Universität
Bremen

Sustainable
Communication
Networks

Prof. Dr. Anna Förster

Underground Communications: Technologies and Open Research

Communication in Extreme Environments for Science and Sustainable Development
Trieste, November 2023

comnets

Overview

→Why underground sensors? Applications

→Communication technologies for underground sensing

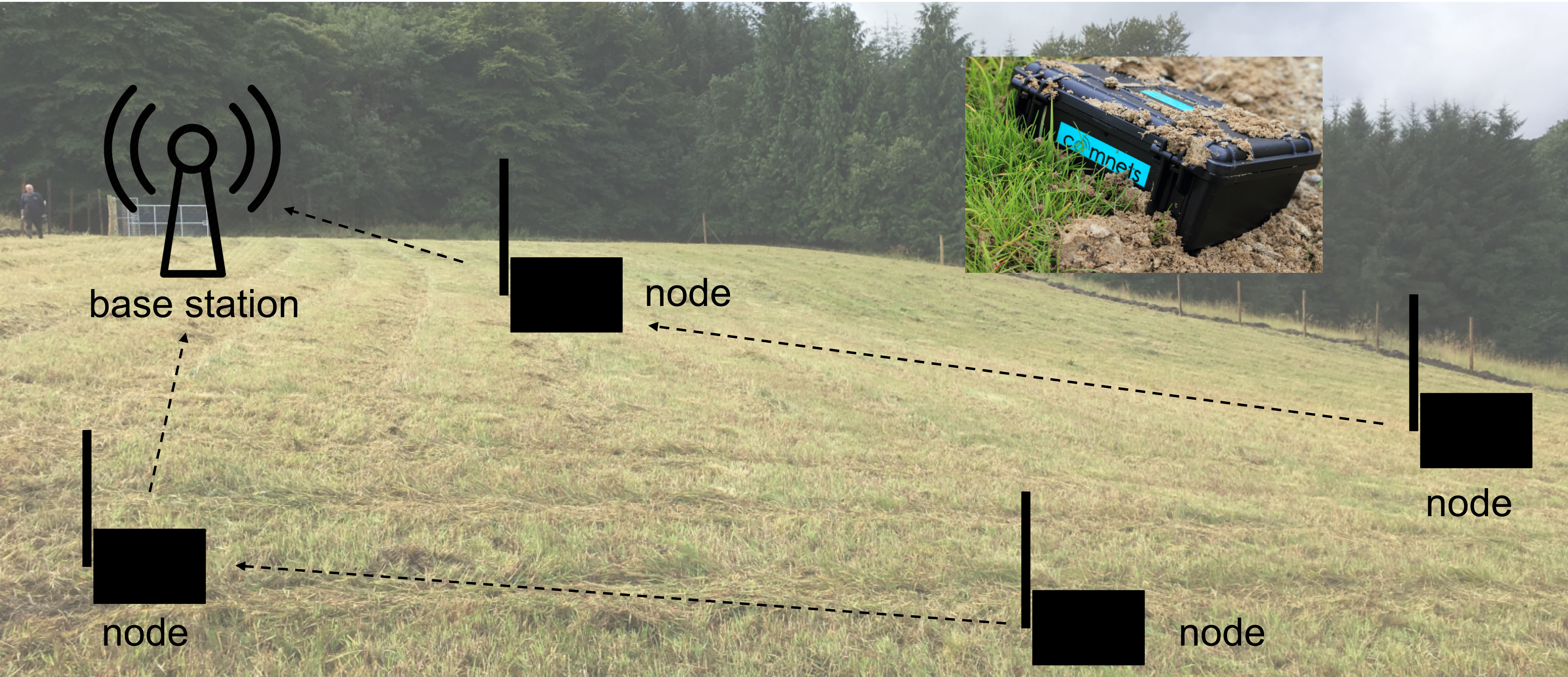
→System architectures for underground sensing

→Path loss models for underground communication

→Learning to communicate underground

Prof. Dr. Anna Förster

What are wireless (underground) sensor networks?



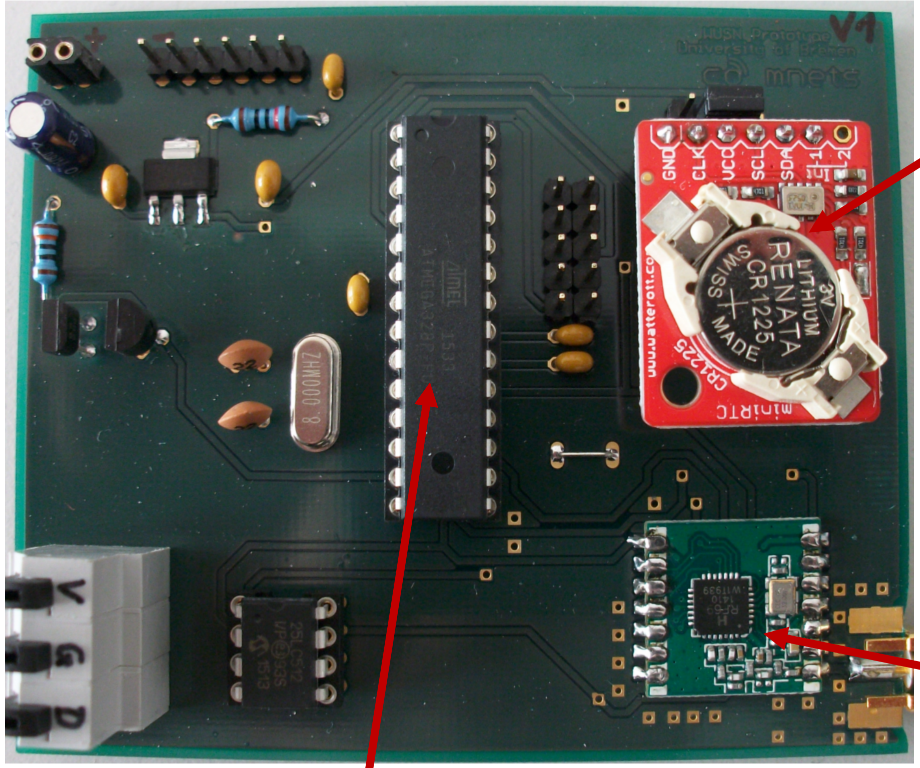
MoleNet: Underground Soil Monitoring

→MoleNet Node: self developed sensor platform, Arduino-based

→Wireless communication over 434 MHz

→Sensors: Water content, temperature, humidity, pH value, dissolved oxygen, …

MoleNet: Hardware



Real time clock

Radio transceiver (RFM69CW), at 434 MHz

Microcontroller

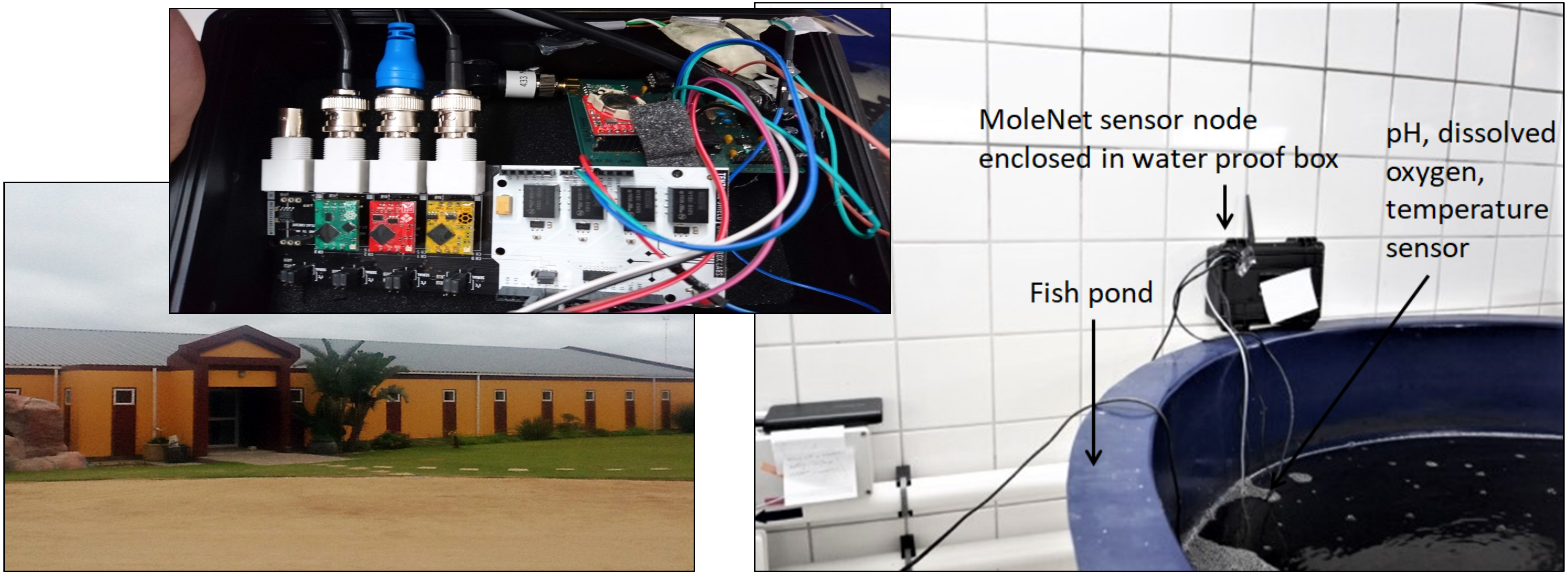
Components	Cost
Micocontroller	€ 2.85
RFM69CW	€ 4.35
EEPROM	€ 2.15
RTC	€ 10.00
Antenna	€ 6.27
Res, Cap, etc.	€ 5.00
PCB	€ 15.35
Total	**€ 45.97**

ReviTec: Reforestation Monitoring in Cameroon

Coffee bags with plant seeds and good soil

Sensor nodes below the coffee bags to measure humidity

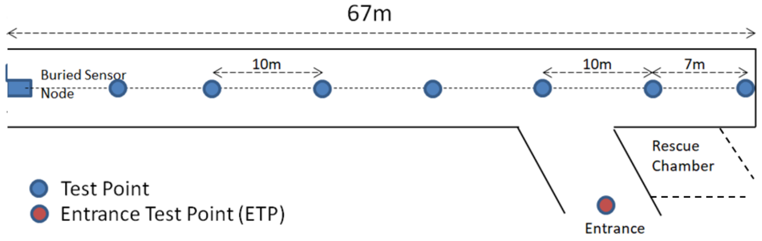
Aquarium Monitoring



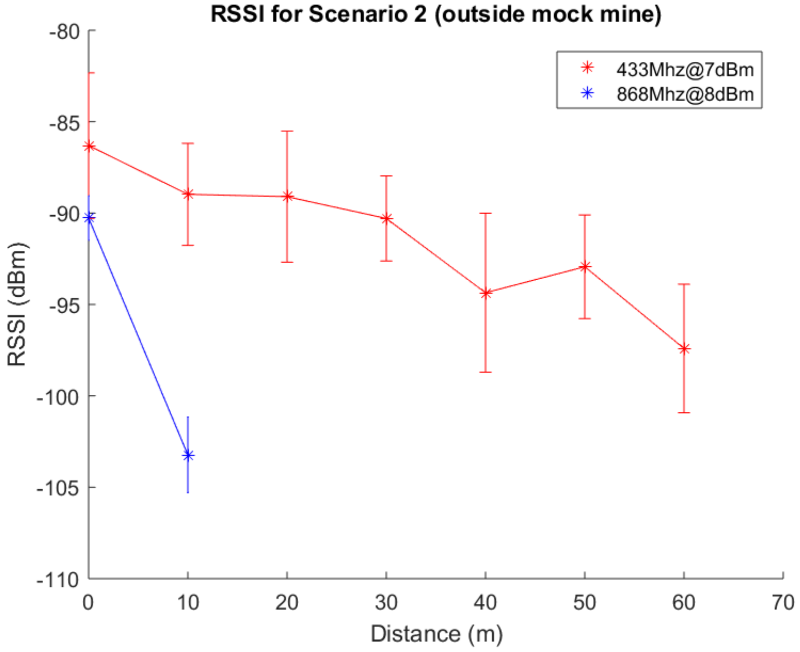
K. Qayyum, I. Zaman, A. Förster: H2O Sense: a WSN-based monitoring system for fish tanks, Springer Nature Journal on Applied Sciences, 2020.

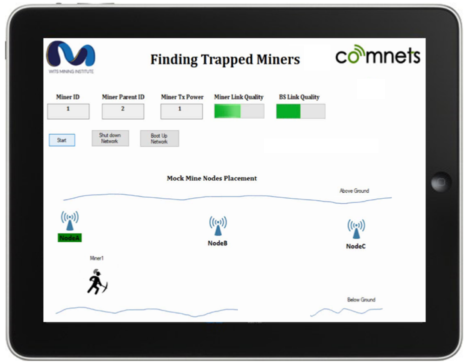
Finding Trapped Miners

a) Sensor node burried under the emulated rockfall



b) Test points for miner trapped under the emulated rockfall





Idrees Zaman, Anna Förster, Asad Mahmood and Frederick Cawood: Finding Trapped Miners with Wireless Sensor Networks, 5th International Conference on Information and Communication Technologies for Disaster Management, 2018

Elephant detection in Sri Lanka

→Regular conflicts between elephants and people

→Recognize elephants by underground seismic sensors

→Same idea for train recognition (and similar)

APPLICATIONS OF WUSN

ENVIRONMENTAL AND AGRICULTURAL MONITORING

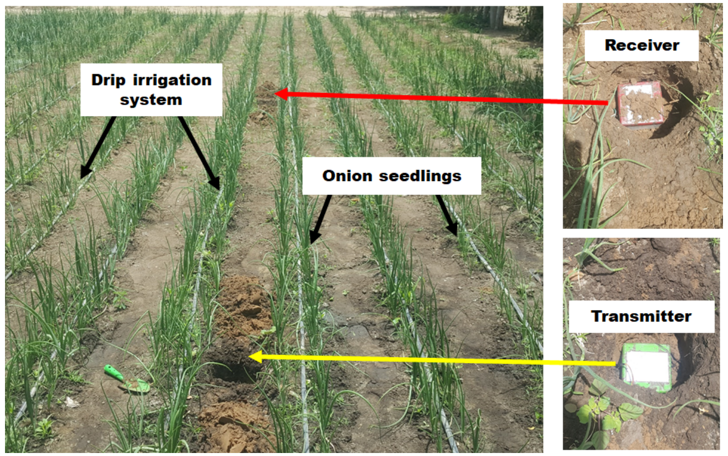
- Soil moisture monitoring;
- Agricultural monitoring;
- Mobile data harvesting;
- Smart irrigation;
- Ecological monitoring;

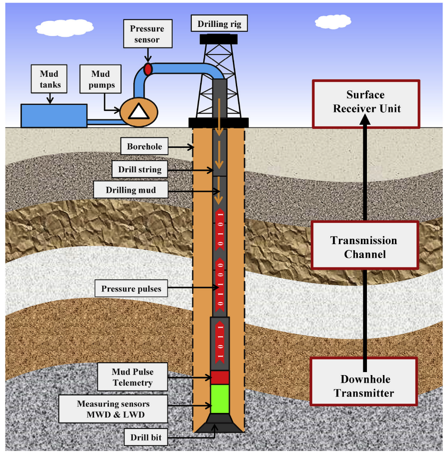
UNDERGROUND MONITORING

- Monitoring of oil and/or gas reservoirs;
- Underground drilling;
- Artifact detection;
- Down-hole telemetry;
- Coal mine;
- Rescue of miners;
- Detection of landslides;

INFRASTRUCTURE MONITORING AND INTRUSION TRACKING

- Animal tracking;
- Borders monitoring;
- Monitoring of high voltage cables;
- Monitoring of gas and/or oil pipelines;
- Water leakage detection;





Communication Technologies for WUSN

Parameters	EM	MI	ACW	MPT	VLC
Burial depth	Low (few meters)	Low (few centimeters)	High (hundred of meters)	High (hundred of meters)	High (hundred of meters)
Communication range	Low (few meters)	Low (few meters)	High (hundred of meters)	High (hundred of meters)	High (hundred of meters)
Frequency range	High (433MHz-2.4GHz)	Medium (4MHz-16MHz)	Low (100Hz-16KHz)	Low (1Hz-1kHz)	Very high (400THz-800THz)
Data rate	Medium (in hundreds bytes/s)	Medium (in hundreds to thousands bytes/s)	Low (in tens bytes/s)	Low (in bytes/s)	High (in thousands to millions bytes/s)
Attenuation	High	Low	High	Medium	High (in the soil)
Deployment cost	Low(depends on the area's size)	Low (Depends on number of relays)	Average	Low	Low

→Only EM is practical (affordable and available) for all applications

Communication Technologies

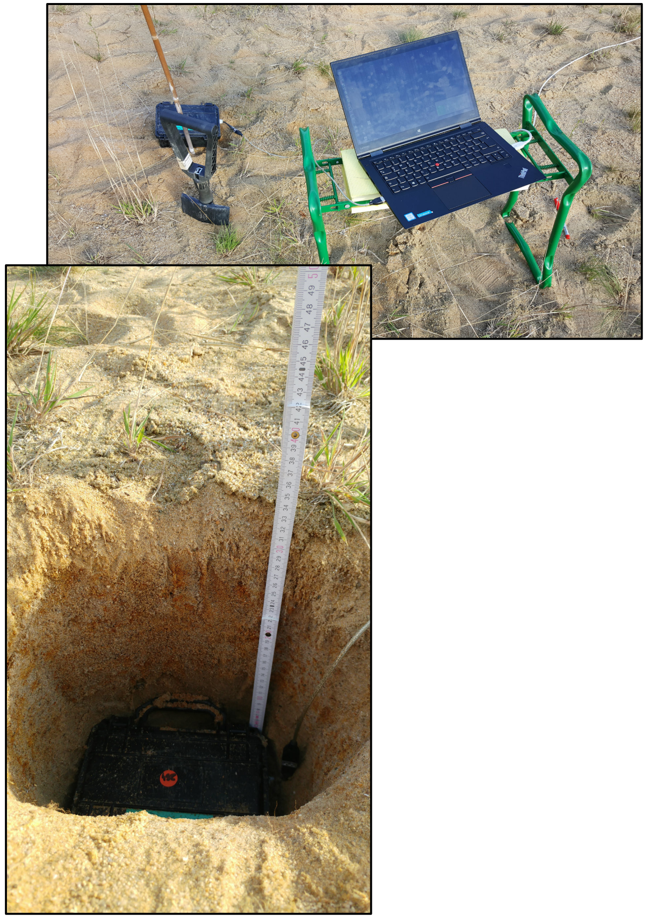
→LoRa and LoRaWAN

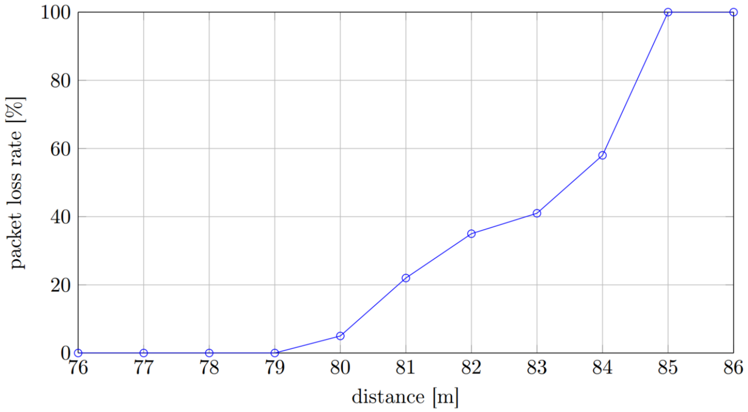
- → High range
- → Good soil penetration
- → Low cost of devices
- → Low operational cost
- → Low energy consumption
- → Low bandwidth
- → Similar: SigFox, NB-IoT (but higher operational costs)

→WLAN

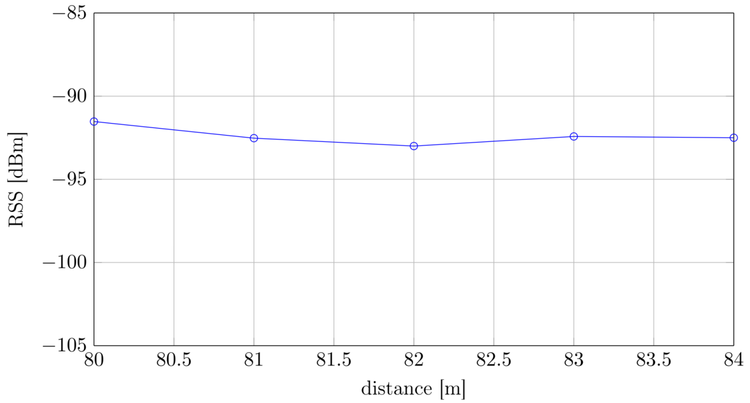
- → Low range
- → No soil penetration
- → Low cost of devices
- → Low operational cost
- → High energy consumption
- → High bandwidth
- → Similar: ZigBee

UG2AG Experiment with 434 MHz and 868 MHz

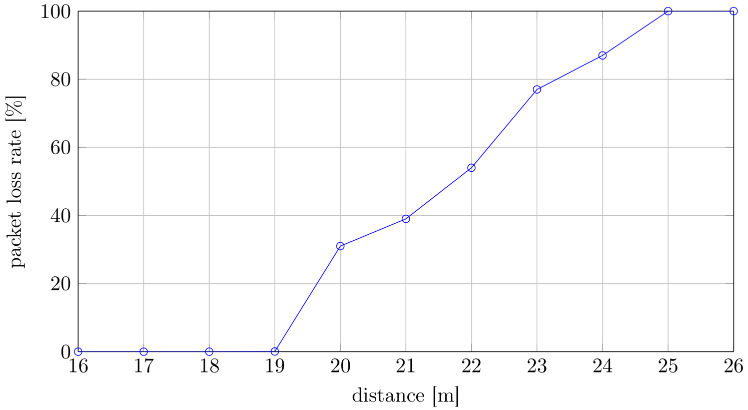




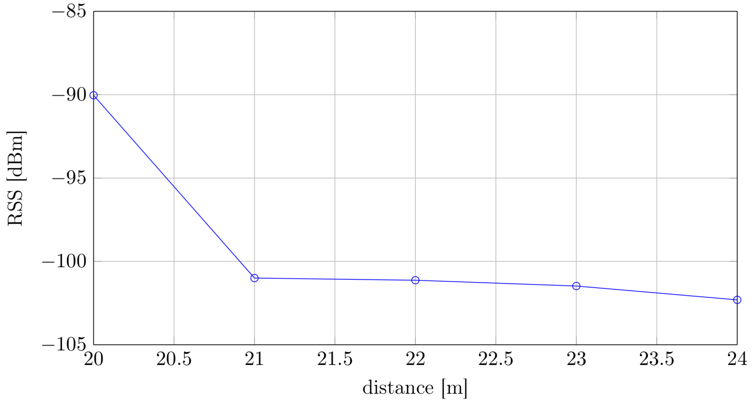
(a) Packet loss rate at 434MHz



(b) Received Signal Strength at 434MHz



(c) Packet loss rate at 868MHz



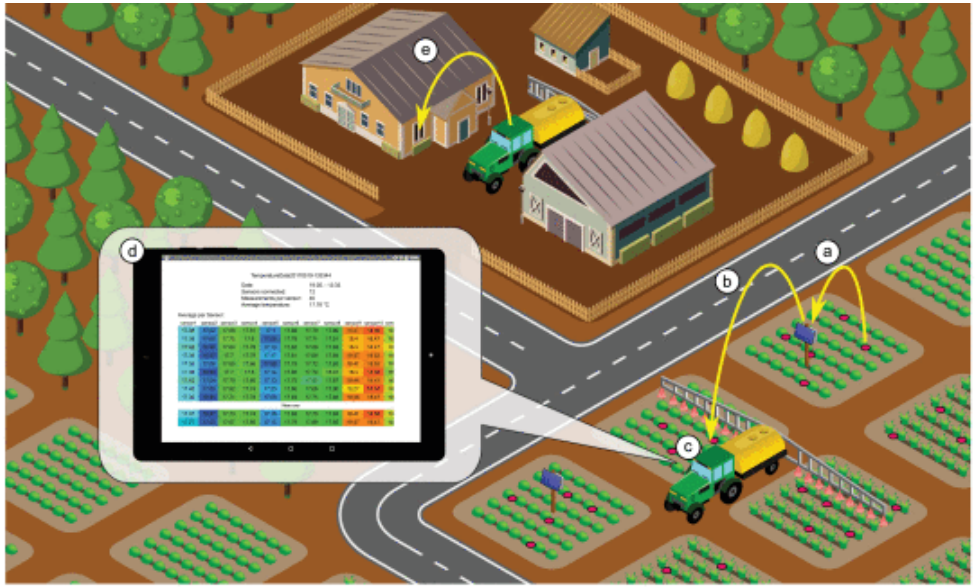
(d) Received Signal Strength at 868MHz

System Architectures

→Dictated by the communication technology selected or vice versa

Sensors underground, communication overground

Star topology to gateway



- → Sensor nodes send data to in-network gateways (a to b)
- → A mobile mule (a tractor, c) gathers the data from the gateways …
- → … And delivers it to the server

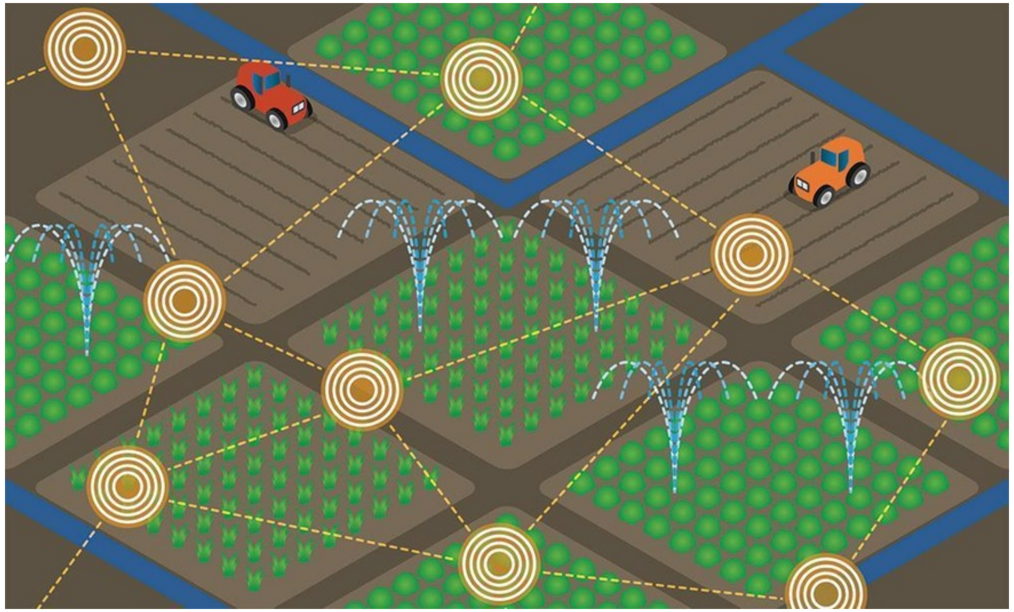
Björn Gernert; Jan Schlichter; Lars Wolf: PotatoScanner – A Mobile Delay Tolerant Wireless Sensor Node for Smart Farming Applications, 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS)

System Architectures

→Dictated by the communication technology selected or vice versa

Sensors underground, communication overground

In-network multihop



dataflog.com

- → Sensor nodes form an ad hoc network
- → The sink (server) is somewhere on the border of the network

System Architectures

→Dictated by the communication technology selected or vice versa

Sensors underground, communication mixed

Star topology to gateway

MoleNet sensor, molenet.org

- → Sensor nodes completely burried
- → Gateway in the field
- → Sensor nodes communicate directly with gateway
- → Gateway connected to the Internet

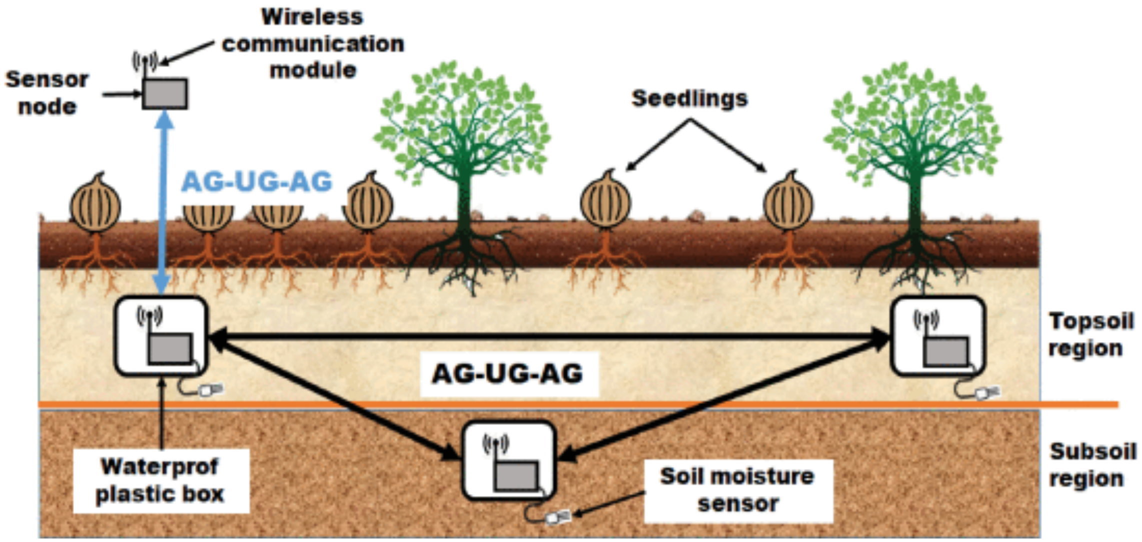
System Architectures

→Dictated by the communication technology selected or vice versa

Sensors underground, communication mixed

In-network multihop

Rarely seen in practice



Damien Wohwe Sambo, Anna Forster, Blaise Omer Yenke, Idrissa Sarr, Bamba Gueye, Paul Dayang,
Wireless underground sensor networks path loss model for precision agriculture (WUSN-PLM), IEEE Sensors Journal 2020

Underground-2-Underground Communication

- →Why UG2UG?
  - → Cost of gateways
  - → Theft protection of gateways
  - → Additional soil sensor
- →Depends mostly on soil moisture and distance
- →Current channel models depend on various lab measurements
- →Our work with predicting the channel state with soil moisture only

Path loss model for underground communication

→ General link budget equation:

$$P_R = P_T + G_T + G_R - PL - L_T - L_R$$

→ Add the attenuation due to soil $\boldsymbol{L_s}$; $\boldsymbol{L_{tot} = L_0 + L_s}$

→ $L_{tot}(dB) = 6.4 + 20\log(d) + 20\,log(\beta) + 8.69\alpha d$

→ α, β are related to soil conditions:

→ $\alpha = 2\pi f \sqrt{\frac{\mu_0 \mu_r \varepsilon_0 \varepsilon'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)}$ $\quad \beta = 2\pi f \sqrt{\frac{\mu_0 \mu_r \varepsilon_0 \varepsilon'}{2}\left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1\right)}$

→ ε', ε'' are the real and imaginary parts of the Complex Dielectric Constant (CDC)

→ Soil sample analysis in a laboratory setting required to evaluate CDC

Channel prediction with path loss models

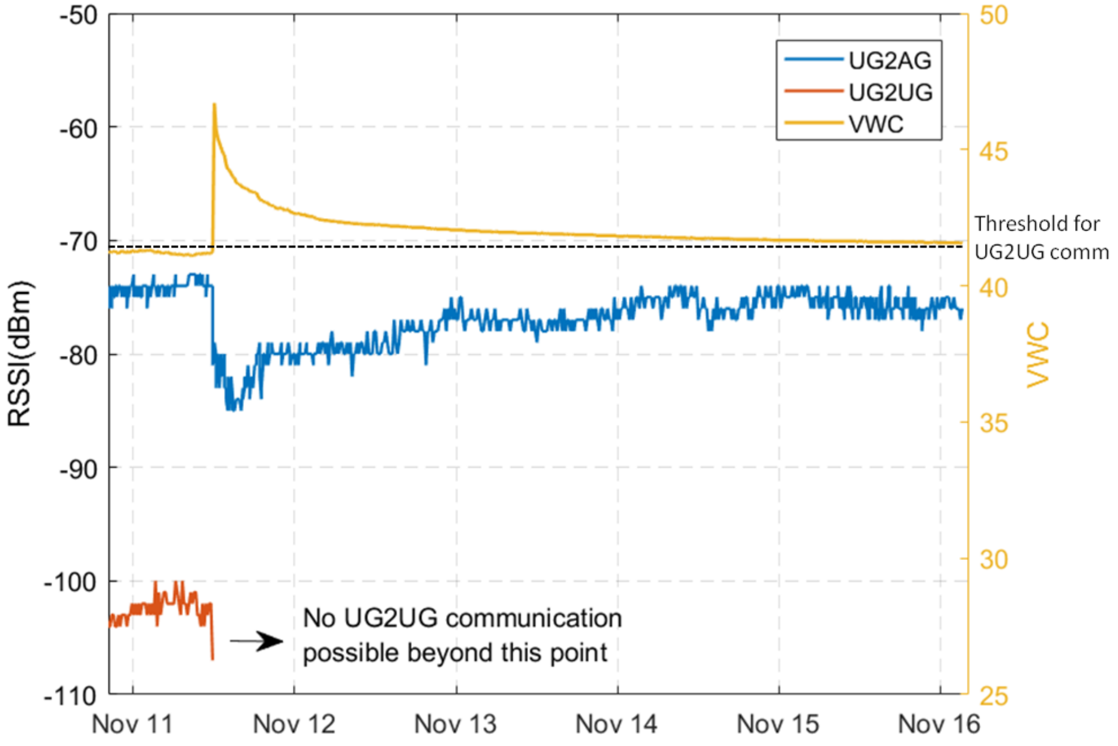
→Use a path loss model to predict the channel

→ Complex models, but still too simplistic.

→ Needs information about **soil composition**, soil moisture, **exact geographic locations of nodes and gateway**, etc.

Channel prediction with ML

→Soil moisture: driving force in the underground communication



Channel prediction with path loss models

Changing Volumetric Water Content (VWC)

Identify most suitable path loss model

Good estimation only, too complex to model completely

GPS not working underground and otherwise costly

Identify distances to all neighbour nodes

Distance measurements not precise enough

Differ from spot to spot, very costly to acquire precisely

Identify path loss exponents

Measure VWC

Readily available for application purposes

Adapt to new VWC

increase/decrease transmission power; switch on/off radio

Channel prediction with ML and soil moisture

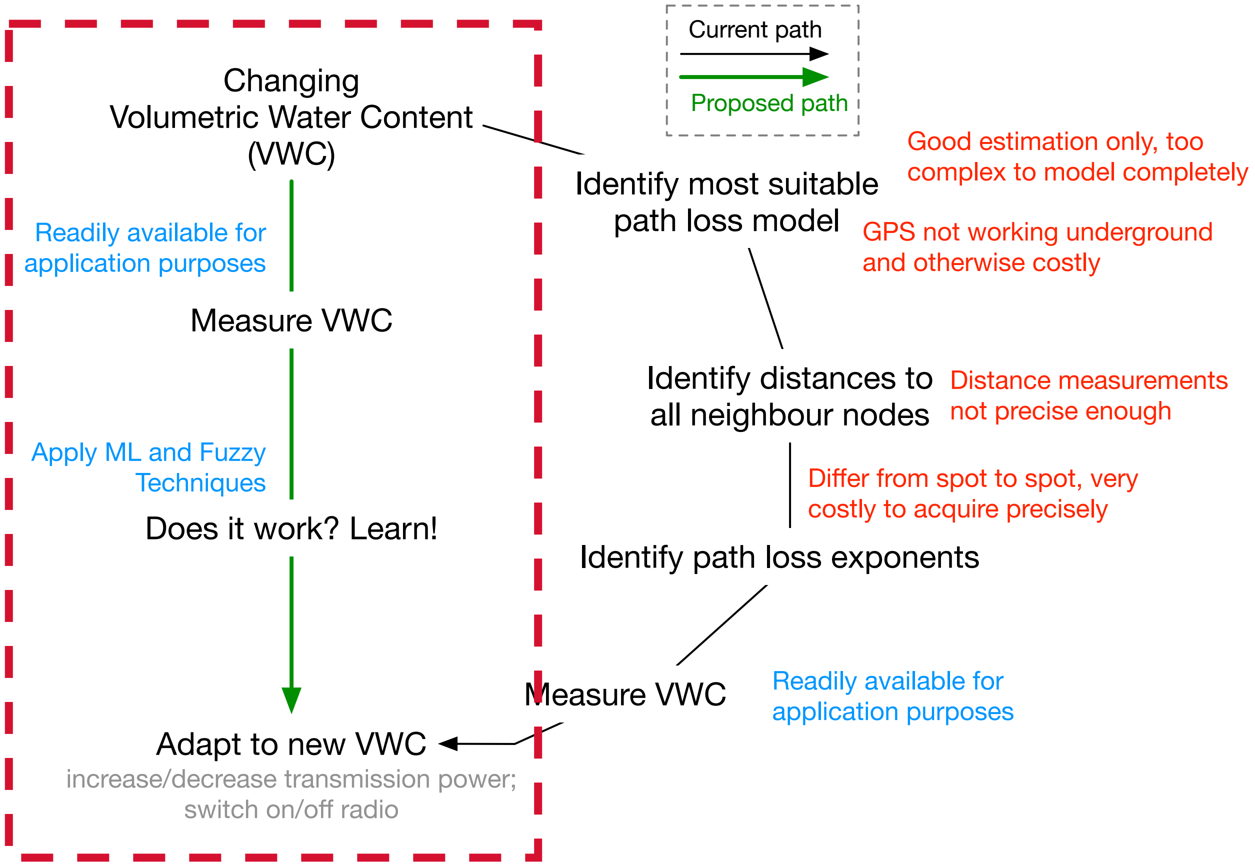
→Mathematical models to calculate the path loss (the decreasing signal strength) of underground communications

→ Complex model, but still to simplistic.

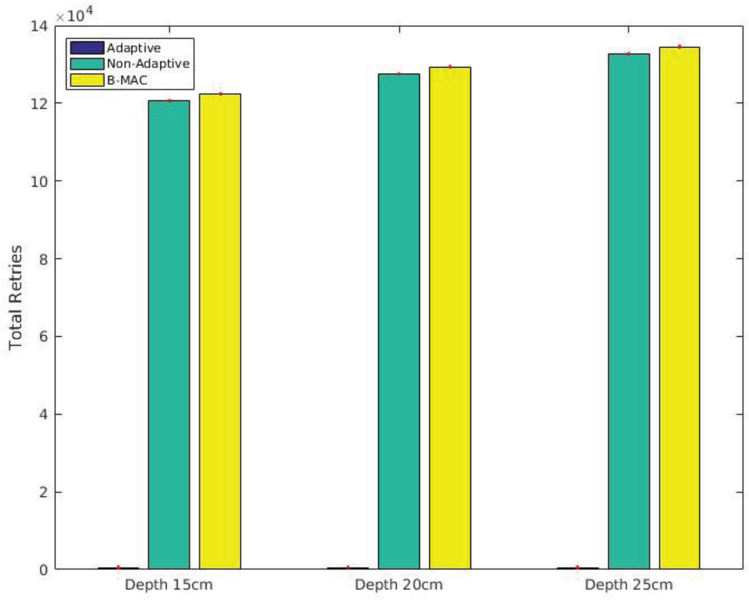
→ Needs information about ~~soil composition~~, soil moisture, ~~exact geographic locations of nodes and gateway~~, etc.

→Our idea: use ML based on soil moisture only to predict the success of a transmission

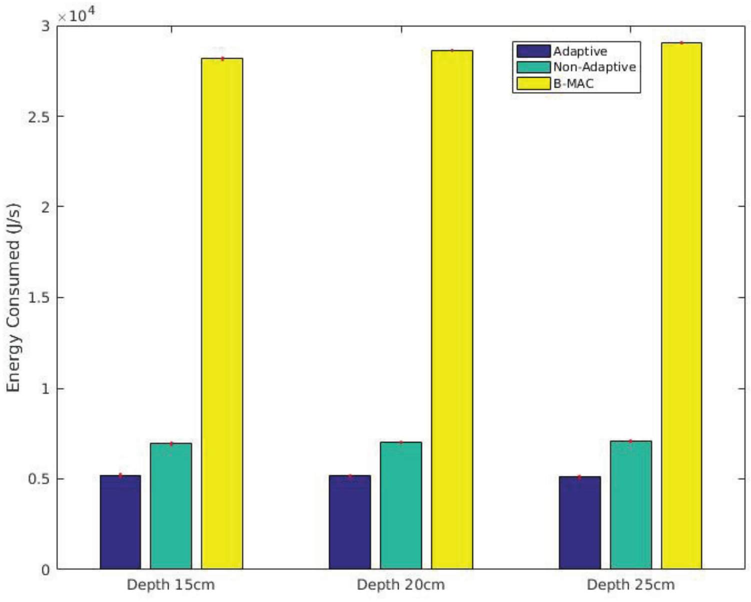
Channel prediction with ML and soil moisture



Preliminary Results



(a) Total retries (averaged) for different depths



(b) Energy consumed (averaged) for different depths

Anna Förster, Adapting Sensor Network Protocols to Environmental Changes through Machine Learning, KuVS Fachgespräch Machine Learning & Networking 2020

Zaman, Idrees, and Anna Förster. "Self Adaptive Communication based on Soil Moisture for Wireless Underground Sensor Networks." (2020)

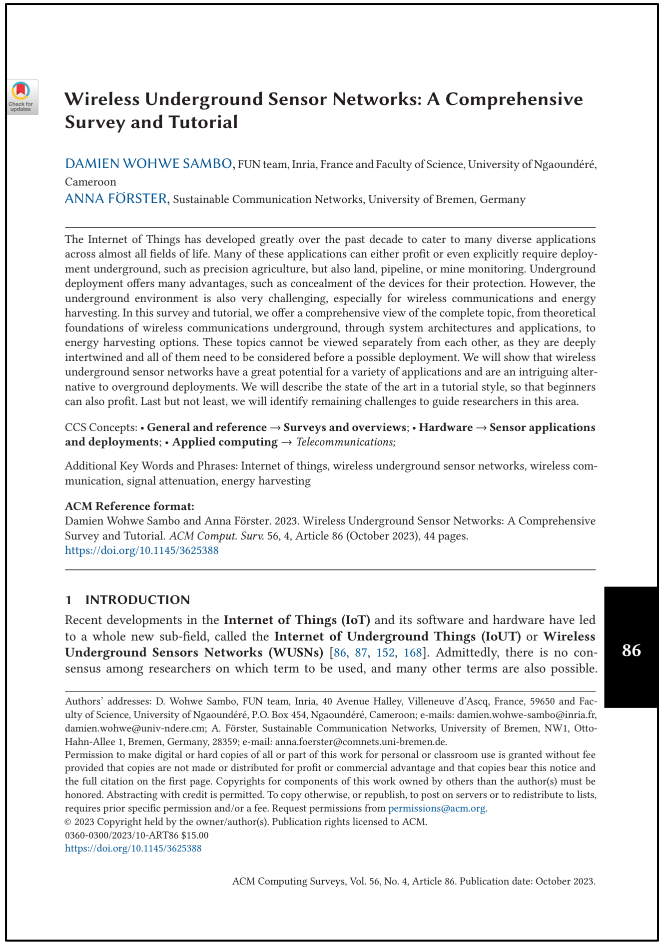
Summary

→Various unique applications and properties

→Underground environment is challenging, but fluctuates less then air.

→Wireless sensing is a promising field with various applications

→New survey on underground sensor networks https://dl.acm.org/doi/full/10.1145/3625388



Wireless Underground Sensor Networks: A Comprehensive Survey and Tutorial

DAMIEN WOHWE SAMBO, FUN team, Inria, France and Faculty of Science, University of Ngaoundéré, Cameroon
ANNA FÖRSTER, Sustainable Communication Networks, University of Bremen, Germany

The Internet of Things has developed greatly over the past decade to cater to many diverse applications across almost all fields of life. Many of these applications can either profit or even explicitly require deployment underground, such as precision agriculture, but also land, pipeline, or mine monitoring. Underground deployment offers many advantages, such as concealment of the devices for their protection. However, the underground environment is also very challenging, especially for wireless communications and energy harvesting. In this survey and tutorial, we offer a comprehensive view of the complete topic, from theoretical foundations of wireless communications underground, through system architectures and applications, to energy harvesting options. These topics cannot be viewed separately from each other, as they are deeply intertwined and all of them need to be considered before a possible deployment. We will show that wireless underground sensor networks have a great potential for a variety of applications and are an intriguing alternative to overground deployments. We will describe the state of the art in a tutorial style, so that beginners can also profit. Last but not least, we will identify remaining challenges to guide researchers in this area.

CCS Concepts: • **General and reference** → **Surveys and overviews**; • **Hardware** → **Sensor applications and deployments**; • **Applied computing** → *Telecommunications;*

Additional Key Words and Phrases: Internet of things, wireless underground sensor networks, wireless communication, signal attenuation, energy harvesting

ACM Reference format:
Damien Wohwe Sambo and Anna Förster. 2023. Wireless Underground Sensor Networks: A Comprehensive Survey and Tutorial. *ACM Comput. Surv.* 56, 4, Article 86 (October 2023), 44 pages.
https://doi.org/10.1145/3625388

1 INTRODUCTION

Recent developments in the **Internet of Things (IoT)** and its software and hardware have led to a whole new sub-field, called the **Internet of Underground Things (IoUT)** or **Wireless Underground Sensors Networks (WUSNs)** [86, 87, 152, 168]. Admittedly, there is no consensus among researchers on which term to be used, and many other terms are also possible.

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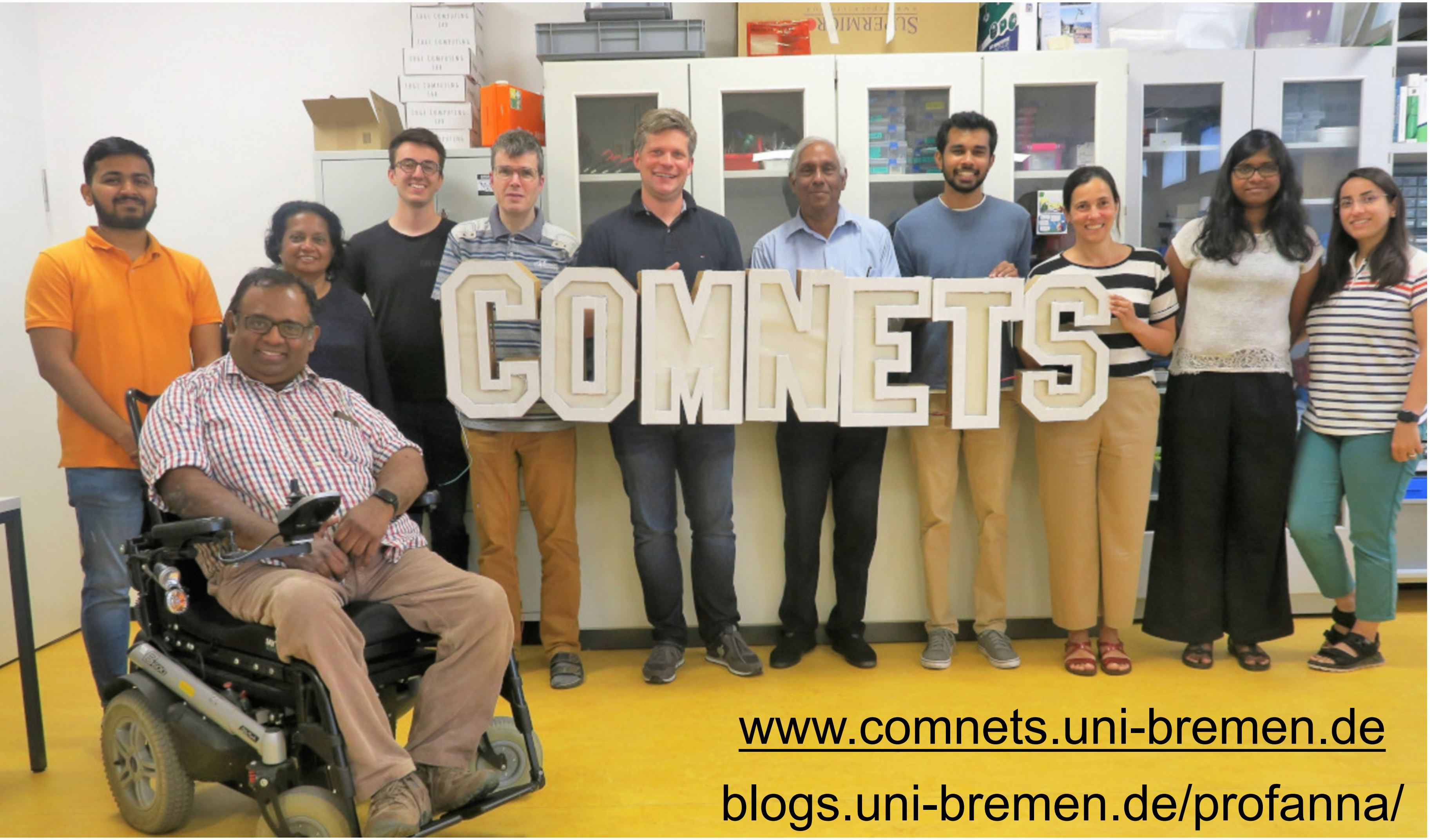

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