A Novel Soil Measuring Wireless Sensor Network

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***Abstract*—Emerging technologies have made low-power and low-cost wireless sensor networks feasible. This paper presents a hierarchical wireless sensor network for measuring soil parameters such as temperature and humidity. Specifically, we designed sensor nodes that are placed completely underground and are used to collect soil measurements. These nodes use their radios to deliver the collected measurements to one of multiple relay nodes located above ground. In turn, relay nodes that are capable of long-range communications forward the data collected from the network's sensor nodes to a base node, which is connected to a workstation. The proposed hierarchical wireless sensor network uses a probabilistic communication protocol to achieve a very low duty cycle and hence a long lifetime for soil monitoring applications.**

Keywords-wireless sensor networks; soil measremen; low power communication

I. INTRODUCTION AND PREVIOUS WORK

Soil moisture plays an important role in the dynamics of land-atmosphere interactions and many current and upcoming models and satellite sensors. There is therefore a need for sensor networks at a variety of scales that provide near-real-time soil moisture and temperature measurements combined with other climate information for use in natural resource planning, drought assessment, water resource management, and resource inventory [1]. Without an autonomous sensor system, experiments in need of accurate information about a multitude of environmental parameters on various spatial and temporal scales require superhuman data collection efforts.

The recent emergence of small sensors can fundamentally change the way we can approach many scientific problems, some of them totally intractable in the past. The wireless capabilities of these low-power sensors result in an easily deployable, scalable design for large-scale monitoring systems. Furthermore, the inexpensive nature of these sensors enable scientists to place a high resolution grid of sensors in the field, and acquire frequent measurements, providing an extremely rich data set about the correlations and subtle differences among many correlated parameters [2].

The goal of the *Life Under Your Feet* (LUYF) project, started at the Johns Hopkins University four years ago, is to develop wireless sensor network (WSN) technologies that soil ecologists can use to measure the abiotic parameters of forest soils (e.g., soil temperature and humidity) [2]. Because WSNs collect measurements at fine temporal and spatial granularities, soil scientists can now study subtle spatial gradients and small temporal changes.

WSN routing protocols for long term data gathering applications, such as environmental monitoring, must support low duty cycles (<1%), reliably deliver collected measurements, and operate unattended for long periods of time. In response to these requirements, WSN networking stacks employ techniques to coordinate the nodes' sleep schedules and maintain states at each of the network's motes (e.g., routing entries, link quality information, etc.) [3]. In turn, implementing these techniques leads to networking software with increased complexity running on resource constrained motes. This complexity coupled with the unexpected and untested environment in which the network is deployed can lead to failures [4].

The nodes in LUYF implement a Flexible Control Protocol (FCP), which is a signaling protocol to install routing paths on the network's motes. A WSN gateway uses FCP to create the multi-hop paths over which it downloads data from the network's nodes. FCP supports ephemeral paths that transmit a single datagram and persistent paths that persist until explicitly torn down. Both paths can offer reliable transfers. As part of LUYF we also developed the Koala system for reliably downloading bulk data, targeting data gathering applications with no real-time requirements. Koala uses FCP to establish network paths, coupled with Low Power Probing (LPP), an efficient technique for waking up the network's nodes before a download occurs. Furthermore, Koala leverages the availability of multiple channels in IEEE 802.15.4 radios to perform data downloads over different channels, thereby minimizing overhearing costs [4].

Figure 1. Sensor node and data collection architecture for the Life Under Your Feet project.

Figure 1 shows the sensor node (also known as *mote)* developed for Life Under Your Feet, as well as the architecture of the Koala data collection system [2,5].

The system has been persitently deployed in multiple locations over the last two years and has collected thus far more then 80 million measurements. At the same time, these deployments exposed a number of system limitations that motivate this work.

As one can see from Figure 1, the mote is connected to the soil temperature and moisture sensor through long cables. These cables complicate the deployment process and are prone to failures. Furthermore, the fact that the mote itself is above ground complicates the deployment of the system in farms and yards. Placing the whole device below ground would protect it from accidental damage (e.g., getting run over by farm equipment and lawn mowers). However, doing so would severely hinder wireless transmissions since the nodes use IEEE 802.15.4 radios in the 2.4 GHz frequency range. The reason is that wet soils severely attenuate RF signals in this range. Last but not least, the cost of the current sensor node is currently the main obstacle to large scale deployments.

II. HIERARCHICAL STRUCTURE

Next, we describe the proposed tiered design with three node categories: sensor nodes, relay nodes, and a base node. Nodes are classified into three categories according to their functions. Table I lists the functions of each node category and Figure 2 presents a schematic of the system's operation and the relationship among the three node types.

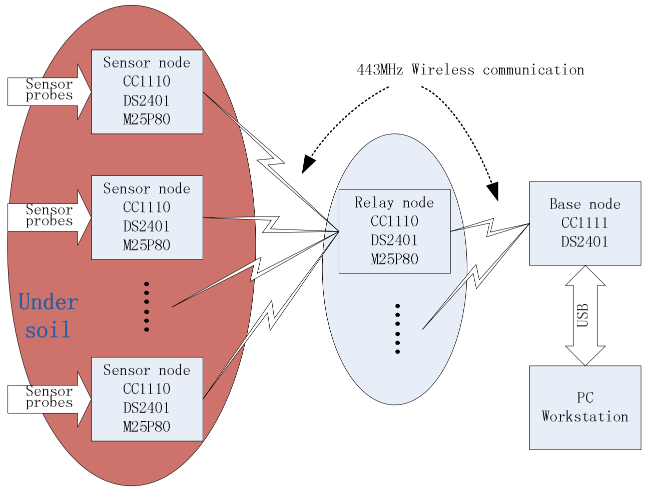

Figure 2. Structural diagram of the proposed soil measuring WSN.

TABLE I. NODE FUNCTIONS AND TYPES.

Node Type	*Data Collection*	*Storage*	*Identification*	*Radio*	*USB*
Sensor	√	√	√	√	
Relay		√	√	√	
Base			√	√	√

Sensor nodes are placed below ground to collect soil measurements through directly integrated sensors. They transmit these measurements through the soil to nearby relay nodes. The ability to directly place sensors below ground significantly improves our ability to monitor soil conditions. The relays are above ground and are responsible for forwarding data to other relay nodes or the base node. The base node delivers the whole network's data to a workstation for persistent storage and analysis. The relay-to-relay and relay-to-base distances are significantly longer (~50 meters) than the distances between sensor and relay nodes (~0.3 meters under the soil and 3 meters above). This configuration achieves a fully wireless soil-measuring network.

Sensor nodes collect measurements and temporarily store them in their flash memory before transmitting them to one of the above ground relays. Relays do not collect measurements but rather forward the sensor nodes' measurements. Finally, the base node delivers all the measurements to the locally attached workstation over a USB connection.

We use the CC1110 System on a Chip (SoC) from Texas Instruments to implement the sensor node. The CC1110 combines an MCU with an RF transceiver which operates in the 433 MHz frequency range, enabling efficient transmission of the collected data. We experimentally measured that the received signal strength is > -80 dBm (the transmitter's output power is set to +10 dBm) at 10 m away from a sensor node buried 30 cm below ground (see Figure 3). However, the transmission range varies based on soil type and soil conditions such as water content.

III. HARDWARE DESIGN

The kernel of the soil measuring wireless sensor networks node is the state-of-the-art CC1110F32 SoC from Texas Instruments [6]. The CC1110F32 includes an industry-standard 8051 MCU with 32KB of in-system programmable flash memory and 4KB of RAM. To store the large volume of sensed data, we integrated the M25P80 8Mbit serial flash chip with SPI interface to the board. Each node has a unique 64-bit network identifier hardcoded into a DS2401 silicon serial number chip. We use the MCP9803 digital temperature sensor that achieves 0.3 ^{o}C accuracy (after appropriate compensation) and has a operating range of -40 ^{o}C to 125 ^{o}C. The sensor is connected to the MCU through the I^2C interface. Other analog sensors, such as Decagon's EC-5 Soil Moisture Sensor, can be easily connected to the ADC interface of the CC1110F32.

Figure 4 presents the main components of the common board shared by the sensor and relay nodes. Sensor and relay nodes can be connected to a PC via the UART interface during debugging, while the base node is the only node type that communicates with a PC through its USB interface. It should also be noted that the base node is implemented using TI's CC1111F32, which provides a quick and easy-to-use full-speed USB 2.0 interface, avoiding the bottleneck of communicating over RS-232.

Figure 3. Sensor board of WSN node in the lab. The same node is shown inside a field enclosure before placed below ground for radio communication experiments.

The picture of the sensor board in Figure 3 indicates the two antenna options available: (a) chip antenna (rectangle on the left side of the board) or (b) external antenna connected through the SMA connector. As the relay nodes are designed for long-range transmissions, one can use a zero register to select the external antenna for relay nodes and the chip antenna for sensor nodes. In this way, the same design applies to all three node types in our soil sensing system.

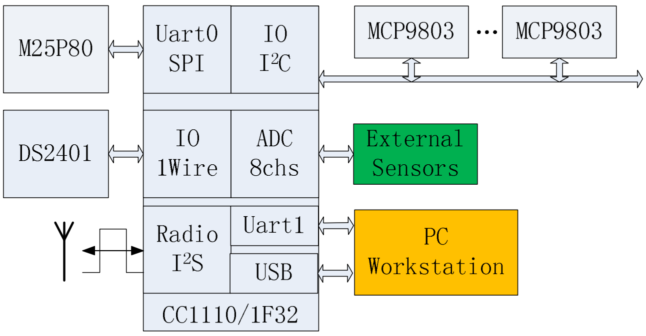

Figure 4. Components and connections of proposed soil-measuring WSN node.

IV. COMMUNICATION AND POWER MANAGEMENT

Data collection and transmission can be divided into three sections: (1) hourly sampling and buffering, (2) daily transmission, and (3) transmission of status messages. The hourly sampling section encompasses the data collection process from a sensor node's local sensors including measuring the mote's reference voltage and the time stamps associated with the sensor measurements. Each status message contains the sensor node's identity, the amount of data collected thus far, the current battery voltage reading, and information about the wireless link (i.e., RSSI and LQI). Finally, the data transfer section includes all the data that a sensor has collected and the current status.

Sensor nodes have to include non-volatile storage such as flash memory to be able to temporarily store the collected measurements before they are reliably transferred to one of the relays. Relay nodes have storage capability as well, as they must also temporarily store the sensor nodes' data. On the other hand, the base-station can directly deliver the received data to the locally attached workstation through its USB port. Therefore, it only requires a wireless radio and a USB slave port.

Figure 5 presents the basic data transfer concepts in this soil-measuring sensor network that we describe next. Every node (other than the base node) wakes up at a random interval and keeps its radio on for a minimum period. If another node (relay or base) asks for a data transfer during this wake-up period, the node will stay on until the transfer completes. Otherwise, the node goes to sleep until its next wake up time. By altering the random distribution from which nodes select the duration of their sleep intervals and the minimum length of the active time one can control the average data upload latency. This probabilistic wake up mechanism is similar to the idea proposed by Santashil et al. who developed a communication protocol that leverages the birthday paradox to conserve energy [7].

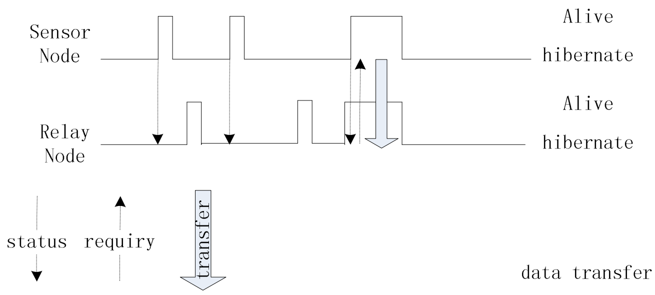

Figure 5. Opportunistic rendezvous and data download between a sensor and a relay node.

Since the base station is always active, the communication between relay nodes and the base station is somewhat simpler. Each time a relay node that is within communication range to the base station wakes up, it sends its status message to base station. If the base station wants its data, then the communication starts. The routing path from sensor nodes to base station is predetermined by their locations in the deployment. If a relay node cannot reach the base station directly, its data must be forwarded by using other relays as intermediate points.

Assuming a one hour sampling interval, a sensor node collects and stores 24 sensor samples per day. Furthermore, the mote sends on average 720 status messages per day, matching the 2-minute sleep interval currently used in Life Under Your Feet, and keeps its radio on for one second each time it wakes up. The resulting duty cycle due to the periodic wakeups is then 0.833%.

Given that nodes do not synchronize their sleep schedules, it is possible that a sensor node is not able to rendezvous with the relay(s). To determine the probability of this event we consider a sensor-relay pair. Furthermore, we assume that the distribution of sleep intervals is uniform and that each node keeps its radio on for at least one second. Then, the possibility that this pair of nodes do not 'meet' each other within single day is equal to $(1-\frac{1}{120})^{720}$ =0.0024.

This analysis suggests that sensor nodes will be able to deliver their data to one of the network's relays at least once per day with high probability. Nevertheless, in the unlikely event that a node cannot reach a relay for multiple days it can continue buffering its data to its onboard flash. Considering that nodes collect ~25 KB data per day, the 1 MB on board flash supports more than 40 days of disconnected operation.

If nodes need to achieve an even smaller duty cycle, one can increase the duration of the sleep interval or decrease the radio on time. Figure 6 presents the probability of having at least one rendezvous per day as a function of the sleep interval when the on time is fixed to one second. It is evident from this graph that if a rendezvous probability $p=0.5$ is acceptable nodes can increase their sleep interval to 354 seconds (i.e., 0.28% duty cycle). If a duty cycle of 1‰ is necessary, then p reduces to ~0.082 and thus data delivery latency increases to ~13 days.

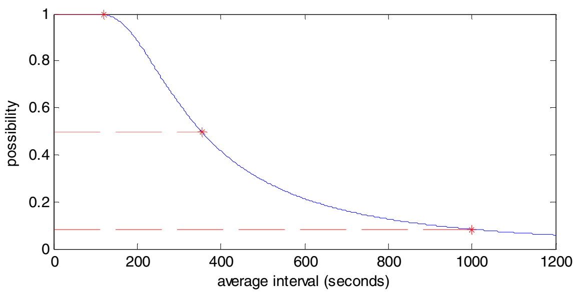

Figure 6. Relationship between the possibility of at least one successful connection a day and the average wake-up interval. In all cases radio on time is fixed to one second.

We experimentally measured the mote's power consumption and Table II shows the power consumption of each of the mote's components. While the flash draws considerable current in write mode (15 mA) it is active for very small amount of time due to its high speed. It is therefore safe to assume as a first approximation that the node's energy consumption while the radio is turned off is almost zero. Therefore, if we can achieve a 1% duty cycle in the data transmission section, the power consumption for a sensor node in one day will be 16mA*24h*0.01=3.84mA*h. In this case a sensor node may work for approximately three years using two 2100 mAh AA batteries (2100 mA*h *2 / 3.84 mA*h /365 ≈ 3 years). The node lifetime increases to 10 years if a duty cycle of 0.28% is used instead.

The cost of the sensor board shown in Figure 3 is $10 including all electronic components and the cost of manufacturing the PCB in large quantities. This low cost makes our design very appealing for large-scale deployments of soil monitoring networks.

V. SUMMARY AND FUTURE WORK

We present a hierarchical soil measuring wireless sensor network, which includes sensor nodes, relay nodes, and base nodes. The system operates in the 433 MHz frequency range enabling sensor nodes to transmit their data even when buried in the soil. The ultra-low cost and low power consumption of the presented soil-sensing network make it suitable for large scale deployments.

TABLE II. POWER CONSUMPTION OF EACH SECTION.

Working Section	Operation	Power Consumption
Data Transmission (radio)	RX	16.2mA
	TX	15.2mA
	low power	1 uA
Data storage (flash)	Reading	4mA
	Writing	15mA
	Erasing	15mA
	Low power	1uA
Data collection (sensor)	Sensing	200uA
	Low power	1uA

We are currently at the project's early stages having accomplished the system's hardware and software design and performed small-scale experiments. As part of our future work we will conduct large-scale deployments and analyze the performance of the system in the field. Furthermore, the probabilistic protocol outlined in Section IV requires further investigation in the case of multi-hop networks.

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