Tragedy of the Coulombs

Federating Energy Storage for Tiny, Intermittently-Powered Sensors

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Sensing
This Talk

1. Batteryless sensing challenges
2. Problems with centralized energy
3. Federating energy
Vision

Sophisticated sensing on batteryless devices
Batteryless Devices

UMass Moo
Batteryless Devices
Batteryless Devices
Batteryless Devices

UMass Moo
Batteryless Devices

As small as possible

- Minimal energy storage (Cap)
- Harvest energy (RF, Solar, Glucose)

Run when you can

- Frequent failures
- Erratic supply
Applications

Infrastructure Monitoring
- Pipelines
- Bridges
- Roads

Wildlife Tracking
- Small animal
- Implant once

Building Monitoring
- Occupancy
- Energy Waste

Wearables
- Clothing
- Jewelry
Tragedy of the Commons
Tragedy of the Commons
Tragedy of the Commons
Tragedy of the Commons
Greenhouse Monitoring

Water waste is a problem

• Overwatering typical
• Coarse data on plants

Dense sensing is a solution

• Fine grained plant information
• Cheap, non-invasive, long lived
Greenhouse Monitoring

- Radio
- Computation
- Harvesting
- Storage
- Sensing
Batteryless Sensing

Supply Voltage (V)

MCU

Humidity Sensor

Leaf Wetness

Radio
Batteryless Sensing

- Supply Voltage (V)
  - MCU
  - Humidity Sensor
  - Leaf
  - Wetness
  - Radio

- Usable Range
Batteryless Sensing

Voltage requirements vary
Batteryless Sensing

![Diagram of sensor voltage over time](image)

- **Sensor Voltage**
- **Time (s)**
Batteryless Sensing

Sensor Voltage vs Time (s)

- Attempt Send Pkt
- Sensor
Batteryless Sensing

![Diagram showing sensor voltage over time with attempt to send a packet and reset action.]

Sensor Voltage vs. Time (s)

- Attempt Send Pkt
- Reset
Batteryless Sensing

Sensor Voltage

Attempt Send Pkt

Reset

Task coupling increases failure

Time (s)
Batteryless Sensing

Sensor Voltage

Time (s)

0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8

0 0.7 1.4 2.1 2.8 3.5

Could have sent

Overestimate

Actual
Batteryless Sensing

Task coupling decreases utility

Sensor Voltage

Sensor

Time (s)

Overestimate

Actual

Could have sent

Could have sent

0
0.7
1.4
2.1
2.8
3.5

0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Scheduling Tasks

Energy Cost (mJ)

- 1s Computation
- 10x Leaf Rds
- 10x Humidity Rds
- Send 1 Packet

Greenhouse Monitoring
Scheduling Tasks

- Energy Stored (mJ)
  - 0
  - 0.125
  - 0.25
  - 0.375
  - 0.5

- Time (s)
  - 0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1
  - 1.2
  - 1.4
  - 1.6
  - 1.8

- 1s of Computation
- Sample 10x Humidity
- Sample 10x Leaf
- Send 1 Pkt
Scheduling Tasks

Energy Stored (mJ)

Time (s)

0
0.125
0.25
0.375
0.5

0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Scheduling Tasks

Start Threshold

1.3 seconds charge time
Scheduling Tasks

Capacitor Voltage

Time (s)

Start Threshold

Large

Small

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8

0 1 2 3 4

Capacitor Voltage
Scheduling Tasks

Start Threshold

1.2s charge
Scheduling Tasks

![Graph showing capacitor voltage over time with two charging thresholds: 0.4s charge and 1.2s charge. The graph compares Large and Small charging processes, with a start threshold indicated.]

- Large charging process reaches a capacitor voltage of approximately 3 units at around 1.2s charge.
- Small charging process reaches a capacitor voltage of approximately 3 units at around 0.4s charge.

Time (s):
- 0 to 1.8

Capacitor Voltage:
- 0 to 4

Thresholds:
- Start Threshold
  - 0.4s charge
  - 1.2s charge
Batteryless Sensing

Batteryless sensing is hard

- Tasks are coupled, causing death
- Execution is not predictable
- Low energy tasks wait on high energy tasks

Because energy storage is centralized
Batteryless Sensing

Batteryless sensing is hard

- Tasks are coupled, causing death
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Because energy storage is centralized

What if we federate energy storage?
Benefits

• useful work starts sooner
• fewer power failures
• simpler application decisions
• relaxes voltage coupling
• increases energy harvested
Multiple capacitors

- One for microcontroller
- One for each peripheral
- Static rate and priority
Start work sooner

[Diagram showing a circuit with labeled components: MCU, Radio, UFoP, and voltage-time graphs indicating readiness]
Decrease power failures

**Centralized**

- Capacitor Voltage
- Time (s)

**Key Events**

- Attempt
- Send Pkt
- MCU Reset
Decrease power failures

![Graph showing decrease in power failures with federated capacitor voltage]

- Capacitor Voltage on the y-axis
- Time (s) on the x-axis
- Radio Cap and MCU Cap lines on the graph
- Federated context
- Attempt Send Pkt and Radio Fail annotations
Simplify app decisions

Centralized

Capacitor Voltage

Time (s)

Compute
Send Pkt
Simplify app decisions

Federated

Radio Cap
MCU Cap

Capacitor Voltage

Compute
Send Pkt
Compute

Time (s)

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8
0 1 2 3 4

Send Pkt
Relax voltage constraints

Supply Voltage (V)

MCU

Humidity Sensor

Leaf

Wetness

Radio
Relax voltage constraints

Supply Voltage (V)

MCU

Humidity Sensor

Leaf

Wetness

Radio

Centralized Range
Relax voltage constraints

Supply Voltage (V)

MCU

Humidity Sensor

Leaf

Wetness

Radio

Centralized Range

Federated Range
Harvest more energy
Harvest more energy
Harvest more energy

Sun → Power

volts

Load
Harvest more energy

Power, \( P=IV \)
Harvest more energy

Federated

Centralized

Time (s)

Volts

Volts
Harvest more energy

Federated

Centralized

Time (s)

Volts

Volts
Harvest more energy

Federated

Volts
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4 2.6

Centralized

Volts
0 1 2 3 4

Reduces voltage volatility
Implementation

Energy Harvesting
- Solar
- Thermal
- RF
- Kinetic

Charging Control
- UFoP Controller (Custom PCB)
- DC Power
- 1st stage Capacitor
- Cap

Peripheral Control
- MCU (MSP430)
- Sensor
- Radio

Current Flow

Control Signals
Results

Evaluation

• Availability
• Resiliency
• Energy harvested

Deployment

• Greenhouse monitoring
Methodology

RF Low  RF High
Methodology
Methodology

RF Low

RF High

Solar
Availability

Centralized

Federated

More computational availability
More resilient than without federating
Energy Harvested

More energy harvested
Deployment

![Deployment Chart]

- **Centralized MCU**
- **Centralized Radio**
- **UFoP MCU**
- **UFoP Radio**

**Availability**

- **Afternoon**: 100%
- **Evening**: 50%
- **Morning**: 75%

**Storage**

- **Centralized MCU**
- **Centralized Radio**
- **UFoP MCU**
- **UFoP Radio**
Future Work

Dynamic UFoP

- Dynamic priority, capacity, thresholds
- Resiliency
- Energy harvested

Language

- Manage energy and time
Summary

Federating energy storage dramatically improves the utility of batteryless sensors.

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