equiv F_n$$

Analog Identifier of *n*-th port

Received Backscattered signal@ turn-on

Turn-on power



Analog IDs give information about the inner structure of the grid

Grid's Fingerprint

analog digital

$$F(\omega) = \begin{bmatrix} AID_1(\omega) & ID_1 \\ AID_2(\omega) & ID_2 \\ & \\ AID_N(\omega) & ID_N \end{bmatrix}$$

- Angle and position invariant
- Environment invariant
- Frequency dependent

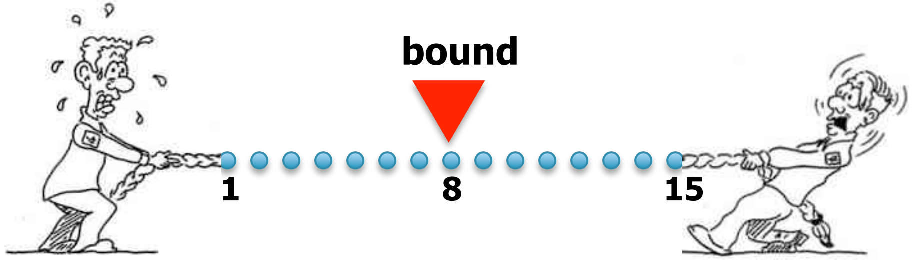
Data security

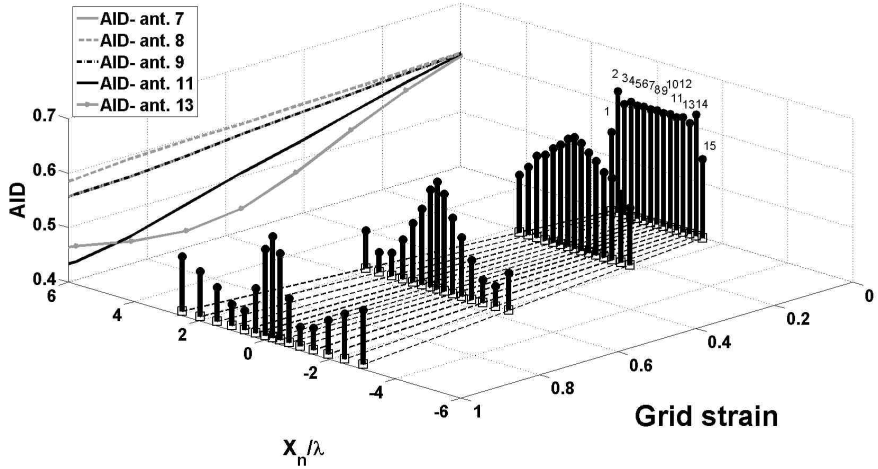
Multi-variate sensing

G. Marrocco, **"RFID Grids – Part I: Electromagnetic Theory",** *IEEE Trans. Antennas. Propagat*, 2011

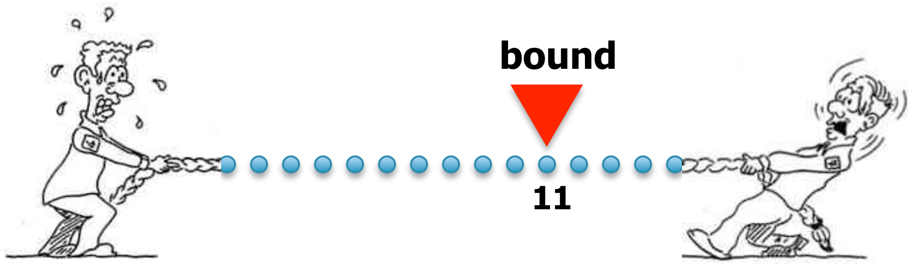
S. Caizzone, G. Marrocco, **"RFID Grids – Part II: Experimentations",** *IEEE Trans. Antennas. Propagat*, 2011

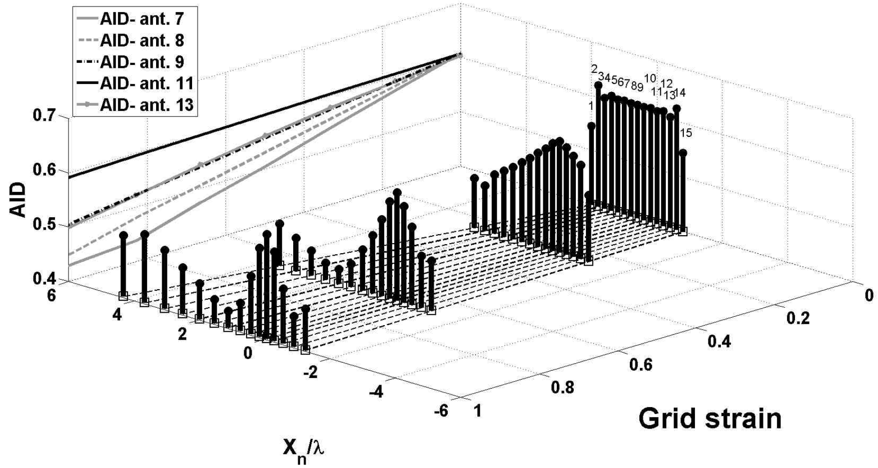
Applications
Localizing deformations





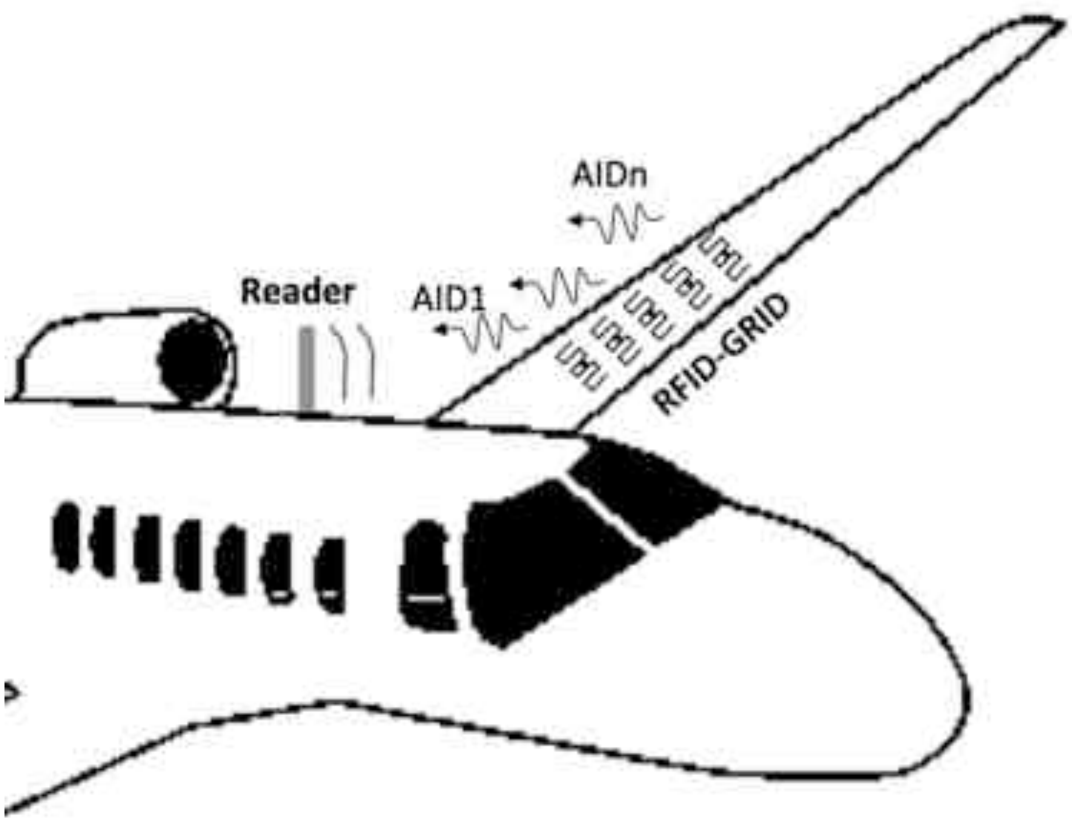
f=870 MHz





Possibility to recognize the position of a crack

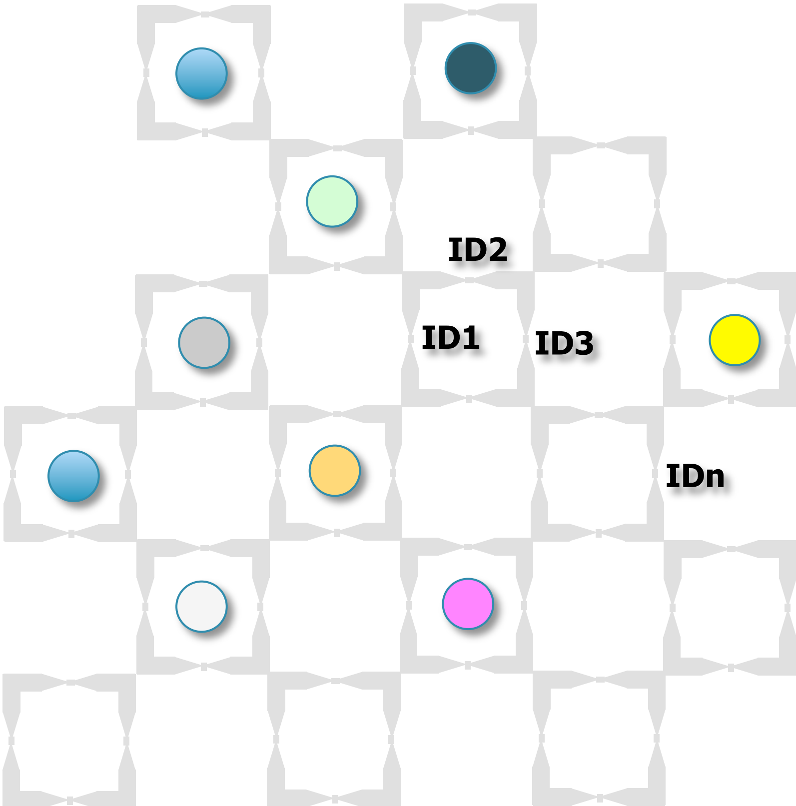
Applications
Deformation Sensing



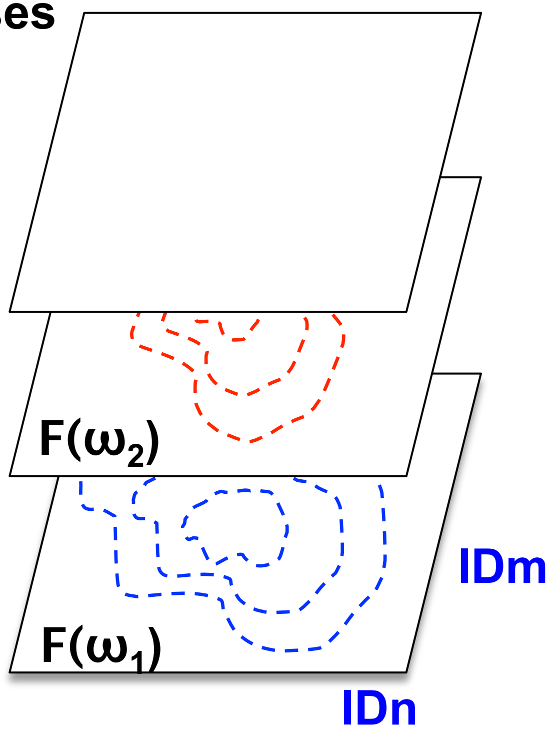
Applications

Lab-on-Tag

Smart skin



Grid IDs localize the multiple responses

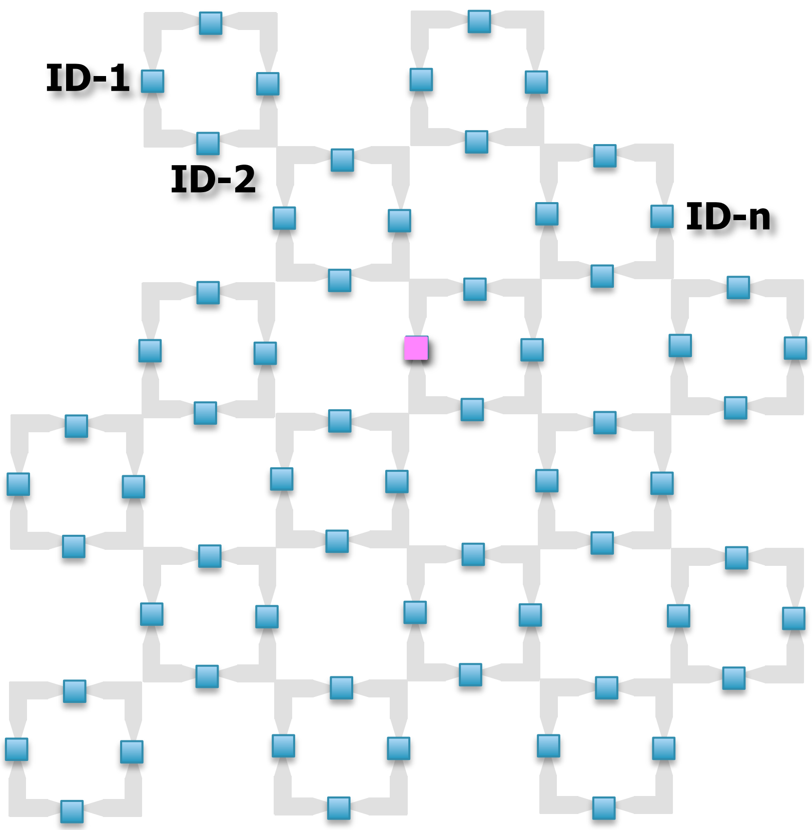


Conductors may be doped by several species of chemical receptors. It is conceivable to develop **smart self-sensing skins** suited to envelope things, plants and even body regions.

Applications

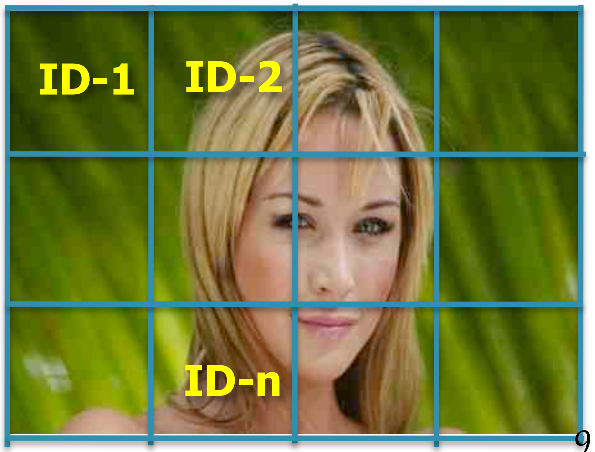
Distributed Wireless Access Memory

- **Memory node**
- **Index node (list of the sequence of IDs)**



- The grid is seen as a memory matrix wherein complex data are decomposed into packets and stored into the micro-chips' EPROM.
- Packets are recomposed by the Reader according to the list of IDs stored into the Index node.

Augmented version of a 2D-barcode



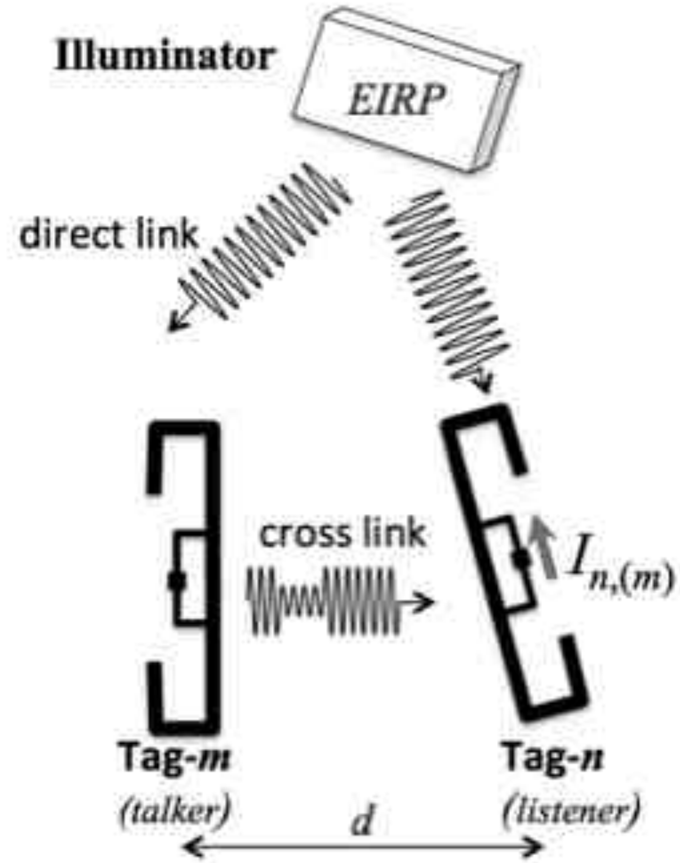
Tag 2 Tag Communication

Tags placed in close proximity may in principle directly communicate even in the absence of an RFID reader.

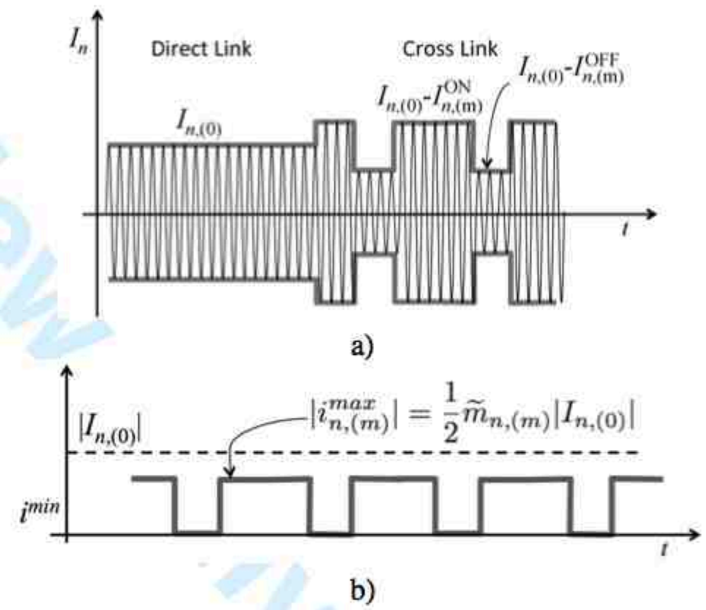
What is required is just an **illuminator** radiating a continuous wave able to power up the tags.

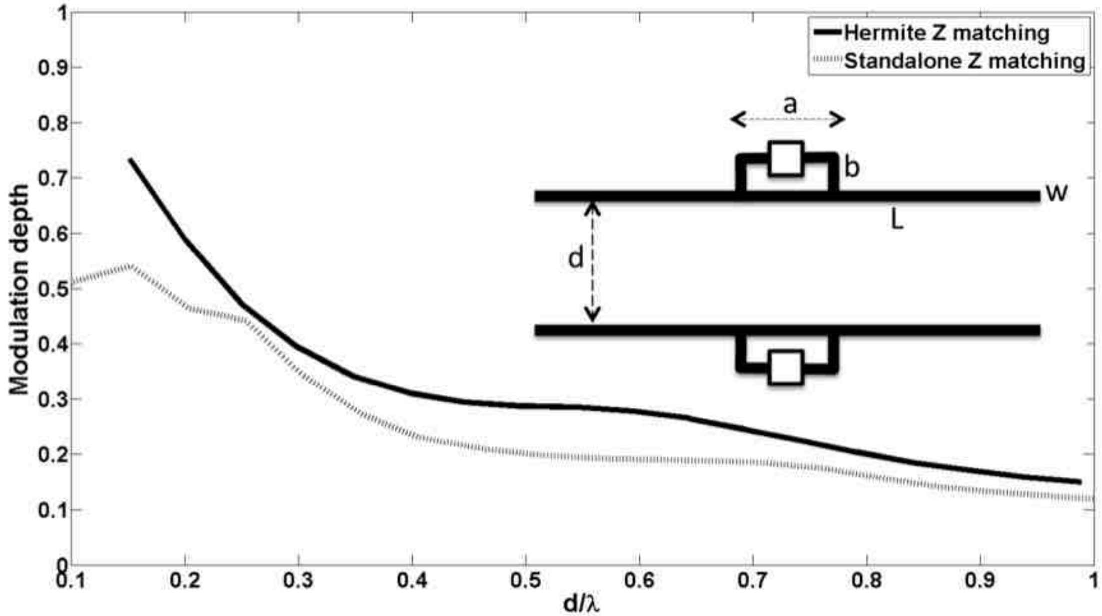
They could hence **communicate through backscattering modulation** of such a CW carrier.

(Nikitin, Rao and Lam, 2010)



Tag 2 Tag Communication





The performance parameter is the **modulation depth** which degrades along with the distance. It can be improved by mastering electromagnetic coupling

$$\tilde{m}_{n,(m)} = \frac{|Y_{G,mn}|}{|Y_{G,mm}|}\sqrt{\frac{\tilde{G}_m}{\tilde{G}_n}} \qquad BER_{n,(m)} = \frac{1}{2}erfc\left(\frac{|I_{n,(0)}|\tilde{m}_{n,(m)}}{2\sqrt{2\sigma}}\right)$$

S. Caizzone, G. Marrocco, "**Eletromagnetic Models for Passive RFID Tag-to-Tag Communications**", IEEE-TAP, under reviews

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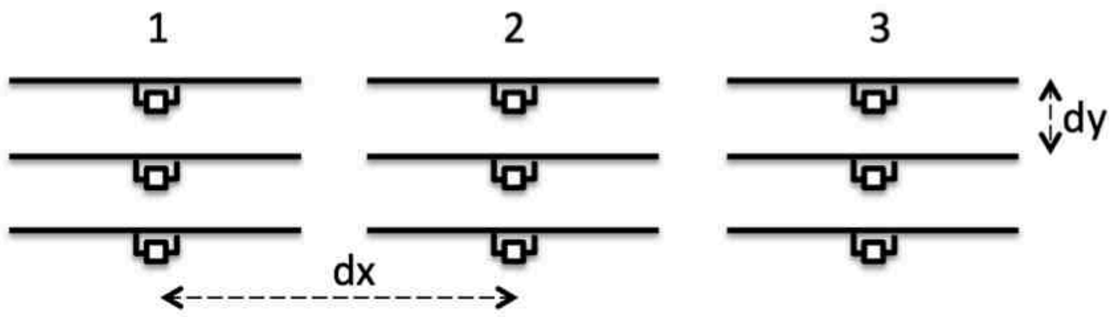
Rectangular Network



Circular-polarized illumination

Figure 7. 3x3 grid of T-match tags as in Fig.6. Grid spacing: $dx = 180$mm, $dy = 52.5$mm

$$m_{pq,(hk)}$$

pq: Listener position

hk: Talker position

$\tilde{m}_{pq,(1,1)}$		
-	0.12	0.08
0.53	0.04	0.01
0.23	0.1	0.04

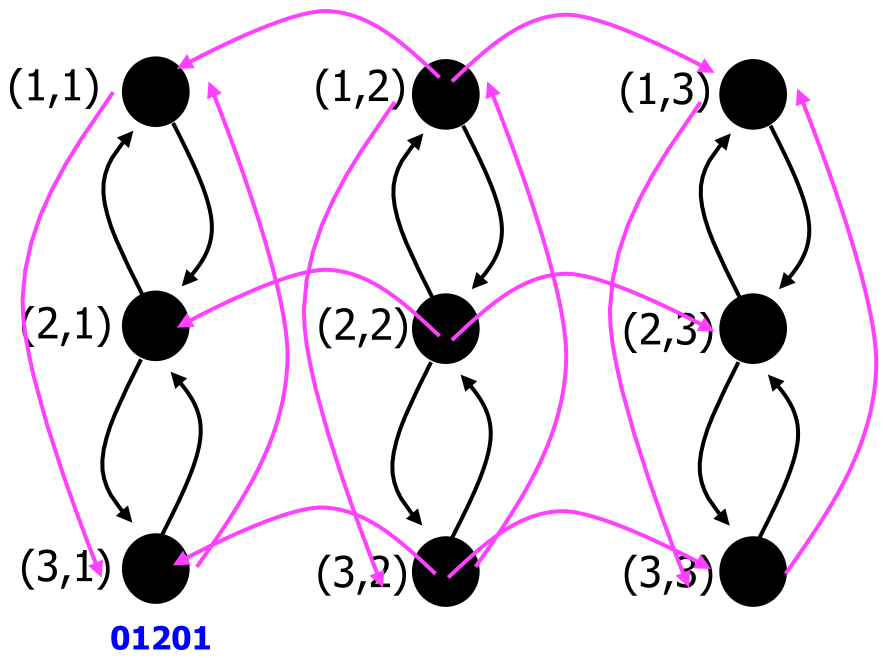
$\tilde{m}_{pq,(2,1)}$		
0.46	0.06	0.03
-	0.11	0.03
0.44	0.07	0.03

$\tilde{m}_{pq,(1,2)}$		
0.23	-	0.29
0.13	**0.43**	0.05
0.15	0.20	0.04

$\tilde{m}_{pq,(2,2)}$		
0.10	**0.54**	0.10
0.29	-	0.21
0.10	**0.51**	0.04

Figure 9. Modulation depth $\tilde{m}_{pq,(hk)}$ for the 3x3 grid of Fig.7 when the following elements act as talker: $(h,k) = \{(1,1),(2,1),(1,2),(2,2)\}$.

Rectangular Network
interconnection graph



$m_{pq,(hk)} \geq 20\%$

Two hops is enough to interconnect all the nodes

Tag 2 Tag Communication

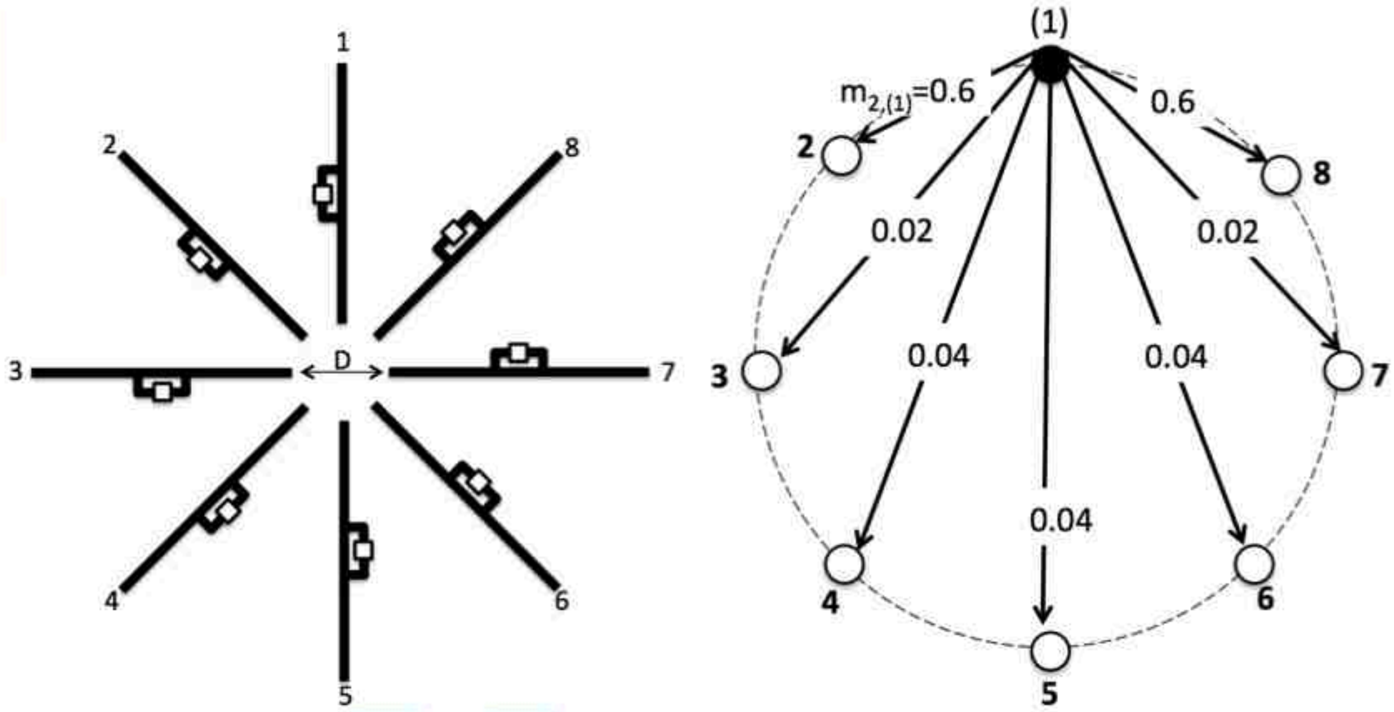


Figure 10. A circular grid of equal dipoles with distance D=40mm. right) Modulation index $\tilde{m}_{n,(1)}$ when the tag m=1 is talking.

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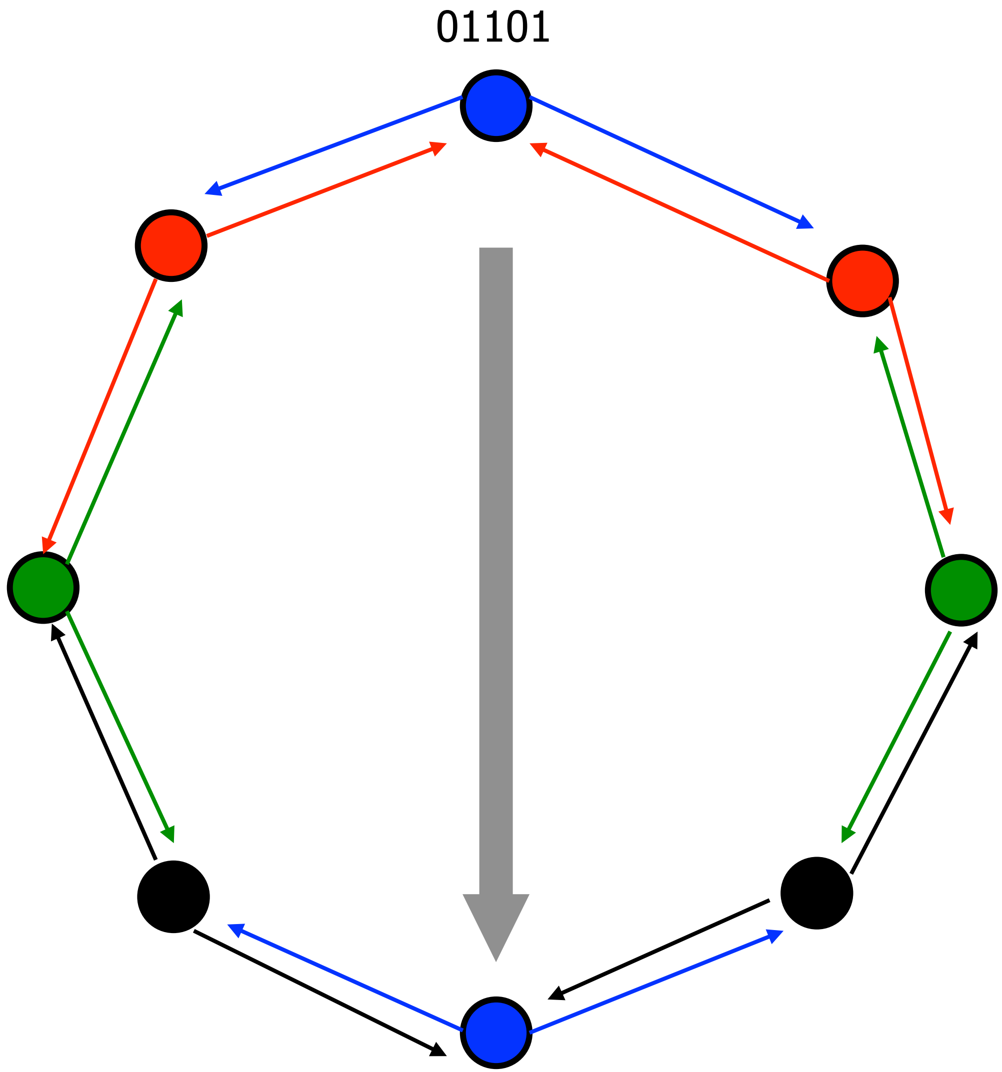
Circular Network
interconnection graph



The network is interconnected by multi-hop routing

Three hops to interconnect all nodes

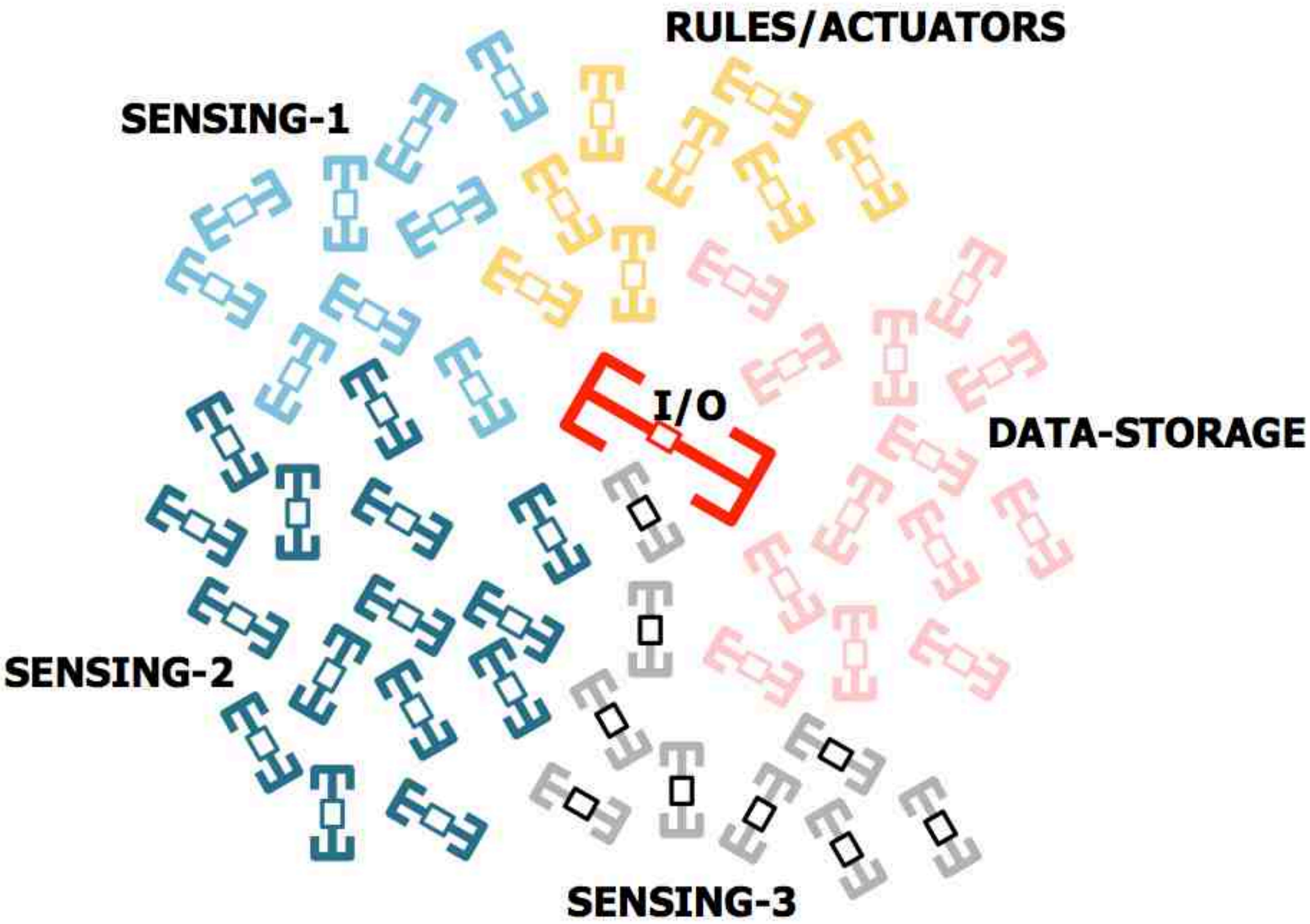
Tag 2 Tag Communication

Distributed computing

Random coalition of tags

Information and commands **percolate** from each node to the master.

The system could be anyway **scalable**



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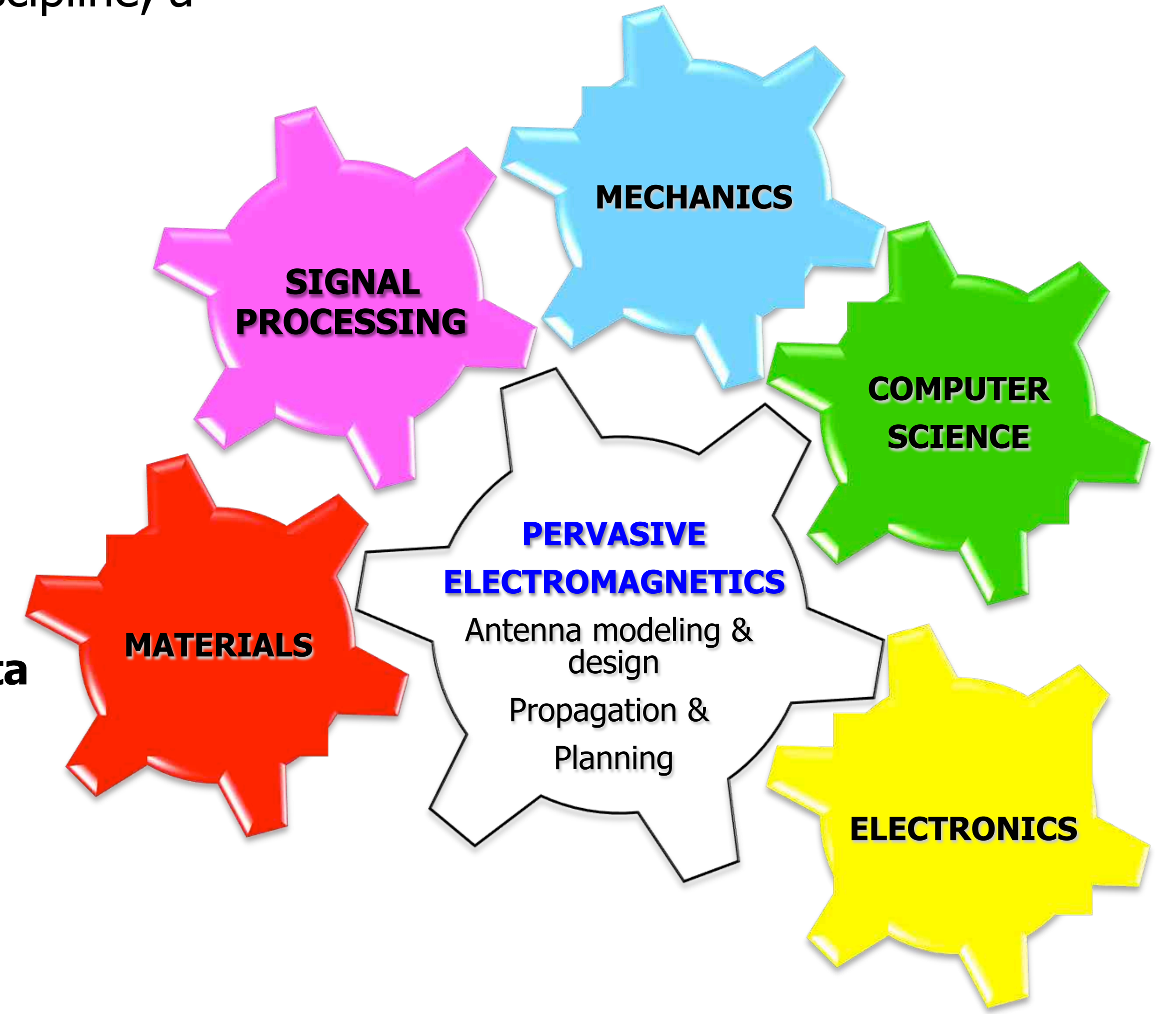
Conclusion

The research on the basic physics of data-capture, tag design, together with the low-level data processing can be considered as a particular edge discipline, a

Pervasive Electromagnetics

- different from the well assessed Remote Sensing, generally based onto the raw scattering from objects,
- addresses seamlessly **both the design of devices and the data processing**
- may profit by the digital intelligence distributed into the Things.



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Conclusion

- **RFID chemical sensors** could have a great commercial interest thanks to the fabrication simplicity and for the potential mass diffusion in food and pharma control chains.

- The design of S-tags is **not yet a mature discipline** since unified methodologies are still required to efficiently handle multi-physics optimization. **More on data processing**

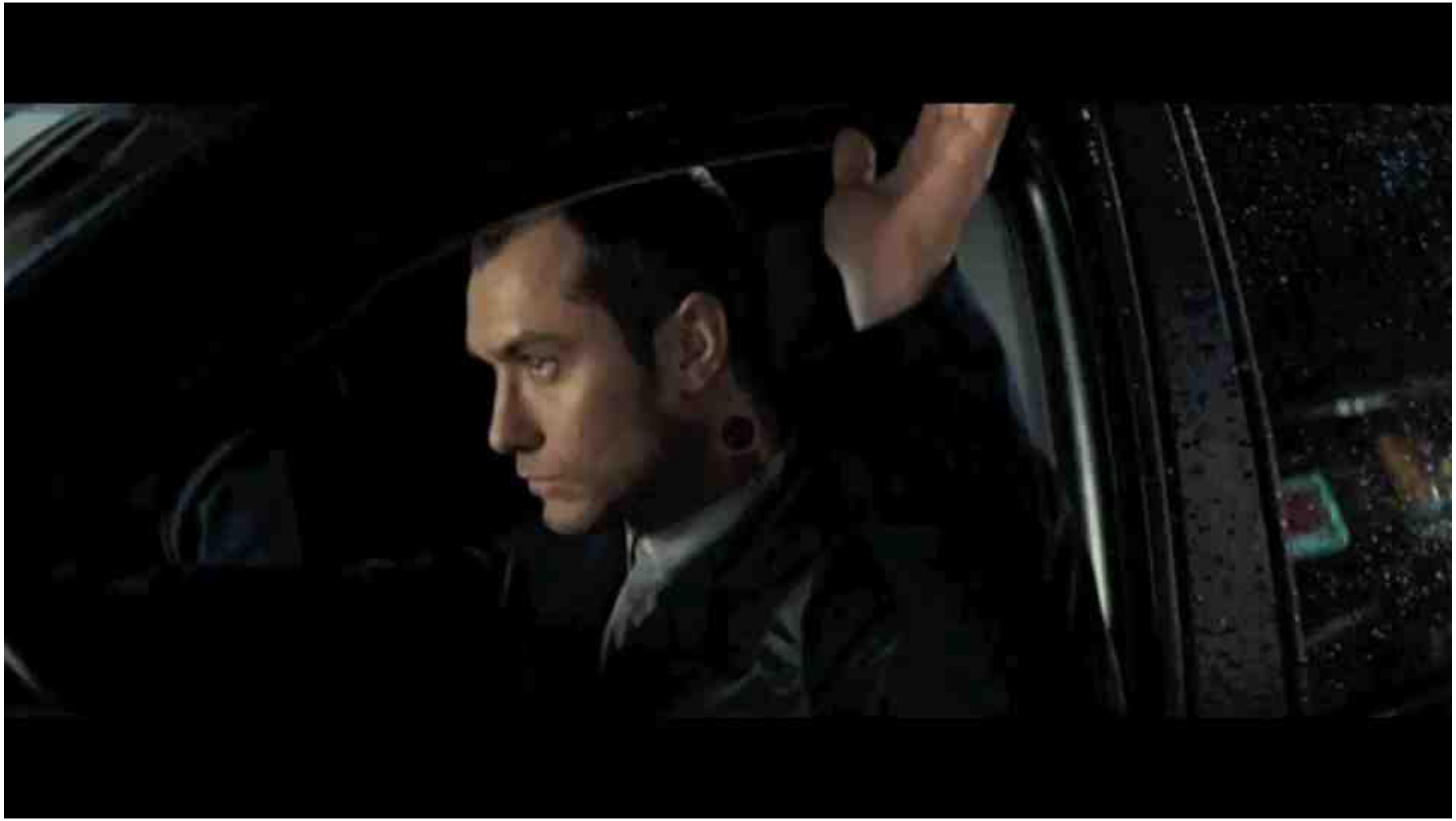
- Reduction of the chip sensitivity and improvement in reader's resolution,

- Multi-chip systems (**grids**, **tag to tag** passive communications)
  ➔ distributed computing

- Integration with **smartphones** with unpredictable applications in the distributed or ubiquitous computing boosting the evolution of the Internet of Things.

… the Dark Side …

From: **The Repo Man (2010)**



University of Roma

Tor Vergata

Many thanks !!

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