Thoreau: A subterranean wireless sensing network for agriculture and the environment

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***Abstract*—This paper presents the deployment of a working Wireless Underground Sensor Network (WUSN) on a university campus using existing wireless networking technology at 902 MHz. This is the first full system of its kind that is operational over a long time, with the data being gathered available in real time on an open website. Design details of the WUSN are described, including the network architecture, sensor nodes, user interface and power management techniques. Initial results obtained from the sensor network are provided and analyzed, showing information regarding soil properties and their influence on the performance of the wireless transmission.**

I. Introduction

Wireless sensor networks (WSNs) have great potential in various applications ranging from health-care and logistics to industry and agriculture. They enable continuous gathering of sensed information over a large area and can thus deliver unique solutions for cost and manpower savings. In particular, when deployed in extreme conditions, such as underground or underwater, WSNs can be used to access information that is otherwise difficult to obtain.

Specifically, wireless underground sensor networks, or WUSNs, are of significant importance for applications such as precision agriculture, environmental protection and geophysical monitoring[1], [2], [3], [4], [5], [6], [7]. Deployed underground, WUSNs can be used to continuously monitor parameters related to soil properties, underground water flow and plant growth. Since all the sensor nodes, along with the radio and antennae, are fully buried, they do not interfere with any natural or human activities (plowing or harvesting, for instance) above ground, and hence can stay in place and keep functioning undisturbed for very long periods of time.

However, technical difficulties related to cost, power, wireless transmission, etc. [1], pose significant challenges to the deployment of WUSNs. Significant effort has been made in the past decade to tackle these challenges. Development guidelines are provided by early research in [3]. Various techniques for underground transmission, such as Mica2 motes [4], [8], Zigbee[9] and magnetic inductive waveguides [10], [11], [12], [13], have been proposed. Intensive theoretical and experimental studies on characterizing wireless transmission in underground channels have been performed [3], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. Furthermore, novel supporting techniques have been developed, including underground antenna design [25], energy harvesting for underground sensor nodes [26], mobile data harvesting [27], etc. Based on these developments, various functional WUSNs that not only serve as research platforms but also show practical applications have been successfully deployed [4], [5], [8], [7].

However, due to the limitation of available technology, previous demonstrations of WUSNs are mostly in open rural environments with relatively small coverage area. With the development of the Internet of Things (IoT), new solutions and opportunities have emerged, allowing one to deploy WUSNs in ways previously thought impossible. A large number of options are available today for building a WUSN based on existing wireless technologies: cellular (narrow-band IoT or NB-IoT), Wi-Fi (based on 802.11ah) or other non-standard systems such as Sigfox and LoRa [28], [29].

In this paper we demonstrate the first deployment of a large-scale, cloud-based WUSN with a very long, continuous operation time on an university campus in an urban area – the Thoreau WUSN at the University of Chicago, built using the Sigfox wireless network. Thoreau consists of an aboveground base station (BS) with a receiving antenna and a number of underground sensor nodes. All the sensor nodes communicate directly with the receiving antenna through a single hop. The system supports two-way communications, but to simplify the design, we only use the uplink data transmission from sensor nodes to the receiving antenna. Thoreau covers an area of about one square mile on the university campus, and all the sensors nodes are buried 6 to 14 inches underground in different soil conditions. We estimate that the Sigfox low-power IoT solution will allow Thoreau nodes to operate on eight AA batteries for about five years. In this paper we first describe the design details of Thoreau, and then show initial results and analysis of the soil properties, as well as their influence on the performance of the wireless transmission.

II. Materials and methods

A. Architecture of Thoreau

Thoreau is being developed based on the Sigfox IoT solution which operates in the unlicensed ISM band at 902 MHz with an ultra-narrow band (UNB) technique. The Sigfox solution

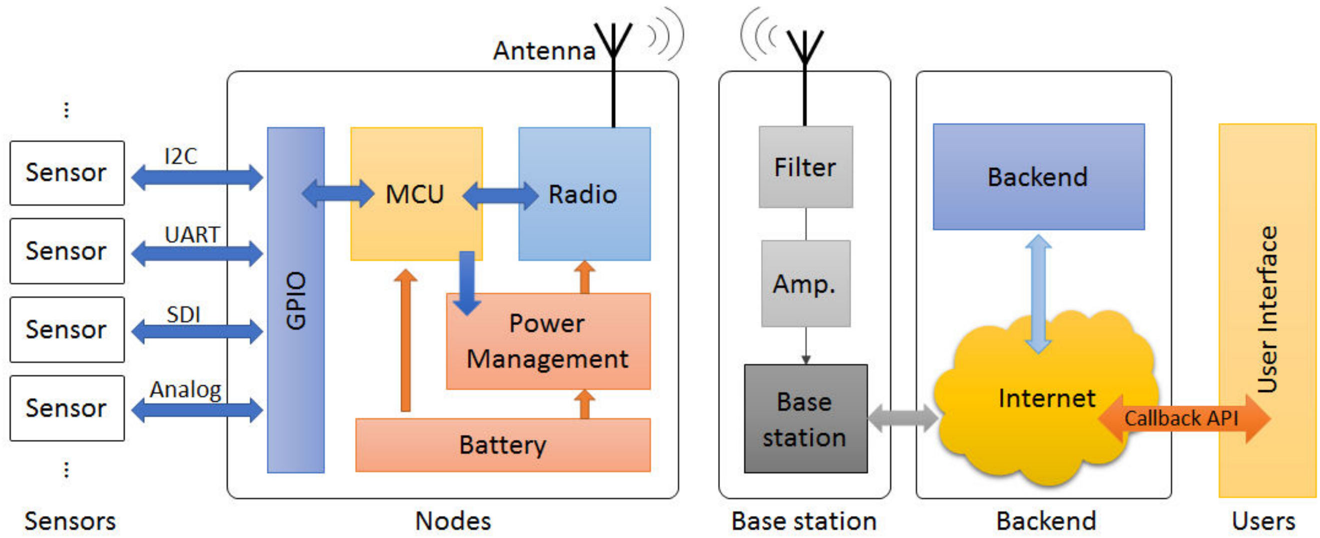

Fig. 1. System diagram of Thoreau WUSN.

consists of three parts: a backend system, a BS, and multiple sensor nodes. The cloud-based backend allows users to conveniently manage devices and curate data through the internet. All data communication, authentication and processing takes place in the backend and Sigfox provides the related internet services. The backend system can be easily connected to any online platform using callback APIs.

The technical advantage of the Sigfox solution provides scalability for the Thoreau WUSN. Using UNB with BPSK, the bandwidth for each packet is only around 100 Hz [30], with a transmitted power of 22 dBm. Each packet is transmitted three times sequentially on three randomly chosen frequencies [30], thus providing both temporal and frequency diversity. Furthermore, packets received by up to three BSs in the reception area can be combined in the backend, thus providing spatial diversity as well. The maximum number of messages each node can transmit per day is 140, and the maximum payload size per packet is 12 bytes[30]. The medium access protocol is extremely light: devices transmit on the uplink asynchronously, without any collision avoidance mechanism, and hence do not need to stay awake to receive synchronization signals from the base station. Messages are not acknowledged or retransmitted, which reduces power but may lead to missed packets. In our application, this is an acceptable trade-off, since soil parameters are fairly stable and a few missed measurements are tolerable. All these measures help to reduce power consumption, increase the reception range, reduce the interference from other users in the unlicensed band, and allow a single base station to handle millions of messages per day. Therefore, the Thoreau WUSN can be conveniently scaled up to a very high node density. While it is well known that frequencies lower than 902 MHz are preferred for underground transmission [1], [2], we nevertheless chose this frequency for the proof-of-concept deployment since commercial products like Sigfox are readily available and the required antenna size is more manageable in the sensor node.

B. Base station

The Sigfox BS is equipped with a modem and RF antenna that provides two-way wireless coverage. For the uplink a low-noise amplifier (LNA) and a cavity filter are added to guarantee high sensitivity, providing a link budget of around 160 dB. The BS is connected to the internet through cabled Ethernet and can be accessed through the backend. Theoretically, the Sigfox wireless network is capable of supporting over-the-air communication ranges of 30-50 km in rural areas and 3-10 km in urban areas. By adopting the UNB technique, the power consumption can be reduced to a very low level, which is essential for building wireless sensor networks. The goal of Thoreau is to utilize the 160 dB link budget to overcome the severe attenuation faced by wireless signals as they propagate through soil.

C. Sensor nodes

The sensor nodes are wireless modules controlled by micro-controller units (MCUs), which interface with the sensors and communicate with the base station. The sensor nodes in Thoreau are based on the Texas Instrument MCU MSP430F5529 with the CC1120 RF transceiver. Each node contains two sensors (Decagon GS-3 and MPS-6) that measure four different soil properties: temperature (T), volumetric water content (VWC, indicative of soil moisture), electric conductivity (EC), and water potential (WP). The MCU communicates with these sensors through certain protocols for sensor control and data acquisition. Multiple analog and digital protocols are supported in our firmware, including commonly used I2C and UART protocols. Specifically, the SDI-12 protocol is used for the Decagon sensors.

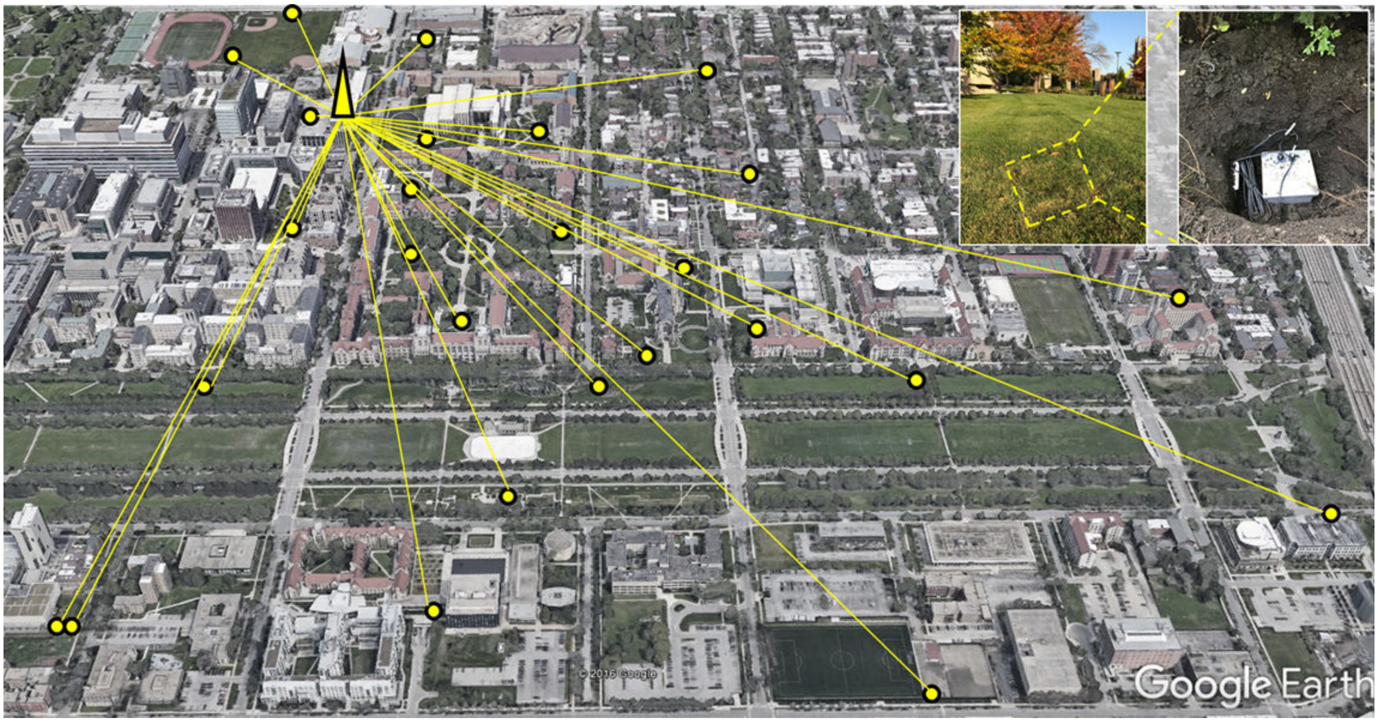

Fig. 2. Deployment map of Thoreau WUSN [31]. Yellow dots represent the underground sensor nodes, while the triangle represents the base station antenna. One sensor node that is far away from the main campus is not shown. Insets show a sensor node deployed under turf.

An important consideration when building a large WSN with many sensor nodes is low power consumption. In some applications such as agriculture, sensor nodes can only be powered by batteries, so lower power consumption also gives longer operation time. Particularly, for WUSNs the sensor nodes will be buried underground, so it is desirable to have years of operation time without having to replace the battery. All components in the WUSN, including MCU, RF modules, and sensors should use low power components that not only consume little energy when operating but also can be put into sleep mode during idle times.

The TI MSP430F5529 MCU is a module optimized for low power operation. Most of the time the MCU stays in the sleep mode, where all unnecessary activities (and supporting hardware such as clock generation circuitry) are shut down and only limited functions that consume little energy are kept running. A watchdog timer is set to wake the MCU up after a predetermined period of time, at which time the sensors are also woken up to take measurements. The TI CC1120 wireless module is then powered up to transmit the signal once the measurement finishes. Upon completion of the transmission, the whole unit returns to the sleep mode and waits for the next cycle. To extend the battery life, the sensor nodes measure and transmit the measurements every half an hour, which is adequate considering that soil properties typically vary slowly. Among the various components, the wireless module consumes the most power. In principle, reducing the transmitted power helps reduce the power consumption. However, the transmission power of the CC1120 board is fixed in the Sigfox solution to guarantee a large link budget. However, other optimizations can be made to reduce the power consumed by the transceiver. For instance, the CC1120 board is not optimized for low power operation and consumes a considerable amount of power even in the standby mode. To conserve energy, we developed a custom power management board that is inserted between the MCU board and the CC1120 board. The MCU controls a solid state relay in the power management circuit that shuts off the power supply to the CC1120 board when the transmission is completed. With these power management measures, the sensor nodes can operate continuously on eight lithium ion AA batteries for more than five years according to our laboratory tests. We chose lithium ion batteries because of their excellent performance over a large temperature range, which is necessary in order to guarantee normal operation of Thoreau in the cold winters and warm summers of Chicago and provide non-stop monitoring of the environment.

All the circuits, including the MCU and RF modules, together with the battery packs, are enclosed in a $4'' \times 6'' \times 6''$ PVC plastic box which is sealed to be watertight using rubber bands and silicone. The sensor cables are inserted into the box through waterproof cable glands, which are further sealed using silicone gel to eliminate any potential leaks. Note that the size of the enclosure can be further reduced through custom design. All components are glued to the interior of the box. The sensors and battery packs are soldered to the power management boards, which was designed to provide soldering holes, to guarantee reliable connections.

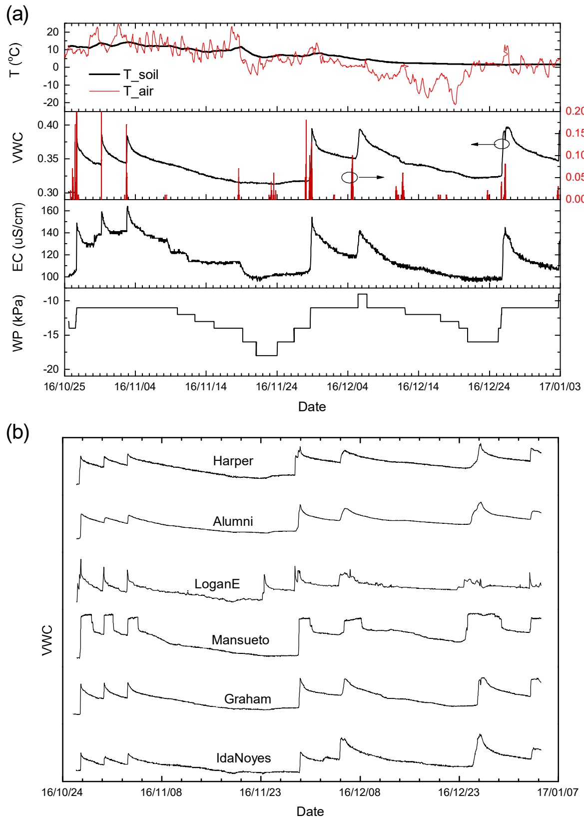

Fig. 3. (a) Measured soil properties from one sensor node. WP: water potential; EC: electric conductivity; VWC: volumetric water content; T: temperature. (b) Soil moisture measured at six different locations.

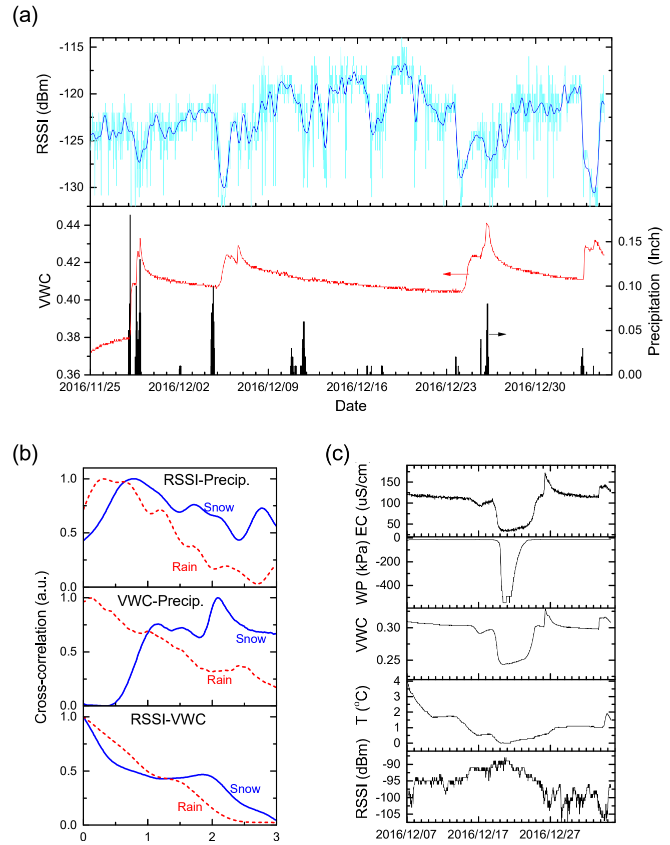

Fig. 4. (a) RSSI (relative signal strength indicator) and VWC (volumetric water content) as a function of time measured by the North Winter Garden node. (b) Time-lag correlation between RSSI, VWC and Precipitation. (c) Soil properties measured by Snell-Hitchcock node.

D. Web-based user interface

An open web interface, http://thoreau.uchicago.edu, has been developed to facilitate the data curation and network management. Data is retrieved from the Sigfox backend using callback APIs such that whenever the sensor nodes collect sensing data and transmit to the BS, the information is displayed in real time on the website, time-stamped, and logged for future analysis.

E. Field deployment

Thoreau has been deployed across the campus of the University of Chicago and covers an area of about one square mile. The BS antenna is installed on the rooftop of a tall building (41 meters above ground). There are currently 27 sensor nodes buried underground in randomly chosen outdoor environments, either close to buildings (within a few feet) or in open areas (for instance the athletic field, where the sensor node is more than 250 feet away from the closest building). These locations have distinct soil types and vegetation conditions. The burial depth ranges from 6 to 14 inches, some of which exceeds the range of the top soil where agricultural activities take place. After burial, the soil is restored to its normal condition. As a result, the deployed sensor nodes can stay underground and function normally without interfering with daily activities in the top soil. Soil type and surrounding environments vary significantly at different locations, thus providing an unique opportunity to study the diverse vegetation and growing conditions around the campus. The longest distance between sensor nodes and the BS is 1.13 miles (1.82 km). Furthermore, the complex urban environment also provides an ideal testbed for studying wireless communications in realistic instead of laboratory situations. To the best of our knowledge, this is the first demonstration of a long-term, large-scale, cloud-based, fully functioning real-time WUSN on a university campus in an urban environment in the United States.

III. Results and Discussion

A. Analysis of soil properties

Thoreau allows us to monitor the soil properties in real time and record the results. Figure 3(a) shows the soil properties obtained from the Graham School node, which is buried 8 inches underground, over a period of more than two months through the winter (from the end of October 2016 to the beginning of January 2017). The air temperature and precipitation during that period are also provided as a reference [32]. These results not only provide us real-time measurements of soil properties for applications such as agricultural decisions,

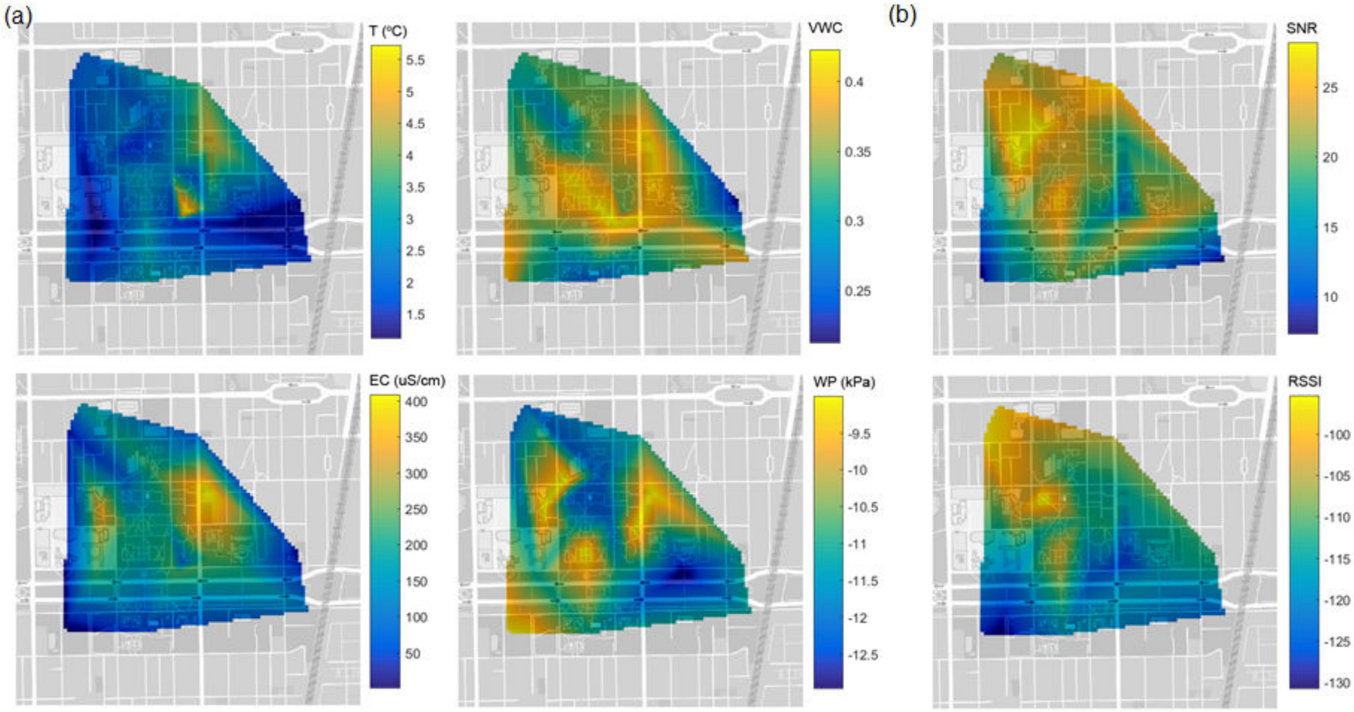

Fig. 5. Intensity maps of different soil properties. (b) Intensity maps of wireless channel properties. Each map is 1×1 mile^2 in area.

but also allow us to study how these parameters vary with time and various events either caused by natural (rain or snow) or human activities (irrigation or fertilization) and how they are correlated. From the data we can see that the soil temperature varies much slower than the air temperature because of the relatively large heat capacity of soil. The other three parameters are all related to water content in soil. Precipitation causes VWC to increase, and the elevated water content leads to a higher electric conductivity and a higher water potential. The WUSN also allows us to compare results at different nodes to obtain further information. Figure 3(b) plots the measured soil moisture as a function of time at six different locations, which clearly shows different responses to precipitation depending on the soil type. For very sandy soil (Mansueto node, with 87% of sand composition), the soil moisture saturates after rising to a certain level and stays at this level for a period of time before it suddenly drops, while for soil with little sand content (Logan East node, with only 20.8% of sand composition) the soil moisture spikes after precipitation and then gradually decreases.

B. Wireless transmission performance and effect of soil moisture

The data curated from Thoreau also provides valuable information for underground wireless transmission analysis. Among the various soil properties that may affect wireless signal transmission, water content plays the most important role as water is known to absorb microwave energy and therefore attenuates the signal, while other soil properties such as soil composition and bulk density are usually fixed. However, due to the complexity of our deployment environment (transmission through varying soil depth and air, multipath transmission, etc.) and the low intensity level of the received signal, in most situations the dependence of the wireless channel loss on the soil moisture is not obvious. The North Winter Garden node suffers the least from multipath interference (away from buildings), and therefore clearly shows such correlations. From Fig. 4(a) we can see that each time the soil moisture increases as a result of precipitation, the RSSI (received signal strength indicator) decreases. From the time-lag correlation in Fig. 4(b) we can see that the RSSI does not respond to precipitation instantaneously but with a delay of a few hours for rain and one to two days for snow, which is similar to the response of VWC to the precipitation. In fact, the dependence of RSSI on VWC is clearly reflected in the calculated RSSI-VWC correlation. These results indicate that the precipitation is not the direct cause of path loss increase. Particularly this is more evident for snow. The RF signal is not attenuated by the snow accumulation on the ground right after snowing, but instead only when the snow starts to melt and penetrate into the soil underneath, which causes the increase of VWC.

Since Thoreau is deployed underground, any change in the soil will affect the wireless channel. During winter, the ground freezes and accordingly the soil texture changes significantly. From the measurement results of the Snell-Hitchcock node, we can see that as the soil temperature approaches 0 °C, dramatic changes are observed in other soil properties. The soil moisture shows an abrupt drop which causes the decrease of electric conductivity. Particularly, the water potential experiences a

TABLE I

PARAMETERS OF EIGHT SENSOR NODES WHICH IS USED FOR PATH LOSS CALCULATION: BURIAL DEPTH, DEPLOYMENT DISTANCE TO THE BASE STATION ANTENNA, SOIL BULK DENSITY, AND THE WEIGHT PERCENTAGE OF SAND, SILT AND CLAY COMPOSITION.

Location	Depth (inch)	Distance (ft)	Density (g/cm^3)	Sand wt%	Silt wt%	Clay wt%
Logan E.	6	2580	1.45	20.8	49.5	29.7
Ida Noyes	8	2058	1.32	68.5	19.7	11.8
Logan W.	10	2580	1.45	20.8	49.5	29.7
Harper	7	1328	0.82	52.2	31.9	15.9
Graham	8	3883	1.07	57.5	27.0	15.5
Mansueto	6	315	1.76	86.0	8.0	6.0
Alumni	8	1639	0.81	58.0	26.0	16.0
Kenwood	6	5966	0.63	64.2	25.9	9.9

significant drop. But interestingly, the RSSI increases during this period, indicating that ice is less lossy to microwaves than water at our operation frequency of 902 MHz.

C. Location dependence and intensity map

With a total of 27 sensor nodes, Thoreau allows us to monitor soil properties over a large area and study the location dependence of soil properties. Figure 5(a) plots the intensity map (taken on 1/4/2017) generated using Matlab for different soil properties within a one square mile area that covers the whole campus. These distributions of soil properties, upon further data mining, allow one to extract relations between soil properties and soil types or human activities. Further deployment of more sensor nodes will provide intensity maps with much better resolution. Thoreau also allows us to analyze the wireless channel over the large coverage area, as shown in Fig. 5(b). Generally, channel loss increases with distance, so we see lower RSSI at locations far away from the BS, but their signal-noise-ratios (SNRs) can also be good depending on the specific interference level.

D. Wireless channel path loss: theory vs measurement

We compare the measured path loss of the wireless channels in the Thoreau WUSN with theoretical calculations. To theoretically calculate the path loss, we first measured location information of the system, including sensor node distance from the BS and depth, elevation of the receiving antenna, and the operating frequency. We then calculated the microwave propagation and absorption constants in soil using the semiempirical dielectric mixing models described in [33], [34] based on the knowledge of soil properties: bulk density and composition of sand, silt and clay, which we obtained from lab tests using soil samples taken at each deployment location. With these known parameters, the path loss (in our case we only consider the uplink, which transmits the signal from the underground sensor nodes to the aboveground BS) can be calculated using the models provided in [35]: $P_{u-a} = P_u + P_a + P_i$, which separates the WUSN path loss P_{u-a} into three parts (all in unit of dB in this expression): underground (P_u), aboveground (P_a), and at the interface (P_i). Particularly, the underground path loss $P_u = 6 + 20\log_{10}\beta d + 8.69\alpha d$ [35] is significantly affected by soil characteristics since α and β, the real and imaginary part of the microwave propagation constant, are determined by the soil properties (while d is the underground path length).

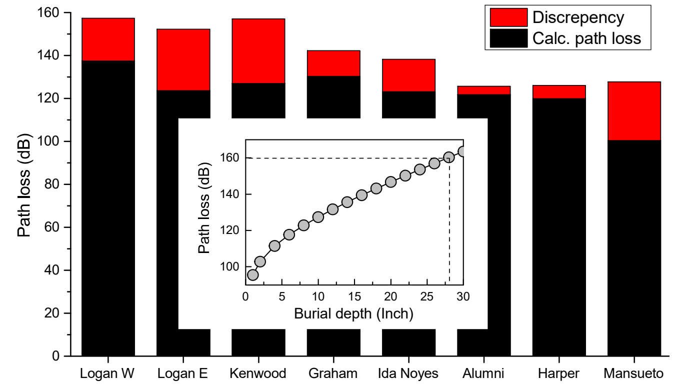

Fig. 6. Calculated and measured channel loss for eight different sensor nodes. Inset: calculated channel loss versus burial depth for sensor node “Alumni”.

Figure 6 shows the calculation versus the measurement results. Clearly, the theoretical calculation provides a lower bound for the channel loss, while in practice the loss is much higher than the predicted values. Such discrepancies can be attributed to antenna loss, multipath, and attenuation due to obstacles, considering the complex, real-world environment that Thoreau is deployed in which includes buildings, plants, machines and human activities. Generally, measured path losses for sensor nodes that have fewer buildings in the aboveground path are closer to the predicted value (Alumni and Harper), while those which have more buildings in the path deviate more from the predicted path loss (LoganW, LoganE, Mansueto, Kenwood).

We also studied the channel loss as a function of the burial depth. Inset of Fig. 6 plots the calculated channel loss at different burial depths for a sensor node (node “Alumni”) which has a moderate distance (1639 feet) and burial depth (8 inches). When the depth is larger than 4 inches, the path loss in dB increases linearly with burial depth. For this specific sensor node, the burial depth can go up to 28 inches within the 160 dB link budget. For sensor nodes with shorter distance from the BS and less fading effects, the burial depth can be even larger.

IV. CONCLUSION

To conclude, we report the successful proof-of-concept, ongoing deployment of a large-scale, long-term, urban-area WUSN, Thoreau, that operates on a university campus and serves as a sandbox for underground sensor and wireless transmission research. Even in the extreme conditions that it is deployed in (underground, in an urban area with extreme winters), and using a wireless network that is not optimized for underground transmissions, its sensor nodes can be deployed as far as 1.13 miles away from the base station antenna (and could possibly be even further). All sensor nodes are deployed underground with a depth of 6-14 inches and therefore will not interfere with any human activities in the top soil layer. Initial results have been collected and analyzed, providing information about soil properties that can be used for landscape management, flood management, etc. Furthermore, this information also helps the wireless channel analysis and reveals correlations between soil moisture and channel loss. In future, Thoreau will be scaled up to provide larger coverage area and finer resolution. Further performance improvements (power consumption, coverage, etc.) can be achieved by optimizing the wireless communication module, which is currently not optimized for underground transmission in the Sigfox IoT solution. In addition to underground sensor nodes, other types of sensors, for example sensor nodes for measuring water bodies, will be included in Thoreau, thus enriching its functionality.

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