6.S062: Mobile and Sensor Computing

Lecture 14: Bringing Connectivity “Everywhere”
Aerial-based Connectivity & Agriculture IoT

Some material adapted from Deepak Vasisht (MIT/MSR)
High Interest in Aerial-based Connectivity

Google X’s Project Loon

Facebook’s Project Aquila

Others including Microsoft, Boeing, etc.

Goal: Bringing Connectivity to the Remote and Disconnected Areas of the Planet
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- Bring connectivity to rural areas
- Disaster Relief
Challenges

- **Power**: Constrained
  - Need to last for a long time

- **Control**: Flight paths
  - Minimal power consumption

- **Communications**: Long-range links

- **Data Rates**
Challenges

• **Power:** Constrained
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• **Communications:** Long-range links

• **Data Rates**

Solar Energy

• Stratosphere
• Drone paths

Low Frequencies

• 10s MHz bandwidth
• Millimeter waves
Common Opportunities: Atmospheric Conditions and Predictability

- Leverage Stratosphere in Loon/Aquila
  - No “problematic” weather conditions (rain, winds, etc.)

- Different stratospheric layers have different predictable currents

- Thermodynamics for changing levels in stratosphere
FarmBeats: An IoT System for Data-Driven Agriculture

NSDI 2017
Why Agriculture?

Agricultural output needs to **double by 2050** to meet the demands
- United Nations\(^1\)

\(^1\): United Nations Second Committee (Economic & Financial), 2009
Why Agriculture?

Agricultural output needs to **double by 2050** to meet the demands
- United Nations

But...
- Water levels are receding
- Arable land is shrinking
- Environment is being degraded

1: United Nations Second Committee (Economic & Financial), 2009
Why Agriculture?

Agricultural output needs to **double by 2050** to meet the demands
- United Nations

Number of World’s Hungry People

Population (Billions)
Solution: Data-Driven Agriculture

Traditional vs Data-driven approach

Ag researchers have shown that it:
• Reduces waste
• Increases productivity
• Ensures sustainability
But…

According to USDA, high cost of manual data collection prevents farmers from using data-driven agriculture.
IoT System for Agriculture
Problem 1: No Internet Connectivity

- Most farms don’t have any internet coverage

- Even if connectivity exists, weather related outages can disable networks for weeks
Problem 2: No Power on the Farm

- Farms do not have direct power sources

- Solar power is highly prone to weather variability
Problem 3: Limited Resources

• Need to work with sparse sensor deployments
  • Physical constraints due to farming practices

• Too expensive to deploy and maintain
Beyond Agriculture

How can one design an IoT system in challenging resource-constrained environments?
Rest of this lecture

• FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture
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• FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

• Solves three key challenges:
  • Internet Connectivity
  • Power Availability
  • Limited Sensor Placement

• Deployed in two farms in NY and WA for over six months
Challenge: Internet Connectivity

(Farmer’s home/office)  Cloud

Microsoft Azure
Challenge: Internet Connectivity

(Farmer’s home/office)

Cloud

Sensors

- Few miles away
- Obstructed by crops, canopies, etc
Approach: Use TV White Spaces

- Can provide long-range connectivity

- Can travel through crops and canopies, because of low frequencies

- Large chunks are available in rural areas=> can support large bandwidth
Idea: Use TV White Spaces

- Weak Connectivity
- Prone to outages

Base Station

TV White Spaces

Few miles

(Farmer’s home/office)

Cloud

Wi-Fi, BLE

Sensors
Approach: Compute Locally and Send Summaries

- PC on the farm delivers time-sensitive services locally
- Combines all the sensor data into summaries
- 2-3 orders of magnitude smaller than raw data
- Cloud delivers long-term analytics and cross-farm analytics
FarmBeats Design

Base Station

TV White Spaces
Few miles

Gateway PC
(Farmer’s home/office)

Sensors

Cloud

Microsoft Azure
In this lecture

• FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

• Solves three key challenges:
  ✓ Internet Connectivity
  • Limited Sensor Placement
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• Deployed in two farms in NY and WA for over six months
Challenge: Limited Resources

- Need to work with sparse sensor deployments
  - Physical constraints due to farming practices
  - Too expensive to deploy and maintain

- How do we get coverage with a sparse sensor deployment?
Approach: Use Drones to Enhance Spatial Coverage

- Drones are cheap and automatic
- Can cover large areas quickly
- Can collect visual data

Combine visual data from the drones with the sensor data from the farm
Idea: Use Drones to Enhance Spatial Coverage

Drone Video → Panoramic Overview → Precision Map

Sparse Sensor Data
Formulate as a Learning Problem

Training Data

Prediction

Panoramic Overview
Model Insights

- **Spatial Smoothness**: Areas close to each other have similar sensor values.

- **Visual Smoothness**: Areas that look similar have similar sensor values.
Model: Gaussian Processes

- **Features (visual)**
- **Kernel (Model visual similarity)**
- **Output (say, moisture)**
- **Spatial Smoothness**

### Training Phase:
- Learn K and W

### Test Phase:
- Generate outputs for unknown areas
FarmBeats can use drones to expand the sparse sensor data and create summaries for the farm.
In this talk

• FarmBeats: An end-to-end IoT system that enables seamless data collection for agriculture

• Solves three key challenges:
  ✓ Internet Connectivity
  ✓ Limited Sensor Placement
  • Power Availability

• Deployed in two farms in NY and WA for over six months
Challenge: Power Availability is Variable

Farm

Battery dies due to cloudy/rainy/snowy weather

TV White Spaces

Gateway
(Farmer’s home/office)

Microsoft Azure

Cloud
Challenge: Power Availability is Variable

• Solar powered battery saw up to 30% downtime in cloudy months

• Miss important data like flood monitoring

How do we deal with weather-based power variability?
Approach: Weather is Predictable

- Use weather forecasts to predict solar energy output
- Ration the load to fit within power budget
Idea: Weather is Predictable

- $\gamma$: Duty Cycle ratio, $T_{on}$: On time in each cycle, $T_{off}$: Off time

\[
\gamma = \frac{T_{on}}{T_{off}}
\]

- Constraints:
  - Power Neutrality: $\gamma P \leq C$
  - Minimum Transfer Time: $T_{on} \geq T_{connect} + T_{transfer}$
Solution: Weather is predictable

FarmBeats can use weather forecasts to duty cycle the base station, with minimum latency.
How would you design the sensors?

- Low-power — backscatter
  - problems: intermittent, or base station runs out of power
  - Limited range

- Semi-passive?

- Power decays with $1/d^2$ (Sphere) => waste less energy by multiple harvesters

- Can even harness power from whitespace emissions
In this lecture

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• Deployed in two farms in NY and WA for over six months
Deployment

- Six months deployment in two farms: Upstate NY (Essex), WA (Carnation)
- The farm sizes were 100 acres and 5 acres respectively
- Sensors:
  - DJI Drones
  - Particle Photons with Moisture, Temperature, pH Sensors
  - IP Cameras to capture IR imagery as well as monitoring
- Cloud Components: Azure Storage and IoT Suite
Deployment Statistics

• Used 10 sensor types, 3 camera types and 3 drone versions

• Deployed >100 sensors and ~10 cameras

• Collected >10 million sensor measurements, >0.5 million images, 100 drone surveys

• Resilient to week long outage from a thunderstorm
FarmBeats: Usage
Example: Panorama

- Water puddle
- Cow excreta
- Cow Herd
- Stray cow
Precision Map: Panorama Generation
Precision Map: Moisture
Precision Map : pH
FarmBeats can accurately expand coverage by orders of magnitude using a sparse sensor deployment.
Weather-Aware Duty Cycling

Reduced downtime from 30% to 0% for month long data (September)
Other Related Works

• **Wireless Sensor Networks:** Sensor networks for agriculture (Baggio `05, Sanchez et al `11, Lee et al `10,...), LPWAN technologies (LoRA, SIGFOX, ...)

• **Agriculture:** Precision agriculture (Bratney et al `99, Mueller et al `12, Cassman et al `99,...), Nutrient measurement (Kim et al `09, Hanson et al `07)

• **ICTD:** Information access and user interfaces (Zhao et al `10, Doerflinger et al 2012)
Summary

• Aerial-based Connectivity (Loon, Aquila) & Agriculture IoT

• Challenges: Power, Control, Communication Range, Bandwidth, Weather

• Opportunities: Duty cycling, sparse sampling, weather prediction, thermodynamics, learning and sensor fusion, Drones

• Farmbeats: End-to-end IoT system for Farming