Long-Range Bluetooth Smart Stakes and High-Gain Receiver for High-Density Sensing in Precision Agriculture

Samuel Craven[1], James Subieta[1], Coby Sandholtz[1], Brian A. Mazzeo[1]

Abstract

To achieve the goals of precision agriculture, accurate spatial-temporal soil information is needed, especially because soil properties can change within and between growing seasons. The design of low-power, long-range Bluetooth transmitter nodes for high-density deployments is presented. They are paired with a high-gain receiver antenna that enables transmission distances up to several hundred meters.

A prototype system has been fielded. Received data from transmitter nodes is used to reconstruct soil moisture histories at each node location. Correlation with local weather data validates the data captured by the system.

The entire system is economical to produce, especially because the components are commoditized items used in other mass-produced consumer applications. Thus, systems with many dozens of nodes are possible for similar costs as existing industry solutions with less than a handful of nodes. The idea of using high-gain receivers for localization and communication with low-cost transmitters represents a potential solution for high-density spatial-temporal soil surveillance. This novel system represents a significant step towards a high-density, low-cost sensing solution for precision agriculture.

Keywords: precision agriculture, soil, sensors, Bluetooth, broadcast

Brian Mazzeo

bmazzeo@byu.edu

[1] Ira A. Fulton College of Engineering, Brigham Young University, Provo, Utah, United States

Introduction

Several studies have demonstrated increased water efficiency and other benefits of site-specific irrigation. The available water holding capacity (AWC), loss to runoff, and other characteristics of soil significantly impact the amount of irrigation needed to prevent crop water stress (O'Shaughnessy et al., 2015). These characteristics often vary significantly within a single field so that uniform irrigation strategies necessarily either over- or under-water large parts of the field. Tailoring the irrigation strategy to the needs of specific zones can reduce the amount of water used without reducing crop yield (Flint et al., 2023; Woolley, 2020). These water savings in turn reduce chemical runoff as fewer pesticides and fertilizers are washed off plants. These gains are realizable even with simple sector-based irrigation schemes that vary the speed of the center pivots rotation to avoid the need for adjustable-rate sprinkler heads or other additional, more sophisticated equipment.

Soil properties from zone to zone have been shown to vary spatially at scales as small as several meters, resulting in differing yields for regions across a uniformly farmed and irrigated field (Yang et al., 2002). To date, efforts in precision agriculture that use direct sensing (i.e. in-ground sensors as opposed to ground or aerial vehicle platform surveying or satellite imaging) have been limited to low density sensor networks.

Direct sensing approaches have some key benefits compared to spectral image-based remote sensing and other indirect methods. Though satellite-based imaging has increased in resolution significantly over the past several years, high costs remain a challenge, and sampling rates are limited by flyover times, the best of which are currently at about 24 hours (Shafi et al., 2019). This is a problem because the indices used to analyze spectral imaging, such as Normalized Difference Vegetation Index (NDVI), require accurate timing for best results in detecting various crop characteristics (Maresma et al., 2020). Moreover, both satellite and UAV-based imaging are subject to weather conditions and can lose functionality entirely in the case of dense cloud cover and high-winds respectively. Direct data acquisition with sensors physically located in the soil can capture data without interruption and will continue to do so passively without further investment by the farmer after installation. Further, directly acquired soil moisture data may be actionable without interpretation by skilled data scientists, as is necessary for spectral imaging-based techniques (Tsouros et al., 2019). For determining soil moisture zones for precision agriculture, direct tests may be more accurate than NDVI and other approaches (Kerry et al., 2023).

Though higher resolution irrigation strategies based on dense sensor networks seem likely to yield more efficient water usage without sacrificing crop yields, it is not known how much efficiency can be gained by increasing in-ground sensor density before returns diminish. A long-term goal of this project is to gain greater understanding of the efficiency gain limits at increased in-ground sensor densities under typical field conditions.

Obstacles to High Density Sensing

Conventional in-ground soil moisture sensors have a variety of drawbacks that make them infeasible for high density sensing. To facilitate communication with cellular towers or other receivers that may be several kilometers away, many systems have a high profile above the ground that necessitates their removal any time machinery needs to be driven over the field, which can be many times during a season. Moreover, instrumenting a field for a single growing season is often insufficient for long term

VRI accuracy, because soil zones shift over time (Kerry et al., 2023). The timescales of soil measurement require that characterization of a field be obtained before the beginning of the growing season for best results. Therefore, any potential sensing platform ideally would be able to function for several years after deployment.

A survey of retailers that sell sensing equipment for precision agriculture found that the average cost per sensor was in the hundreds of dollars, with the most affordable system coming in at several hundred dollars for a network of 4 sensors and one hub. This cost limits the practical achievable spatial resolution of collected data to the order of dozens of acres per sensor. By using commoditized hardware, the Smart Stakes platform outlined in the following section is a potential solution to deploy hundreds of sensors at similar costs to tens of sensors now. By deploying many Stakes it is envisioned that high spatial-temporal resolution can be obtained at sufficient data quality to delineate dynamic management zones and eventually drive irrigation and resource application prescriptions.

Platform

Overview

The Smart Stakes platform shown in Figure 1 prioritizes low cost, easy deployment, and high sensor density. Design decisions have been made to make the Stakes affordable to maximize the number that can be deployed for high-density sensing networks. The core innovation behind the platform is the use of one-way transmission broadcasts of sensor data from Stakes to receiver, which eliminates many of the challenges of long-range transmission under strict power constraints. Each Stake spends most of its time in a dormant state and wakes up periodically to broadcast its recorded measurements. Because a Stake does not need to hear back from the receiver, it can immediately go back to sleep without listening for return packets. Since the receiver is only listening, not broadcasting, it can make use of a far higher-gain antenna than would otherwise be allowed by regulatory bodies using a typical chipset at normal transmission power.

Using Bluetooth Low Energy (BLE) instead of other common protocols in industrial agriculture has several advantages. The shorter wavelength of BLE (~2.4 GHz) as compared to ~900 MHz frequencies in protocols such as LoRa makes transmission more susceptible to attenuation through many materials, but it also means antennas can be more compact with the same gain performance when compared to lower frequency protocols, especially on the receiver side. Since BLE is used extensively in consumer applications such as wireless personal electronics, there has been a tremendous investment over time in its development, making chips with advanced features highly affordable. Advanced protocols such as coded long-range BLE can also extend range. Because the data rate can also be high, bursts of small data packets do not take up substantial airtime.

The physical Stake platform is designed with existing farm infrastructure in mind. The Stakes protrude less than 0.1 m above the ground, so that most farm equipment will be able to pass harmlessly above them. The receiver has been designed to be compact, lightweight, and fully self-contained so that it can be deployed to any location without worrying about wires for power or data.

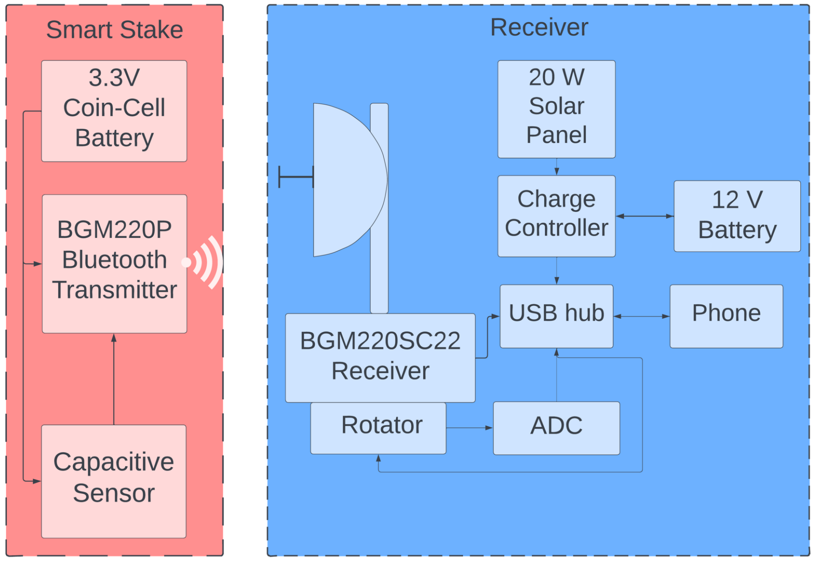

Fig. 1 Smart Stakes platform overview illustrating the Smart Stake transmitter and a solar-powered receiver with a high-gain antenna that receives transmitted packets.

Smart Stakes

The Smart Stake pictured in Figure 2 is based on a Silicon Labs Gecko BGM220P System on a Chip (SoC) which has several desirable features for low-power operation and communication.

The BGM220P can switch between a higher power mode while broadcasting and an ultra-low-power sleep mode the rest of the time. When in sleep mode, the BGM220P consumes less than 1 μW. Since the needed sampling rate for soil measurements is low (on the order of minutes and hours), the sensors can conserve power with an extremely low duty cycle, i.e. 0.02% with about 1 second of awake time every hour. At that duty cycle, the average current draw is about 3.5 μW. This version of the Smart Stakes is powered with a CR2032 coin cell battery, which has the energy capacity to keep them running for several years depending on the chosen duty cycle. Additionally, the extreme power efficiency of the system lends itself to solar-charging variations that our group has also explored that can be self-powered indefinitely (Yirenya-Tawiah et al., 2022).

Fig. 2 Smart Stake before weatherproofing.

The Gecko SoC supports BLE Coded PHY, which trades bitrate for transmission range by sending 8 symbols for every data bit. This results in a gain of about 8-10 dBm. The low bandwidth needed for soil moisture measurements is easily satisfied by the lowered bitrate of 125 Kbps.

The combination of low-power and long-range characteristics of the system coupled with a rotating high-gain antenna which may not be always pointed in the most favorable direction for reception means that successful reception of a given packet is not guaranteed. To prevent gaps in the moisture data record from missed transmissions, the Stakes store measurements in their onboard non-volatile memory, and the history of measurements is broadcast with each packet. The BLE advertisement protocol used allows a maximum data payload length of 192 bytes per packet. To use this space as efficiently as possible, a custom encoding scheme was implemented to take advantage of the low temporal resolution needed for soil moisture and thereby allow up to 7 days of measurement history to be broadcast with every packet.

The BGM220P SoC comes factory-programmed with a Universally Unique Identifier (UUID) which is broadcast with each packet to identify the transmitting Stake. Throughout the remainder of this paper the Stakes will be referred to by the last two 4-bit hexadecimal representations of their UUID.

The current version of the Stake uses capacitive sensing to estimate soil moisture. The long strips along the body of the Stake act as opposite plates of a capacitor. The capacitance depends on the permittivity of whatever fills the air gap and the fringing fields between the two electrode plates. Since the permittivity of water is by far the highest of any of soil constituents (Mohan et al., 2015), soil wetness is highly correlated with the soil estimated permittivity, and capacitive sensors have been shown to accurately measure soil moisture content (Adla et al., 2020). The capacitive trace on the sensor projects about 0.09m into the ground.

To prevent water damage and corrosion, the exposed electronics on the Stakes were coated with silicone sealant. GE Silicone II sealant was used as it is widely available and does not use acetic acid as a curing agent, which several common formulations use, and which quickly corrodes and destroys electronics if applied to them. A small plastic cover with about 1mm of clearance above the Gecko SoC was fabricated and placed over each SoC to form a dielectric gap and improve transmission.

The current prototype Stakes cost approximately $15 USD each when produced at low volume. With economies of scale, this number can fall below $10 USD, at least an order of magnitude less than industry-standard sensors. Further cost improvements can be made as parts convenient to prototyping, such as an overly robust battery holder and oversized battery, can be swapped out for more cost-effective components. Moreover, the BGM220P used for this model has several convenient components that will not be necessary past the prototyping phase. The BGM220S, which has similar capabilities to the BGM220P but without some unused features for our application, retails at around half the cost, potentially reducing the bill of materials total by another 30%.

Receiver

The receiver pictured in Figure 3 uses an off-the-shelf antenna rotator to allow the high-gain 2.4GHz antenna to rotate 360 degrees. It is important that the antenna rotates, since the long distance and low power characteristics of the system impose a link budget that requires the maximum possible receiver sensitivity.

Fig. 3 (Left) Receiver with mast and high-gain antenna deployed at BYU Life Sciences Greenhouse plot. (Right) Receiver junction box internal electronics, including solar charge controller, mobile phone, and BLE receiver SoC.

The receiver system uses an off-the shelf budget Android smartphone as a central computer. This approach has several advantages; GPS, cellular data, magnetometer, USB port, battery, and screen are all integrated into a single compact package that costs about $130 USD. Experiments found that some phone manufacturers include aggressive thread-killing code as part of their implementation of Android OS, which can cause problems with keeping the system running constantly. The phone chosen for this system was selected with that specific issue in mind and has been consistent throughout field testing.

The high-gain antenna and junction box are mounted on a 3-meter-long steel pipe, which, when combined with the base and mast rotator, places the antenna itself about 3.5m above ground level. Adding height is necessary to mitigate link connection difficulties under field conditions in which receivers may need to be several meters above ground level to have approximate line-of-sight to the entirety of a field with natural variations in elevation.

The low total power draw of the system has allowed it to successfully run off a 6Ah battery and 20W solar panel both mounted near the weatherproof junction box; measurements in the field during previous tests have indicated an average power draw under 1 watt during typical operation. Since the power circuitry has already been validated, this generation of receiver was deployed with an external battery and solar panel for the sake of simplicity.

Experiment

Data were gathered from a test which started with the deployment of 7 Stakes in December 2023 and which is still ongoing. Testing goals were to gather data on received transmission power, collect moisture measurements and correlate them with externally obtained measurements, and validate the long-term operation of the Stakes.

The system was deployed to the BYU Life Sciences Greenhouse plot several blocks away from the main BYU campus in Provo, Utah. As shown in Figure 4, the Stakes ranged from approximately 60 to 100 meters from the receiver. To characterize the difference in transmission strengths at different heights above ground, the Stakes were deployed in pairs, with one in a 5-gallon bucket and another in the ground at the foot of the bucket, as shown in Figure 4. The buckets had drainage holes cut in the bottom and were filled to a height of 0.15m with large gravel and then the remainder of the volume was filled with garden store potting soil.

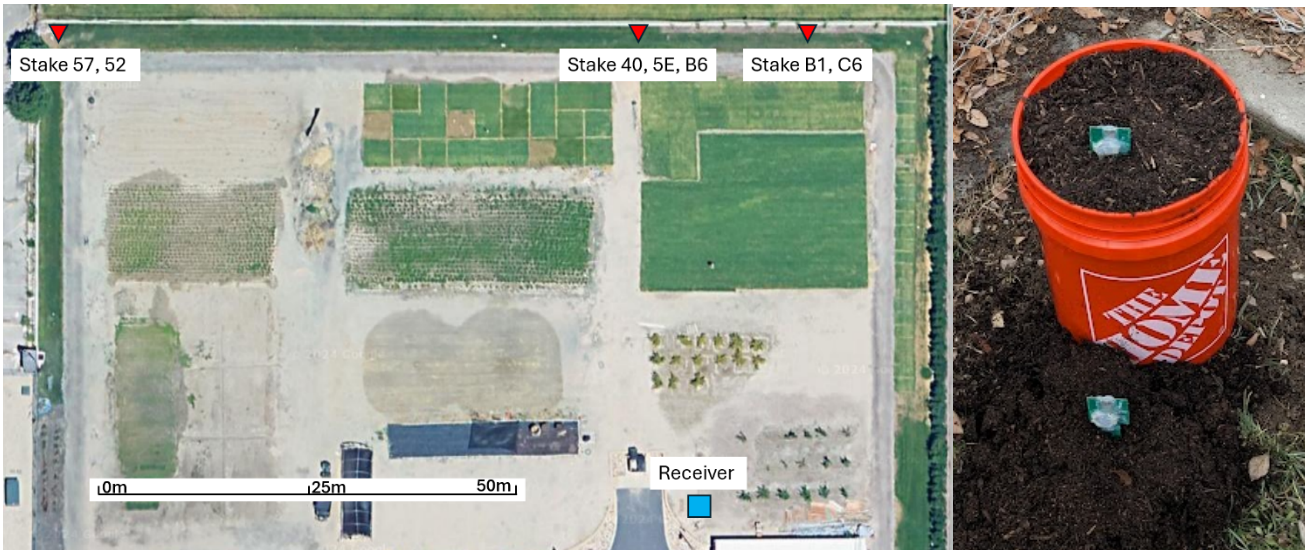

Fig. 4 (left) Map of Smart Stake and receiver locations during deployment at the BYU Life Sciences Greenhouse fields. (right) Smart Stakes in and adjacent to bucket.

Weather data during the experiment were obtained from the National Weather Service's station at Provo Municipal Airport. This location is 7.5 km away from the plots where the Smart Stakes are located. While some deviation is to be expected, the weather data broadly captured main weather events during the experimental period.

The receiver was programmed to rotate counterclockwise over antenna angle orientations of approximately 180 degrees, from approximately due east to due west, over a period of about 30 minutes. This was followed by a similar rotation clockwise over a period of 30 minutes. The angle of the receiver was captured by the phone magnetometer as well as via feedback from the rotator potentiometer.

For this test, the Stakes were programmed to wake up every 5 minutes for an approximately one-second period, during which the soil capacitance was measured and BLE packets were broadcast. After the clock pulses for the capacitive measurement circuit were started, the system waited several milliseconds for the circuit to settle and then measured the corresponding voltage related to the capacitance. The analog-to-digital on the Gecko SoC was polled 32 times per measurement and averaged to reduce noise. Then a BLE advertisement packet was broadcast every ~100ms during the remaining time that the Gecko was awake, for a total of 5-6 packets per wakeup.

Results

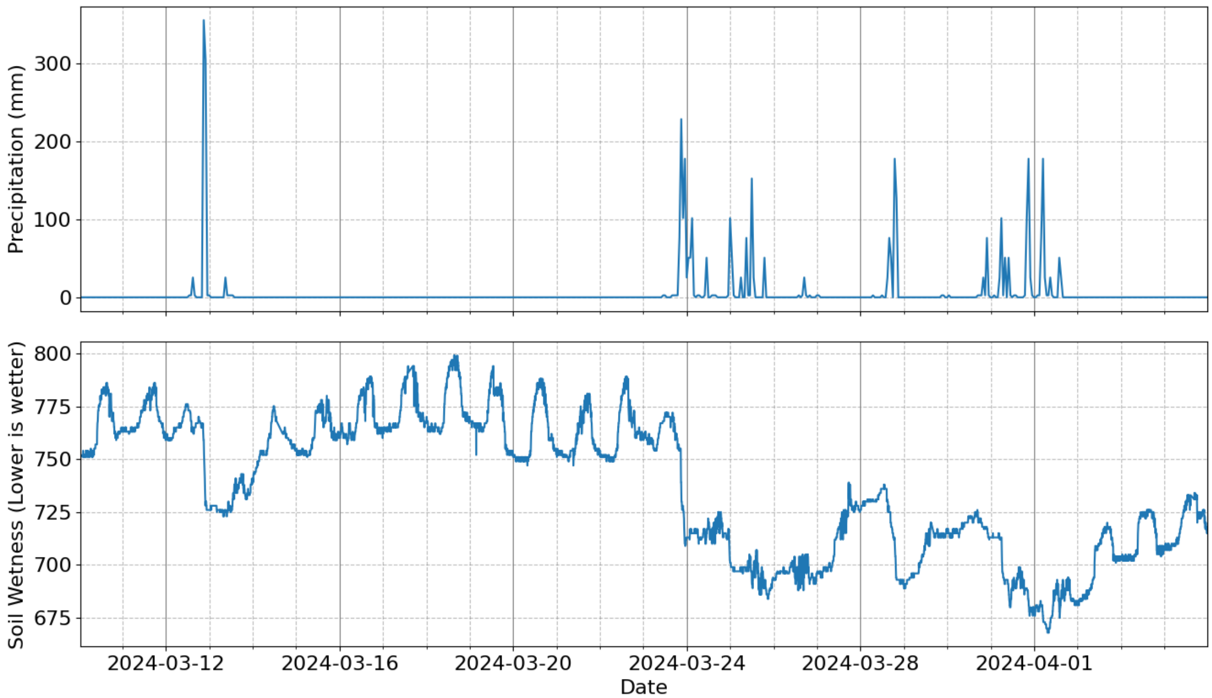

Fig. 5 (Top) Local weather data during a 4-week period during the experimental run. (Bottom) Soil moisture estimates of the top layer of soil from capacitance measurements from a Smart Stake.

In Figure 5, precipitation data from the local weather station is plotted with raw soil wetness capacitance data obtained from one of the Smart Stakes. Precipitation events are seen on March 13 and throughout the week of March 25-April 2. As shown in Figure 5, these spikes correspond to increases in measured soil moisture by the Smart Stake capacitive sensors. Figure 6 shows a five-day period from the above dataset with the National Weather Service temperature overlaid. Consistent diurnal temperature variations are reflected in the moisture measurements in which the moisture of the topsoil layer decreases during the hottest parts of the day.

Throughout the experimental period, the heading of the antenna at the time a packet was received was recorded along with the Received Signal Strength Indicator (RSSI) of the packet. RSSI is calculated automatically by the Silicon Labs Bluetooth stack and is a good metric for overall signal strength. Many algorithms use RSSI as a proxy for distance in that RSSI generally falls as distance between receiver and transmitter are increased.

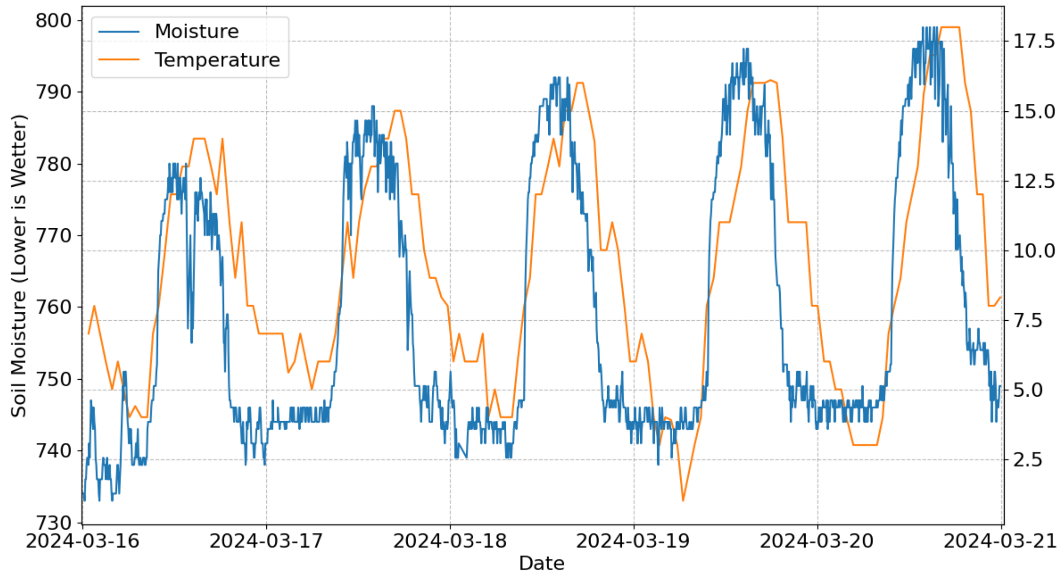

Fig. 6 Measured soil moisture through capacitance of Smart Stakes and temperature obtained from local weather station.

The RSSI of packets gathered over the course of the same March 10 – April 15 period shown in Figure 5 are shown in Figure 7. In that figure the actual angle of the Stake location relative to the receiver is plotted for reference. The relationship between Smart Stake RSSI and receiver angle was not as strong as expected, with peaks at multiple different angles for most stakes. Moreover, the variation in signal strength pattern between individual Bluetooth channels was much higher than anticipated. Some Stakes demonstrated some channel coherence, such as stake 5E, but in others the channels appear to vary mostly independently from each other.

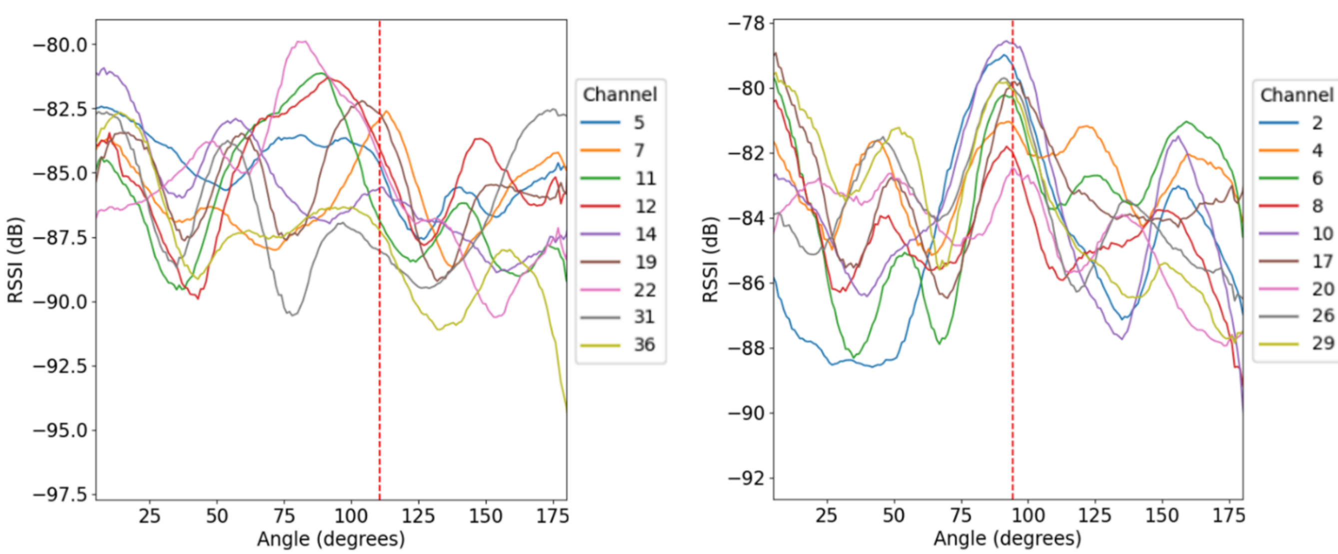

Fig. 7 RSSI plotted against receiver antenna angle for two different Stakes (Left: B1; Right: 5E). The red dashed line indicates the expected angle-of-arrival of signals for that particular Stake.

To better understand the channel dispersion, measurements were taken of a single stationary Stake that was placed in a large open area near BYU campus. A parabolic receiver was placed about 30 meters away and the Stake was rotated around an axis perpendicular to the ground around an axis perpendicular to the ground in 5-degree increments, with enough time to collect approximately 150 broadcasted packets per increment. The results of this experiment are shown in Figure 8.

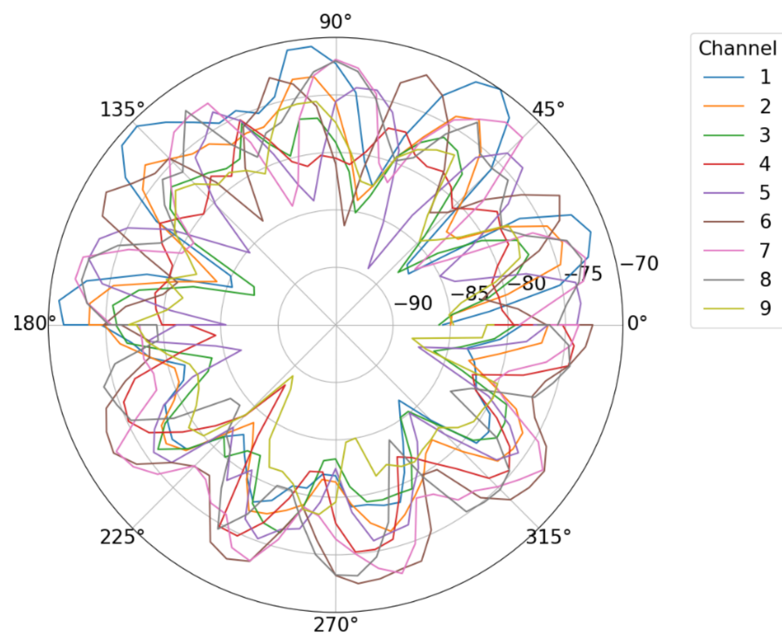

Fig. 8 Received antenna radiation pattern of multiple BLE channels for a Smart Stake in vertical orientation (rotation around axis perpendicular to earth) as measured by a parabolic receiver 30m away.

Discussion

As is typical with this type of capacitive soil moisture sensor (Kizito et al., 2008), the soil capacitance is quantized into a 1024-bit scale, with lower values corresponding to higher soil moisture. A minimum value of 300-500 corresponding to immersion in water is typical, as is a maximum value between 800 and 1024. The range and sensitivity of the measured value is dependent on several factors including switching frequency, probe geometry, and solder mask dielectric coefficient.

The moisture data have a clear relationship with diurnal temperature change, as shown in figure 6. This is an established characteristic of capacitive soil moisture sensors since the dielectric coefficient of the soil itself is temperature dependent. Various calibration methods have been shown to correct for this and enable highly accurate and repeatable soil moisture measurements. (Baumhardt et al., 2000; Kizito et al., 2008). However, trends of wetness are clearly visible and correlated with precipitation events, indicating that the simple capacitance measurements do report simple soil moisture metrics that are correlated as expected.

Previous research suggested that the measured RSSI of the received packets would have a strong dependence on the angle of the high-gain antenna on the receiver relative to the location of the broadcasting node (Jiang et al., 2013). The measurements from this test, however, exhibit distinctly different nodal patterns for different broadcast channels. The BLE standard dictates that the total allocated bandwidth between approximately 2.402 and 2.480 GHz be divided into 40 channels through which transceivers will ‘hop’ during broadcasts. Typically, it would be expected that multipath propagation of the different channels would be similar, given their proximity in frequency, and there are few examples of other work that investigates this near-frequency scattering effect.

There are several likely explanations for the observed effect. The BYU Greenhouse plot is bordered by a chain-link fence, and to maximize test distance the Stakes were located within a few meters of the fence. Since the wavelength of Bluetooth transmissions is about 0.125m, and the chain links are separated by about 0.05m, the fence mesh functionally acts as a solid reflective surface. The reflections from the fence could cause peaks in signal strength when the receiver is aimed at their point of incidence rather than at the locations of the stakes themselves.

The follow-up antenna pattern test found that the channel differences are similarly stark when there are no nearby reflective surfaces. This result suggests that the channel differences are not specific to RF characteristics of the larger testing field and are instead the result of the design of the Stake itself. After conducting the above tests, it was realized that the manufacturer specifications for ground plane stitching vias had been overlooked when this version of the Stake was designed. Without the vias, voltage differences between different areas on the ground plane could build up during the high frequency oscillations associated with transmission, resulting in unpredictable RF effects. For the purposes of Stake location estimation using RSSI and multiple receivers, it may be necessary in future iterations to consider individual channel effects, but more likely the issue is solvable by updating the stake design to create a more isotropic antenna pattern across the various BLE channels.

Conclusion

A self-contained sensing platform was deployed to a field-like environment, where it demonstrated reliable operation over the course of several months. Advertised packets with soil moisture information were successfully collected and correlated well with a nearby independent weather monitoring station. Packets transmitted by the stakes had a strong enough signal for collection at these distances on the order of 100m and demonstrate the potential for far further distances. Problems with the RF design of this version of the Smart Stake were the likely cause of unanticipated channel effects in Bluetooth transmissions and will be resolved in future iterations of the Smart Stake. Despite this, the Smart Stake platform promises to be a cost-effective solution for the continuous monitoring and profiling of an agricultural field for precision agriculture. Future testing will explore longer-range capabilities and effects of higher numbers of deployed sensors.

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