Evaluation of communication in wireless underground sensor networks

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Abstract. Wireless underground sensor networks (WUSN) are an emerging area of research that promises to provide communication capabilities to buried sensors. In this paper, experimental measurements have been conducted with commodity sensor motes at the frequency of 2.4GHz and 433 MHz, respectively. Experiments are run to examine the received signal strength of correctly received packets and the packet error rate for a communication link. The tests show the potential feasibility of the WUSN with the use of powerful RF transceivers at 433MHz frequency. Moreover, we also illustrate a classification for wireless underground sensor network communication. Finally, we conclude that the effects of burial depth, inter-node distance and volumetric water content of the soil on the signal strength and packet error rate in communication of WUSN.

1. Introduction

Wireless underground sensor networks are a promising new measurement technology for monitoring soil information with a high spatial and temporal resolution for large areas \cite{1,2}. It is a specialized kind of Wireless Sensor Networks (WSN) that mainly focuses on the use of sensors that communicate through soil and are a natural extension of the WSN phenomenon to the underground environment \cite{3}. WUSN have several remarkable merits, such as concealment, ease of deployment, timeliness of data, reliability and coverage density. 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 \cite{4-6}. 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. This is possible by exploiting real-time soil condition information from a network of underground sensors.

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. 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.

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. In this paper, the results of experiments for wireless underground sensor networks at the frequency of 2.4GHz and 433MHz using commodity sensor nodes are presented. Moreover, lessons learned from
these experiments for the received signal strength and the packet error rate of efficient communication for WUSN are discussed.

2. Related work
Research reports of wireless underground sensor networks in agricultural application are few [7-11], the present studies include mainly path loss, bit error rate, maximum transmission distance, test error of water content of path transmission of the electromagnetic wave under the main influence factors, these factors are soil types, volumetric water content of the soil, depth of nodes buried, internodes distance, the range of frequency, etc.

Network system structure of wireless underground sensor networks system aiming at intelligent transportation system and maintenance of the near surface soil was designed in [12]. It also studied that the performance of the wireless underground sensor networks which was influenced by propagation of electromagnetic waves in the soil and underground channel model, electrical characteristics of soil. In the laboratory of [13], wireless signal attenuation of ZigBee wireless transceiver module of the 2.44 GHz frequency was researched by using soil column in different soil types and the water content. Experimental results showed that increase of soil column depth and volumetric water content of the soil could lead to increase of signal attenuation, the relationship could be expressed in linear model. The near surface WUSN system used for golf course was developed and the acquisition node, relay node and gateway node were designed in [14]. The sink nodes collected the data of acquisition nodes and could communicate with other sink nodes and gateway nodes in the certain routing algorithm. In [15], there has been studied found that rainfall and stormy weather environmental conditions, and the soil compactness, soil density and vegetation cover degree, topology structure parameters of wireless underground sensor networks, sampling time and sampling density had great influence on the distortion degree of the soil moisture acquisition signal.

To the best of our knowledge, we particularly consider agricultural applications of WUSN, which usually require burial depths greater due to plowing and similar mechanical activities occur at the soil. Accordingly, the majority of the experiments consider a better burial depth. In this work, we provide a characterization of the aboveground to underground, underground to aboveground and underground to underground communication based on experiments realized at both the node frequencies.

3. Materials and methodology
In this section, the details of the outdoor environment and the methodology for the experiments are presented. In the trial, we assume the clay percent as 15%, the silt percent as 35%, the sand particle percent as 50%, the bulk density as 1.5 g/cm$^3$, and the solid soil particle density as 2.6 g/cm$^3$ unless otherwise noted. The underground experiments with 2.4GHz and 433MHz 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. To observe the effects of soil moisture, two different volumetric water content values are considered. Experiments realized in dry and wet conditions correspond to volumetric water content of 10% and 30%, respectively.

For the experiments, WUSN nodes from Crossbow that operate at 2.4GHz and 433MHz band are used. The output power were always set to maximum transmit power of 0 and 10 dBm, respectively. The antenna of sensors motes are a standard one-quarter wavelength monopole antenna with 17cm lengths, and the antennas are vertically oriented. 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, which result in a total of 1050 packets. To prevent the effects of hardware failures of each individual node, qualification tests have been performed before each experiment.

4. Experiment results
4.1. Tests of burial depth

To investigate the effects of burial depth on the signal strength and packet error rate, the horizontal inter-node distance between the sender and the receiver is fixed at 50 cm. The aboveground sensor node was on the surface of the ground, the depth of the underground node is varied from 10 cm to 100 cm. In Figure 1 (a) and (b), the received signal strength and packet error rate values are shown, respectively, as a function of the receiver depth.

Experiments show that a higher burial depth also implies an increase in the soil path, higher attenuation is observed at higher depth. As shown in Figure 1 (a), a decrease of the frequency of the wireless signal implies a smaller soil attenuation rate. The communication depth is about 50 cm when the sensor nodes using 2.4 GHz frequency. An important observation is the significant difference of received signal strength values at the same inter-node distances but at different burial depths. This behavior occurs mainly due to the reflection of radio frequency signals from the soil surface, which positively affects the received signal strength when nodes are buried closer to the surface.

![Graph](https://via.placeholder.com/150)

(a) Received Signal Strength vs. the underground node depth

![Graph](https://via.placeholder.com/150)

(b) Packet Error Rate vs. depth of the underground node

**Figure 1** Tests for the received signal strength and packet error rates. The underground node varied from 10 cm to 100 cm.

It can be observed in Figure 1 (b), that the packet error rate is higher in node frequency 2.4 GHz than 433 MHz. Note that the burial depth are 80 cm and 40 cm, respectively, when the frequency are 433 MHz and 2.4 GHz, the packet error rate of communication starts to increase till to the maximum.

4.2. Tests of inter-node distance

In the tests, the fixed burial depth 40 cm, the aboveground sensor node was on the surface of the ground and the horizontal inter-node distance is varied from 10 cm to 100 cm. In Figure 2 (a) and (b), the received signal strength and packet error rate values are shown, respectively, as a function of the horizontal inter-node distance.

In the communication between aboveground and underground under 433 MHz and 2.4 GHz node frequency, the received signal strength of aboveground-to-underground communication is higher than underground-to-aboveground communication when horizontal inter-node distance changes. When the
horizontal inter-node distance changes from 10 cm to 100 cm, the received signal strength of 433MHz frequency underground-to-aboveground communication is close to the received signal strength of 2.4GHz aboveground-to-underground communication. At the same time, it can be observed in Figure 2 (a) that the received signal strength is lower in the higher frequency.

![Graph](image)

(a) Received Signal Strength vs. horizontal inter-node distance

(b) Packet Error Rate vs. horizontal inter-node distance

**Figure 2.** Test for the received signal strength and packet error rates. The horizontal inter-node distance varied from 10cm to 100cm.

In Figure 2 (b), the packet error rate values are shown for different the inter-node distance. The variances of the racket error rate values are also shown. In 433MHz frequency, the packet error rate of aboveground and underground communications are nearly linear when the horizontal inter-node distance changes. The maximum packet error rate are about 0.1 and 0.2, respectively. When node frequency is 2.4GHz, Figure 2 (b) shows the packet error rate increases quickly at the horizontal inter-node distance 60 cm and reaches the maximum horizontal inter-node distance 100 cm.

**4.3. Tests of volumetric water content of the soil**

In the section, the tests of the volumetric water content on the received signal strength and packet error rate are discussed. In the communication, the aboveground sensor node was on the surface of the ground, the depth of the underground node was fixed 40 cm. In the experiments, the horizontal inter-node distance changes from 10 cm to 100 cm with two different volumetric water content levels 10% and 30%, respectively. As shown in Figure 3 and Figure 4., the received signal strength and packet error rate values are shown, respectively.
Figure 3. Test for the received signal strength and packet error rates. The volumetric water content levels 10%.

Figure 4. Test for the received signal strength and packet error rates. The volumetric water content levels 30%.
As shown in Figure 3 (a) and Figure 4 (a), the variation from 10% to 30% in the volumetric water content level causes an additional attenuation of 1 dB. We can also observe, from the Figure 3 (b) and Figure 4 (b), that the negative effect of the volumetric water content over the quality of the communication is reduced when the horizontal inter-node distance is increased. An increase in the soil moisture has two main effects on the wireless underground sensor networks communication. First, the wavelength of the signal is decreased, which causes indirect loss due to the antenna mismatch. Second, an increase in soil moisture significantly increases the soil attenuation. This result shows that soil moisture has a significant influence on the quality of WUSN communication. Therefore, the design of the WUSN protocols should carefully adapt to the variation of the volumetric water content of the soil.

5. Conclusions
In this paper, we propose a classification of wireless underground sensor networks and present experiment results for aboveground-to-underground and underground-to-aboveground communication for WUSN.

Despite their potential, the proliferation of WUSN has been delayed by the unique challenges of the underground environment. Some of these challenges are related to the communication involving an underground node and an aboveground device. The experiment results reveal the feasibility of using 433MHz frequency sensor motes for WUSN. 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, we have shown that the inter-node distance plays an important role in the communication of WUSN. Finally, the direct influence of volumetric water content of the soil on the communication success is shown. The results reveal that a 20% increase in the soil moisture decreases the communication range by more than 70%. These results have a significant impact on the development of multi-hop networking protocols for WUSN.

In addition to the characteristics of wireless underground sensor networks communication, the limitations of the sensor nodes for WUSN are also observed as a result of these experiments. It can be observed that for this specific burial depth, the inter-node distance was smaller than 1 m. In terms of signal attenuation, this corresponds to roughly a 1:20 attenuation rate compared to through air communication in an outdoor environment. Consequently, we expect that a new generation of nodes with more powerful transceivers and more efficient antennas are required for the actual deployment of WUSN applications.

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References
[1] L.Li, C.Mehmet and I.F.Akyildizy. 2007. “Characteristics of Underground Channel for Wireless Underground Sensor Networks”, The Sixth Annual Mediterranean Ad Hoc Networking Workshop, 6, pp. 12-15
[2] I.F.Akyildiz, E.P.Stuntebeck, 2006. “Wireless underground sensor networks: Research challenges”, Ad Hoc Networks, (4), pp. 669-686
[3] A.R.Silva, M.C.Vuran, 2010. “Communication with above devices in wireless underground sensor networks: a empirical study”, 2010 IEEE International Conference Proceedings, IEEE Communication Society, Cape Town, pp. 23-27
[4] I.F.Akyildiz, W.Su, Y.Sankarasubramaniam and E.Cayirci, 2002. “Wireless Sensor Networks: A Survey”, Computer Networks, 38(4), pp. 393-422
[5] I.F.Akyildiz, M.C.Vuran and Z.Sun, 2009. “Channel modeling for Wireless Underground Communication in Soil”, Physical Communication
[6] Z.Sun, I.F.Akyildiz, 2008. “Channel Modeling of Wireless Networks in Tunnels in Proc”, IEEE Globecom 2008, New Orleans, USA
[7] J.Carle and D.SimPlot-Ryl, 2004. Energy Efficient Area Monitoring by Sensor Networks, IEEE Computer Magazine, 37(2), pp. 40-46
[8] M.K.Watfa, H.Al-Hassanieh and S.Salmen, 2013. “A novel solution to the energy hole problem in sensor networks”, Journal of network and computer applications, 36(2), pp. 949-958
[9] F.I.Lamiaa, A.F.S. Hesham, 2013. “Applying Clustering Techniques in Hybrid Network in the Presence of 2D and 3D Obstacles”, COMPUTING AND INFORMATICS, 32(6), pp.1170-1191
[10] J.A.Lopez, F.Soto and J.Suardiaz, 2009. “Wireless sensor networks for precision horticulture in Southern Spain”, Computers and Electronics in Agriculture, 68(3), pp. 25-35
[11] T.Rafael, M.O.Juan, P.Maurizio and D.Jose, 2012. “A Topology-Independent Mapping Technique for Application-Specific Networks-on-Chip”, COMPUTING AND INFORMATICS, 31(5), pp. 939-970
[12] L.Li, X.M.Wen, 2008. “Energy Efficient Optimization of Clustering Algorithm in Wireless Sensor Network”, Journal of electronics & information technology, 30(4), pp. 966-969
[13] H.R.Bogena, J.A.Huismana, H.Meierb, U.Rosenbauma and A.Weuthena, 2009. “Hybrid wireless underground sensor networks: Quantification of signal attenuation in soil”, Vadose Zone Journal, 8(3), pp. 755-761
[14] J.R.Coen, K.Henk and K.Leon, 2009. “A new wireless underground network system for continuous monitoring of soil water contents”, Water resources research, 45(36), pp. 36-44.
[15] D.Xin, C.Mehmet, 2010. “Spatio-temporal Soil Moisture Measurement with Wireless Underground Sensor Networks”, Ad Hoc Networking Workshop