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
- Networking cost: sending data to cloud
- ...

Cost of individual sensors (100s - 1000s of USD per sensor)
Soil moisture and EC: key indicators in data-driven agriculture

- 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

<table>
<thead>
<tr>
<th>Price</th>
<th>Accuracy</th>
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<tbody>
<tr>
<td>&lt; 20 USD</td>
<td>Hobbyist sensors</td>
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<tr>
<td>&gt; 100 USD</td>
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Hobbyist sensors:
- Not reliable, degrade fast

Commercial-grade sensors:
- Tensiometer
- Capacitance-based
- Resistivity-based
- Neutron probe
- Time domain reflectometry (TDR)
- Ground penetrating radar (GPR)
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

\[ v_{\text{air}} = c = 3 \times 10^8 \text{m/s} \]

Slower speed: due to higher dielectric permittivity (moisture)

Higher attenuation: due to extra transmission loss (EC)

Slower speed: \( v_{\text{soil}} = \frac{c}{\sqrt{\varepsilon}} \)

(\( \varepsilon \): dielectric permittivity)

Transmission loss: \( e^{2\alpha d} \)

(\( \alpha \): attenuation coefficient, a function of EC)
Existing RF-based soil sensing systems

E.g., ground penetrating radar (GPR) and time domain reflectometry (TDR)
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- **Challenge 1:** Require ultra-wide bandwidth for moisture sensing
  - Measure time-of-flight (ToF) to estimate wave velocity change in soil
Existing RF-based soil sensing systems

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

• **Challenge 1:** Require ultra-wide bandwidth for moisture sensing
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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 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

Existing RF-based methods: ultra-wide bandwidth
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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

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

- Relative ToF estimation is based on phase rotation

Antenna 1: \( h_1(t) = a(t)e^{-j2\pi ft} \)
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

Soil Moisture

Wi-Fi transmitter

Wi-Fi receiver

Air

CSI reported by Wi-Fi receiver

Resolve multipath

Shortest path

Resolve ambiguity

Relative ToF

Apparent permittivity

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

Soil Moisture

Soil Salinity

Relative amplitude

Apparent EC

Apparent permittivity

Relative ToF

Resolve multipath

Shortest path

Resolve ambiguity

CSI reported by Wi-Fi receiver

Wi-Fi transmitter

Air

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

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

### RMSE measured for different antenna distances (0.1m to 0.5m)

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

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

(Background: soil EC increases as soil moisture increases)

* 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

* EC is a measure of soil salinity
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

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