EXPERIENCES DEPLOYING AN ALWAYS-ON FARM NETWORK

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Data-driven techniques for agriculture can help farmers reduce waste, increase farm output and ensure sustainability for the environment. The key enabler for such techniques is an always-on connected IoT system that can sense the different characteristics of the farm and generate short-term and long-term actionable insights for the farmer. Yet building such a system is very challenging due to sparse Internet connectivity and lack of reliable power sources. This is further exacerbated by weather variability that stresses the system in numerous ways. We discuss how we built and deployed Farmbeats [6] in the face of these challenges. We hope our experiences will aid researchers who are beginning to explore deployments in farming or other weakly connected, power-starved scenarios, such as construction, oil fields, mining, and others.

F ueled by increasing population and upward social mobility, the worldwide demand for food is expected to double by 2050 [5]. Achieving this growth is an uphill task, given receding water levels, climate change and shrinking arable land.

Data-driven techniques for farming can help alleviate this problem by reducing waste, increasing productivity and ensuring environment sustainability. For example, precision irrigation, a technique that adapts water input across different parts of the farm based on the measured moisture value, has been shown to increase output by as much as 45% while reducing water intake by 37% [2]. Similar gains have been shown for other data-driven farming techniques in different field trials. Although these techniques were conceptualized a couple of decades ago and have shown promising results in field trials, these techniques have failed to make it to practice owing to the high cost of manual data collection [4].

This necessitates the need for an IoT system that can automate the data collection process by sensing different characteristics of the farm at a fine spatial granularity. Such a system could enable the farmer to get a heat map of his field, showing the variations of each characteristic across the farm. The farmer could get this heat map on-demand, whenever he is about to carry on a farming activity, at no additional cost.

However, enabling such a system faces significant challenges:

- Farms have poor connectivity to the internet. Since most farms are located in sparsely populated rural areas, they seldom have cellular coverage. Even if they have coverage, the bandwidth of the connection is low. Furthermore, even these connections are prone to weather-related outages.
- There are no power lines on the farm. While one may try to rely on solar power, solar power is variable depending on the weather. Consistently cloudy, rainy or snowy weather can discharge the solar-powered batteries and leave the system dysfunctional.
- Finally, weather-based variability can wreak havoc on all the components of the system. It can render sensors unusable by corrupting their electronics. It can disrupt networks; thunderstorms have been known to disable the network for weeks. Moreover, it can shut down the power available to the system.

So the key question is: how does one go about building an always-on system in the face of these challenges? We attempt to answer this question by discussing our design of FarmBeats, an end-to-end IoT system for agriculture that ingests data from various sources, such as sensors, cameras, and drones, to produce actionable insights for the farmer. FarmBeats can extend connectivity to the farm, deal with power variability and weather-related outages to provide an "always-on" system for farmers. As of writing, FarmBeats has been deployed in two different farms for more than a year and has collected more than 20 million measurements. FarmBeats has been used for several applications by the farmers, like storage monitoring, generating sensor maps of the field, animal-shed monitoring, etc.

While we discuss the design of FarmBeats in the subsequent sections, here we list the general principles that have been crystallized by our farming experiences and have helped us design an always-on farm IoT system:

- **Leveraging farm resources:** While working in sparsely populated rural agricultural areas has its challenges, it provides new opportunities. One such opportunity is the availability of free TV white spaces (TVWS) spectrum, which is in abundant supply in these areas. Further, due to its low-frequency operation, the signal in this spectrum has long range and can go through crops, canopies and forest covers, which are standard farm features. FarmBeats leverages TVWS to establish a persistent, high bandwidth connection between the sensors and the farmer's PC.

Photo, istockphoto.com

- **Distributed operation:** FarmBeats splits computational responsibilities between the cloud and the farmer's PC in their home/office. By doing so, FarmBeats can continue to provide time-sensitive services to the farmer, even when the connection to the internet (and, hence the cloud) is disrupted. The PC at the farm also does novel data compression to work with narrow bandwidth connections.

- **Embracing unpredictability:** While weather variability leads to adverse system effects, recent scientific advances have ensured that weather can be predicted with a reasonable accuracy. FarmBeats uses these forecasting capabilities to deal with unpredictability in weather. Specifically, in the context of solar power generation, FarmBeats can use weather forecasts to estimate solar power output. It can then use this output estimate to ration the load of the system accordingly. So, if a cloudy day is coming up, the system can save some of its battery for use on the next day.

- **Multi-modal sensing:** New modes of sensing, like drones and cameras, provide exciting opportunities for the design of IoT systems in resource-constrained environments. Instead of treating each mode of data independently, we can use these modes to complement each other. For instance, FarmBeats uses aerial imagery collected by drones, to extrapolate sensor data to areas where you do not have sensors at all. Thus, by deploying a small number of sensors, one can obtain a fine-grained map of sensor values all across the farm. This also means that missing sensor values (because of disconnection or otherwise) can be filled up with the help of drone-based aerial imagery.

In the following sections, we describe how these principles were instantiated in the design of FarmBeats and how this has enabled us to deliver an always-on farm IoT system. A detailed design of FarmBeats is described in [6]. Here, we focus on discussing the hacks, the software and hardware patches, and the engineering challenges that we had to overcome in implementing our algorithms in a resource-constrained, non-traditional networking research environment.

(a) Sensor with big solar panel

(b) Portable solar-powered sensors

FIGURE 1. Sensor deployment.

DEPLOYMENT

FarmBeats is a low-cost end-to-end IoT platform for agriculture that enables seamless data collection from various sensors, cameras and drones [6]. To enable FarmBeats, we setup an IoT basestation on the farm. This IoT basestation connects over TV White Spaces to connect to the farmer's home or office, which is a few miles away and connected to the Internet for personal use by the farmers. The sensors, drones and cameras connect to the IoT basestation over Wi-Fi. All this data generated by the sensors is processed locally at the farmer's PC in the home/office and time-sensitive services are delivered locally. The farmer's PC also compresses this data into summaries that can be sent to the cloud for long-term and cross-farm analytics.

So far, we have deployed FarmBeats on two farms located in Washington state (WA) and upstate New York (NY). The farmer in WA grows vegetables that he sells in the local farmers market and to restaurants. The farm in NY grows vegetables, fruit, grains, and also produces dairy and meat. The FarmBeats deployment on each farm is comprised of sensors, cameras, drones, an IoT base station, Gateway PC, the cloud service, and a dashboard (smartphone app and webpage).

Sensors: Each farm was equipped with sensors that measure soil temperature, moisture, and pH. The sensors were interfaced with either Arduinos or Particle Photons to process and transmit data over Wi-Fi. Power was provided to each sensor by integrating a solar panel, charge controller, and battery with the sensors. Over 100 sensors were deployed across the span of two farms for varied applications. We also deployed Microseven IP cameras to monitor the farms as well as capture IR images of crops. Figure 1 shows an example of sensor deployments on both farms.

Drones: We used DJI Phantom 2, Phantom 3, and Inpsire 1 to perform drone flights. We also designed an auto-pilot application using the DJI Mobile SDK to interface with FarmBeats.

Base Station: Each IoT base station was equipped with FCC certified Adaptrum ACRS 2 radios to setup a TVWS network. Internet connectivity was provided by the home network of each farmer. We powered the base station by constructing a solar charging station. The charging station consisted of two 80-watt solar panels connected in series, a charge controller, and four 12V-44Ah sealed lead acid batteries connected also in series. The power output goes to an 8-port Digital Logger POE injector, which controls the power output to individual devices at the base station. We used a Raspberry Pi 3 with 64GB SD card as the base station controller. Communication with the sensors was enabled by using a 802.11b router, with a range of over 100m. Figure 2 shows the base station deployment on the farm in WA.

(a) IoT base station

(b) TVWS client and antenna
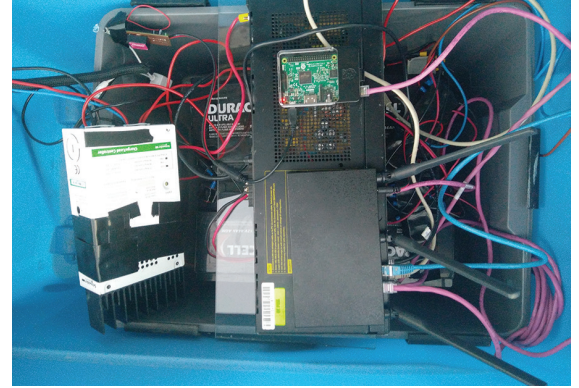
(c) Digital logger

FIGURE 2. IoT base station deployment in Carnation, WA.

Gateway: The gateway is a Lenovo Thinkpad on the WA farm and a Dell Inspiron laptop on the farm in upstate NY.

Cloud: Azure IoT Suite serves as the cloud for FarmBeats. The sensor data, images, and drone video summaries are populated through the Azure IoT hub to storage. We use blobs for images and tables for the sensor readings.

CHALLENGES

The underlying problem with enabling an always-on farm network is the unpredictably of the deployment environment. This gives rise to the following challenges:

Power

Most farms lack a reliable power source and this is needed to enable the base station and sensors. We addressed this challenge by relying on solar power. That is, we equipped both the sensors and basestation with a solar charging system.

However, even solar power is not fully reliable. For instance, at the farm in Washington state, we experienced a lot of cloud coverage and rain. This limited the amount of direct sunlight hours per day and eventually the base station could not be maintained.

To work around this, we implemented weather-aware duty cycling at the base station. We wanted to be able to modify the duty cycling rate of the base station at any given moment depending on current weather conditions. This means that we must be able to remotely control the power source at the base station.

Our approach was to leverage a remotely programmable POE injector that would then connect to all devices at the base station. The POE injector enables us to control the duty cycling rate of each device connected at the base station, which in turn significantly lowers the down time of the base station.

Once we were able to bring power to the farm, we were told by the farmers that the most urgent need was a way to charge their phones using this power source. Hence in our IoT base station we added a 48V to 12V DC-DC converter, and provided a micro-USB interface to connect phones or other devices.

Next Steps: We are investigating alternative sources of power, such as RF, for powering the sensors. Even though our techniques helped increase the uptime to more than 30 days, there are periods of cloudiness that extend beyond this period. Since we have RF transmitters on the field, we are studying whether they can be used to power the sensors.

Another approach we are studying is the use of wireless charging of UAVs, such as quadrotors, out in the field, using techniques such as those developed by WiBotic [1]. The battery life of the commercial quadrotors is less than 30 minutes, and wireless charging stations could be a useful technique to extend the flight time of the drones.

Connectivity

A typical farm is in the middle of nowhere, where few people live. Therefore, cellular carriers have little economic incentive

to provide connectivity in those regions. Even though there is usually low bandwidth connectivity at the farmers home or office, there is weak connectivity on the farm, which could be a mile away. For instance, at the farm in Washington state, the farmers home was approximately one mile away, where his home connection cannot reach the farm due to distance and heavy forest canopy. We work around this by leveraging TVWS to provide Wi-Fi–like connectivity on the farm. That is, we setup a TVWS base station at the farmer's home and a client on the farm to extend connectivity. We then added a wireless AP to the base station on the farm to create a Wi-Fi connection for sensor communication.

However, enabling this connection was not a straightforward process. The antennas need to be configured such that there is a strong link between the farm end point and the base station in the farmer's house. This can get challenging when using sectored antennas, and when there are multiple endpoints that need to be connected.

Another challenge was to provide connectivity inside the refrigeration units, where the farmer stores dairy, produce, and meat. To monitor the temperature of these units, we installed temperature and humidity sensors. However, getting these sensors connected is usually a challenge over 2.4 GHz Wi-Fi. Sensors do not easily connect to a Wi-Fi AP placed outdoors because of two reasons. The antenna on the sensors themselves is weak, and the Wi-Fi signal does not propagate well through the metal enclosure of the refrigeration units. To solve this challenge, we used Wi-Fi

repeaters, which were installed inside the refrigeration units themselves. They have good antennas, and are able to relay the signal inside the refrigeration unit.

We also needed to connect cameras to the IoT Gateway, which is the PC that sits in the farmer's house. However, even with three remote cameras, the network started to get congested. To resolve this problem, we significantly reduced the frame rate from these cameras. We also installed repeaters to reduce the airtime that would be consumed by the frames [3].

Next Steps: As a first step we relied on Wi-Fi enabled sensors, but this solution does not scale for large farms. We need sensors to be able to communicate at a long-range (many miles). To remedy this, we are currently developing Whisper. Whisper is a long-range low-power TVWS radio. It addresses the scalability challenge in long-range low-power networks by utilizing the additional spectrum offered by the TV White Spaces. With this solution we will be able to deploy significantly more sensors in comparison to the existing system.

Fault Tolerance

Maintaining an end-to-end connection and accurate data collection for an outdoor IoT network is difficult. The system must be able to adapt to harsh and unpredictable weather and even animal disturbances. We also must be able to maintain and troubleshoot the system remotely. Farmers have many day-to-day tasks they need to complete and, therefore, they cannot afford extra time to address problems occurring in the system.

The most obvious failure for an outdoor system is hardware being exposed to harsh

(a) Moisture map (b) pH map
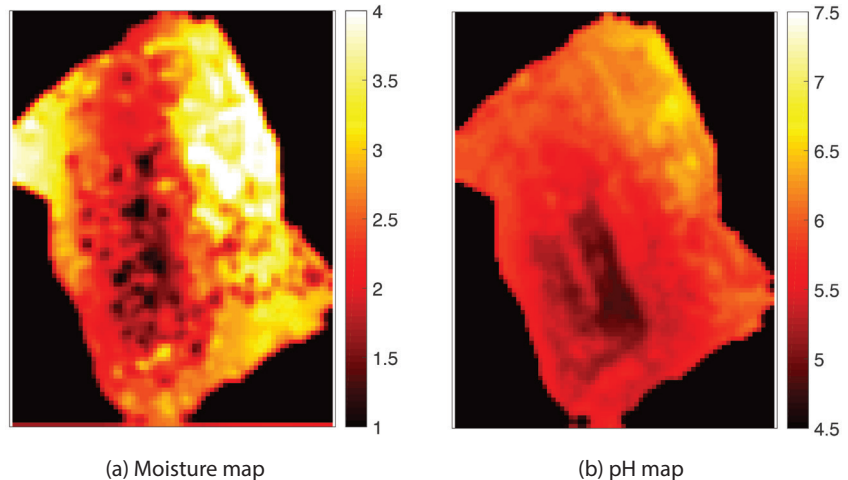
FIGURE 3. Heat map generation.

weather conditions, such as rain or flooding. To avoid failures due to weather exposure, we placed all hardware in waterproof housing. Another issue is exposed wires. For instance, wires going from the solar charging systems to the devices or wires from sensors that are being placed in the soil can be chewed on or displaced by animals. To avoid this, we wrapped all wires in plastic braided sleeving to prevent damage.

Finally, we had to be able to monitor sensor modules for bad values, loss of power, or loss of connection. To do this, we created a web server and smartphone application that report sensor data in real time. With this, we are able to catch when a sensor module goes offline or reports data that seems inaccurate. We also needed a way to act on this information. If a sensor is reporting inaccurate values we needed a way to troubleshoot remotely before resulting to manual inspection on the farm. We do this by using remotely programmable

microcontrollers for the sensor modules. This allows us to remotely power cycle the sensor module or modify device firmware, which often times resolves the problem of inaccurate data reports.

We also added extensive logging to various components in the system to remotely diagnose failures. In particular, the Raspberry PI at the IoT Base Station logs the times when different components in the system are being duty cycled. It also creates ping records for reachability to the sensors, the Wi-Fi Access Point, the white spaces router, and a server on the Internet. This helps us diagnose the cause of the problem when we don't get data from the farm.

Next Steps: Despite the above, we note that the White Spaces link is a single point of failure. If that breaks, we are unable to diagnose the system further. We are actively working on a fault diagnosis system that can identify when, which part of the farm has failed – battery failure, physical disruption, network connectivity, etc. – based on observations from the farm.

Ease of Use

FarmBeats gives farmers access to drone flights so they can get a more insightful view of their farm. It also collects multitudes of sensor data like soil moisture, which can be used for smart irrigation. However, the challenging aspect of this is that we need to convey this information efficiently and make the system easily accessible.

We created a smartphone application

FARMBEATS IS AN END-TO-END IOT SYSTEM FOR AGRICULTURE THAT INGESTS DATA FROM VARIOUS SOURCES, SUCH AS SENSORS, CAMERAS, AND DRONES, TO PRODUCE ACTIONABLE INSIGHTS FOR THE FARMER
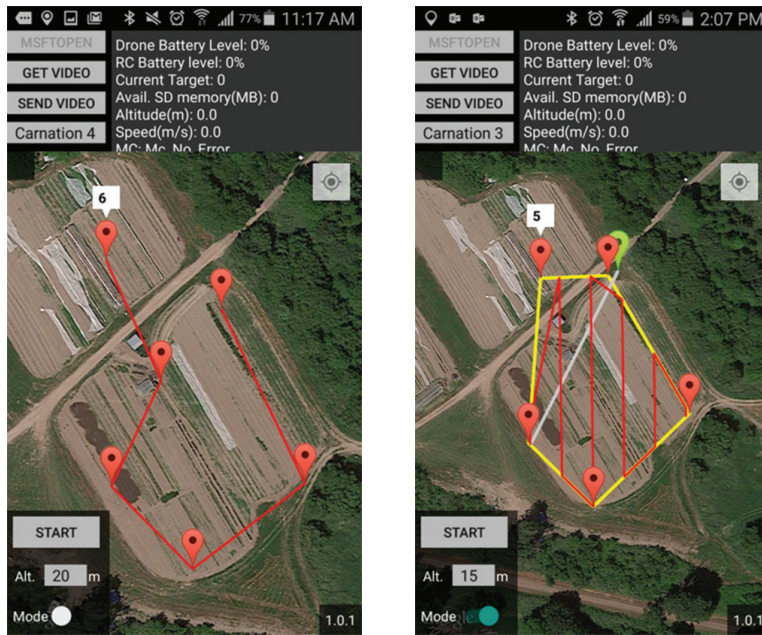
(a) Moisture map   (b) pH map

FIGURE 4. FarmBeats application for drone flight planning.

that provides farmers information about their crops, storage units, real-time views of their farm, auto-piloting for drones. At the farm in WA, the farmer used the app to monitor his fields and soil conditions for the crops he was growing. For instance, he would check a map of moisture and pH content of an entire field, shown in Figure 3a and 3b, to know where he needs to irrigate and apply lime the next day rather than covering the entire field. Whereas, at the farm in upstate NY, the farmer was more concerned about maintaining appropriate temperatures for his storage units of produce, dairy, and meat. With the FarmBeats app, he would get alerts for when the temperature goes past a certain threshold and this would indicate that perhaps someone left the storage door open or there is something wrong with the refrigeration unit.

The farmers also need to get updated panoramic views of their farm and so they used the FarmBeats app to trigger the drones. The app allows farmers to select the flight altitude and area to be covered on an interactive map. This can be seen in Figure 4. It plans the most efficient flight path given the selection and initiates the drone flight. The video recordings of the flights are used to generate panorama images of the farm fields.

Next Steps: We have provided the FarmBeats app to two farms in the United States and it has enabled farmers to utilize the insights that FarmBeats provides in an efficient manner. Our next goal would be to provide the FarmBeats system to developing countries. However, this would require changes to how we convey information to farmers. Not all farmers will be well educated and tech savvy, so we need to develop a user interface that can be used by farmers universally.

SUMMARY

In this article, we have described our experiences deploying an always-on system in the farm. We used innovative techniques and new hacks to overcome these challenges, such as lack of power, reliable connectivity, fault tolerance, and ease of use. We note that most of the challenges we describe in this paper are general, and will be encountered in various other IoT applications as well, such as in mining, construction, forestry, and oil and gas explorations, among others. ■

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