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A multi-hop wireless sensor network for in-situ agricultural applications

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Abstract

This paper presents the design and implementation of a wireless sensor network (WSN) for agricultural monitoring applications using a multi-hop tree based architecture. Each sensor node is equipped with different sensors such as soil moisture (custom built), atmospheric temperature and relative humidity sensors. The nodes use TelosB modules for wireless communication. The implemented testbed consists of 20 nodes covering an area of 120 $m \times 150$ m. Each node reported its sensor data at every 1 hour interval to the base station along the data collection tree following a time synchronized periodic sleep wake-up schedule. The maximum depth of the constructed data collection tree was observed as 5 hops in the implemented network. The performance of the in-house developed soil moisture sensors are evaluated through the implemented WSN and the difference between the measured soil moisture and the commercial time domain reflectometry is observed as $\pm 3\%$.

1 Introduction

The rapid progress of technology has opened avenues for the enhancement of the productivity of resource-challenged agricultural practices in developing countries. In a country such as India, where dry farming is pervasive, efficient irrigation technology would be valuable. To enhance the crop productivity, optimum irrigation practices need to be followed in the agricultural fields. Moreover, optimum irrigation is not only required in dry farming, but also in all locations in which irrigation is expensive or waste of water is forbidden [1] [2]. Optimum irrigation helps to enhance the crop productivity and also to conserve water. In agricultural fields, for optimum irrigation, the water content of the soil in the root zone of the crops needs to be maintained between two limits, referred to as the field capacity and the wilting point [3]. To maintain the optimum irrigation in agricultural fields, soil-moisture sensors are widely used.

Researchers have reported different in situ-soil moisture measurement techniques such as neutron scattering probe technique, time domain reflectometry (TDR) [4], and frequency domain reflectometry (FDR) [5], micro electro mechanical systems (MEMS) [6]. But a major drawback of TDR and FDR sensors is that they are very expensive [1]. On the other hand in MEMS based sensors, packaging is crucial and also long term in-situ field measurements and reliability still need to be explored [6]. Thus, considering the price and reliability, researchers have explored capacitive and heat pulse based soil moisture sensors.

In a large agricultural field, a single soil moisture sensor does not suffice due to spatial variations in the soil moisture level. Hence, the need for a wireless sensor network (WSN) arises [7]. A WSN consists of a collection of sensor nodes which are deployed in an ad-hoc manner to perform a co-ordinated sensing task for a specific application. The major application categories of WSN are classified as event detection, tracking and periodic monitoring applications [8]. Our work focuses on the design and evaluation of a sensor network targeted for periodic data collection in agricultural fields. Energy efficiency and network lifetime are the important criteria which need to be considered while designing the architecture of a sensor network.

Several researchers have employed WSNs to collect periodic measurements from their agricultural fields. A review of various sensor network implementations for precision agriculture is presented in [9]. ZigBee (which uses IEEE 802.15.4 protocol) and LoRa [9] are the preferred wireless technologies for agricultural applications because of their low power consumption and communication range. The solutions which are designed for agricultural domain in developing countries need to be affordable and easy to use. Star networks of sensor nodes using ZigBee devices are discussed in [10] and [11] for irrigating the agricultural fields. However, a multi-hop wireless network architecture is essential to cover large farms.

This paper presents the design and implementation of a tree based WSN for agricultural applications. The sensor nodes are equipped with affordable in house developed soil moisture sensor, atmospheric temperature sensor and relative humidity sensor. Section 2 outlines two types of custom developed soil moisture sensors. The proposed wireless network architecture is detailed in Section 3. The implemented testbed along with the measurement results are discussed in Section 4 and the paper is concluded in Section 5.

2 In-house developed affordable soil moisture sensors

The in-house developed heat-pulse (shown in Fig. 1) and capacitive (shown in Fig. 2) based soil moisture sensors are reported in [12], [13] respectively. Heat pulse based sensors work on the principle of sending a heat pulse (using heater probe) through the soil mass and measuring the rise in the temperature (using temperature sensor) over a certain time duration (180 seconds in our work). As shown in Fig. 1, the measured rise in temperature is a function of the soil water content.

Soil acting as a dielectric medium between two probes is used as a capacitance in capacitive soil moisture sensors. With a change in the amount of water content, the dielectric constant of the soil-water mixture varies producing a change in the capacitance and this property is exploited to measure the soil moisture in capacitive sensors. As shown in Fig. 2, the sensor output is a square wave whose frequency decreases with increase in the soil water content.

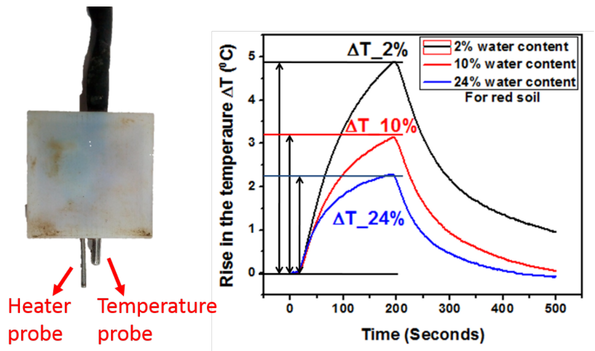

Figure 1. In-house developed heat-pulse sensor and its response

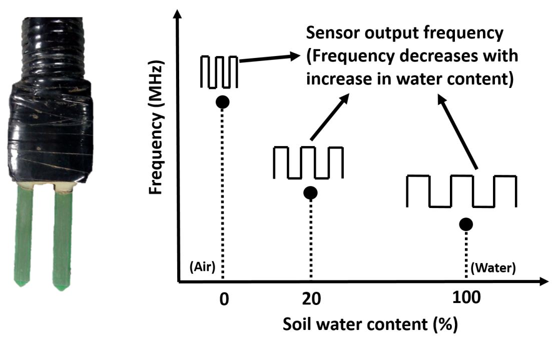

Figure 2. In-house developed capacitive sensor and its response

As discussed in our earlier comparative study [13], both heat pulse and capacitive based soil moisture sensors are economical for in-situ measurements. However, capacitive sensors are better than heat pulse sensors in terms of response time and power consumption. Hence, we have used capacitive based soil moisture sensors for obtaining the measurements reported in Section 4 of this paper.

3 Network architecture

The sensor network under consideration consists of n nodes which are deployed in a random fashion in an agricultural farm. Each node has its sensed information which needs to be wirelessly transported to a central node (sink node). The sink node is connected to a base station (a powerful device) where decisions are made based on the analysis of the collected data. The considered network is not a dense deployment and hence we are interested in the reading from each sensor instead of only aggregated information (e.g., min, max, average). Hence no data aggregation/fusion schemes are incorporated in the network design.

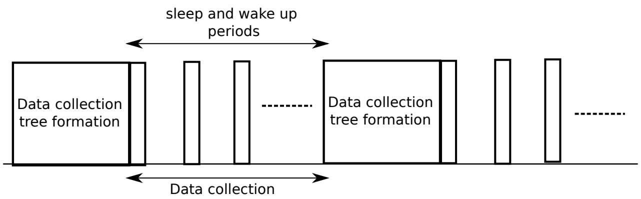

Figure 3. Sequence of operations occurring in the network

Fig. 3 shows the various activities occurring in the network which involve mainly two stages; formation of the data collection tree followed by the synchronized periodic sleep-wake up scheduling of the nodes. The tree formation stage builds a data collection tree through which the data from each sensor node is collected at the sink node (see Fig. 7). To increase the lifetime of the node (time until it gets depleted of battery), each node follows a synchronized periodic sleep- wake up schedule. A node will be in sleep state (wireless radio is OFF) for most of the time and when it enters the active stage, it senses different parameters and sends the data to its parent node in the tree.

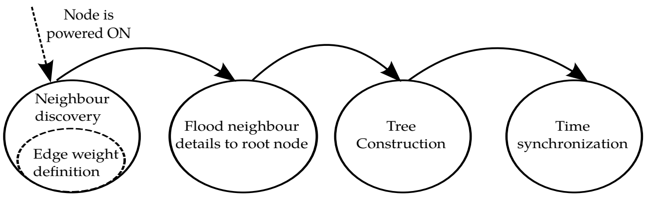

Figure 4. Various operations during the tree formation

The tree formation stage includes four different operations as shown in Fig. 4. In the neighbour discovery phase, each node finds all its neighbours and assigns a weight to each of them. The weight between two nodes is a function of the nodes's battery levels and the quality of the wireless link connecting the nodes as detailed in [14]. In the flooding phase, each node transfers its neighbour details to the sink node and thus the sink will have the complete connectivity information about the network which is represented in the form of a graph. The sink node can construct different spanning trees (like shortest path tree, minimum spanning tree) which can be used for the data collection. We use a shortest path tree for the data collection since it provides better energy efficiency [15] and hence improved lifetime.

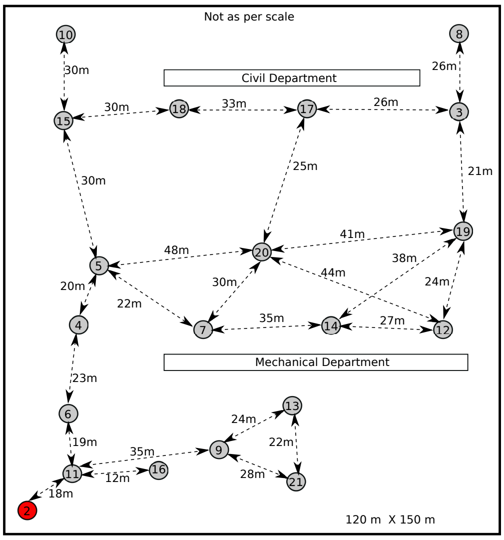

Figure 5. Placement of nodes

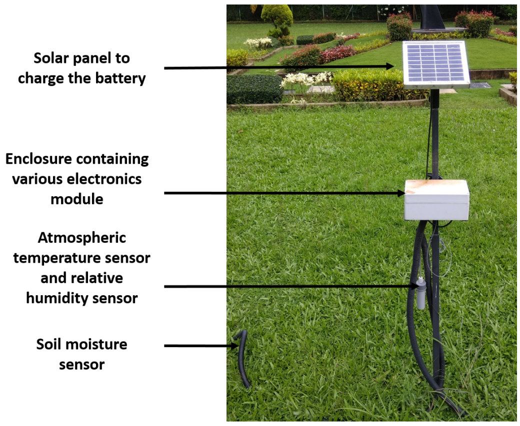

Figure 6. Structure of a sensor node

Once the data collection tree is built, the sink node informs each node about its parent and all the nodes are synchronized to the sink node along the edges of the tree using a modified version of the flooding time synchronization protocol (FTSP) [16]. Time synchronization helps the nodes to follow a coordinated periodic sleep wake-up schedule to save the energy (see Fig. 3).

4 Implemented testbed

We have implemented a WSN consisting of 20 sensor nodes in the IIT Bombay campus (red soil) covering approximately $120m \times 150m$. The sensor nodes are placed randomly as shown in Fig. 5. The nodes are represented by circles with node IDs inside. The node ID - 2 (marked in red color) acts as the sink node to which a laptop (base station) is connected for logging the sensor data.

Each sensor node is equipped with an in-house developed capacitive soil moisture sensor, atmospheric temperature sensor and relative humidity sensor as shown in Fig. 6. The system is powered with the help of a lithium ion battery

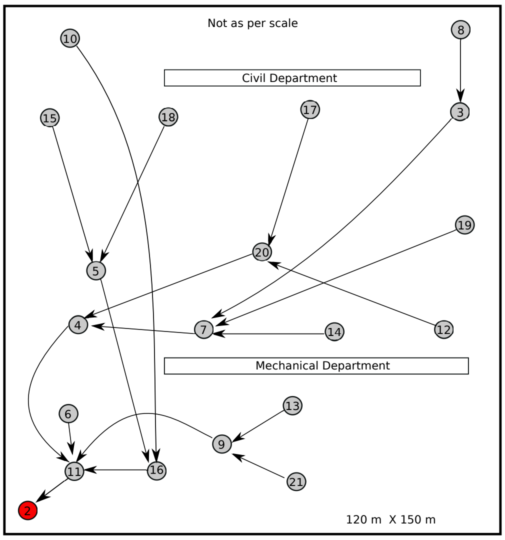

Figure 7. Tree used for the data collection

which gets recharged using solar energy. The soil moisture sensor is deployed at a depth of 10 cm from the surface. We have used MCP9700A [17] for atmospheric temperature measurement and HIH5030 [18] for measuring the relative humidity. Each node is equipped with a TelosB mote which uses an IEEE 802.15.4 compliant radio chip, CC2420, for wireless communication [19].

The interval between two consecutive data collection time slots in the experiment was 1 hour and the data collection tree was rebuilt once every 10 hours. In actual field applications, the same data collection tree can be used to collect the sensor readings for a longer period of time so that the energy overhead because of the tree construction phase can be minimized.

Fig. 7 shows the constructed data collection tree (as explained in Section 3) through which the sensor data was collected. The maximum depth of the tree is observed as five hops for Node ID 8. Fig. 8 shows the variations in the sensed parameters during one data collection round. The water content in the field was observed as 36% when measured using a commercial TDR (TRIME PICO 64) [20]. The measured volumetric water content using the in-house developed capacitive sensors was in the range of 33% - 39% ($\pm 3\%$ variation with respect to TDR). We observed 88% - 99% as the measured RH across all the nodes while temperature sensors reported $24°C$ - 30 $°C$.

5 Conclusions

In this paper we have designed and implemented a multi-hop wireless sensor network using in-house developed soil moisture sensors. We have demonstrated a 20 node network implementation in the IIT Bombay campus. The proposed network architecture helps to conserve energy for each sensor node, and thereby enhances the network lifetime. With the implemented WSN, we evaluated the performance of

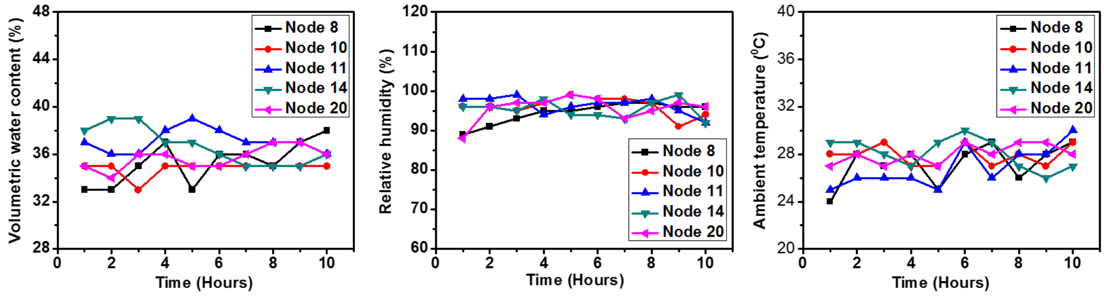

Figure 8. Sensor measurements collected at the sink node

the in-house developed soil moisture sensors and the measurement results were within the limit of ±3% when compared with commercial TDR.

6 Acknowledgements

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