Implantable Antennas: The Challenge of Efficiency

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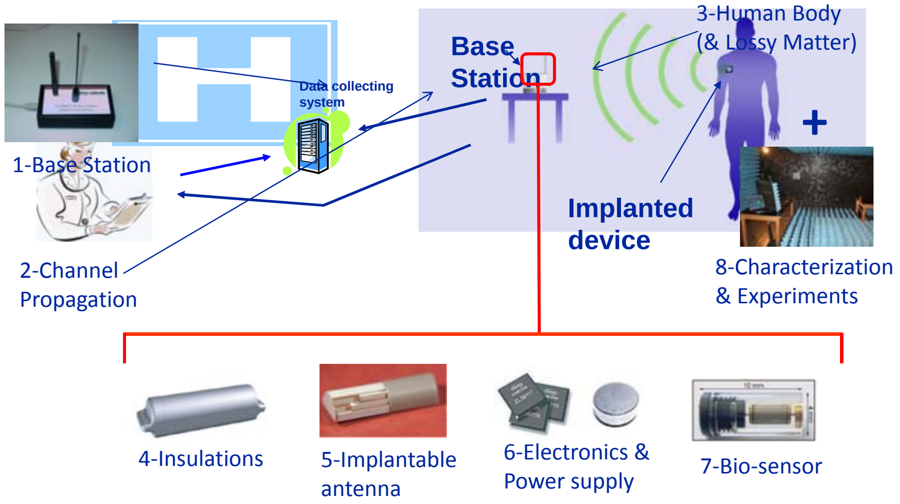
Outline

- Introduction
- Antennas in a lossy medium
- Design and Measurement issues
- Two examples
- Conclusions

Main Aspects of a Wireless Telemedicine System



System Requirements

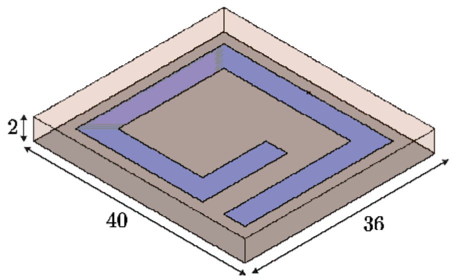
- Data transmission
- Patient comfort
  - autonomy of several years => Low power consumption
  - small volume
  - sufficient reading distance
- Patient health
  - avoid battery if possible
  - biocompatible encapsulation
  - emission values have to be respected
  - max SAR has to be respected
  - high reliability

Antenna requirements

- Physically small => electrically very small @ MedRad (401-406 MHz) and ISM (2.45 GHz)
- Enough bandwidth for the required data transmission
- Good radiation efficiency

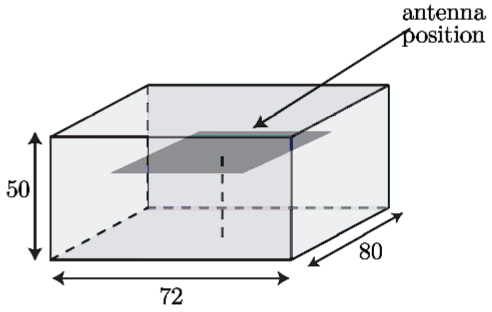
We want to maximize the power radiated out of the body

Antennas radiating into a lossy medium



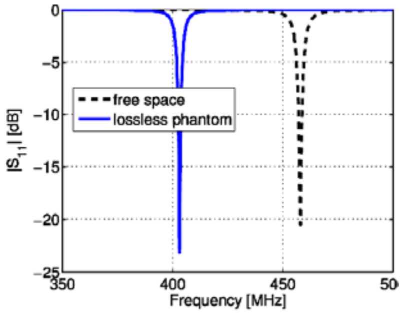
(a)

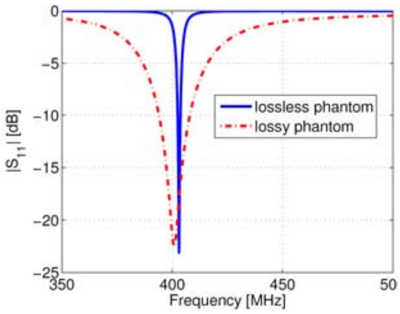
generic antenna for MedRadio, derived from design in:
J.Kim and Y. Rhamat-Samii, IEEE Trans. MTT, vol. 52. pp. 1934-1943, 2004



(b)

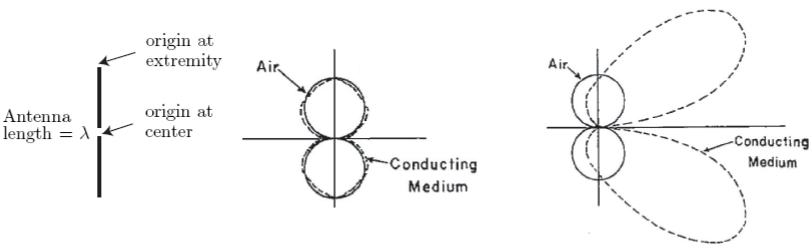
Antennas radiating into a lossy medium : effect on bandwidth





What is the meaning of the bandwidth ?

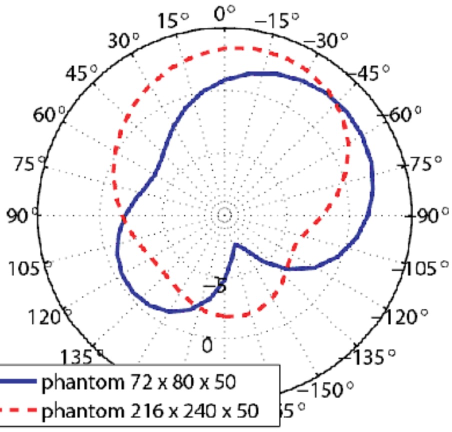
Antennas radiating into a lossy medium : effect on the pattern



Antenna with uniform curent | Origin at center | Origin at top

R. Moore, “Effects of a surrounding conducting medium on antenna analysis,” IEEE Trans. AP., vol. 11, no. 3, pp. 216–225, May 1963

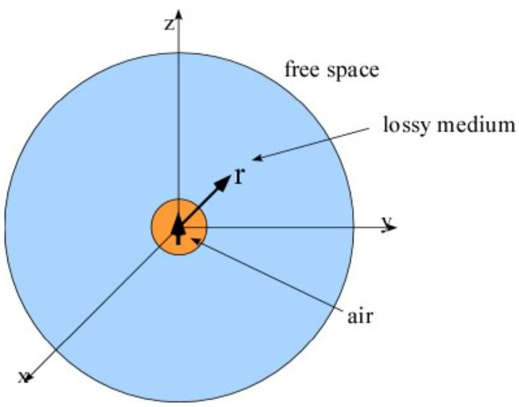
Antennas radiating into a lossy medium : effect on the pattern



In the case of our implantable antenna

What is the meaning of the radiation pattern ?

Antennas radiating into a lossy medium : Definition of efficiency ?



$$P_{Rad}^{TE} \sim \frac{1}{r^3}$$

$$P_{Rad}^{TM} \sim \frac{1}{r}$$

In the case of an implanted antenna :

$$\eta_{Rad} = \frac{P_{Rad}\big|_{\text{free space}}}{P_{Source}}$$

Depends on the host body !!!

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Main issues

- We have an electrically small antenna problem
- But : the antenna radiates into a lossy medium first, then into free space
- An insulation layer is required between the antenna and the lossy medium
- How does this modify our design strategy from a classical electrically small antenna design ?
- How does this affect the antenna characterization ?
- What is an adequate model of the host body ?
- What implications do the safety issues have ?

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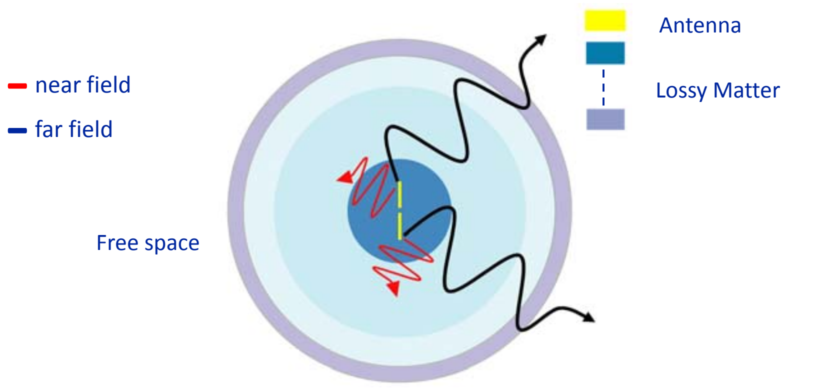
Antennas in Lossy Matter



- Strong coupling between the near-field and the surrounding materials
- Attenuation of the far field propagating in the lossy dielectrics

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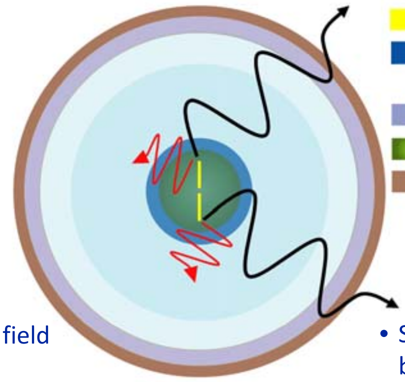
Biocompatible Insulation Layers: Motivation

near field

far field

Free space



Antenna

Lossy Matter

Internal insulation

External insulation

- Reduce the near field coupling
- Smooth the transition between the body and the free space

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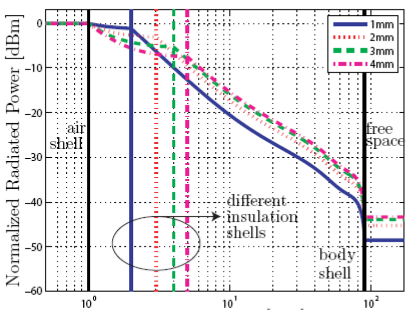
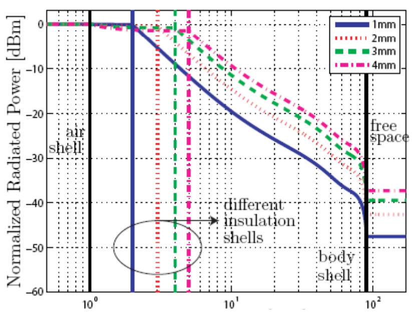
Effect of insulation layers

For an electric source and a classical muscle-fat-skin model



Radial distance [mm]



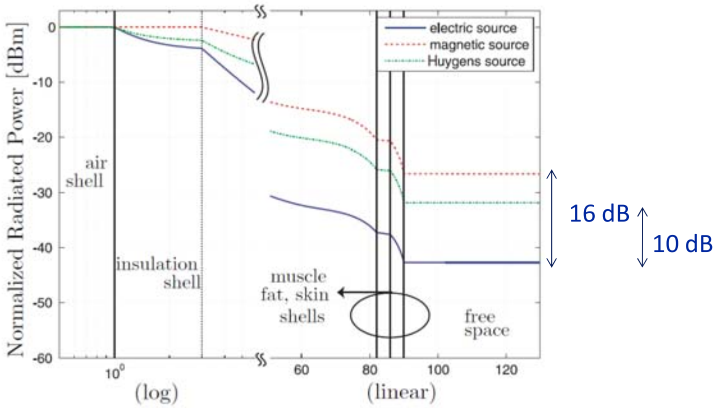
Radial distance [mm]

Polyethylene (εr=2.55 tgδ=0.003)

Zirconia (εr=29 tgδ=0.002)

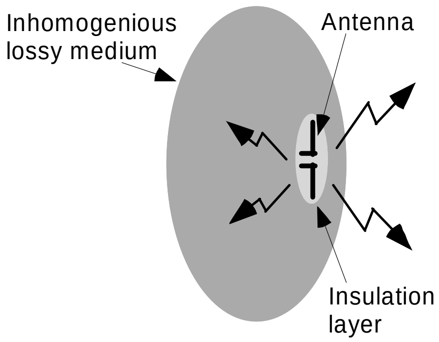
Internal Insulation: Different sources

With a 2 mm thick polyamide internal insulation



Radial distance [mm]

Main conclusions



The insulation layer should be used to help mitigating the losses

The near field region should as far as possible be in the insulation layer rather than in the lossy body

The type of antenna is of importance

Design procedure different then for classical ESA !!!

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Design Considerations

Classical ESA

- The figure of Merit is the efficiency bandwidth
- The near field should be min inside the antenna to maximize the bandwidth

Antenna for Implant

- The figure of Merit is the total radiated power (outside the host body) bandwidth, or the reading distance bandwidth
- The near field should be minumum in the lossy host medium to minimize the losses

Select an appropriate antenna family and use standart miniaturization techniques

- Analyze the effect of miniaturzation on FoM
- Analyze the effect of miniaturization on FoM

Different miniaturization techniques optimal for the two cases

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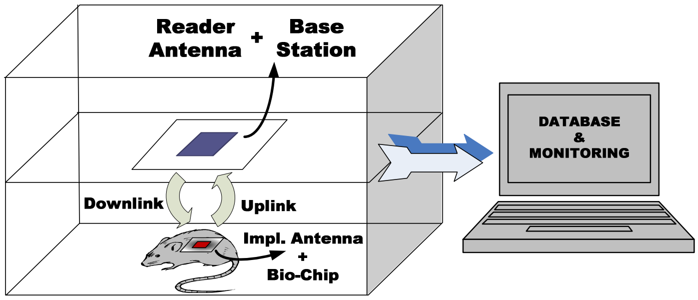
EXAMPLE 1: ANTENNA FOR A GENERIC IMPLANTS FOR RODENTS (MICE)

Remote powered transmitter @ ISM 2,45 GHz Band

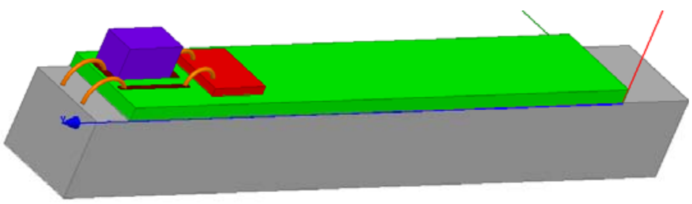
Figure of Merit: comply to regulatory safety issues

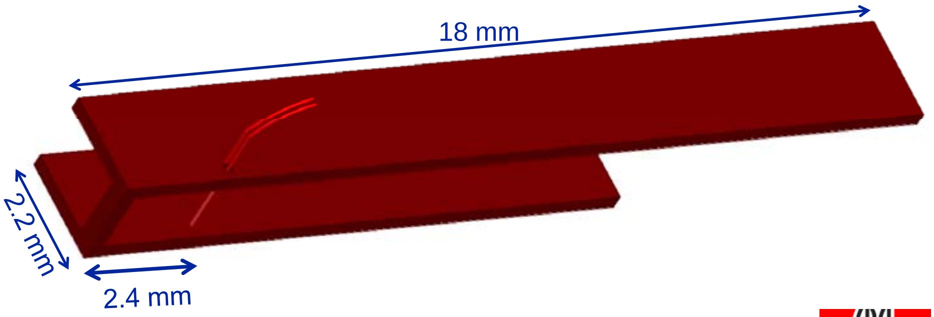
The problem



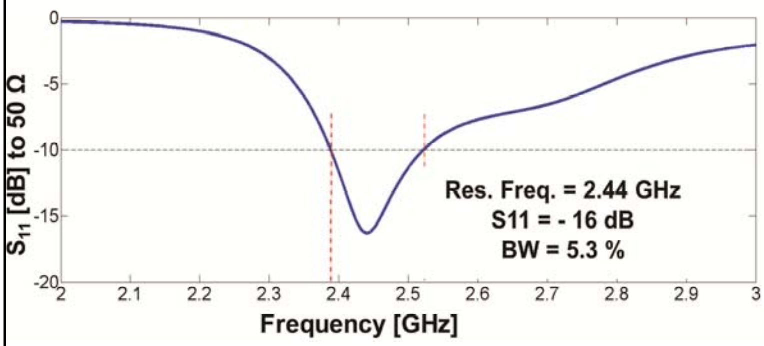
- Remote powering
- Short reading distance (5-10 cm)
- Small volume

The Implant and the antenna



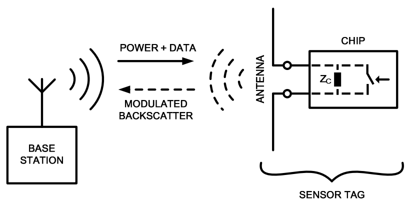


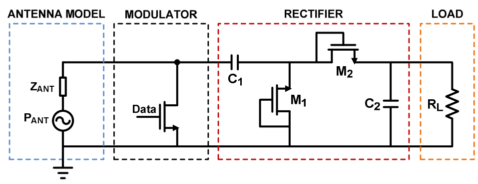
Antenna characteristics



Efficiency including the mouse : -3 dB
Matched to 30-j250 Ω

The system





- Regulation issues, Base station :
  - Max EIRP (EU RFID regulation): 27dBm
  - Max Re[S] at mouse position: 10 (50) W/m^2
  - Max field level at mouse position: 87 (193) V/m
- reading distance: 6 cm
- We would like a backscattered power of 0.8 mW

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Is it safe ?

- Human: In general, these have demonstrated that exposure for up to 30 min, under conditions in which whole-body SAR was less than 4 W/kg, caused an increase in the body core temperature of less than 1°C.
- Rodents: Decreased task performance (thermoregulatory response) by rats and monkeys has been observed at SAR values in the range 1–3 W/kg
- Rabbits: Ocular damage can be avoided if the microwave power density is less than 50 W/m^2
- adverse biological effects can be caused by temperature rises in tissue that exceed 1°C.

[4] ICNIRP Guidelines FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz) 1998

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Safety: Basic Restrictions at the considered frequencies

10 MHz – 10 GHz	occupational	public exposure
whole Body SAR [W/Kg]	0.4	0.08 (aver. 6 min.)
local Body SAR [W/Kg]	10	2 (aver. 10 g)

Safety: Reference Levels

2– 3 GHz	occupational	public exposure
|E| [V/m]	193	87
S [W/m^2]	50	10

ICNIRP Guidelines FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (UP TO 300 GHz) , 1998: "The reference levels are intended to be spatially averaged values over the entire body of the exposed individual, but with the important proviso that the basic restrictions on localized exposure are not exceeded".

IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, 2005.

http://www.bafu.admin.ch/elektrosmog/01100/01101/01103/index.html?lang=fr

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The system

We would like a re-emitted power of Pout=0.8 dBm

$$P_{out} = \text{Real}\{S_{in}\}\ \frac{\lambda^2}{4\pi}\ G_{rx}\ \chi\ \tau\ \eta_{rect}$$

P_{out}= 1.2 mW (+0.8 dBm)
S_{in}= Poynting vector at the mouse surface
λ = 12.24 cm at 2.45 GHz
G_{rx} = -1.5 dBi gain of the implanted antenna LP (incl.body losses)
χ = 0.5 pol. mismatch (impl. antenna is LP)
τ= 0.7 power transmission coefficient (antenna to implant rectifier)
η_{rect}=0.2 rectifier efficiency

This implies $\text{Real}\{S_{in}\} = 20.36\ \text{W}/m^2$

Regulatory compliant level ($\text{Real}\{S_{in}\} = 10\ \text{W}/m^2$) -> P_{out}= 0.588 mW (-2.3 dBm)

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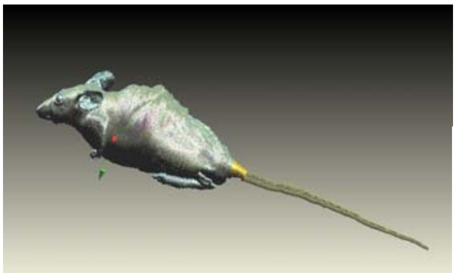
SAR and Temperature increase

B6F3Cl female Mouse, pregnant
28.7 g developed by IT'IS [5]
voxeled at 0.5 mm

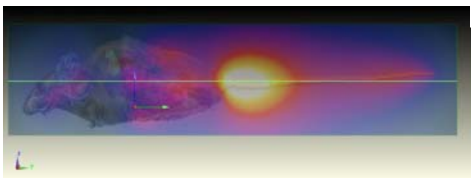


Whole Body SAR = 0.66 W/kg
(lim. 0.4 / 0.08)

10-g av. SAR = 0.78 W/kg
(lim. 10 / 2)

@ 120 s = max increase 0.151º

$\text{Real}\{S_{in}\} = 10\ \text{W}/m^2$



To ensure SAR limits, we have
P_{out}=-11.5 (-4.5) dBm

[5] ITIS FOUNDATION http://www.itis.ethz.ch/services/anatomical-models/animal-models/

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EXAMPLE2 : THE DESIGN OF ANTENNA FOR AN IMPLANTABLE GENERIC BODY MONITORING MODULE

dual band antenna : data transmission @ 401-406 MHz, wake up signal @ 2.45 GHz

Figure of merit: maximize reading distance

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Antenna conception

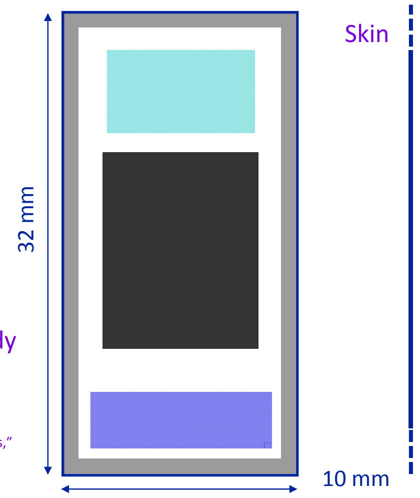
- Biocompatible insulation
- Circuitry
- Battery
- Sensor

a) Improve EM performance

A. Barraud, "Molecular Selective Interface for an Implantable Glucose Sensor Based on the Viscosity Variation of a Sensitive Fluid Containing Dextran and Concanavalin A," Ph.D. Thesis, EPFL, Lausanne, 2008.

b) Enhance radiation out of the body

- F. Merli et al., "Implanted Antenna for Biomedical Applications," *AP-S 2008, San Diego*.



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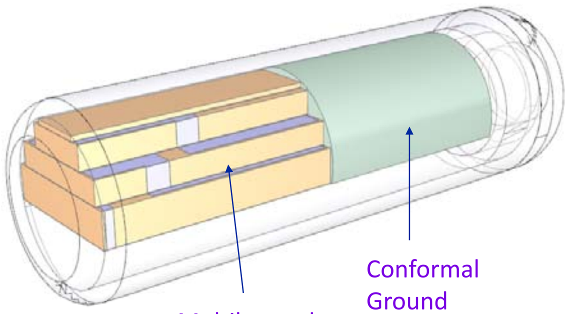
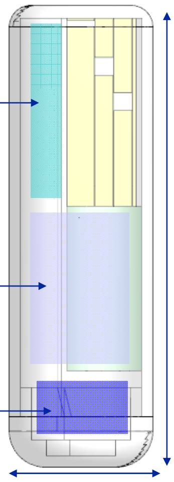
Antenna Structure





- F. Merli et al., "Design, realization and measurements of a miniature antenna for implantable wireless communication systems," *IEEE Trans. on AP.*, submitted for publication.
- L. Bolomey et al., "Telemetry system for sensing applications in lossy media", Patent application: 00335/10.

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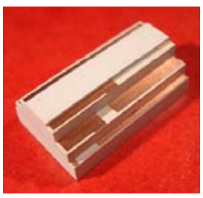
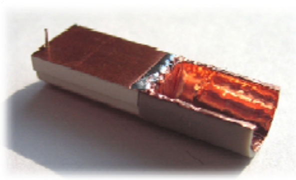
Antenna Realization

Substrate: Roget TMM (ε_r = 9.2)

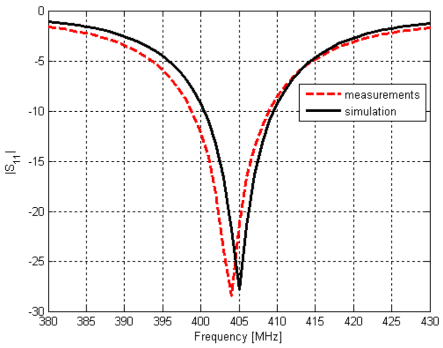
Insulation: PEEK (ε_r = 3.2)

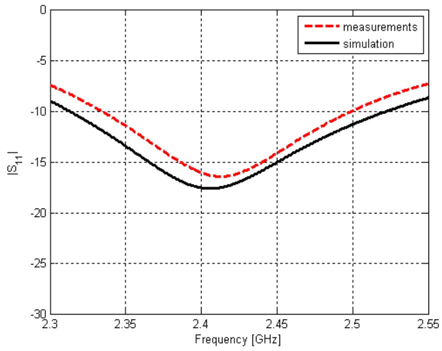




Antenna Matching measurement (*in-vitro*)

EM performances of the antenna alone have been checked with a feeding coaxial cable (present only for testing purposes).



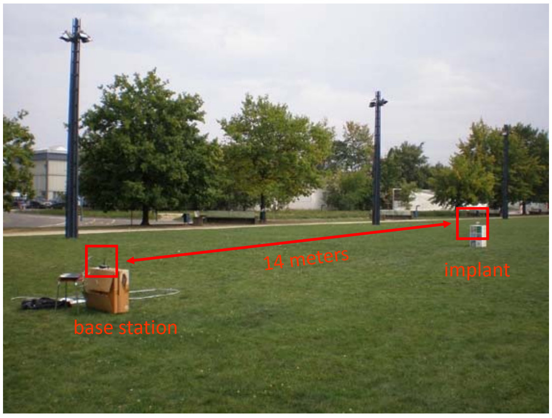


System Measurements *In-vitro*

Zarlink BS is considered
System controlled via a laptop (*Labview*)

Outdoor MedRadio Tests:
- TX power -3 dBm

channel	max range [m]
0	7
4	14
9	14



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System *In-vivo*

Implantation (*in collaboration with* the Stem Cell Dynamics Laboratory, LDCS):

Two devices have been implanted at different locations,

- subcutaneous (5 mm)
- in muscle tissue (30 mm)

Target:

Continuous monitoring of subcutaneous temperature of a pig

Characteristics:

- Measurement during the implantation procedure
- Temperature check every 5 min. Complete working cycle (*wake-up, measurement, transmission…)* for 15 days

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System *In-vivo*

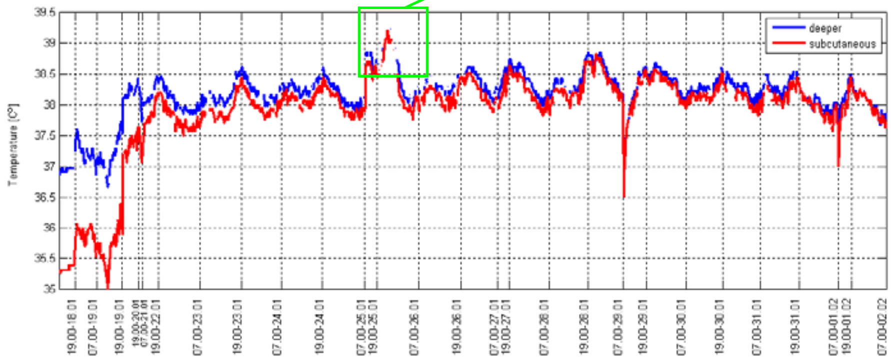
Implantation in accordance to all ethical considerations and the regulatory issues related to animal experiments.

In vitro sensor for room temperature comparison

System Measurements *In-vivo*

Highest relative error

(*biological explanation*)



Conclusions

- Implantable antennas are ESAs
- Classical ESA design techniques can be used, but :
  - The critical issue is to control the near field
  - Use the insulation layer as an additional degree of freedom to optimize the data link
  - check the link budget versus regualtions
- Key Figure of Merit always linked to efficiency
- Take great care when performing measurements

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Aknowledgements

The antenna guys

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Francesco Merli

Eric Meurville

Léandre Bolomey

The system guys

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François Gorostidi

The doctors