

# Experiment study on the wireless sensor networks with 2.4GHz for underground communication

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**Abstract.** Wireless underground sensor networks (WUSN) are an emerging research area that promises to provide communication capabilities for buried sensors. The main difference between the WUSN and the terrestrial wireless sensor networks is the aspect of wireless underground sensor networks which communicates in the soil. Although its deployment is mainly based on underground sensor nodes, WUSN still requires above ground devices for data retrieval, management, and relay functionalities. Therefore, the characterization of the bi-directional communication between a buried node and an aboveground node is essential for the realization of WUSN. In this paper, experiments are run to examine the packet error rate and the received signal strength of correctly received packets for a communication link between an underground sensor node and an aboveground sensor node and between two underground sensor nodes.

## Introduction

The usefulness of Wireless Sensor Networks (WSN) as a node monitoring technology is not limited to traditional terrestrial applications, WSN technology can also be deployed in the underground [Akyildiz et al.,2009; Akyildiz et al.,2006]. Wireless underground sensor networks (WUSN) consist of wireless underground sensor nodes that communicate through soil. The realization of wireless underground communication and networking techniques will lead to potential applications in the fields of intelligent irrigation, border patrol, sports field maintenance, and infrastructure monitoring [Akyildiz et al.,2009]. Despite their potential advantages, however, the realization of WUSN is challenging due to the significant and direct impact of soil characteristics and its dynamics on communication.

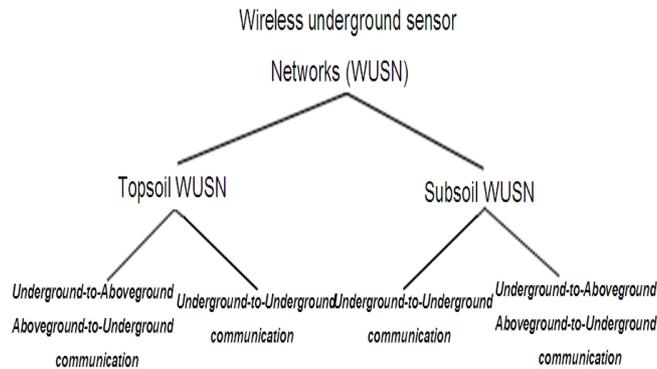
Wireless underground sensor networks are a new research subject, at present, it is in the experimental study phase and also no mature products are in the market. While wireless underground sensor networks are already in use for many of applications, most existing solutions are wired [Chehri et al.,2006;Sun and Akyildiz,2008;Lopez et al.,2009;Abrams et al.,2004]. Those underground sensors that are wireless require above ground antennas and are only capable of direct communication with a centralized base station. WUSN devices are deployed completely below ground and do not require any wired connections. Wireless communication within a dense substance such as soil or rock is, however, significantly more challenging than through air [Akyildiz et al.,2002;Sheth et al.,2005;Berman et al.,2004;Carle and SimPlot-Ryl,2004].

Given the usefulness of monitoring conditions in the underground, we set out to determine whether current wireless sensor networks solutions are applicable to the underground sensing environment. To determine this, we performed tests of the communication capabilities of the terrestrial WSN nodes when buried in soil at various depths.

The remainder of the paper is organized as follows. We first provide an overview on wireless underground sensor network along with a classification of the WUSN. The testbed architecture for the experiments and the experimental methodology are described in Section 3. The experiment results for the communication of WUSN are presented in Section 4. Finally, the lessons from the experiments and the future work are discussed in Section 5.

### Classification of wireless underground sensor networks

Wireless underground sensor networks have been investigated in many contexts recently. The concept of WUSN and the challenges related to the underground wireless channel have been introduced in [Akyildiz et al.,2006; Allen et al.,2006]. As shown in Figure 1, communication of the WUSN can be mainly classified into two: topsoil wireless underground sensor networks and subsoil wireless underground sensor networks.



**Figure 1. Classification of wireless underground sensor networks**

Soil subsurface is classified into two regions [Li et al.,2007]: the topsoil region, which refers to the first 30cm of soil, or the root growth layer, whichever is shallower and the subsoil region, which refers to the region below the topsoil, i.e., usually the 30-100cm region. Accordingly, as shown in Fig.1, WUSN can be classified as a function of the deployment region: Topsoil WUSN, if the WUSN is deployed in the topsoil region, or Subsoil WUSN, if deployed in the subsoil region. Moreover, these networks are further classified into underground-to-aboveground (UG-AG), underground-to-underground (UG-UG), and aboveground-to-underground (AG-UG) communication [Silva and Mehmet,2010;Fukatsu and Hirafuji,2005]. For topsoil and subsoil WUSN, the majority of the communication flows in the UG-AG and AG-UG direction.

To the best of our knowledge, the topsoil region is not feasible for agricultural applications, where plowing and similar mechanical activities occur at the topsoil region [Bogena et al.,2009;Coen et al.,2009;Hart and Martinez,2006;Aqeel et al.,2011;Kima et al.,2011]. Therefore, characterizations of the UG-AG and AG-UG communication links are required at the subsoil region for cost-effective solutions. In this work, we provide a characterization of the UG-AG and AG-UG communication based on experiments realized at both the subsoil and topsoil regions.

### Materials and methodology

In this section, the details of the outdoor environment hardware, software, and the methodology for the experiments are presented. The underground experiments with 2.4GHz sensor nodes were carried out in the laboratory of the Research Institute of Water-saving Agriculture of Arid Regions of China in the Northwest Agriculture and Forestry University. In the trial, we assume the bulk density as 1.3 g / cm<sup>3</sup> and the solid soil particle density as 2.6 / cm<sup>3</sup> unless otherwise noted. The analysis of the particle density is shown in Table 1 according to laboratory analysis.

**Table 1 Soil parameters used in the experiments**

Sample Depth	Sand %	Clay %	Silt %
0-20cm	13	26.3	60.7
30-50cm	9.8	24	66.2

Soil properties such as density, water content, and mineral content play an important role in determining losses for a propagating electromagnetic wave [Phocaides,2007;Irmak and Haman, 2001;Tiusanen,2008;Tiusanen,2005], and so we report that the experiments were carried out in the laboratory, where soil had moderate water content 25%. For the experiments, sensor nodes from

Crossbow that operate at 2.4GHz band are used. The device is built upon the IEEE 802.15.4 standard. The node is ZigBee compliant, as of this writing TinyOS, the node's operating system, implement the ZigBee standard. The node's radio supports variable output power, which can be set anywhere between -24 and 0 dBm. In our experiments, the radio was always set to its maximum transmit power of 0 dBm. Crossbow advertises the indoor communication range of the nodes as 20 to 30 meters, and an outdoor range of 75 to 100 meters. The nodes were used with the supplied quarter-wavelength whip antenna.

In the experiments, 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. Each experiment in this work is based on a set of 3 experiments with 350 messages or 2 experiments with 500 messages, which result in a total of 1000 packets. The number of packets correctly received by one or more receiver nodes is recorded along with the signal strength for each packet. Accordingly, the packet error rate and the received signal strength level from each receiver are collected. To prevent the effects of hardware failures of each individual sensor nodes, qualification tests have been performed before each experiment.

### Experiment results

The results are presented considering how some important parameters affect the wireless underground sensor networks communication: the burial depth and the inter-node distance. Although tests were attempted between two underground nodes at the same depth, we found communication to be impossible when the horizontal inter-node beyond 40cm. We therefore focus on communication between one underground node and one aboveground node. Data were also gathered for the underground sensor node at a depth of 0cm, 20cm and 40cm.

When the aboveground sensor node was on the surface of the ground, the tests were designed to collect packet error rates and the received signal strength of AG-UG and UG-AG communication. Moreover, the underground sensor node was buried at the depth of 0cm, 20cm and 40cm, respectively. Figure 2 clearly illustrates the variety of the received signal strength and packet error rates for WUSN communication from AG-UG and UG-AG when underground node is buried at the depth 0cm. While underground nodes are buried at the depth 20cm and 40cm, the variety of the received signal strength and packet error rates for WUSN communication from AG-UG and UG-AG were shown in Figure 3 and Figure 4.

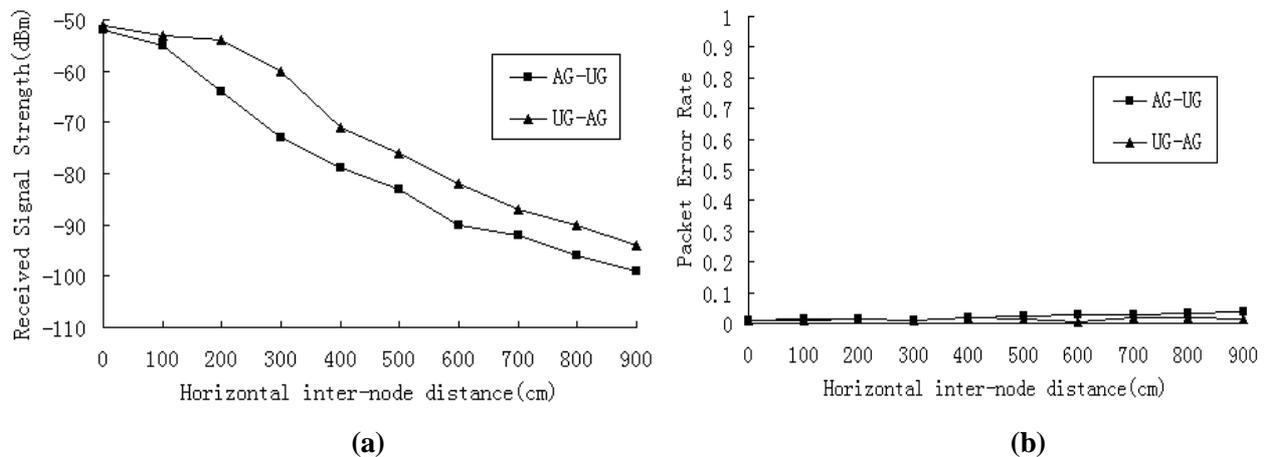
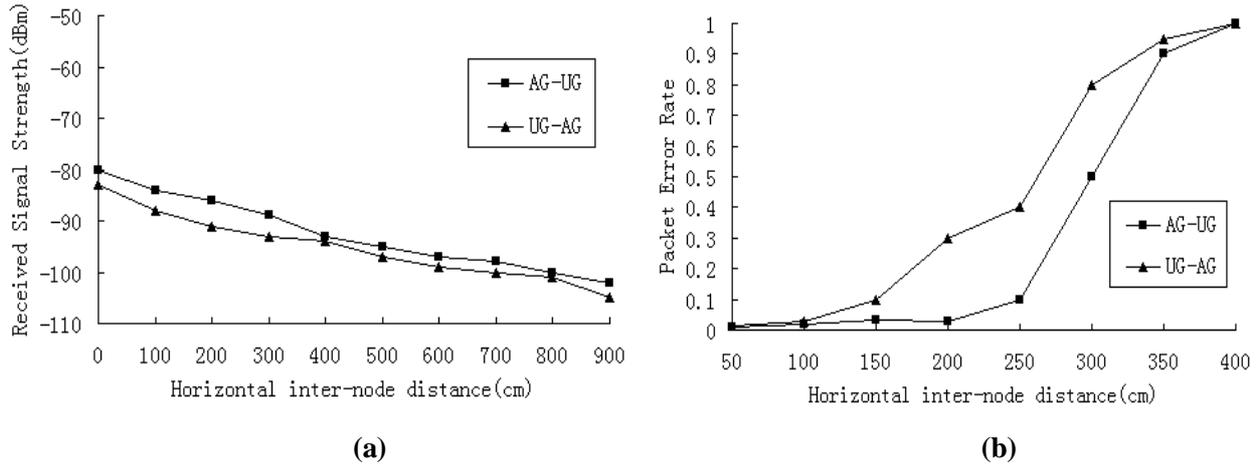
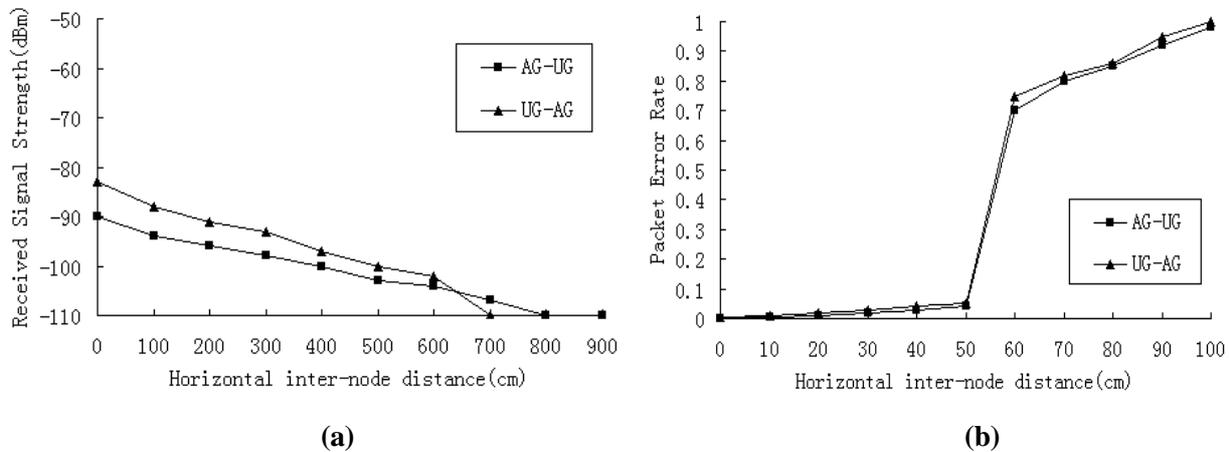


Figure 2. Test for the received signal strength (a) and packet error rates (b) vs. horizontal inter-node distance. The underground node buried at depth=0cm.



**Figure 3. Test for the received signal strength (a) and packet error rates (b) vs. horizontal inter-node distance. The underground node buried at depth=20cm.**



**Figure 4. Test for the received signal strength (a) and packet error rates (b) vs. horizontal inter-node distance. The underground node buried at depth=40cm.**

For any given horizontal inter-node distance, when comparing the attenuation to that experienced by both sensor nodes at a depth of 0 cm, an additional attenuation of 25-30 dB is seen for underground sensor node at a depth of 20 cm. At a depth of 40 cm, the difference in attenuation increase to about 40 dB. The figures illustrate a clear advantage for transmissions in the UG-AG channel. In all tests, the strength of the signal received in UG-AG direction was 3-4 dB stronger than a transmission in the AG-UG direction.

Figure 2 demonstrates that the packet error rate of AG-UG communication is higher than UG-AG communication. As shown in Figure 3 and Figure 4, the change of the packet error rate is higher in the reverse communication direction. Furthermore, the packet error rate values are not obvious and horizontal inter-node distance can reach 9 m when underground node is buried at the depth of 0 cm. When underground node at the depth of 20 cm, the communication distance between aboveground node and underground node is not more than 4 m, and the packet error rate increase nearly to 100% when the horizontal inter-node distance range from 170 cm and 230 cm to 400cm, respectively. Figure 4 (b) shows the packet error rate increase quickly at the horizontal inter-node distance 45 cm and reaches 100% at the maximum horizontal inter-node distance 96 cm. All the figures demonstrate that as the received signal strength approaches the receiver sensitivity of -95 dBm, the packet error rate approaches 100%. The packet error rate typically remains less than 30% as long as the received signal strength was greater than about -90 dBm.

Although this result is interesting, it may not be a concern since most communication will be directed from the underground sensor nodes to an aboveground sink node. WUSN terrestrial 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 data readings.

## Conclusions

In this paper, we propose a classification of wireless underground sensor networks and present experiment results for AG-UG and UG-AG communication for WUSN. The work provides insight to communication through soil using commodity sensor nodes.

The experiment results reveal the feasibility of using commodity terrestrial sensor nodes for WUSN as well as their limitations. Moreover, the experiment results show that the burial depth is important for the WUSN tests due to the effects of reflected rays from the underground-air interface at the surface. In addition, the wireless underground channel has been found to exhibit extreme temporal stability, which is important in the design of routing and topology control protocols.

In addition to the characteristics of wireless underground sensor networks communication, the limitations of the commodity sensor nodes for WUSN are also observed as a result of these experiments. While the results are encouraging in that they demonstrate communication with a node 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. It can be observed that for this specific subsoil WUSN scenario, the inter-node distance was smaller than 1 m. Consequently, future work must focus on a new generation of nodes with more powerful transceivers are required for the actual deployment of WUSN applications.

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