Towards Low Cost Soil Sensing Using Wi-Fi

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Data-driven agriculture helps boost agriculture productivity

- Improves yield
- Reduces waste in resources
- Improves sustainability

Soil Moisture Sensors

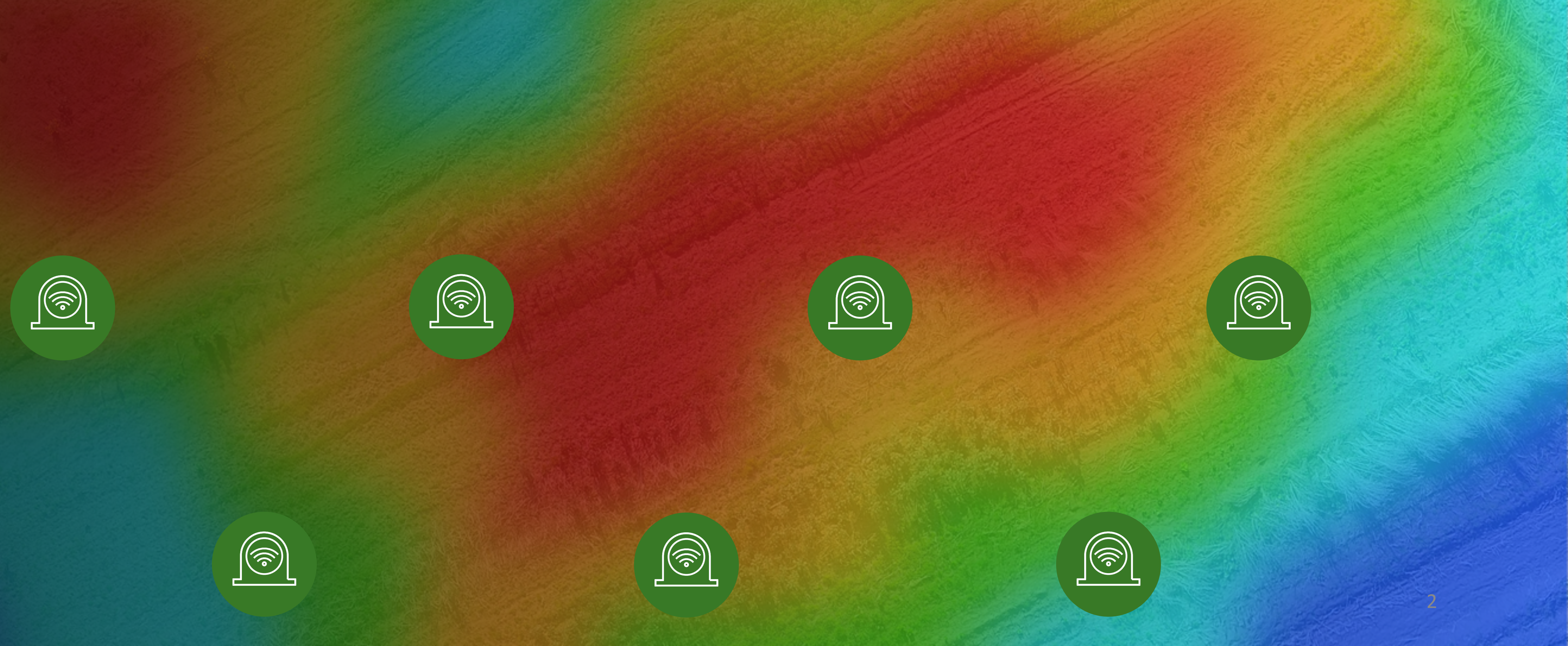
Soil EC Sensors

PH Sensors

Wind Speed/ Direction Sensors

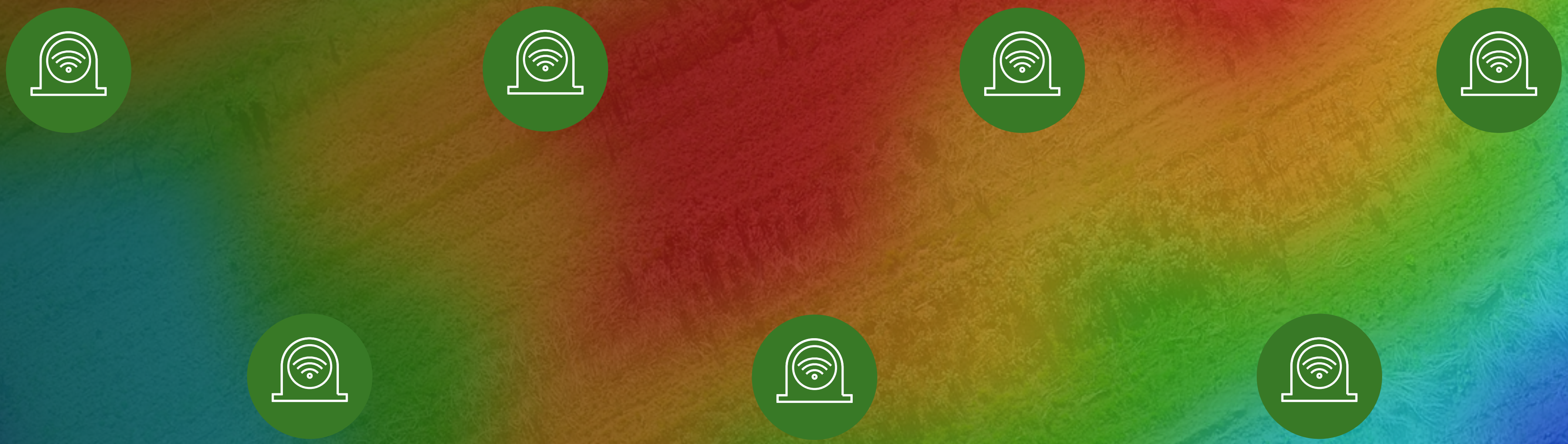
Data-driven agriculture requires a wide deployment of sensors

- Combine data from individual sensors to generate heatmaps
- Heatmaps provide further insights to farmers



Challenge: data collection has a high cost

- Cost of individual sensors (100s-1000s of USD per sensor)
- Density of sensor deployment
- Networking cost: sending data to cloud
- …



Challenge: data collection has a high cost

We focus on reducing cost of individual sensors

- Density of sensor deployment
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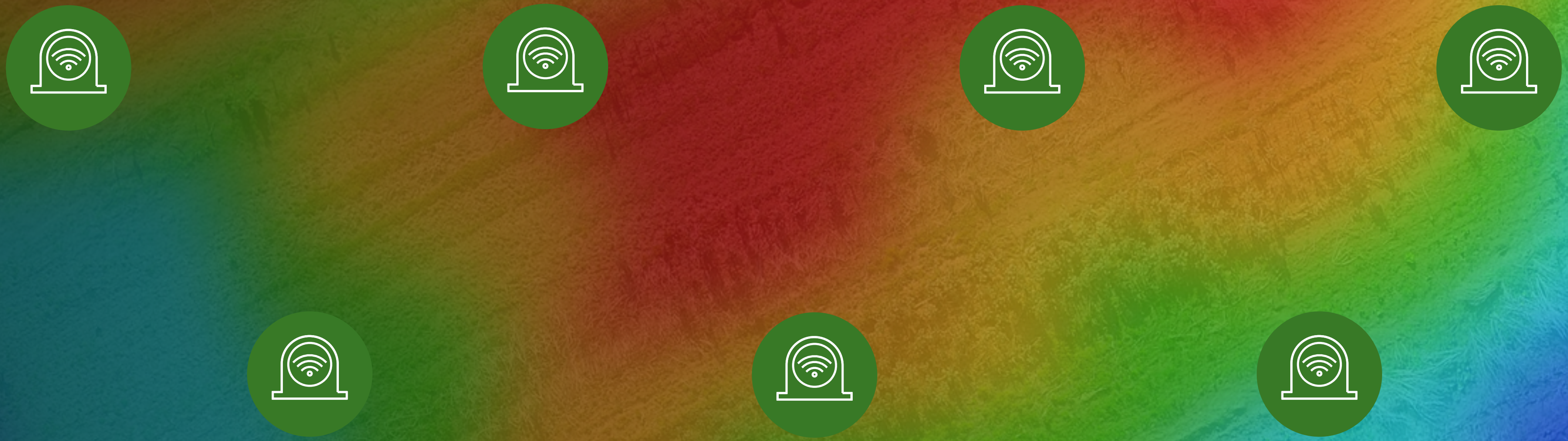


Soil moisture and EC: key indicators in data-driven agriculture

Soil Moisture Sensors

Soil EC Sensors

- Soil moisture: water resource management
- Soil electrical conductivity (EC): correlated with crop yield

Challenge: sensors for data-driven agriculture are expensive

Data-driven agriculture

> 100 USD

> 1000 USD

Price

Accuracy

Commercial-grade sensors

- Tensiometer

- Capacitance-based
- Resistivity-based

- Neutron probe
- Time domain reflectometry (TDR)
- Ground penetrating radar (GPR)

Challenge: sensors for data-driven agriculture are expensive

Data-driven agriculture

< 20 USD

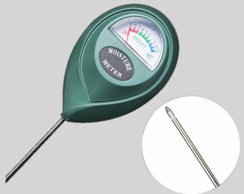
> 100 USD

> 1000 USD

Price

Accuracy

Hobbyist sensors



Not reliable, degrade fast

Commercial-grade sensors

- Tensiometer

- Capacitance-based
- Resistivity-based

- Neutron probe
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Can we **reduce the cost** while achieving **good accuracy** for soil moisture and EC sensing?

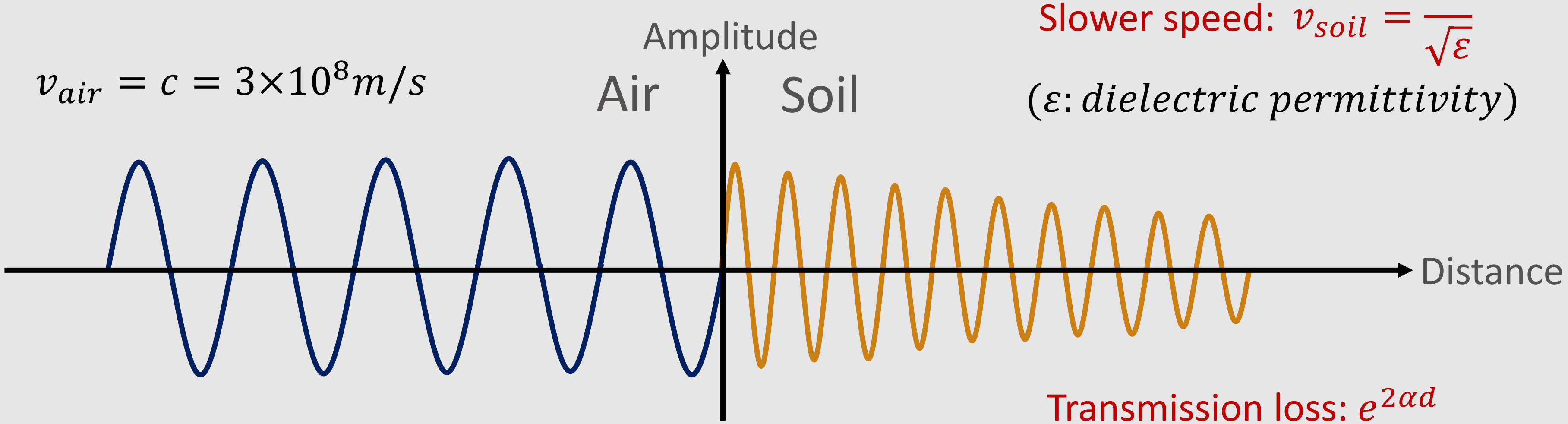
Idea: using RF signals

- Insight: RF wave in soil has a slower speed and higher attenuation

$v_{air} = c = 3\times10^8 m/s$

Slower speed: $v_{soil} = \frac{c}{\sqrt{\varepsilon}}$

$(\varepsilon: dielectric\ permittivity)$



Transmission loss: $e^{2\alpha d}$

($\alpha: attenuation\ coefficient$, a function of EC)

Slower speed: due to higher dielectric permittivity (moisture)

Higher attenuation: due to extra transmission loss (EC)

Existing RF-based soil sensing systems

E.g., ground penetrating radar (GPR) and time domain reflectometry (TDR)

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  - Measure time-of-flight (ToF) to estimate wave velocity change in soil

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- **Challenge 2:** Require accurate system calibrations for EC sensing
  - Measure attenuation to estimate transmission loss in soil

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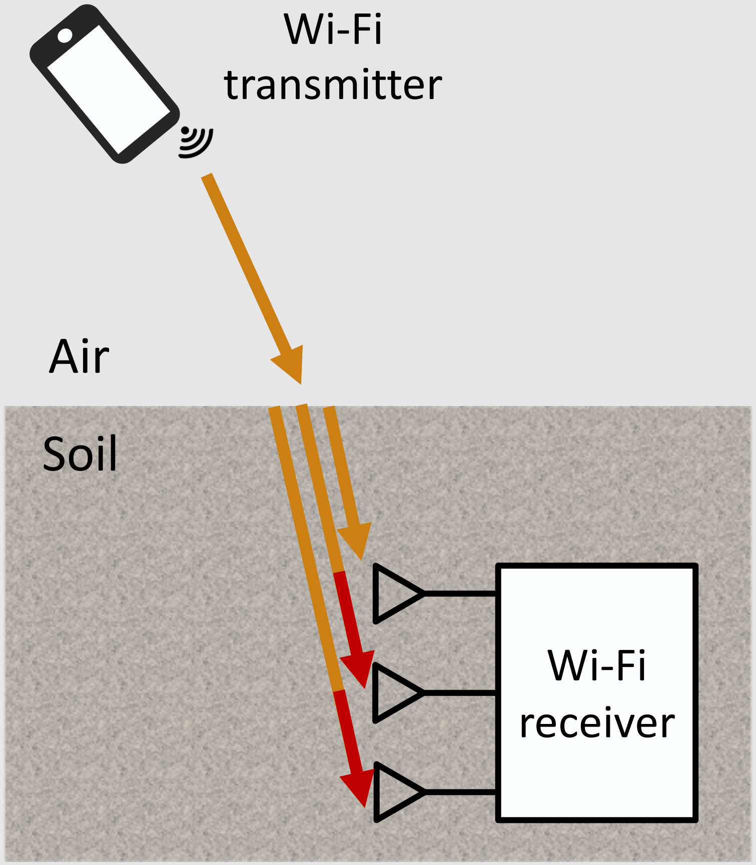
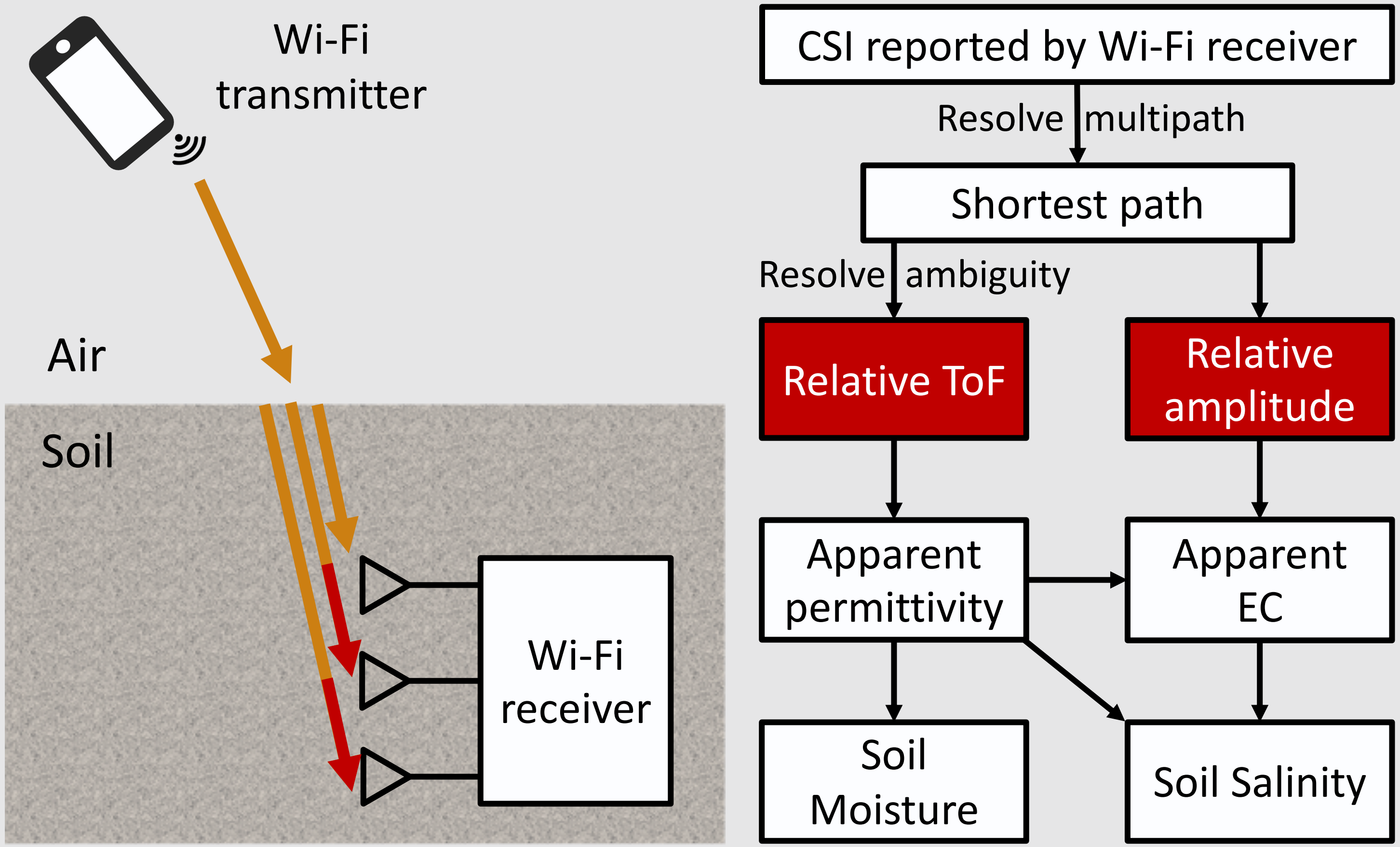
- **Challenge 2:** Require accurate system calibrations for EC sensing
  - Measure attenuation to estimate transmission loss in soil
- **Challenge 3**: High cost (1000s of USD)
  - Specialized hardware design & calibration

Strobe: Enables **accurate** and **low-cost** soil sensing using Wi-Fi

- Addresses bandwidth & calibration challenges
  - Using multi-antenna array as RX
  - A novel algorithm based on **relative ToF and relative amplitude** between antennas
- Addresses the cost challenge by using commercial Wi-Fi devices
  - Single-antenna TX in air & multi-antenna RX array in soil



CSI is all we need to estimate soil moisture and EC



Challenge of using Wi-Fi devices: limited bandwidth at Wi-Fi spectrum

Wi-Fi spectrum: spans 70 MHz at 2.4 GHz

spans 665 MHz at 5 GHz

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vs

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Wi-Fi spectrum: spans 70 MHz at 2.4 GHz

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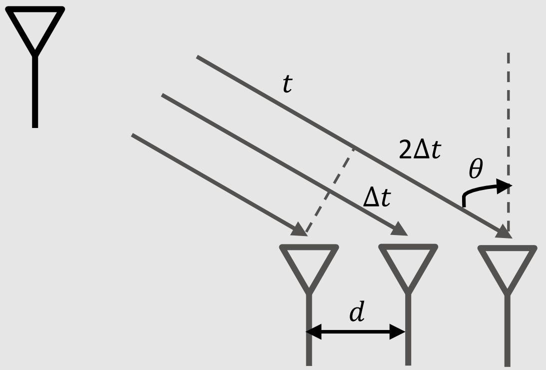
vs

Existing RF-based methods: ultra-wide bandwidth

How can we achieve good accuracy with only 70 MHz bandwidth?

Idea: using relative ToF to overcome bandwidth limit



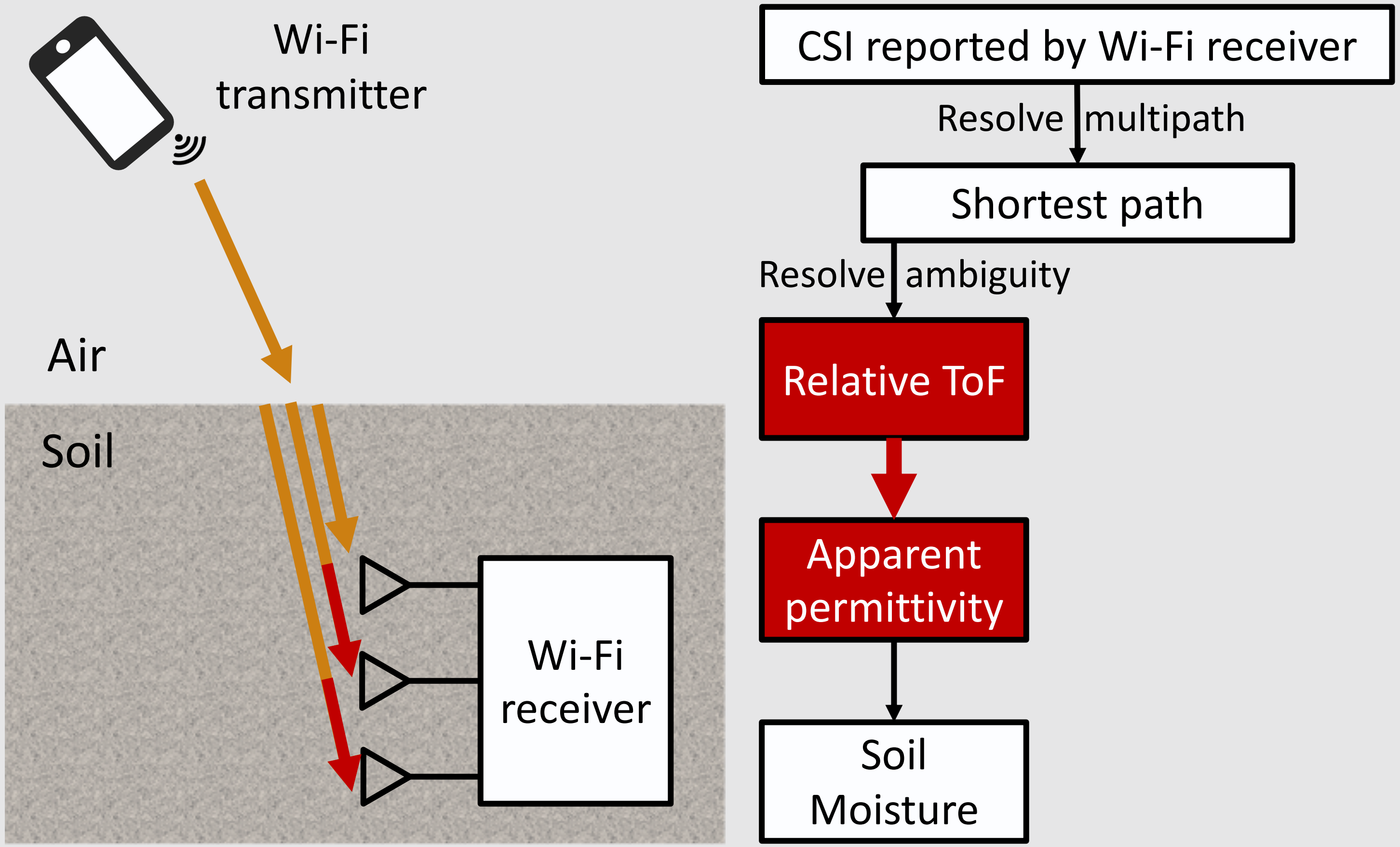
Relative ToF Δt: the time difference of wave travelling to two adjacent antennas

Key insight: resolution of relative ToF is not limited by bandwidth

- Relative ToF estimation is based on phase rotation

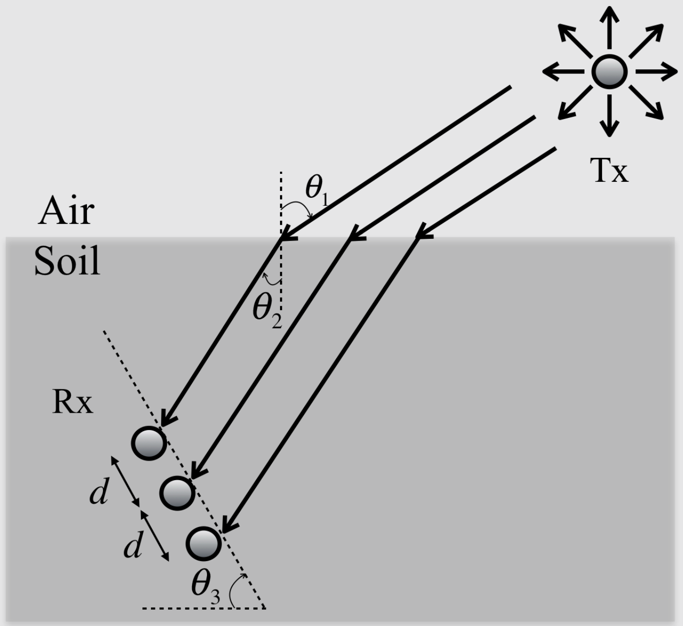
Antenna 1: $h_1(t) = a(t)e^{-j2\pi f t}$
Antenna 2: $h_2(t) = a(t)e^{-j2\pi f(t+\Delta t)}$
Antenna 3: $h_3(t) = a(t)e^{-j2\pi f(t+2\Delta t)}$

Relating relative ToF to soil moisture

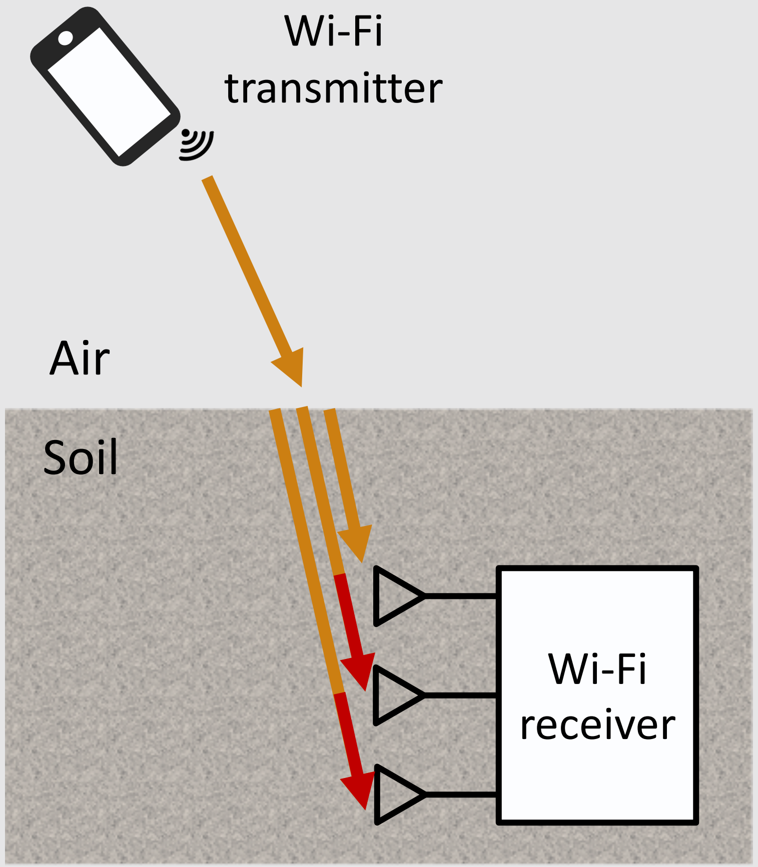


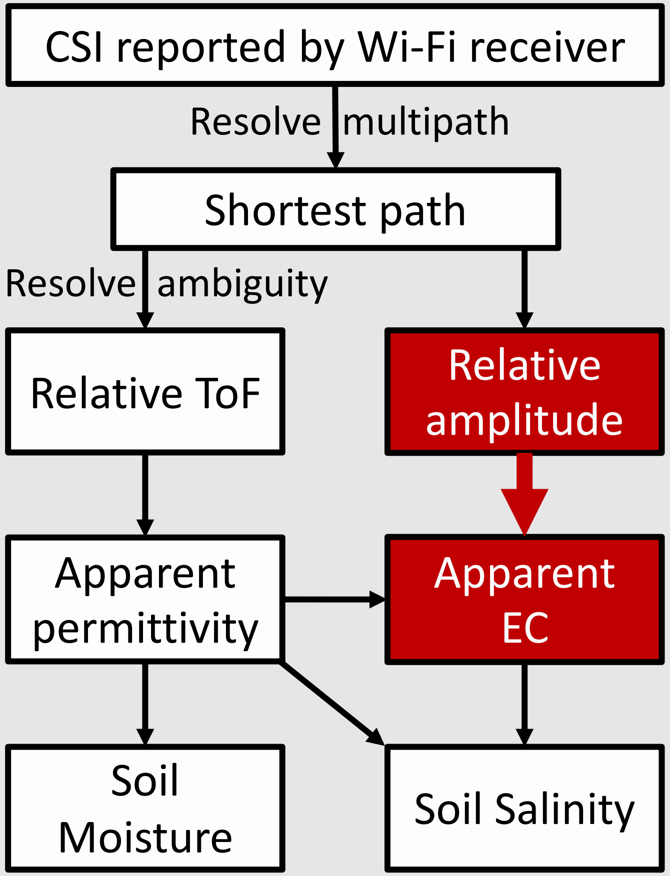
Insight: when path difference happens in soil, relative ToF has a dependency on soil moisture

- **Design objective:** maximize dependency of relative ToF on soil moisture
- **Key design decision**: placing RX antennas in soil and leave TX in the air



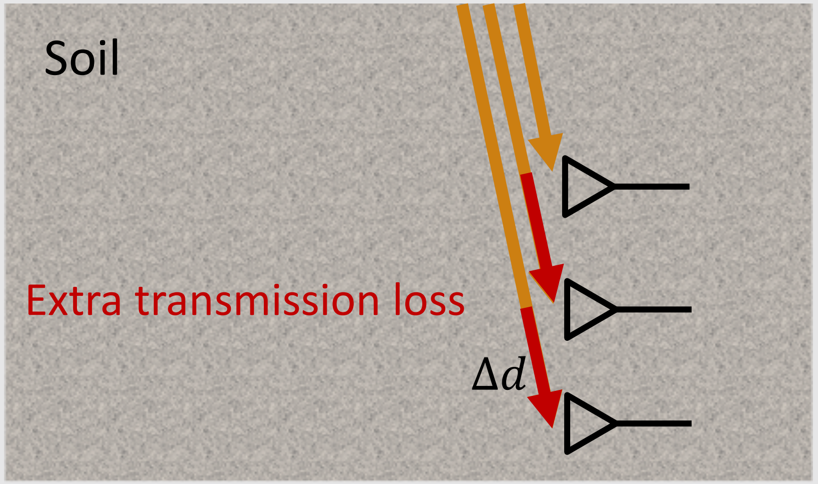
Relating relative amplitude to soil EC





Insight: deeper antennas experience extra transmission loss

- Relative amplitude $\approx e^{2\alpha\Delta d}$ (extra transmission loss)
- Benefit: easier to calibrate than existing techniques using absolute amplitude



Strobe evaluation

- USRP – 1GHz bandwidth
- WARP & Wi-Fi card – 70 MHz bandwidth at 2.4 GHz

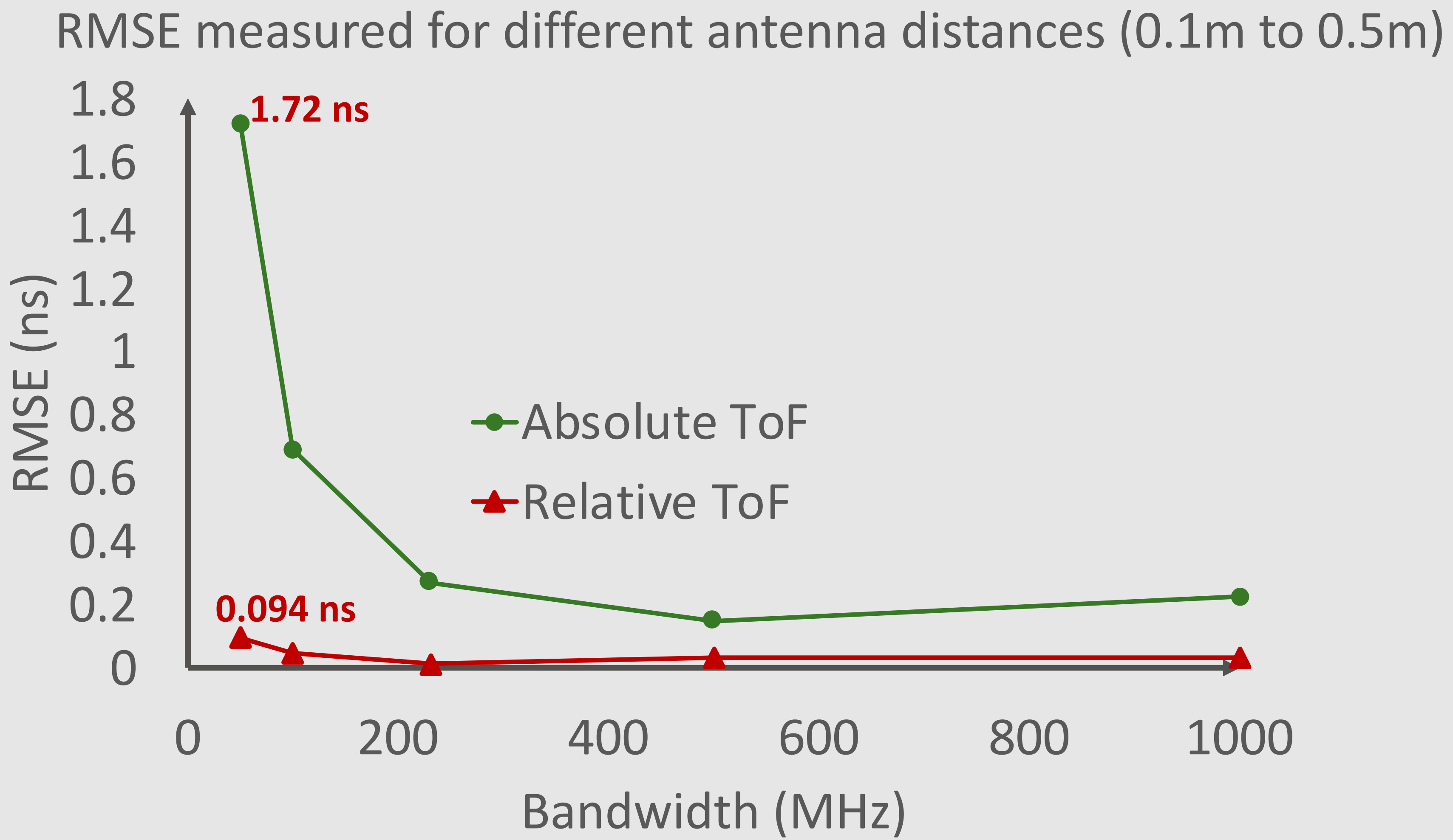
Waterproof box holding the RX antenna array

Soil boxes in a tent

Outdoor Wi-Fi steup

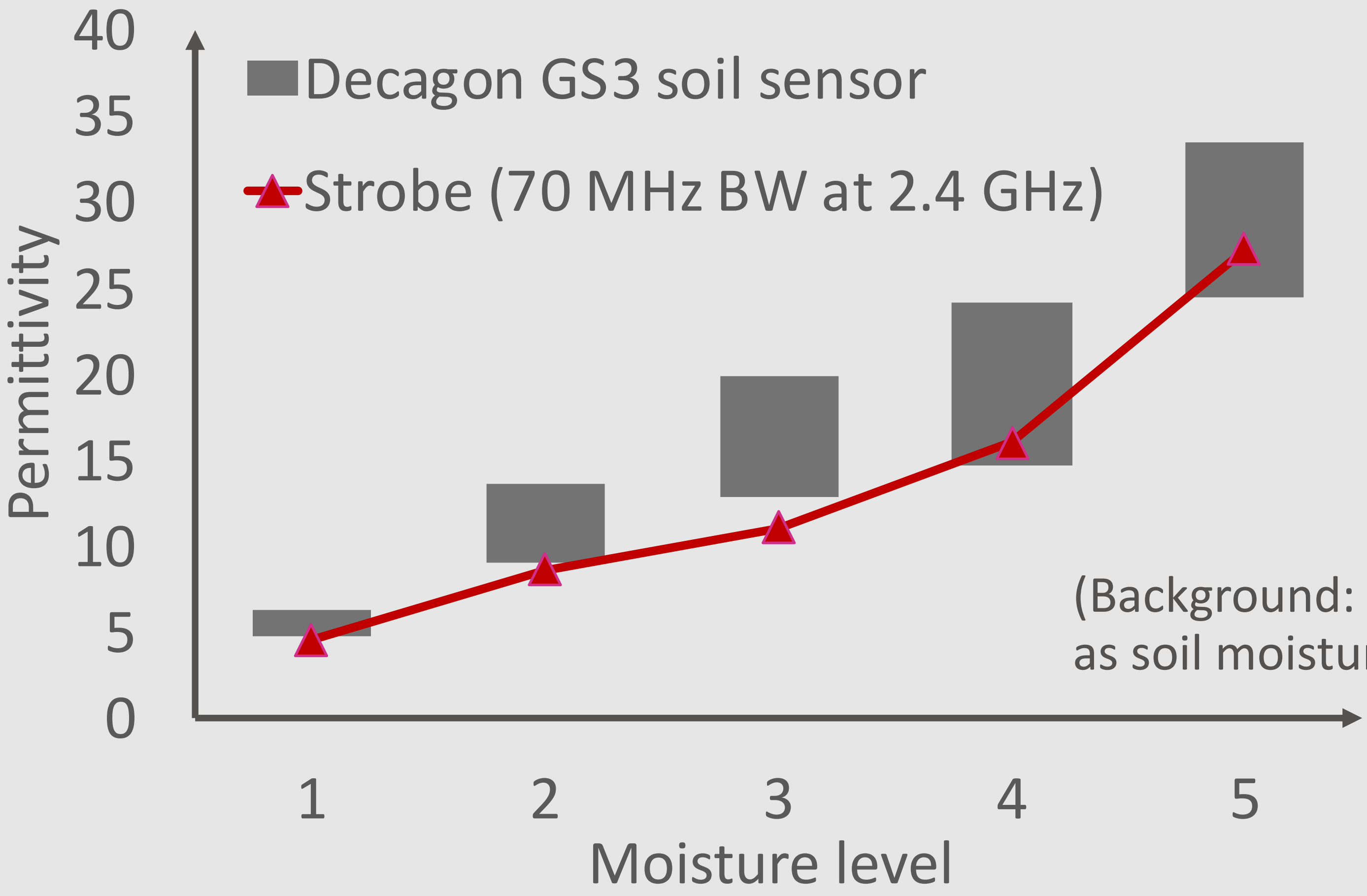
Relative ToF is much more accurate than absolute ToF (over-the-air)

- With 50 MHz bandwidth, relative ToF has 18x less error



Soil permittivity: Strobe only slightly deviates from the commercial-grade soil sensor (300 USD)

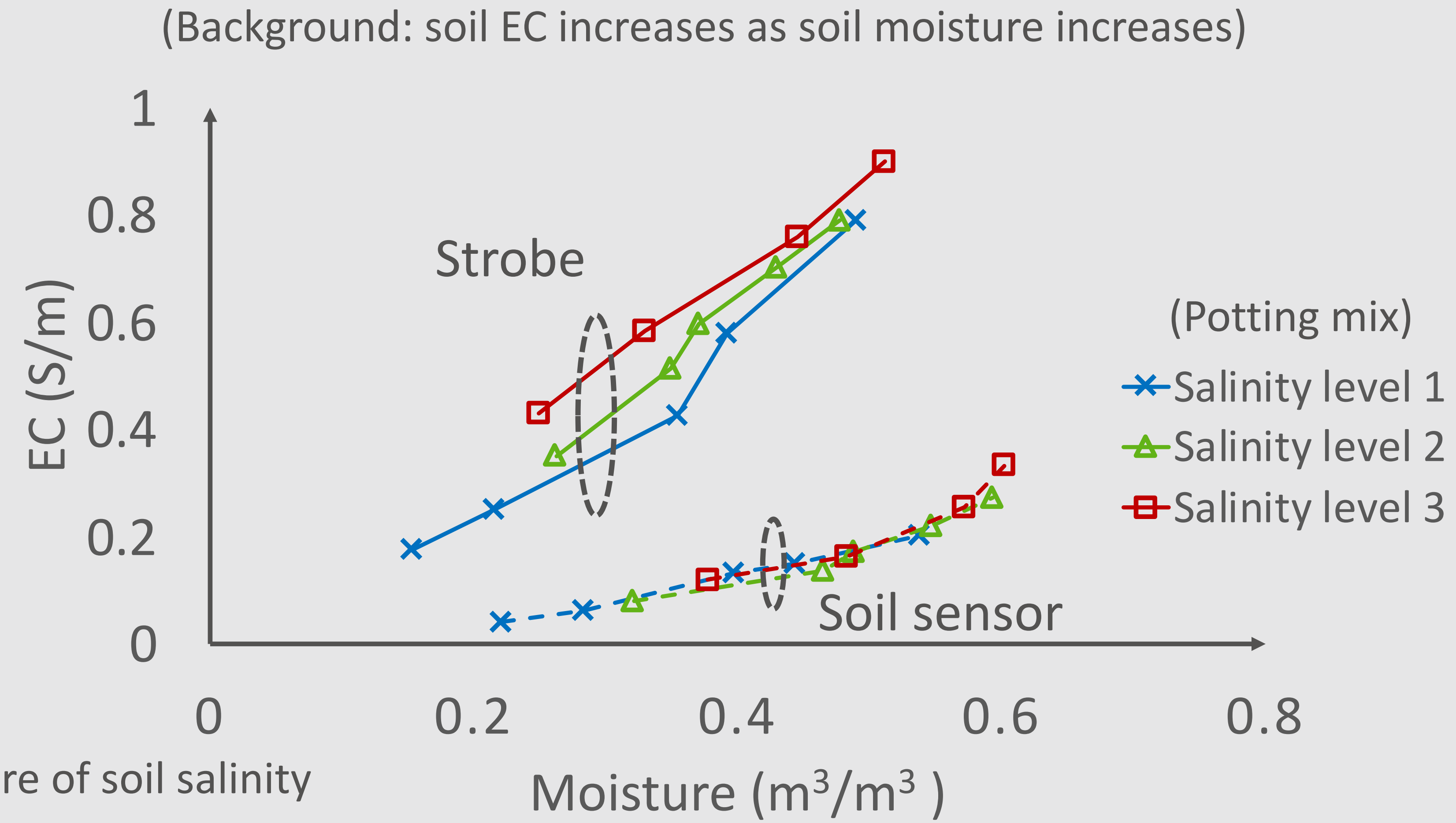
- Average permittivity deviation: 2.83 (moisture deviation: $0.05m^3/m^3$)



(Background: soil permittivity increases as soil moisture increases)

Soil moisture and EC under different salinity* levels: Strobe outperforms the commercial-grade soil sensor

- Strobe can detect different salinity levels while the soil sensor cannot

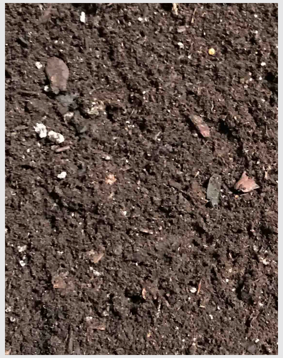


* EC is a measure of soil salinity

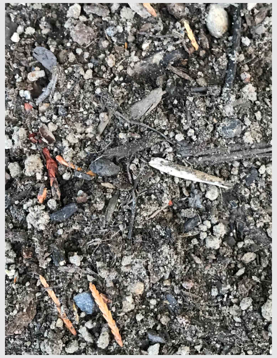
Strobe can measure moisture and salinity for real-world soils

- For each soil, Strobe can correctly detect the moisture changes
- For different soil types, Strobe can detect their different salinity* levels

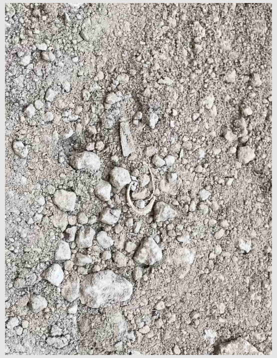
Potting mix

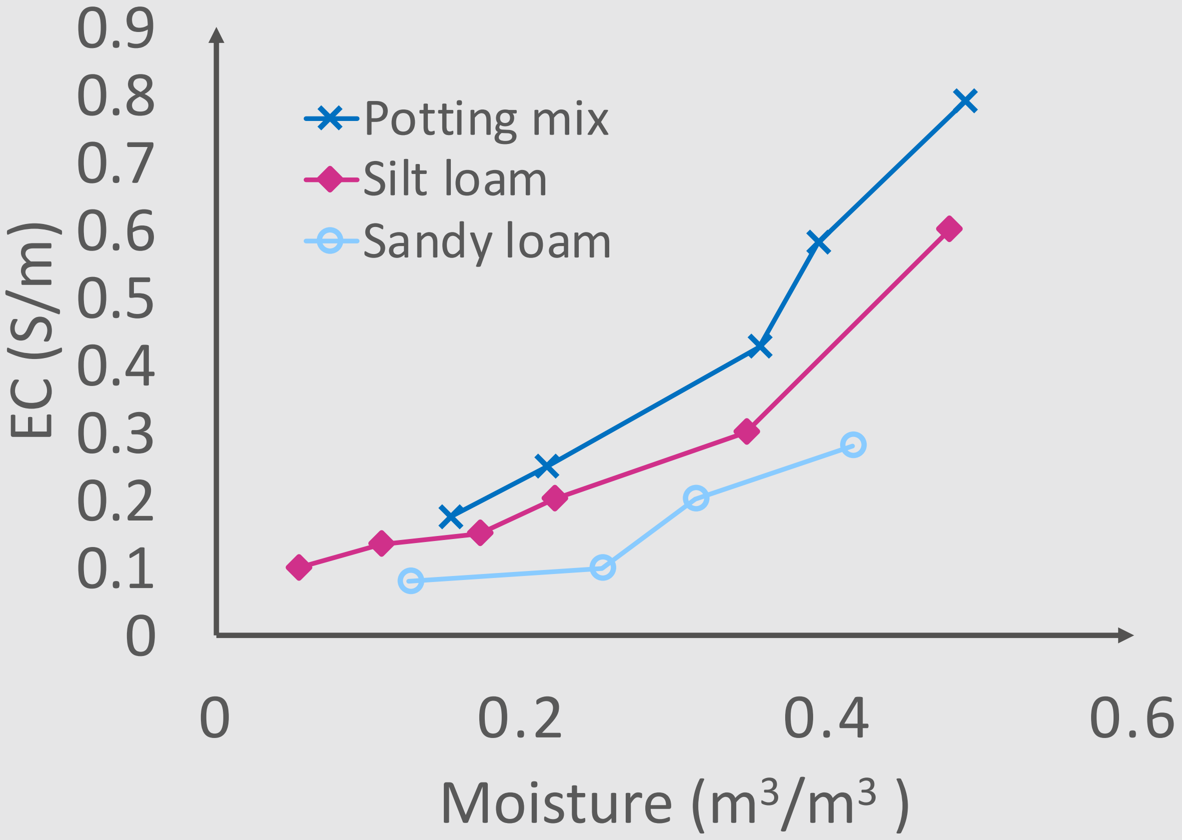


Sandy loam



Silt loam





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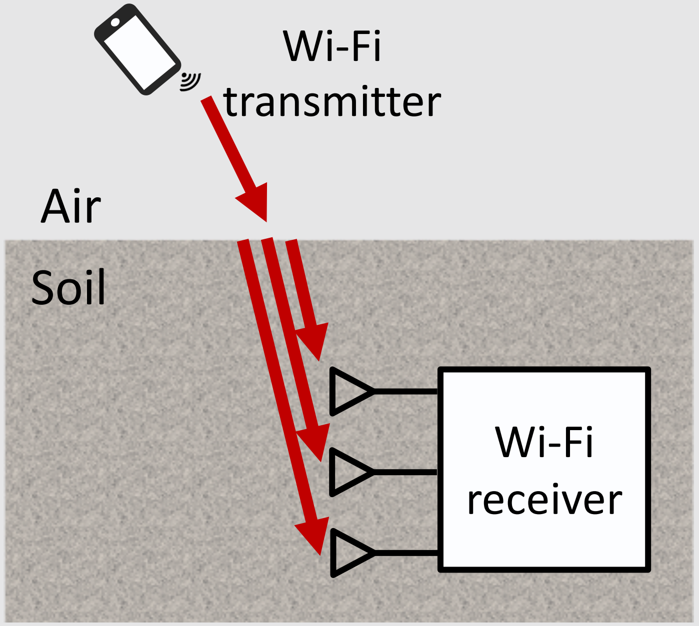
Summary

- Strobe: a new technique towards low cost and accurate soil moisture and EC sensing
  - **Affordability:** commercial Wi-Fi devices
  - **Accuracy:** novel algorithm based on relative ToF & amplitude
- A big step towards the adoption of data-driven agriculture by small holder farmers
  - Enables a future: any farmer can use their smartphone to collect soil data



Future work

- Further reduce cost to be < 10 USD
- Commercialize with traditional sensor manufactures
- Sensing deeper in soil
- …

For more information

Learn more about FarmBeats at Microsoft booth

https://www.microsoft.com/en-us/research/project/farmbeats-iot-agriculture/

A true data farm

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By Bill Gates | October 9, 2018

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