Plant Spike: A Low-Cost, Low-Power Beacon for Smart City Soil Health Monitoring

Caroline Yu, Kevin Kam, Yuliang Xu, Zhihao Cui, Daniel Steingart, Maria Gorlatova, Patricia Culligan, Ioannis Kymissis

***Abstract*—Plant Spike is an in-situ low-cost sensor system that is wireless, miniature, and low-powered. It can be seamlessly implanted in subsurface locations across major cities to measure urban soil health. Plant Spike incorporates non-contact soil moisture monitoring, temperature monitoring, light intensity monitoring, advanced power management, and Bluetooth Low Energy transmit-only communication for transmitting information to a client device. With a novel combination of aggressive power reduction techniques, the system's lifetime is over 2 years with a 500 mAh battery. By connecting on-board sensors to a single-chip microcontroller, the total component and assembly cost of each module is less than $10. The sensor system has been tested within an urban soil testbed located on Columbia University's Morningside Campus in New York City as well as street tree pits located in Morningside Heights, proving the functionality and robustness of the system. Plant Spike is able to measure temperature and light ranges that are comparable to the fluctuations experienced by soils located within the climate zone of New York City.**

***Index Terms*—Smart Cities, Smart Environment, soil health, sensor testbed and implementation, Bluetooth Low Energy, transmit-only sensor**

I. INTRODUCTION

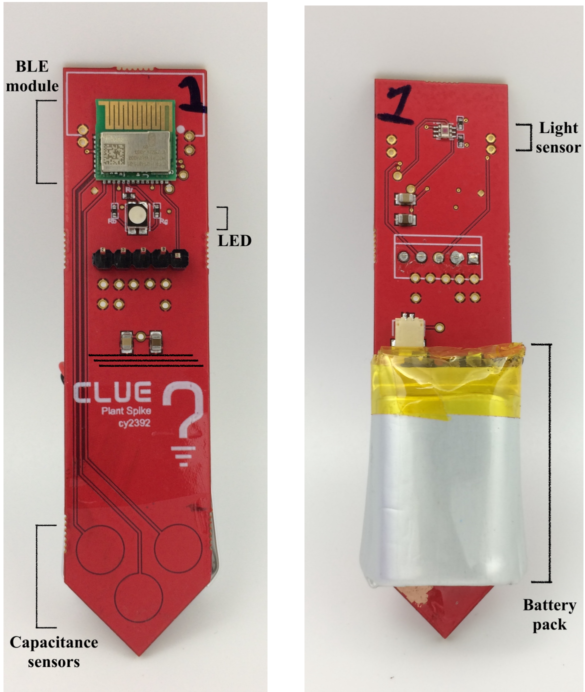
URBAN soils have significant potential to improve urban resilience and climate adaptation through water storage, flood mitigation and carbon sequestration. Urban soils can also advance urban sustainability by facilitating temperature regulation, air quality improvements, brownfield sites remediation, and provision of recreational greenspace. Viewed from the wider perspective of the future of the urban biosphere, there are massive gains to be had from better use and management of urban soils. For this to happen, significant advances in our understanding of how local conditions and different management practices impact the health of urban soils, and thus the ecosystem services that they provide, are needed. Prior investigations into factors influencing urban soil ecosystem health have primarily involved manual sampling of soils followed by laboratory analysis [1] or labor-intensive site-based measurements [2]. Given the complexity and variety of urban soil systems, and the multiple indicators associated with urban soil health, practices such as intrusive sampling, laboratory testing, and labor-intensive site measurements are unlikely to be effective in generating the knowledge needed to better manage our urban soil systems.

To measure various soil health indicators of tree pits in an urban area, we propose a smart city system that uses a low-cost small form-factor printed circuit board (PCB) that transmits sensor data via Bluetooth Low Energy (BLE). Previous BLE sensor solutions integrated on PCBs focus on optimizing the PCB size, power consumption, or functionalities for wearables [3]–[5]. For example, EcoBT is a miniature wireless sensor node with an on-board accelerometer that uses BLE for direct communication with a BLE-enabled device [3]. By eliminating the need for protocol bridging between smart devices and a wireless sensor network (WSN), EcoBT enables the development of WSN applications without large changes in hardware design. Another wireless sensing platform, Wristband Vital, is a low-cost wearable multi-sensor that communicates via BLE with nearby base stations [4]. Wristband Vital uses a burst-mode based variable-rate sensor sampling scheme and low duty cycle to reduce current consumption. EcoBT and Wristband Vital each have a key drawback for Smart City soil health monitoring: high power consumption for multi-year use and a large 3D form factor that disrupts natural soil processes, respectively. Other works present a model for sensor fusion in urban spaces [6]–[8], including studies on public space utilization and traffic issues in large cities. The system we present in this paper provides a lower cost solution by minimizing components on a custom PCB so that the devices can be scaled up to tens or hundreds of devices.

The key advantages of our proposed telemetry solution, Plant Spike, include being low-cost (less than $10 for a fully-assembled PCB with integrated sensors and a BLE system-on-chip module) and low-power (over two year lifetime with a 500 mAh battery). Plant Spike's low cost is enabled by using a single-chip microcontroller as well as using the PCB as the soil moisture sensor. Plant Spike's low power consumption is enabled by using BLE, which has low peak and ultra-low idle mode power consumption with minimal complexity. Dynamic sensor data is sent through the BLE beacon's universally unique identifier (UUID) fields to further reduce power consumption. In order to quantify soil health, temperature, light, and custom moisture sensors are incorporated on the Plant Spike board (Figure 1). Plant Spike enables seamless data collection through the use of a mobile BLE client. It is shown in an example urban tree and soil pit (Figure 2).

The main contributions of this paper are as follows:

- To our knowledge, Plant Spike is the first sensor network to incorporate BLE transmit-only connectivity in conjunction with moisture, temperature, and luminance sensors on a small form-factor PCB.
- We have implemented Plant Spike in a laboratory-based urban soil test bed as well as various locations around New York City, and tested the system by collecting data on urban soil health.



(a) PCB front.

(b) PCB back.

Fig. 1: Plant Spike custom PCB design.

Fig. 2: NYC urban tree and soil pit.

II. System Architecture

A. Dynamic Transmit-Only Sensor

The system we developed is a variant of an architecture with transmit-only sensors. Because there is no need to reprogram the system once the sensors have been designed and implemented, there is no need for the IoT system to also act as a BLE receiver. The potential of such systems to save power and costs has been noted previously [9]. Transmit-only systems have been studied under a variety of assumptions, including for dense network deployments [10], different network architectures [11], and ultra-wide-band physical links [12]. Transmit-only architectures form the basis for a range of physical layer technologies, including ultra-wide-band communications [12] and backscatter techniques [13]. In this paper, we develop a practical realization of this idea that does not require new communication hardware, software, or protocols.

In this sense, Plant Spike is a beacon that transmits dynamic sensor data instead of just an ID. Beacons are an integral part of different wireless connectivity solutions, including BLE and WiFi. There has been much research on improving the security of beacon contents demonstrating the further usability of beacons in IoT applications. Although beacon ID manipulations can be a part of a beacon hijacking or spoofing attack [14], [15], the use of randomized dynamic beacon IDs has been proposed for stopping third parties from using wireless station information for providing localization services [16].

To the best of our knowledge, the use of beacon UUID fields to carry dynamic sensor data to reduce BLE energy consumption has not been proposed before. This beacon manipulation can coexist well with traditional beacon-based systems. To traditional systems that expect the full UUID field to be used to transmit the beacon ID, our systems messages look like different transient beacons coming and going.

B. Use of BLE

Our platform uses BLE as its wireless communication protocol. BLE satisfies two requirements of our system: connection between peripheral and central devices within a few feet from a tree pit to a user's phone and lower power consumption than other wireless protocols. BLE also has several communication and power consumption advantages over previous Bluetooth standards. There are two features in particular that make BLE advantageous for sensor beacons: fewer channels that advertise and streamlined advertisements.

BLE operates in the 2.4 GHz ISM band. While classic Bluetooth uses 79 channels, BLE uses 40. Three channels (channels 37, 38, 39) are used as advertisement channels to discover devices, initiate connections, and broadcast data. Channels 0 to 36 are used as data channels once devices are connected [17]. The devices communicate using an acknowledged stop and wait protocol so that BLE is inherently duty-cycled [18]. This inherent duty-cyling sets a baseline for Plant Spike's low power consumption. Communication via BLE is also optimized by streamlining the content of advertisements. By setting a unique 128-bit UUID to a custom service, the central device will search for devices with that UUID. Central devices find peripherals faster and use less power doing so.

BLE has a high level of power efficiency, allowing for battery-powered devices. The two main parameters to extend battery life include the advertising interval and the transmittance power, which corresponds to the device's transmit range. The typical range of a beacon is between centimeters and tens of meters [19]. If the output power of the beacon is set to 10 dBm, a range of several hundreds of meters is possible, which is applicable for Smart Manufacturing settings. For Smart Home applications, a range of tens of meters allows for the output power of a beacon to be less than 4 dBm. Other factors that set the beacon range include the sensitivity of the radio receiver, objects in the surrounding environment, and antenna performance.

BLE beacons also conserve power by sleeping for the majority of the time and waking up to only broadcast information. A longer sleep interval decreases the mean duty cycle; this in turn significantly decreases the power consumption of both transmitting and receiving devices by operating in sleep mode instead of transmission mode [20]. Several papers demonstrate the viability of using BLE-enabled battery powered beacons for an extended period of time [21]–[25].

C. BLE Gateway

A BLE-enabled IoT system with smartphones acting as persistent mobile IoT gateways has been proposed relatively recently for bi-directional communication with IoT nodes [26]. In this paper, we develop a complementary and simplified approach that uses the existing BLE beaconing mechanism for one-way communication to reduce IoT node energy consumption.

Our platform uses mobile phones as gateways to address various IoT connectivity issues. Currently, connecting a new IoT device requires a user to download a new mobile phone application or purchase a corresponding computer dongle [26]. Our platform allows users to download one generic mobile or computer application that is able to make link-layer connections and receive BLE advertising messages. If the data needs to be stored for industrial or research applications, the data received by the BLE-enabled gateway can be sent to the cloud or other data storage options. Because the mobile phone is only used to receive transmitted packets of dynamic sensor data, all other computation and required information, such as node location or time, can be done on the mobile phone or sent directly to the cloud. The prototyping and sensor characterization performed in this paper was done using the Silicon Labs Bluegiga Legacy Bluetooth Low Energy Dongle (BLED112) and Bluetooth Smart Software and SDK.

III. Hardware Overview and Design

We combine the BLE beacon model with on-board sensor data to achieve a low-power low-cost IoT node. By using the Generic Access Profile layer to broadcast the data, the beacon is able to send data to any Bluetooth connected device that is configured to receive packets. When the user steps into range of the BLE device, the device receives the transmitted packets, as shown in Figure 3(a). While the mobile app is open and listening for the data, the data is displayed and stored. The only packets that are sent in this setup are the UUID that identifies the beacon and the sensor data packets that are included in the UUID. This means that the total number of bytes is 16 bytes. The sequence of transmitted bytes are shown in Figure 3(b).

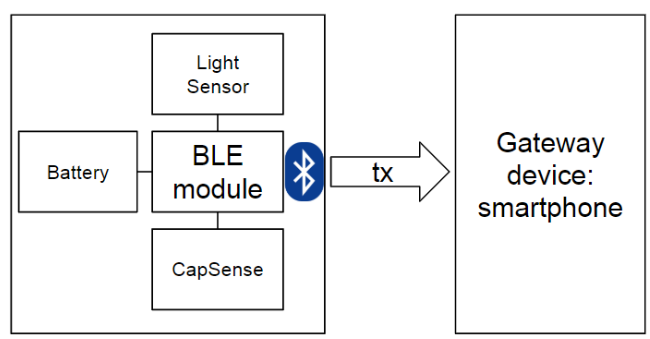
Compared to other BLE-enabled IoT systems, Plant Spike has an overall competitive edge with regards to cost, lifetime, size, and ease of use. Table I references various devices. Compared to other Smart City and wearable applications, Plant Spike has a flattened form factor with the sensors and BLE module only a few millimeters thick on the surface of a standard PCB. The form factor of Plant Spike was chosen so that the moisture sensor can be placed into urban soils while the BLE module is above ground. The PCB size can be reduced by eliminating empty board space; however, the size enables visibility for users that walk up to the implanted system. Compared to miniature BLE platforms, Plant Spike has the same sensing capabilities but can be powered by a battery with a third of the power capacity.

A. Environmental Protection

As Plant Spike is constantly exposed to various weather conditions, an industrial grade silicone (422B, MG Chemicals) is used as a water resistant layer. Once the system-on-chip is programmed, the conformal coating is brushed onto the electronic components and PCB and cured at room temperature. The modules have been tested in normal outdoor weather conditions and have shown to withstand very moist soil as well as rain. The module shown in Figure 1 has been applied with the weatherproof coating. The coating is thin and does not affect the operation of the device.

B. Communication

The microcontroller unit used is the Programmable System on Chip (PSoC) 4 BLE from Cypress Semiconductor (CY8C4247LQI-BL483). PSoC4 BLE has a small form factor of 7 mm x 7 mm, a microcontroller with general purpose



(a) Plant Spike block diagram showing a BLE module in transmit-only mode sending dynamic sensor data to a gateway device.

2 bytes: device	2 bytes: service	6 bytes: sensor data	6 bytes: company ID

(b) Bytes configuration in the 128-bit UUID. Data is placed between the service/characteristic byte and company ID byte.

Fig. 3: Plant Spike system and communication configuration.

input/output pins (GPIO) that can be used as analog or digital pins, and BLE radio. PSoC4 BLE has a Bluetooth Smart, radio and subsystem (BLESS) that contains a physical layer and link layer with an embedded AES-128 security engine. Because the physical layer is already compliant with Bluetooth Specification 4.1, all that is externally needed is an antenna for packet transmission. The RF transceiver contains an integrated balun to drive a 50 Ω antenna. A higher cost option that does not require antenna and peripheral design is the corresponding BLE module by Cypress Semiconductor (CYBLE-214015-01).

When the microcontroller is not transmitting dynamic sensor data, various functions are placed into sleep or deep sleep mode. The deep sleep mode runs with 1.3 μA while the active mode runs with $\sim$ 10 mA. The sleep interval duty cycle is set to 5 seconds so that the system wakes up for 250 millisecond to measure the sensors and transmit data and sleeps for the remaining 4.75 seconds.

To conserve power, each measured sensor value is compared against the most recent measured value. If the value is the same, the value is not sent. The software on the receiving side recognizes that a sensor value has not been sent and stores the identical previously sent sensor value. If the sensor value has changed, the notification is updated and transmitted. This conserves power as the BLE beacon will only transmit data when a noticeable change in the sensor reading is recorded. This combined with the microcontroller's sleep mode functions let Plant Spike aggressively minimize power consumption when both transmitting data and waiting to transmit data.

C. Sensor Design

Vegetation water uptake rates, air humidity, light exposure, and exposed surface area affect the evaporation and drying rate of soil. For this reason, a capacitance sensor was designed to measure soil moisture, a light sensor was chosen to measure the soil's exposure to light, and a temperature sensor was used to measure ambient temperature above the soil.

1) Temperature: The temperature of the air surrounding the tree pit soil measured using the temperature of the Cypress PSoC4 BLE microcontroller chip die. An on-chip analog-to-digital sequencer is used to read out the measurement by sampling the voltage output of an on-chip API. The accuracy is 1°C for an operating range of -40 to 85°C [28].

2) Light: Light is measured using Texas Instruments OPT3001, an ambient light sensor. The sensor's measurement range is 0.01 to 83,865.6 lux. The output interface is an I2C connection, which is provided by the microcontroller. The supply range fits within the microcontrollers voltage range and pulls about 1.8 μA of current while operating. OPT3001 also has a small form factor of 2.0 mm by 2.0 mm by 0.65 mm.

3) Soil Moisture: Previous demonstrations of PCB-based soil moisture sensors use a hygrometer that measures the change in capacitance of a material using either a thin-film semiconductor substrate between two electrodes or MEMs topology [29], [30]. To reduce the complexity and cost of the moisture sensor, Plant Spike measures the capacitance of metal electrodes on the PCB. In our design, the copper that is used for the PCB traces is shaped into circular electrodes and connected to the microcontroller's analog pins. We used Cypress's CapSense technology, which consists of a capacitive sensing algorithm [31]. Although CapSense is most commonly used for capacitive buttons on home appliances and industrial machinery, we have calibrated the copper metal electrodes to precisely measure the relative humidity and soil moisture of the surrounding environment. The electrodes are placed at the base of the board so that the moisture of the soil can be measured without having to insert the entire board in the soil, which would block the light sensor and the antenna.

IV. Urban Ecosystem Testbed

In New York City, common types of urban soils include modified and engineered soils located within bioswales and tree pits. These urban soil systems are located in openings within city sidewalks and are important to the retention of stormwater runoff and the removal of silt and pollution from runoff water [32]. The performance of these urban soils is heavily dependent on the soil's health, including moisture content and temperature. Currently, soil health monitoring has to be conducted manually. Since there have been more 3000 bioswales and tree pits introduced over the past five years into three of the New York City boroughs alone, the scale of manual monitoring required to understand and quantify soil bioswale and tree pit soil health is not feasible [33]. Hence, the utility of the Plant Spike system.

To calibrate Plant Spike's sensors for use in urban soils, a sensor testbed was built. The purpose of the testbed is

TABLE I: Benchmark Table

	Plant Spike	**EcoBT [3]**	**Wristband Vital [4]**	**Smart Cities [27]**
Microcontroller	Cypress PSoC4 BLE	TI CC2540	Atmel ATMega328p	Microchip PIC24F16KA102
Advertisement Current (mA)	$\sim$ 10	19.6	-	11.3
Deep Sleep Current (μA)	1.3	0.4	0.1	32
Sensors	light, temperature, moisture/capacitive	accelerometer	light, temperature, humidity, pressure, accelerometer/gyroscope	temperature, humidity, and CO_2
Sleep Interval	5 s	0.6 ms - 20 s	-	34 s
Battery	500 mAh	2 AAA	150 mAh	3 AAA
Lifetime (days)	700+	-	4+	-
Wireless Connectivity	BLE	BLE	BLE	ISM
Size (mm)	20 × 80 × 4.05	8 × 8	35 × 30 × 11	$\sim$ 40 × 30 × 15

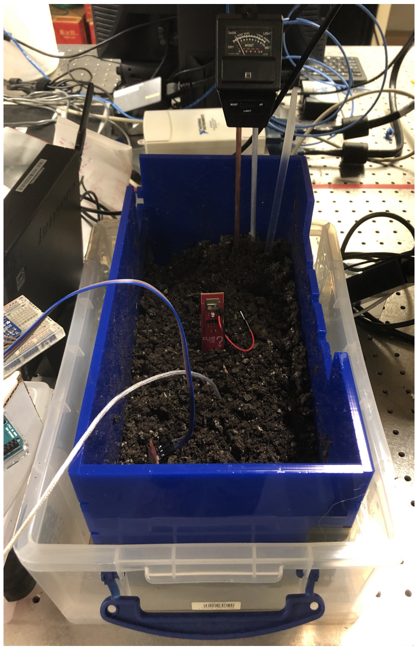


Fig. 4: Indoor testbed with Plant Spike and calibration commercial sensors placed in soil.

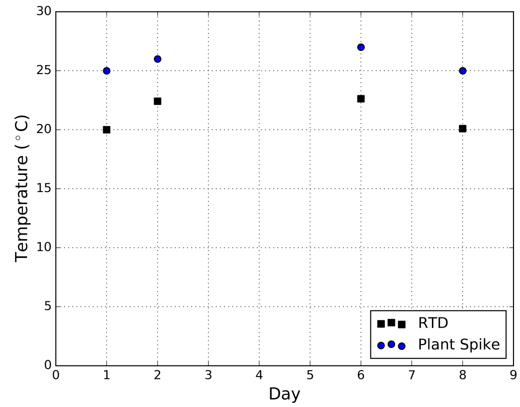


Fig. 5: Temperature measurements comparing the RTD and Plant Spike thermometer values.

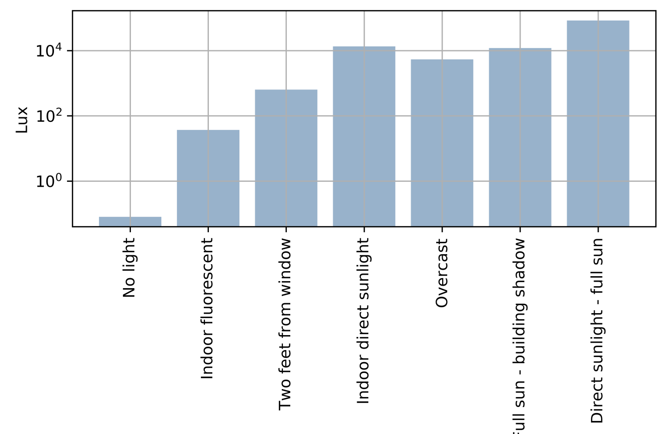


Fig. 6: Lux for various light conditions.

to study samples of urban soils in a laboratory environment and to compare the laboratory soil measurements to that of Plant Spike's. The necessity of this setup is required as many of Plant Spike's on-board sensors need to be calibrated in a controlled environment. The physical testbed is shown in Figure 4. The main part of the soil container consists of a 15 x 10 x 6 cm acrylic box with holes laser cut into the bottom to allow for water drainage. To calibrate Plant Spike's on-board sensors, a commercial moisture and resistance thermometer are placed in the urban soil sample.

Using the commercial sensors as a benchmark, Plant Spike's sensing capabilities were measured for accuracy. This step is important as Plant Spike's PCB humidity sensor needed calibration to a baseline before it could be deployed. This ensured that the humidity data being received was accurate. Similarly, the BLE module's built-in temperature sensor was tested against the commercial RTD sensor seen in Figure 4 to monitor how quickly Plant Spike could sense changes in ambient temperature. To simulate large temperature fluctuations, a Yamata DX600 furnace was used. To test Plant Spike's BLE connectivity, a BLE dongle is placed on a dedicated computer to collect and log all measured data.

A. *RTD Sensor Testbed*

The temperature sensor included in the programmable microcontroller was calibrated with a resistance temperature detector (RTD). The RTD chosen is platinum that has a resistance of 100 Ω at 0°C [34] and a resistance variation of 0.385 $\frac{\Omega}{^\circ C}$. The RTD and Plant Spike were placed in a programmable oven and refrigerator. The RTD output is measured using a resistance-to-digital converter and the Plant Spike BLE transmitted temperature is recorded using a BLE module.

The RTD sensor was also placed directly above the soil's surface at the same distance that the Plant Spike temperature sensor was placed above the soil's surface in order to compare the absolute temperature values. Because of on-board generated heat, the temperature sensor was found to be $\sim$5 ° higher than that measured by the RTD (Figure 5).

B. *Light Sensor Testbed*

Various light conditions were measured and are shown in Figure 6. The location and directionality of the light sensor were taken into account. Under full sunlight conditions, the backside of the PCB was directed towards the sun when there was no cloud cover. The light intensity in this condition reached the full-scale luminance value of the sensor at 83865.6 lux. In New York City, trees, specifically on the south sidewalk of west-to-east streets have buildings shadowing the tree and tree pits throughout the day. The illuminance of a building's shadow with full sun is about an order of magnitude less than that of full sun. For overcast (90% cloud cover) conditions, the illuminance is less than the reflections of direct sunlight off of buildings in building shadow areas. For thorough characterization, indoor light conditions were also measured.

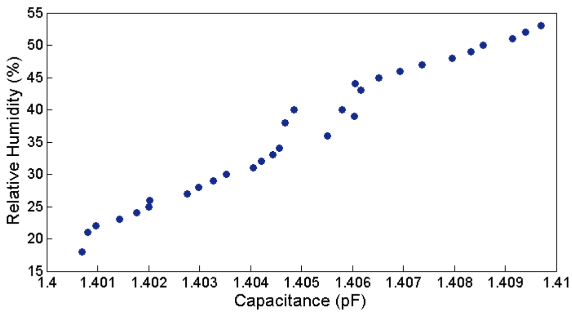


Fig. 7: Capacitance in relation to relative humidity.

TABLE II: Normalized capacitance for various soil moisture conditions.

Condition	Plant Spike	SEN-13322
Immediately after watering	0.99	0.94
2 days after watering	0.95	0.62
1 week after watering	0.84	0.51
Dry	0.68	0.06

C. Humidity Testbed

The capacitance sensors used in this device can be of dual purpose depending on the placement of the sensors. For above soil measurements, the insulated copper pads can be used to measure ambient relative humidity. The humidity of air was increased by evaporating a specific amount of water in an enclosed area. The change in capacitance of one copper pad relative to relative humidity is shown in Figure 7. When the copper pads are embedded in the soil, they can be used to measure water, or soil moisture, content. The capacitance change from dry to wet soil is shown in Table II.

The higher moisture content in the soil leads to a larger capacitance read by the insulated copper pads. To translate this change in capacitance to a value for moisture content, a moisture sensor was used to calibrate the output capacitance of the on-board copper pads. The Plant Spike's on-board capacitance moisture sensor as well as an off-the-shelf moisture sensor (SparkFun SEN-13322) were placed in soil. Both sensor outputs were normalized to their maximum respective values. This normalization is important as it allowed us to compare the moisture readings on a similar scale. The normalized moisture data was collected from soil in the indoor testbed in 4 different states: just watered with 1 liter of tap water for 450 cm^3 of soil, 2 days after watering, 1 week after watering, and purely dry soil.

As seen from Table II, both columns of normalized moisture data show a downward trend. This result is expected as water drains and evaporates out of the testbed over time until the soil returns to a dry state. Thus, when applied to field measurements, values approaching a normalized moisture value of 1.00 correspond to fully saturated wet soil.

V. SYSTEM IMPLEMENTATION

To verify the effectiveness of Plant Spike's ability to monitor tree pit soil health, Plant Spike was placed in tree pits throughout New York City's Morningside Heights neighborhood.

(a) Unguarded tree pit. (b) Guarded tree pit.

Fig. 8: Examples of NYC tree pits.

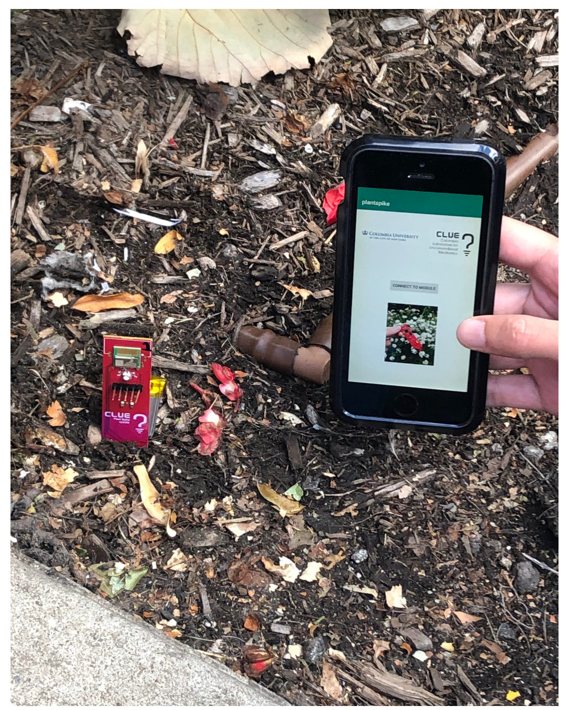


Fig. 9: Smartphone application to connect to Plant Spike module via BLE.

Figure 13 shows the location of the implanted tree pits in the Morningside Heights community. Tree pits in New York City have two primary configurations: guarded and unguarded. Guarded tree pits have fencing that surrounds the recessed soil pit that prevents humans and small animals from stepping on and contaminating the tree pit soil. Unguarded tree pits do not have the protection of the fencing and thus are more prone to soil compaction and contamination, which damage the tree's and by extension the tree pits' ability to deal with stormwater. Examples of New York City tree pits are shown in Figure 8.

Aside from type differences, tree pit sizes range from 0.9 m^2 to 4.6 m^2. A study by [2], explored the influence of tree guards, area and size, ground cover vegetation, and mulch in the tree pit on tree pit soil infiltration rates as an indicator of soil health. The results of the study showed that infiltration rates in guarded tree pits with large areas were higher than rates measured on other tree pit types. To come to this conclusion, researchers used in-field infiltrometer measurements, which were difficult and labor intensive to perform [35] [36]. As Plant Spike is a smaller, cheaper, and easier to use than an infiltrometer, the successful implementation of these modules in the field helps demonstrate that Plant Spike can be used effectively to characterize tree pit health. The data for these measurements can be found in the results section of this paper.

After placing the Plant Spike's soil moisture sensing section into the tree pit soil, the measurement data was collected. A smartphone app was developed to receive data. Although data processing still needs to be performed in a lab, generating the smartphone app provides a future path for integrating Plant Spike into a connected smart city application. Figure 9 shows the smartphone app with an implanted Pant Spike module. In the long term, we hope to monitor urban soil health over longer periods of time that capture varying weather and other environmental conditions. Plant Spike has demonstrated a long battery life in a laboratory setting, and with the continued development of the sensing and weatherproofing capabilities we are seeking to implement a long term study in the near future.

VI. Results

The results present a validation of Plant Spike's low current consumption, device lifetime, field testing, and low cost. These features combined into an integrated flat form-factor PCB enable long-term measurements of tree pit soil health.

A. BLE

To obtain the current consumption of the device, the BLE module was programmed to transmit sensor data values. A source/measure unit is used to supply voltage to the BLE module while measuring the current flow through the device. The

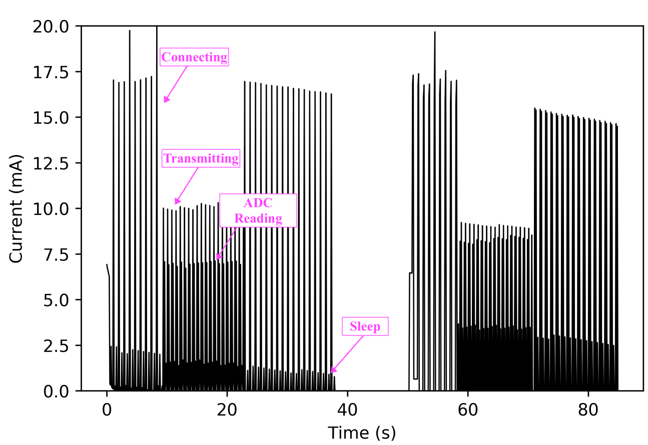


Fig. 10: Two-way communication current consumption. Plant Spike only consumes the power needed for transmitting and reading sensor values, as shown between 10 and 20 seconds.

current consumption of two-way communication is shown in Figure 10. Because the connecting stage of the communication process consumes almost twice the amount of current as the transmitting stage, the power consumption of a transmit-only sensor reduces significantly.

Plant Spike's current consumption is shown between 10 and 20 seconds where it is only consuming power to read sensor values and transmit. Before each transmission, sensor data values are collected and stored from the ADC output, I2C bus, and capacitance readings. For one-way transmission, the BLE module is programmed to only transmit its UUID with dynamic sensor values. The BLE client parses the UUID to identify and store the sensor values. Throughout the transmission state, the BLE module is programmed with a wake/sleep cycle. In this case, the BLE module turns on for 250 ms to collect data and transmit and then sleeps for 4750 ms.

Plant Spike's lifetime is calculated using a sleep/wake battery lifetime model. The equations are shown in (1) and (2), where I_{avg} is the average current in mA, I_w is the wake current in mA, I_s is the sleep current in mA, T_w is the wake time per hour, T_s is the sleep time per hour, and C is the derated battery capacity. The wake current is an average of the current consumption of the (1) light reading using the I2C bus and light sensor (2) capacitance reading using the ADC (3) temperature reading using the ADC and (4) PSoC 4 BLE module in transmit mode. The sensor readings and transmission is performed in the sequential order listed above. With a derated capacity of 90%, Plant Spike is estimated to have a lifetime of 2.35 years.

$$I_{avg}\,[\text{mA}] = \frac{I_w \times T_w + I_s \times T_s}{60 \times 60 \times 1000} \tag{1}$$

$$\text{Lifetime [years]} = \frac{0.85 \times C}{365 \times 24 \times I_{avg}} \tag{2}$$

To determine the operating range of Plant Spike's wireless BLE connectivity, a portable laptop using a Cypress Semiconductor CY5670 CySmart USB Dongle was set up as a BLE receiver. Once connected, the Plant Spike module was moved away from the BLE receiver while the client-side received signal strength indicator (RSSI) was measured. Figure 11 shows the relationship between RSSI and Plant Spike's distance away from the client. Between 0 - 25 cm the RSSI value drops rapidly and then hits a steady value of -90 dBm as the distance increases. This plot demonstrates that BLE receivers should be kept with 25 - 50 cm of Plant Spike's antenna. This distance is reasonable for a researcher or city resident standing by the Plant Spike and tree pit to collect sensor data.

B. Battery Analysis

The main purpose of the battery discharge curve was not to model the system's power consumption. The voltage discharge model is used to determine how much charge is left on Plant Spike's battery. The PSoC4 BLE's ADC measures the battery voltage and compares it to the voltages measured in the discharge experiment. For example, a reading of 3.7 V

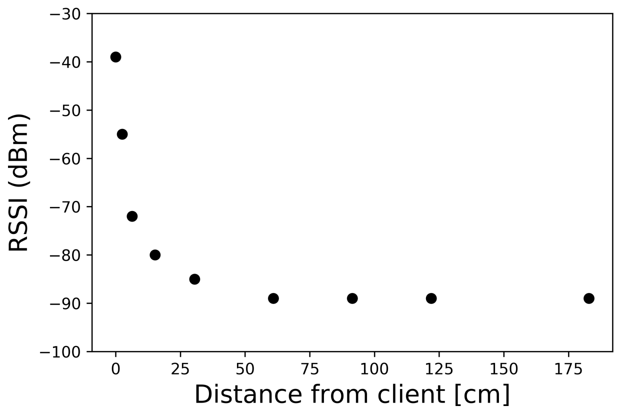
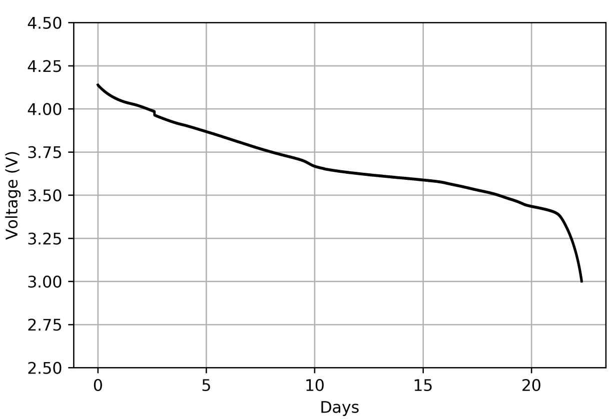


Fig. 11: RSSI vs distance from Plant Spike.

(a) Battery test setup.



(b) Battery discharge over time with cycle parameters of 10 mA for 1 second and 1 mA for 60 seconds. The battery discharge is used to compare against Plant Spike's battery voltage measurements during usage.

Fig. 12: Battery health verification.

would show that the battery has sufficient charge. However, as the measured battery voltage approaches 3 V, the system would then alert the user that Plant Spike's battery is almost completely discharged. The test battery was drained at a higher current than the Plant Spike module thus showing the 20 day battery lifetime as opposed to Plant Spike's actual theoretical lifetime.

To develop the discharge model, Plant Spike's 3.7 V, 500 mAh lithium ion polymer battery manufactured by Tiny-Circuits was tested on a Neware CT-4008-5V10mA-164-U Battery Testing System (Figure 12(a)). To simulate the battery load current draw of a BLE module transmitting wireless packets, the battery was discharged at 1 mA for 60 seconds followed by 10 mA for 1 second. This protocol corresponds to one cycle of discharging. To completely discharge the battery, the process took 25681 cycles. The purpose of this protocol is to model the pulse discharge in a simulated application. The battery was fully charged at 4.2V at the beginning, and experienced 25681 cycles to hit 3V, which is assumed as fully discharged. The discharging curve reflected the expected Nernstian Behavior, and the Coulombic efficiency is 100%, which suggests that the battery is in good condition after field testing. The battery discharge curve is shown in Figure 12(b).

The battery voltage discharge plot provides a model that can be utilized to estimate the current lifetime of the Plant Spike module under test. Plant Spike's on-board ADC can digitize and acquire the battery's voltage and compare it to the discharge model to determine how many cycles Plant Spike has been running and approximate the remaining battery life of the sensors. This analysis will be implemented in future versions of Plant Spike's smartphone app along with other sensor values of interest.

C. Field Data Analysis

Plant Spike modules were placed in four tree pits around New York City's Morningside Heights neighborhood. The locations of the tree pits are labeled on the map in Figure 13. The light measured at each location is shown in Figure 14, where the lines labeled 1 - 4 correspond to the locations 1 - 4 marked on the map. The data shows that locations 2 and 3 have lower light levels as the tree pits were covered with a building's shadow. The tree pit in location 4 was in direct sunlight while the tree pit in location 1 was partly covered by the tree's leaves' shadows. Location 1's light level fluctuations were caused by leaves blowing in the wind.

Temperature and moisture were also measured at each tree pit location and is displayed in Table III. Comparing the temperatures between all 4 spots, location 3 had the lowest temperature by far. There are various factors in tree pits that create temperatures differences. These factors include: the amount of shade from neighboring buildings and trees, the wind speed through the street, and the orientation of the temperature sensor.

Locations 1 and 2 had the highest soil moisture. These locations did not have large trees to prevent precipitation from ponding on the soil surface, and thus were thus less efficient in their water drainage performance. The data collected from the four tree pits demonstrate the information that can be obtained on soil health using light, temperature, and moisture measurements.

D. Cost and Scalability

The reason for using a small footprint and low cost BLE module and sensors is to provide a scalable device for Smart City IoT implementations. The first design of the PCB used a

Fig. 13: Locations of measured tree pits.

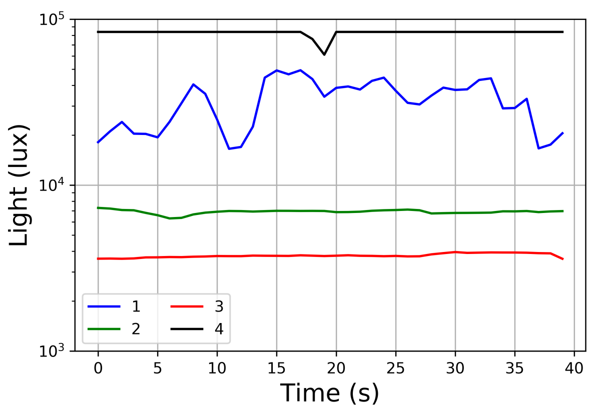


Fig. 14: Fluctuating light at tested locations.

TABLE III: Temperature and soil moisture Measurements at tree pit locations

Location	Temperature (°C)	Soil Moisture	Type
1	20	0.988	Unguarded
2	19	0.980	Guarded
3	16	0.553	Guarded
4	19	0.678	Unguarded

TABLE IV: Plant Spike component, assembly, and total cost (per 1000).

Component	Plant Spike (Custom BLE Peripherals)	Plant Spike (BLE Module)
PSoC4 BLE	1.35	9.66
Light Sensor (OPT3001)	1.14	1.14
Peripherals	0.543	0.103
CR2032 Battery	0.62	0.62
PCB	0.90	1.14
Assembly	4.85	2.52
Total ($)	**9.403**	**15.183**

custom antenna network to reduce the overall cost. For quick prototypes, a BLE module replaced the custom BLE peripheral circuit. Cost comparisons per 1000 manufactured is shown in Table IV.

The cost per unit is less than 10 United States Dollars. This is significantly cheaper than standard infiltrometer measurements in terms of labor cost, material cost, and overall size cost. By connecting on-board sensors to a microcontroller chip instead of a microcontroller development board and using part of the PCB as the capacitance sensor, Plant Spike is also less costly than previously demonstrated tree and soil monitoring IoT systems [37], [38]. The future hope with Plant Spike is that it will be scaled up to be placed in many locations around New York City where soil health is of interest and where data can be easily collected using a BLE client device. Plant Spike's low cost makes it an attractive option for municipal maintenance teams and even for everyday citizens interested in checking on their neighborhood tree pits, for example.

VII. Conclusion

For the first time, a low-cost low-power IoT soil health sensor has been developed and implemented in various locations in New York City. The soil health sensor can monitor various characteristics of the soil such as moisture, light intensity, and temperature to monitor and diagnosis the health of urban soils. In addition to monitoring soil health, Plant Spike is a BLE-enabled IoT system that seamlessly integrates on-board sensors with minimal additional connections needed. In implementing the system, we realized a network of BLE connected low-power sensors that can be placed in urban soils locations, such as bioswales and tree pits, and left for up to two years before replacement with no damage to the battery. The demonstrated sensors can be accessed with a smartphone app for ease of use. This data will provide new information regarding soil quality in urban settings, including measurements for the concentration of contaminants such as animal and chemical waste and the severity of soil compaction. The next generation of Plant Spike will incorporate improved weather resistance, more on-board memory, and a higher sampling and polling rate for data acquisition and transmission. Additionally, we plan to integrate Plant Spike into a wider variety of tree pits and green spaces to monitor water infiltration capacity, pH level, dissolved oxygen content, and other various issues intrinsic to urban soil health. Currently, we plan to incorporate Plant Spike sensors into 40 additional tree pits around various New York City communities. Data will be collected from these tree pits once every week using an improved version of the custom smartphone app.

VIII. Acknowledgements

The authors acknowledge NSF (Award Number: 1841615) and Verizon's Open Innovation Challenge for funding.

References

[1] W. Ding, D. Stewart, P. N. Humphreys, S. Rout, and I. Burke, "Improve efficiency and reliability in single-hop WSNs with transmit-only nodes," *Science of The Total Environment*, vol. 541, pp. 1191–1199, January 2016.

[2] A. E. R. C. P. J. Elliott, R. M. and P. M. I., "Stormwater infiltration capacity of street tree pits: Quantifying the influence of different design and management strategies in new york city," *Ecological Engineering*, vol. 111, p. 157–166, 2018.

[3] "EcoBT: Miniature, versatile mote platform based on bluetooth low energy technology," *2014 IEEE Int. Conf. Internet Things*, 2014.

[4] "Wristband Vital: A wearable multi-sensor microsystem for real-time assistance via low-power Bluetooth link," *IEEE World Forum Internet Things*, 2016.

[5] "CheepSync: A Time Synchronization Service for Resource Constrained Bluetooth Low Energy Advertisers," *14th Int. Conf. - IPSN '15*, 2015.

[6] B. P. L. Lau, N. Wijerathne, B. K. K. Ng, and C. Yuen, "Sensor fusion for public space utilization monitoring in a smart city," *IEEE Internet of Things Journal*, vol. 5, no. 2, pp. 473–481, 2018.

[7] Y. Z. N. U. H. C. Y. M. Z. Billy Pik Lik Lau, Sumudu Hasala Marakkalage and U.-X. Tan, "A survey of data fusion in smart city applications," *Information Fusion*, vol. 52, pp. 357–374, 2019.

[8] A. J. Jara, D. Genoud, and Y. Bocchi, "Short paper: Sensors data fusion for smart cities with knime: A real experience in the smartsantander testbed," in *2014 IEEE World Forum on Internet of Things (WF-IoT)*, 2014, pp. 173–174.

[9] B. Błaszczyszyn and B. Radunovic, "Using transmit-only sensors to reduce deployment cost of wireless sensor networks," *Proc. of IEEE INFOCOM'08*, Apr. 2008.

[10] B. Firner, "Transmit only for dense wireless networks," 2014, ph.D. dissertation, Rutgers University.

[11] J. Zhao, C. Qiao, R. S. Sudhaakar, and S. Yoon, "Improve efficiency and reliability in single-hop WSNs with transmit-only nodes," *IEEE Trans. Parallel and Distributed Systems*, vol. 24, no. 3, pp. 520–534, March 2013.

[12] H. C. Keong, K. M. S. Thotahewa, and M. R. Yuce, "Transmit-only ultra wide band body sensors and collision analysis," *IEEE Sensors J.*, vol. 13, no. 5, pp. 1949–1958, May 2013.

[13] K. Han and K. Huang, "Wirelessly powered backscatter communication networks: Modeling, coverage, and capacity," *IEEE Trans. Wireless Communications*, vol. 16, no. 4, pp. 2548–2561, April 2017.

[14] C. Kolias, L. Copi, F. Zhang, and A. Stavrou, "Breaking BLE beacons for fun but mostly profit," in *Proc. ACM EuroSec'17*. New York, NY, USA: ACM, 2017. [Online]. Available: http://doi.acm.org/10.1145/3065913.3065923

[15] K. E. Jeon, J. She, P. Soonsawad, and P. C. Ng, "BLE beacons for internet of things applications: Survey, challenges, and opportunities," *IEEE Internet of Things Journal*, vol. 5, no. 2, pp. 811–828, April 2018.

[16] M. Gorlatova, R. Aiello, and S. Mangold, "Managing base station location privacy," in *Proc. IEEE Military Communications Conference (MILCOM'11)*, Nov. 2011.

[17] [Online]. Available: https://www.bluetooth.com/specifications/bluetooth-core-specification/technical-considerations

[18] J. Nieminen, C. Gomez, T. Savolainen, and M. a. Isomake, "Networking Solutions for Connecting Bluetooth Low Energy Enabled Machines to the Internet of Things," *IEEE Network*, vol. 28, no. 6, pp. 83–90, 2015.

[19] "A Measurement Study of BLE iBeacon and Geometric Adjustment Scheme for Indoor Location-Based Mobile Applications," *Mobile Information Systems*, 2016.

[20] A. Dementyev, S. Hodges, S. Taylor, and J. Smith, "Power consumption analysis of bluetooth low energy, zigbee and ant sensor nodes in a cyclic sleep scenario," 2013.

[21] "Enhancing iBeacon based micro-location with particle filtering," *IEEE Glob. Commun. Conf. GLOBECOM*, 2015.

[22] "Preliminary Design for Sustainable BLE Beacons Powered by Solar Panels," *INFOCOM WKSHPS*, 2016.

[23] "Cinamin : A Perpetual and Nearly Invisible BLE Beacon," *EWSN '16 Proc. of the 2016 Int. Conf. on Embedded Wireless Systems and Networks*, 2016.

[24] "Bluetooth low energy beacons." [Online]. Available: http://www.ti.com/lit/an/swra475a/swra475a.pdf

[25] "Wireless sensor network based smart home: Sensor selection, deployment and monitoring," *IEEE Sens. App. Symp.*, 2013.

[26] T. Zachariah, N. Klugman, B. Campbell, J. Adkins, N. Jackson, and P. Dutta, "The internet of things has a gateway problem," in *Proc. ACM HotMobile'15*, Feb. 2015.

[27] "IoT enabled Environmental Monitoring System for Smart Cities," *2016 International Conference on Internet of Things and Applications (IOTA)*, pp. 383–388, 2016.

[28] "Psoc 4 die temperature (dietemp)." [Online]. Available: http://www.cypress.com/file/139101/download

[29] A. Rivadeneyra, "Design and characterization of a low thermal drift capacitive humidity sensor by inkjet-printing," *Sensors Actuators, B*, vol. 195, 2014, pages = 123–131,.

[30] H. Ooe, "Low drift mems humidity sensor by intermittent heating," *IEEE Int. Meet. for Future of Electron Devices*, 2015.

[31] "Capsense controller." [Online]. Available: http://www.cypress.com/products/capsense-controllers

[32] C. J. Walsh, T. D. Fletcher, and M. J. Burns, "Urban stormwater runoff: A new class of environmental flow problem," *PLOS ONE*, vol. 7, no. 9, p. e45814–e45814, 2018.

[33] "Green infrastructure - rain garden," https://www1.nyc.gov/site/dep/water/rain-gardens.page.

[34] "Platinum rtd sensor - pt100 - 3 wire 1 meter long." [Online]. Available: https://www.adafruit.com/product/3290

[35] B. Alizadehtazi, K. DiGiovanni, R. Foti, and T. Morin, "Comparison of observed infiltration rates of different permeable urban surfaces using a cornell sprinkle infiltrometer," *Journal of Hydrologic Engineering*, vol. 21, no. 7, pp. 06 016 003–1– 06 016 003–5, 2016.

[36] T. B. Carson, M. D. E., P. J. Culligan, and W. R. McGillis, "Hydrological performance of extensive green roofs in new york city: observations and multi-year modeling of three full-scale systems," *Environ. Res. Lett.*, vol. 8, pp. 1–13, 2013.

[37] B. Shabandri, S. R. Madara, and P. Maheshwari, *IoT-Based Smart Tree Management Solution for Green Cities*. Springer, 2016.

[38] V. Bhatnagar and R. Chandra, *IoT-Based Soil Health Monitoring and Recommendation System*. Springer, 2016.