# Research Roadmap (2009-15) :: Agnelo R. Silva

**Ultimate goal** ➡ **Wireless communication in soil, mid-range distances (15..50m)**

**Initial research aspects**
1. **High energy efficiency** ■ ■
2. **High-reliability** ■ □
3. **Robust underground wireless PHY channel** ■ ■ □

**Additional research line** ➡ **4. Applicability of the Electrode Polarization effects** ■ ■ □

*Wireless communication in the subsurface has many scientific, commercial, disaster management, and security applications. However, no robust method has been practically proven for this application and this is the ultimate goal of our research. It proved to be a multidisciplinary research effort.*

**Precise irrigation**

**Infrastructure monitoring**

**Situational Awareness (SA) systems**

*Knowledge areas:* ■ *Networking* ■ *Elect. Circuits* □ *Software engineering* ■ *Applied EM* □ *Electrochemistry*

*PHY: Physical OSI layer*

## Research Roadmap :: 1) Energy-efficient communication

Buried sensing/communication device

Few/no energy harvesting opportunities

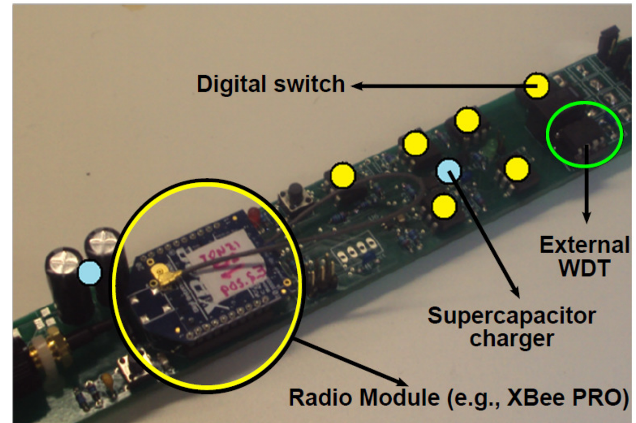
Non-rechargeable batteries

Typical requirement

Multiple-year battery lifetime

Application characteristic

Nodes with static topology




Networking cross-layer solution: Ripple2 architecture

BETS protocol

Energy-aware hardware

Ripple2D+ ED node

Ripple3 ED node

*Used at the NASA-funded SoilSCAPE Project: proven-concept for free-space communication*

*Most important personal achievements*

*BETS: Best-Effort Time-Slot allocation*
*ED: End Device*

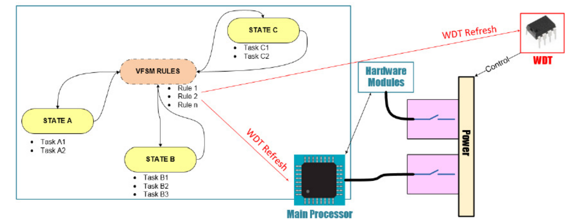
## Research Roadmap :: 2) High-Reliability

Buried sensing/communication device

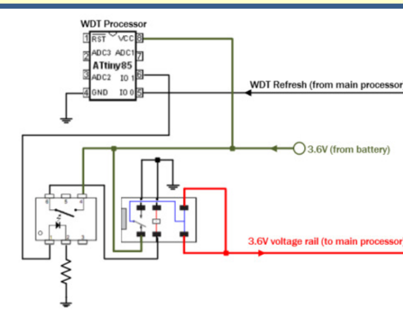
Few/no human intervention

Extremelly reliable system

Novel *software engineering* methodology for unattended embedded systems (VFSM+WDT)




*Watch-dog timer* solution with assured power recycle



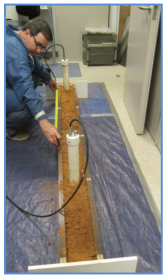

*Intelligent probe* concept:
- self-protection (probe issues)
- data-quality done at PHY layer
- dynamic sampling rate at PHY layer

*This concept was partially demonstrated at the Ripple3 ED node*

*Most important personal achievements*

*VFSM: Virtual Finite-State Machine*
*WDT: Watch-Dog Timer*

## Research Roadmap :: 3) Robust underground wireless PHY channel



Sub-MHz soil dielectric model

*Soil's dielectric properties*

MI signal attenuation model

MIS

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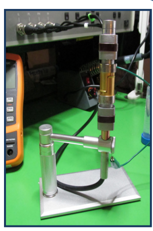
Validation of Sub-MHz soil dielectric models

Reliable dielectric measurements of multi-composite materials (Geophysics & Material Sciences)

EIS

MI design optimization

Real-world implementations of MI comm.systems



EP effects

Method of identification of Electrode Polarization effects in dielectric measurements

Novel sensing applications

*This concept was partially demonstrated at the Ripple3 ED node*

*Most important personal achievements*

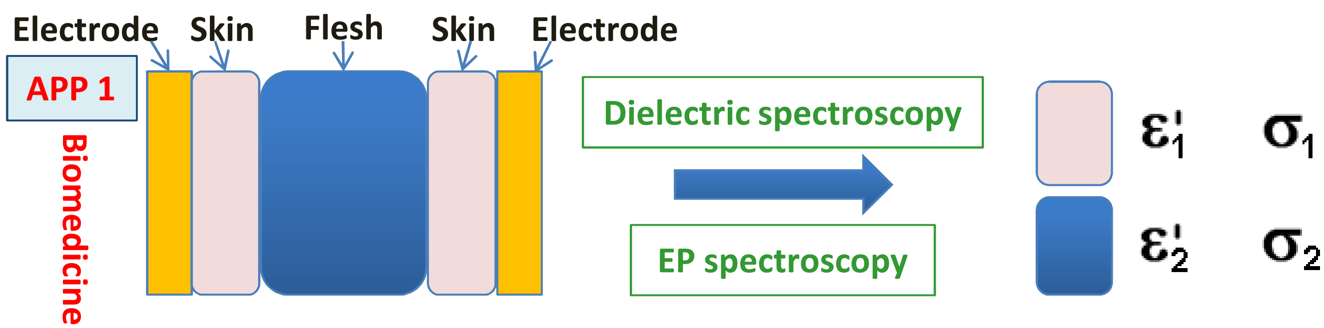
*MI: magnetic-induction*
*MIS: magnetic-induction impedance spectroscopy*
*EIS: electrochemical impedance spectroscopy*
*EP: electrode polarization*

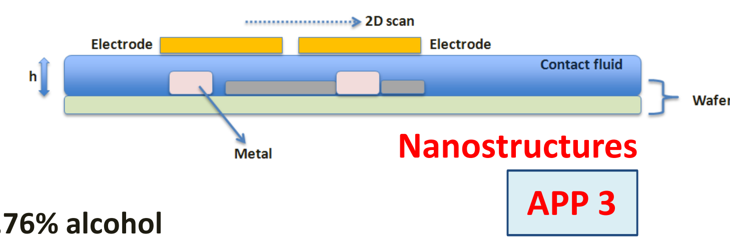
# Research Roadmap :: 4) Applicability of the EP effects

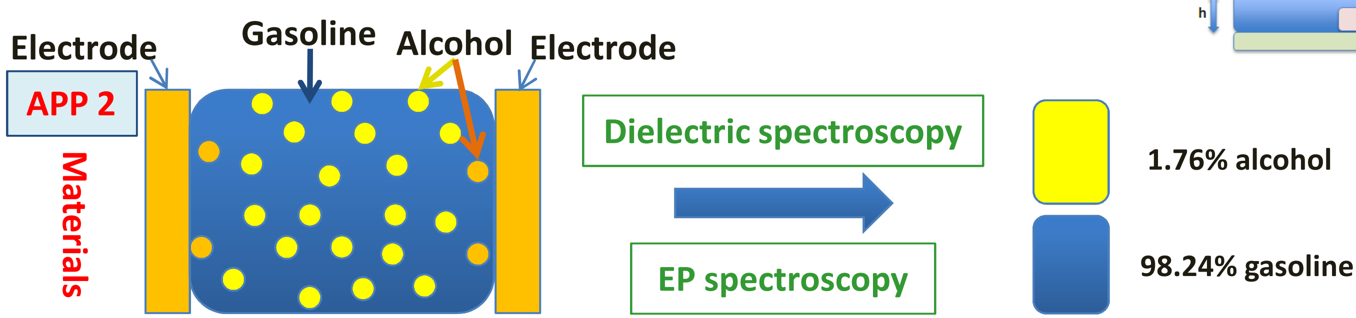
**EP effects** → **Method of identification of Electrode Polarization effects in dielectric measurements** → **Novel sensing applications**

*Probably the most important of our achievements* ➔ *<u>partially related to the original research goal</u>:*

- *the Electrode Polarization (EP) effects at the dielectric measurements have been eliminated by multiple techniques during the last 125 years* ➔ ***our approach is different****:*
  1. *identify (rather than eliminate) these effects* ➔ *calculate the true dielectric values of the material*
  2. *use the EP spectroscopy data* ➔ *infer about the dielectric properties of the region **close** to the electrode*



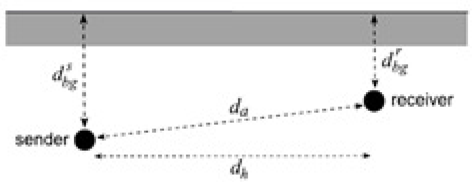

** Note: these very recent end preliminary findings have not been published (consult Ph.D. Thesis)*

## Research Roadmap :: 2009-2015 Achievements

**Initial research aspects**
1. High energy efficiency
2. High-reliability
3. **Robust underground wireless PHY channel (RF)**

Additional research line ➡ 4. Applicability of the Electrode Polarization effects

***2009***: *comprehensive empirical work (433MHz) ➔ identified: soil path signal attenuation >50dB/m* *[1, 2, 3]
***2009***: *identified: noise level in outdoor underground settings is very small for radio frequencies*[1]
***2009***: *proposed: first real-world set of guidelines for RF wireless underground testbed*[4]
***2010***: *implemented: first real-world irrigation system with wireless underground communication*[5,6]
***2010***: *proposed: first RF underground comm. channel with the effects of the lateral waves*[7]
***2013***: *designed & implemented: first RF lateral wave antenna for low-power and mid-range comm. in soil*[8]
***2014***: *proposed: hybrid solution (RF or MI) for short and mid-range WUSNs*[9]

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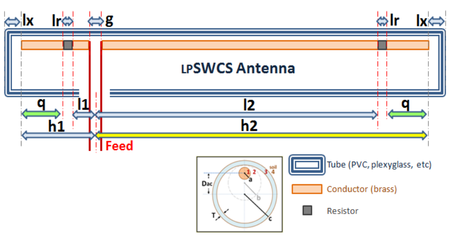


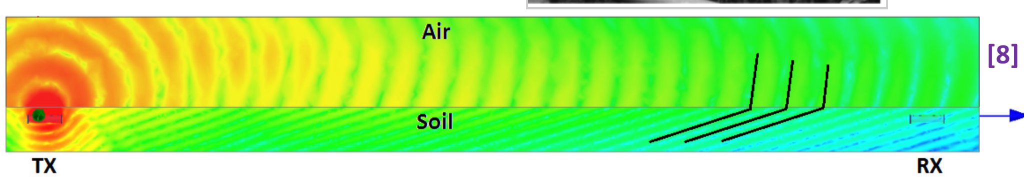


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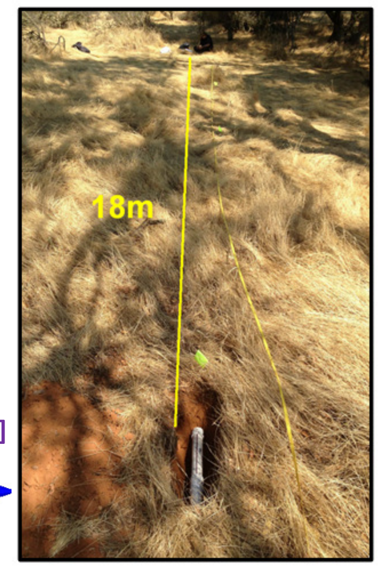


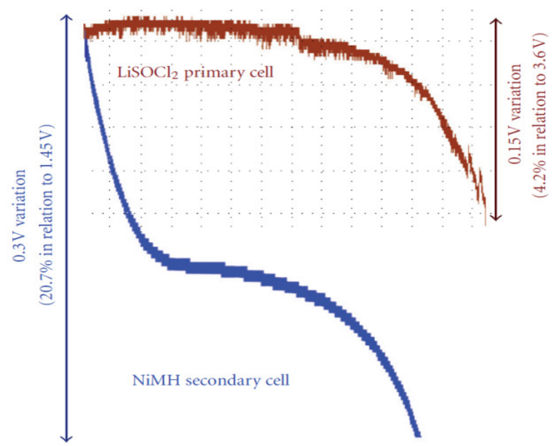

*RF: Radio Frequency*
*WSN: Wireless Sensor Network*
*WUSN: Wireless Underground Sensor Network*

# Research Roadmap :: 2009-2015 Achievements

**Initial research aspects**
- 1. High energy efficiency
- 2. High-reliability
- 3. Robust underground wireless PHY channel

Additional research line ⇨ 4. Applicability of the Electrode Polarization effects

***2012***: *novel and comprehensive study regarding non-rechargeable batteries and WSNs* [10]
***2012***: *proposed: BETS protocol and Ripple2 architecture – first WSN solution with network overhead < 1%* [11]
***2013***: *proposed: metrics for the degree of "sparsity" in a WSN; identified: energy/performance implications* [12]
***2013***: *implemented: Ripple2 network – best energy-efficiency results so far reported for long-term WSNs* [13-15]
***2013***: *proposed: Ripple2 architecture as foundation for disaster management and underground systems* [16]

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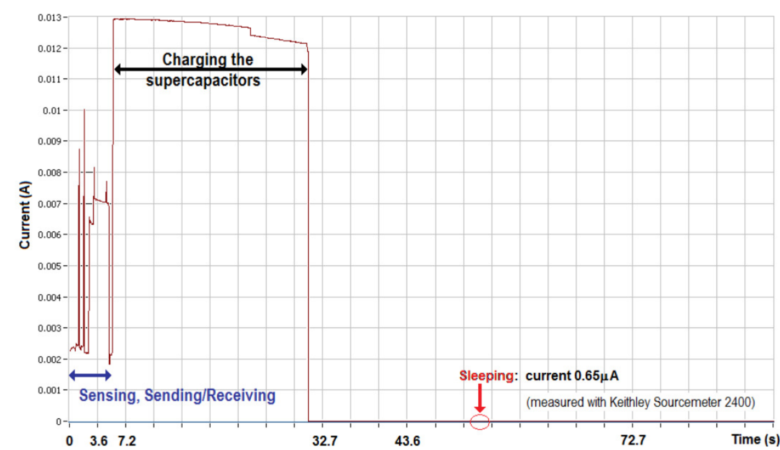


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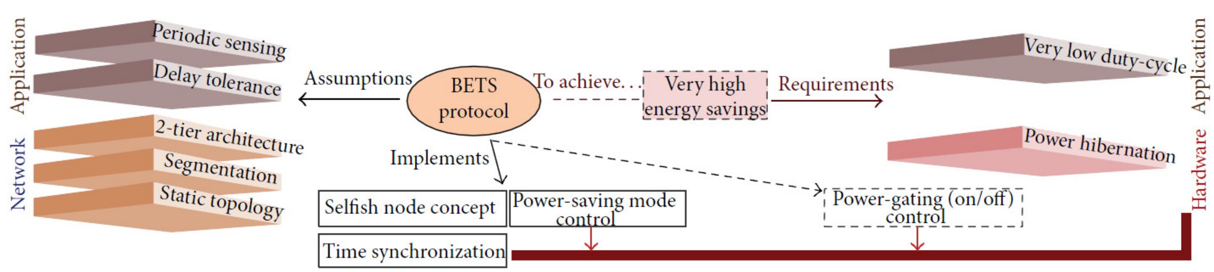


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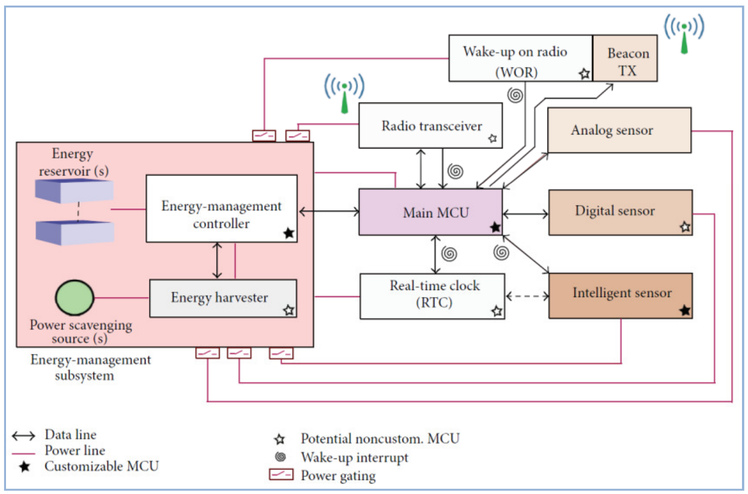
# Research Roadmap :: 2009-2015 Achievements

**Initial research aspects**
1. High energy efficiency
2. **High-reliability**
3. Robust underground wireless PHY channel

Additional research line ➡ 4. Applicability of the Electrode Polarization effects

***2011***: *development of a software eng. methodology for the design of unattended embedded systems*
***2015***: *presented: long-term results (4 years) of our VFSM+WDT approach applied to WSNs*[17]

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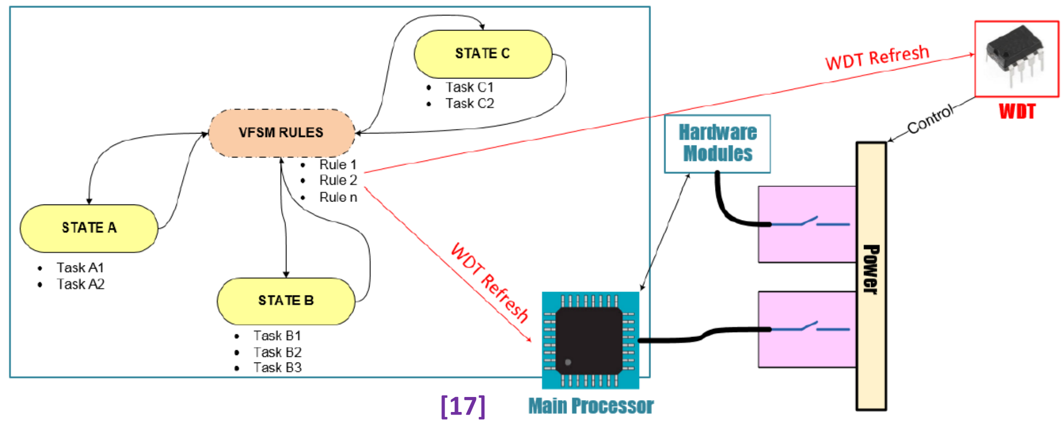


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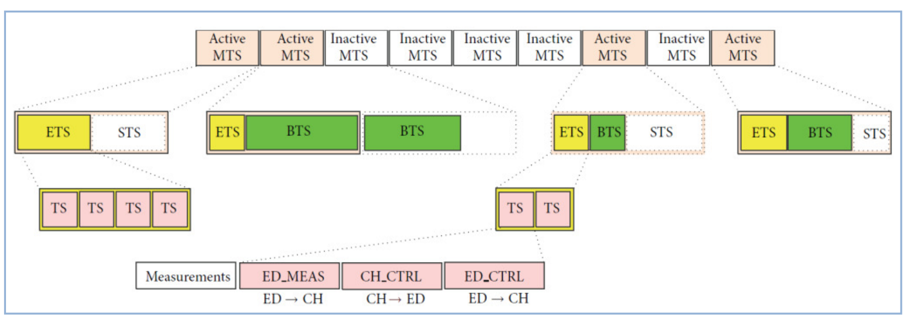
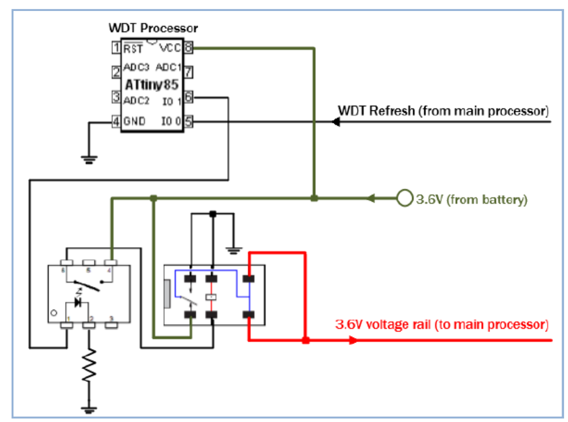


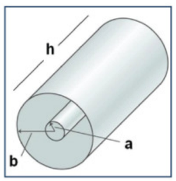
# Research Roadmap :: 2009-2015 Achievements

**Initial research aspects**
1. High energy efficiency
2. High-reliability
3. **Robust underground wireless PHY channel (MI)**

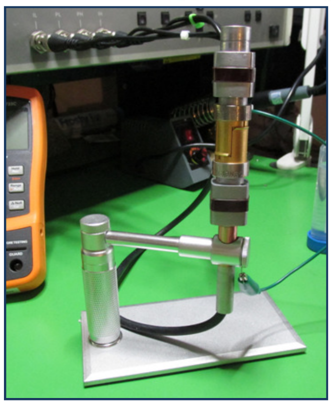
Additional research line ➡ 4. Applicability of the Electrode Polarization effects

***2014***: *studies regarding the applicability and robustness of the MI-method to WUSNs*[18]

***2015***: *proposed: first sub-MHz soil dielectric model with EP-correction*[19]







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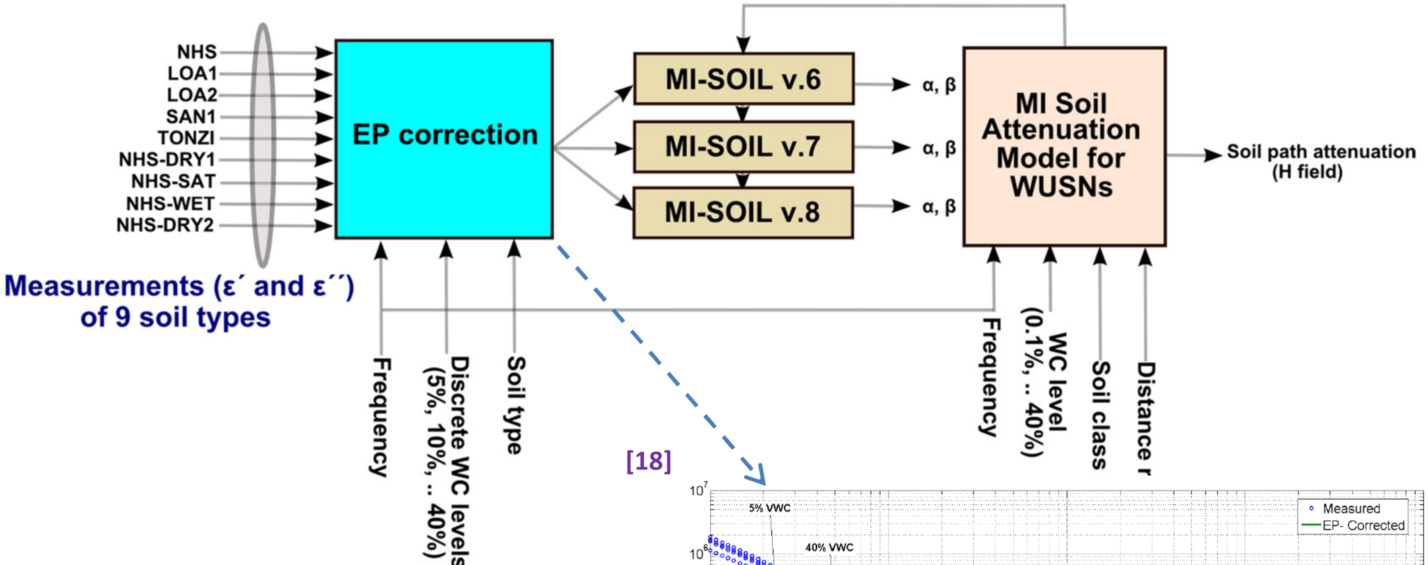


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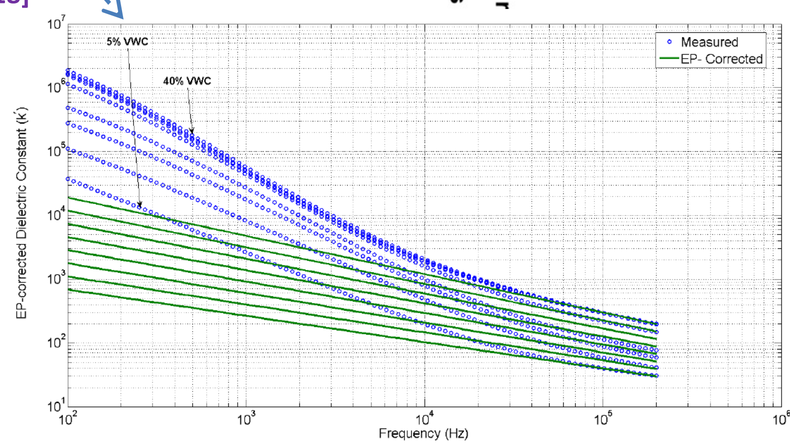


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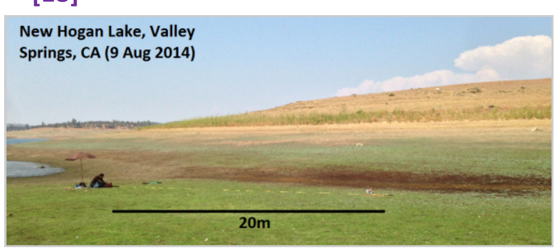
Magnetic induction-based Wireless Communication

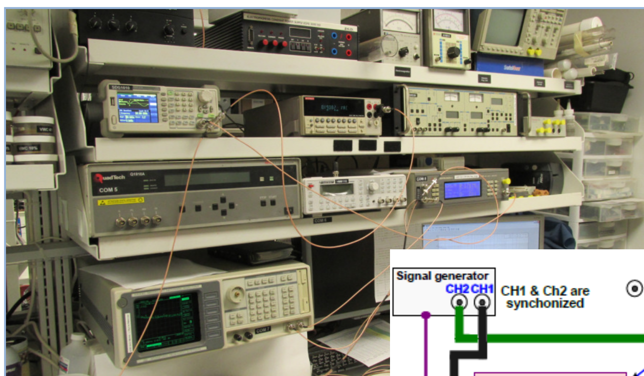



# Research Roadmap :: 2009-2015 Achievements

**Initial research aspects**
1. High energy efficiency
2. High-reliability
3. **Robust underground wireless PHY channel (MI)**

Additional research line ➡ 4. Applicability of the Electrode Polarization effects

***2015***: *identified: frequency range for mid-range MI-WUSNs* [20]
***2015***: *proposed and validated: sub-MHz MI-signal attenuation model for MI-WUSNs* [19, 20]
***2015***: *implemented: mid-range (~20m) MI-based underground communication* [20]
***2015***: *proposed: optimum design algorithm for mid-range MI-WUSNs* [21]
***2015***: *proposed: frequency adaptation technique for mid-range MI-WUSNs* [21]
***2015***: *proposed: novel use of two coils (dual-wiring scheme) for mid-range MI-WUSNs* [22]
***2015***: *proposed and implemented: first indoors sub-MHz MI-soil testbed* [22, 23]
***2015***: *proposed: novel concept of "breakpoint distance" for MI communication channel* [22]
***2015***: *proposed: novel design strategy for increasing bandwidth in mid-range MI-WUSNs* [23]



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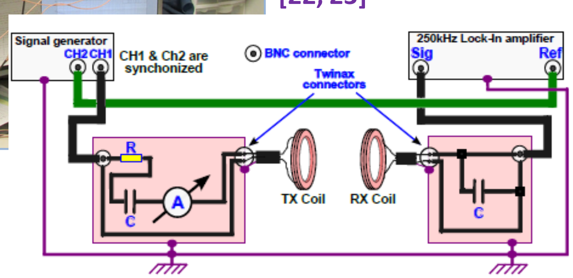
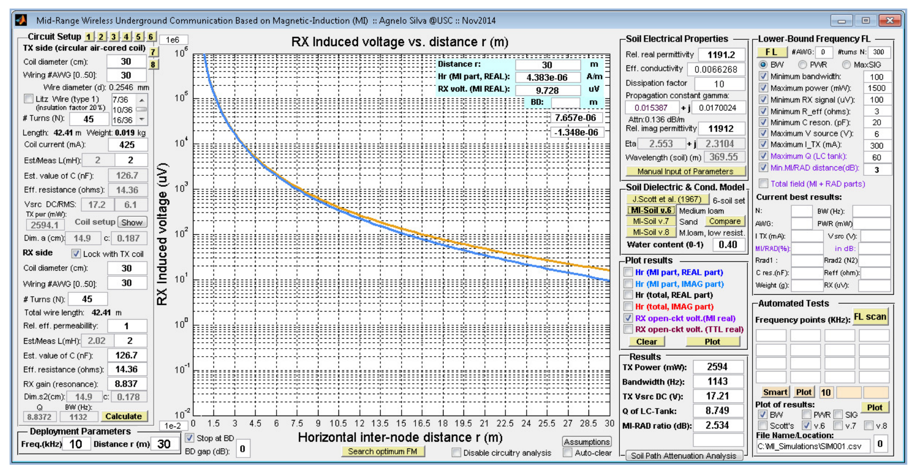



[19]

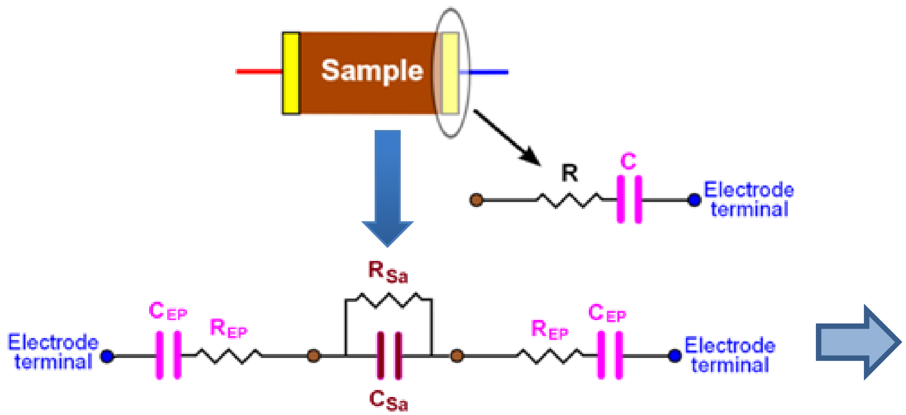
*MI-WUSNs: Wireless Underground Sensor Networks based on Magnetic-Induction*

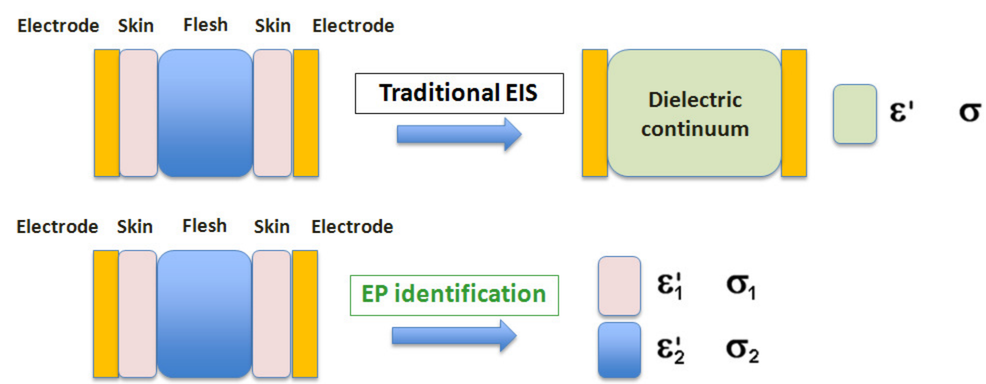
## Research Roadmap :: 2009-2015 Achievements

Initial research aspects
1. High energy efficiency
2. High-reliability
3. Robust underground wireless PHY channel (MI)

**Additional research line ➡ 4. Applicability of the Electrode Polarization effects**

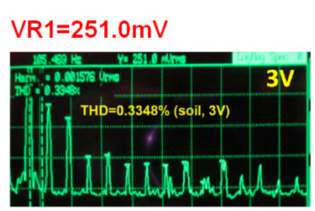
***2015***: *proposed: novel method to accurately identify EP impedance*[19]
***2015***: *preliminary experiments regarding the applicability of the EP effects (novel "EP spectroscopy")* [19]




**EP identification**

- Rsa
- Csa
- REP
- CEP




19]

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