Wireless Underground Sensor Networks using Commodity Terrestrial Motes

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***Abstract*— The concept of a Wireless Underground Sensor Network (WUSN) is introduced and applications are discussed. The feasibility of utilizing commonly available terrestrial Wireless Sensor Network (WSN) hardware solutions in the underground environment is examined. Experiments are run to examine the packet error rate and the received signal strength of correctly received packets for a communication link between two underground sensors and between an underground sensor and an aboveground sensor.**

***Index Terms*— Wireless sensor networks, testbed.**

I. Introduction

THE usefulness of Wireless Sensor Networks (WSNs) as a remote monitoring technology is not limited to traditional terrestrial applications. WSN technology can also be deployed in the underground, where applications include [1]:

- *Agriculture* - Wireless Underground Sensor Networks (WUSNs) can be used to monitor soil conditions so that parameters such as water content, mineral content, salinity, and temperature can be maintained at optimal levels. Real-time knowledge of soil conditions is also beneficial for landscaping, where WUSNs can be combined with automatic sprinkler systems such that grass, trees, and flowers are watered only when needed. Wireless sensors that operate independently using a single-hop link to a base-station are already being used for monitoring of soil conditions in sports fields [2].
- *Security* - Sensors buried at a shallow depth could be used to detect movement via pressure, vibration, or sound. This may be useful for business and home security as well as for military applications. Although aboveground wireless sensor networks can be used for this purpose, security applications make it desirable for sensors to be hidden.
- *Infrastructure Monitoring* - A significant amount of infrastructure, including plumbing as well as electrical and communications wiring, exists underground. Sensors can be used to monitor underground plumbing leakage, for example. With many miles of pipes to monitor, wireless sensors will allow for quick and cost-efficient deployment of a leakage detection system. WUSNs can also be used to monitor the soil around underground storage tanks such as those at a fuel station.

While underground sensors are already in use for many of these applications [1][3], most existing solutions are wired. Those underground sensors that are wireless require aboveground antennas and are only capable of direct communication with a centralized base station. Based on this, we define a WUSN as a group of nodes whose means of data transmission and reception (e.g., an antenna when electromagnetic waves are used for communication) is completely subterranean. This includes situations in which a node is underground, yet in an open space such as a cave or mine, as well as when a node is completely embedded within dense soil or rock.

Given the usefulness of monitoring conditions in the underground, we set out to determine whether current WSN solutions are applicable to the underground sensing environment. To determine this, we performed tests of the communication capabilities of the popular MicaZ WSN motes from Crossbow [4] when buried in soil at various depths.

II. Experimental Setup

Our experiments were designed to test the packet error rate and received signal strength of correctly received packets for a communication link between two underground sensors, as well as between an underground sensor and one on or above the surface. The latter scenario is useful for communication between the WUSN and an aboveground sink. An illustration of the setup is provided in Fig. 1. These parameters were evaluated for both the forward and reverse channel between the sensors while varying the depth (d) of the underground sensor, the height (h) of the aboveground sensor, and the horizontal distance (l) between the two. Here we define the forward channel as transmissions from Sensor A to Sensor B, and the reverse channel as transmissions from Sensor B to Sensor A. The remainder of this section discusses the physical test environment, relevant hardware characteristics of the MicaZ, and the software we implemented on the motes to gather the statistics of interest.

A. Physical Environment

Since soil and rock are lossy dielectric materials, the propagation of electromagnetic waves in the underground environment can be severely impeded [1][5]. Soil properties such as density, water content, and mineral content play an important role in determining losses for a propagating electromagnetic wave [1][5], and so we report that the experiments were carried out in an open field in midtown Atlanta, where the soil had a dense, clay-like consistency with a moderate water

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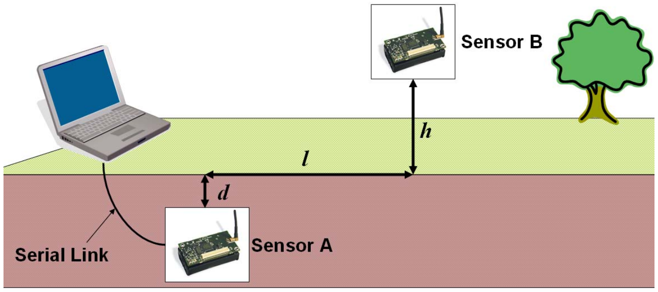

Fig. 1. Experimental setup.

content. Wet clay soils produce the most attenuation of an electromagnetic wave, while dry sandy soils produce the least [1][5].

B. MicaZ Wireless Sensor Motes

The wireless sensor mote we used for these experiments was the MicaZ from Crossbow. MicaZ motes operate in the 2.4 GHz band and use a Zigbee-compliant Chipcon CC2420 radio. Although the MicaZ is Zigbee compliant, as of this writing TinyOS, the MicaZ's operating system, does not implement the Zigbee standard. Instead, the B-MAC media access protocol described in [6] is used. The MicaZ's radio supports variable output power, which can be set anywhere between -24 and 0 dBm [4]. For our experiments, the radio was always set to its maximum transmit power of 0 dBm. The stated receive sensitivity of the radio is a minimum of -90 dBm, with a typical value of -94 dBm [4]. Crossbow advertises the indoor communication range of the motes as 20 to 30 meters, and an outdoor range of 75 to 100 meters. The motes were used with the supplied quarter-wavelength whip antenna.

C. Software Design

The tests were designed to collect packet error rates at the application layer, as well as the received signal strength indicator of correctly received packets. To accomplish this, we created an application using TinyOS designed to send packets of a specified size at a specified rate between a source and destination mote.

One of the motes was connected to the Crossbow MIB510 programming board, allowing for two-way communication with a laptop via a wired serial connection, illustrated in Fig. 1. To begin a test, the parameters (number of packets, packet size, interval between packets, source and destination node IDs) are passed from the laptop through the serial connection to the underground mote. This mote then forwards the parameters to the remote mote and waits for either an acknowledgment of the setup or one of the test packets. The remote mote, upon receiving the setup packet, sends an acknowledgment to the sink and begins transmitting using packets of the specified length and with the specified interval between packets.

III. Experimental Results

The results of the experiments are presented in Figs. 2 - 5. Although tests were attempted between two underground motes at the same depth, we found communication to be impossible regardless of the horizontal separation. We therefore focus on communication between one underground mote and one aboveground mote. Data was also gathered for the underground sensor at a depth of 0 cm (on the surface) as a baseline.

Figures 2 and 3 clearly illustrate a direct correlation between the depth of the underground sensor and the amount of signal attenuation experienced - the greater the amount of soil through which the signal must propagate, the greater the experienced attenuation. For any given horizontal separation, when comparing the attenuation to that experienced by both sensors at a depth of 0 cm, an additional attenuation of 15 - 20 dB is seen for one sensor at a depth of 6 cm. At a depth of 13 cm, the difference in attenuation increases to about 25 dB. Given that the CC2420 radio used on the MicaZ is capable of a maximum transmit power of 0 dBm and typically has a receive sensitivity of -90 dBm, a 25 dB loss overtop losses due to geometric spreading, interference, and other traditional factors, represents a significant reduction of the communication range of these motes. The figures illustrate a clear advantage for transmissions in the forward channel (Sensor A to Sensor B). In all tests, the strength of the signal received in this direction was 2 - 3 dB stronger than a transmission in the reverse direction. The experiments were performed without moving the motes - the direction of the transmission was modified in software. Therefore, issues such as differences in antenna orientation and density of the soil atop the underground mote, which could occur if the placement of the motes needed to be exchanged, have not affected the results. Although this result is interesting, it may not be a concern since most communications will be directed from the underground sensors to an aboveground sink. WUSN sink nodes will likely be located at the surface, where they can more easily be interfaced with a data collection system or long-haul radio to serve as backhaul for sensor readings.

Figures 3 and 5 illustrate the results of the tests when the aboveground sensor was elevated a distance of 1 m off the ground. This scenario may occur with a mobile sink which moves around above the WUSN deployment area to collect sensor readings directly from the motes. In this case, an interesting phenomenon occurs. As shown in Fig. 3, the received power of the signal increases slightly for the underground mote at a depth of 13 cm as the horizontal separation between sender and receiver increases from 50 cm to 200 cm. The signal then falls off with distance as expected. This slight increase is likely due the radiation pattern of the antennas used on the MicaZ. The aboveground mote had its antenna oriented in the vertical direction, where is has a null in its pattern at either end. Thus, as the aboveground mote moved further away, the null of its radiation pattern was no longer pointed directly at the underground mote. Interestingly, the elevation of the aboveground mote improved the achievable communication range from 4 m to 7 m.

Figures 4 and 5 demonstrate that as the received signal strength approaches the receiver sensitivity of -90 dBm, the packet error rate approaches 100%. The packet error rate typically remains less than 20% as long as the received signal

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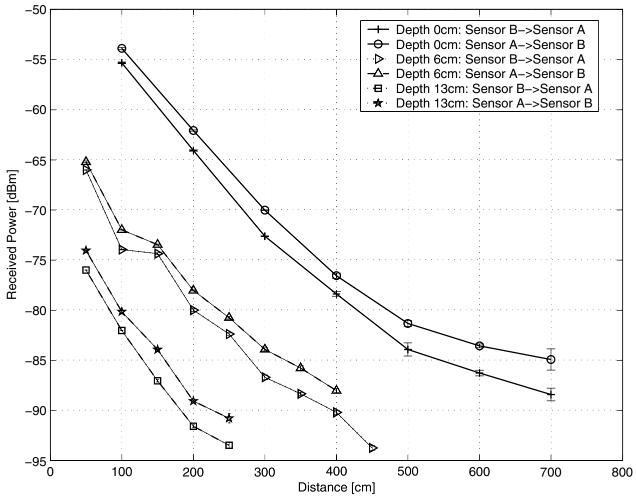

Fig. 2. Received power for remote sensor on ground.

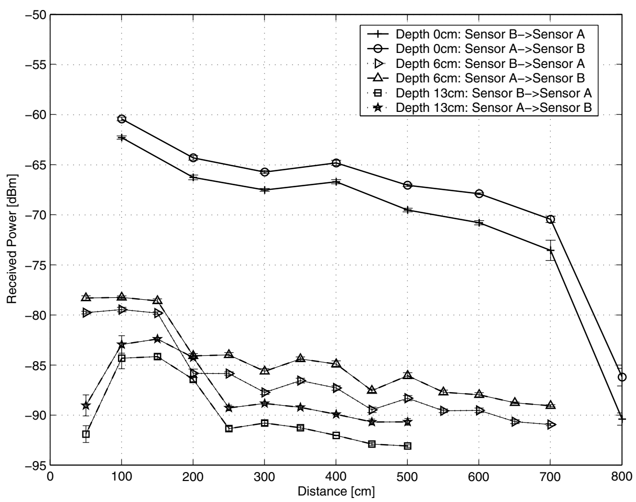

Fig. 3. Received power for elevated remote sensor.

strength was greater than about -85 dBm.

IV. Conclusions and Future Work

Overall, the results of these experiments demonstrate that existing terrestrial wireless sensor network solutions have limited applicability for wireless underground sensor networks. Reliable communication between an underground and a surface node was only achievable over a range of 7 m, even with the underground node placed at a relatively shallow depth of 6 cm. While the results are encouraging in that they demonstrate communication with a mote buried at shallow depths is possible, even at the high frequency of 2.4 GHz used by the MicaZ, they clearly show that challenges exist in the underground environment that are not addressed by terrestrial WSN solutions. Future work must focus on minimizing signal loss at the physical layer, while also appropriately dealing with the higher losses characteristic of the underground in the protocol stack, as described in [1].

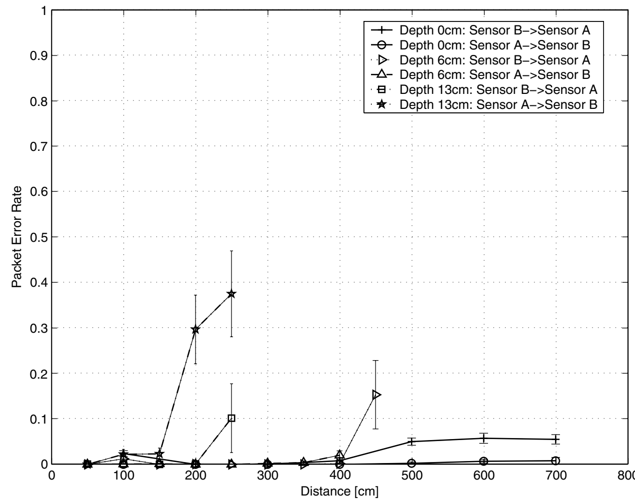

Fig. 4. Packet error rate for remote sensor on ground.

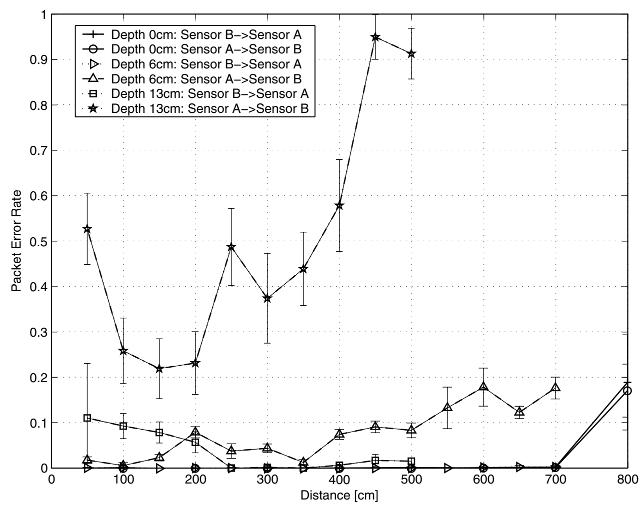

Fig. 5. Packet error rate for elevated remote sensor.

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