

Development of a New Wireless Sensor Network Communication

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Abstract—Wireless underground sensor networks (WUSN) are a natural extension of the wireless sensor networks (WSN) phenomenon to the underground environment. In this work, experimental measurements are presented at the frequency of 433 MHz, which show a good agreement with the theoretical studies. Experiments are run to examine the received signal strength and the packet error rate for aboveground-to-underground and underground-to-aboveground communication links. The results reveal that the effects of burial depth, inter-node distance and volumetric water content of the soil on the signal strength and packet error rate. The tests show that the communication range decreased when the soil moisture increased.

Index Terms—Wireless underground sensor networks, communication, depth, inter-node distance, volumetric water content

I. INTRODUCTION

The usefulness of Wireless Sensor Networks as a remote monitoring technology is not limited to traditional terrestrial applications, WSN technology can also be deployed in the underground [1]. Wireless underground sensor networks consist of connected 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 [2]. WUSN

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have several remarkable merits, such as concealment, ease of deployment, timeliness of data, reliability and coverage density. Besides monitoring soil ingredients in underground, wireless underground sensor network can also be used for monitoring soil motion, forecasting landslide, debris, underground ice motion and volcanic eruptions, and it has higher value for study [3-6].

Given the usefulness of monitoring conditions in the underground [7-8], 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 using the frequency of 433MHz 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.

The remainder of the paper is organized as follows. We first provide an overview on wireless underground sensor network along with communication styles of the WUSN. The materials for the experiments and the experimental methodology are described in Section3. The experiment results for the communication of WUSN using 433 MHz frequency nodes are presented in Section 4. Finally, the lessons from the experiments and the future work are discussed in Section 5.

II. RELATED WORK

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. Research reports of wireless underground sensor networks in agricultural application are little, the present study 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 [9-14].

Network system structure of wireless underground sensor networks system aiming at intelligent transportation system and maintenance of the near surface soil (such as golf courses, a football field) was designed in [15]. The software and hardware systems of the nodes were also designed. In addition, the collect nodes used the low performance microcontroller; the receiving nodes on the ground used the high performance microcontroller, development and testing research of network system were not carried; In the [15], there is also studied that the performance of the wireless underground sensor networks which was influenced by propagation of electromagnetic waves in the soil, underground channel model, electrical characteristics of soil and deployed solutions of wireless underground sensor networks nodes. In 400 MHz frequency, sensor buried depth 0.5m, horizontal spacing of sensor 1m, conductivity 0.1 and dielectric constant 10 under, transmission parameters of electromagnetic wave and energy losses for different volumetric water content of the soil, different proportion sand and clay soil were analyzed through MATLAB mathematical simulation software.

Reference [16], wireless signal attenuation of ZigBee wireless transceiver module (Soil net) 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, and the correlation coefficient R² is greater than 0.90.

Aboveground-to-underground link and underground-to-aboveground link are required for several functionalities of WUSN, such as network management and data retrieval. Thus, the characterization of the bi-directional communication between a buried node and an aboveground device is essential. Both the underground-to-aboveground link and aboveground-to-underground link include underground propagation. Moreover, the soil properties, such as soil moisture, directly impact the communication success [17-21]. Furthermore, the soil-air interface plays an important role in communication. Transmitted rays are reflected and attenuated at this interface, which significantly influences the communication quality.

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 [22-23]. Accordingly, the majority of the experiments consider a better burial depth. In this work, we provide a characterization of the aboveground to underground and underground to aboveground communication based on experiments realized at the depth soil regions.

III. MATERIALS AND METHODOLOGY

In this section, the details of the outdoor environment hardware, software, and the methodology for the experiments are presented, which is different from those reference of last section. 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/cm³, and the solid soil particle density as 2.6/cm³ unless otherwise noted. The underground experiments with 433MHz Mica2 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.

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. For the experiments, Mica2 nodes from Crossbow that operate at 433MHz band are used. The Mica2's radio supports variable output power, the radio was always set to its maximum transmit power of 10 dBm [24]. The size of each packet is 37 bytes and a 100ms delay between each packet transmission is configured. The antenna of Mica2 motes is a standard one-quarter wavelength monopole antenna with 17cm lengths, and the antennas are vertically oriented.

Each experiment in this work is based on a set of 3 tests with 350messages 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 Mica2 nodes, qualification tests have been performed before each experiment.

IV. EXPERIMENT RESULTS

Experiments are conducted in the above condition. It can be concluded that node burial depth, the inter-node distance and the soil volumetric water content have important effect on the WUSN communication.

It can be seen from Fig.1 that node burial depth plays an important role in the WUSN communication when the horizontal inter-node distance is fixed 50 cm. In the experiments, the aboveground sensor node was set on the surface of the ground, the depth of the underground node changed from 10cm to 100cm. We can conclude that a higher node burial depth has a higher signal attenuation. Furthermore, we can know from Fig.1 that the shallower node burial depth can significantly enhance aboveground-to-underground communication. For example, the packet error rate of aboveground-to-underground communication is lower than underground-to-aboveground communication when the node burial depth changes from 10 cm to 60 cm. In addition, when node

burial depth increase from 80 cm to 100 cm, the error rate increases and even loss communication.

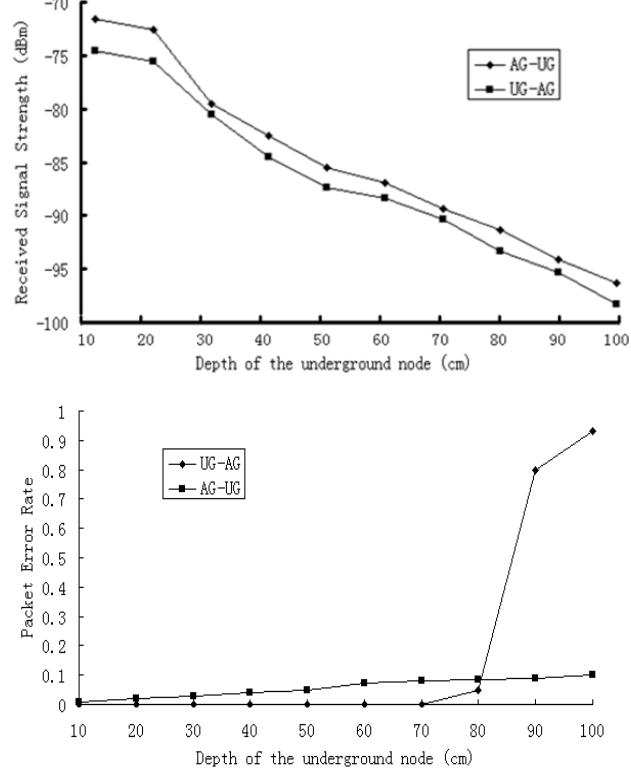


Fig. 1 Effect of node burial depth on the WUSN communication

In the Fig.2, it can be seen that the inter-node distance has also a certain effects on the received signal strength and packet error rate in the WUSN communication. In the experiments, WUSN node is fixed at 40 cm depth and the inter-node distance changes in the range of 10 cm to 100 cm. In the WUSN communication, when the horizontal inter-node distance is not more than 40 cm, the received signal strength in aboveground-to-underground communication is higher than underground-to-aboveground communication. When the horizontal inter-node distance increases from 40 cm to 100 cm, the communication result is opposite. In addition, when the inter-node distance is not more than 60 cm, the packet error rate is nearly the same in the WUSN communication. In the whole, the packet error rates are less than 20%.

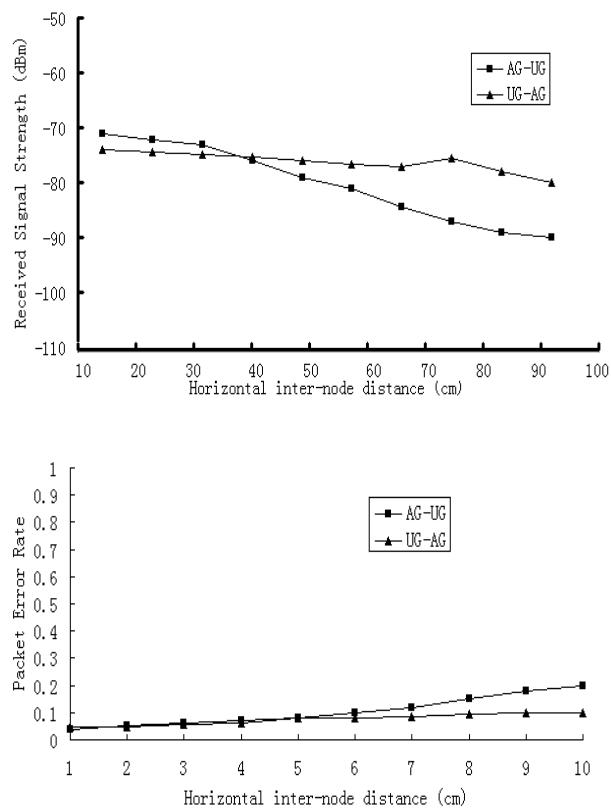
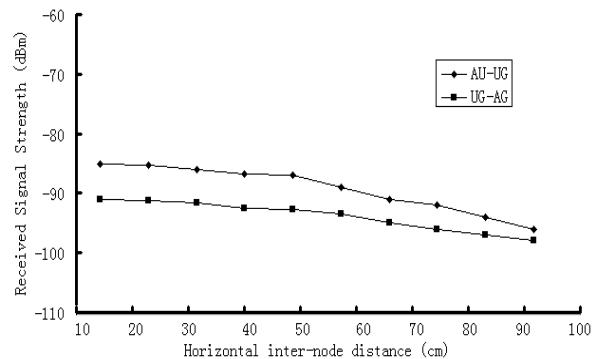


Fig. 2 Effect of the inter-node distance on the WUSN communication

Fig.3 and Fig.4 show that the soil volumetric water content is an important factor in the WUSN communication. In the WUSN inter-node communication, one node is set on the surface of the ground, the other node is fixed at 40 cm soil depth. 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.



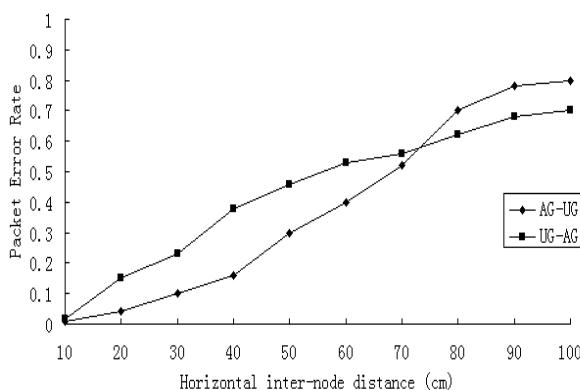


Fig. 3 Effect of volumetric water content levels 10% on the WUSN communication

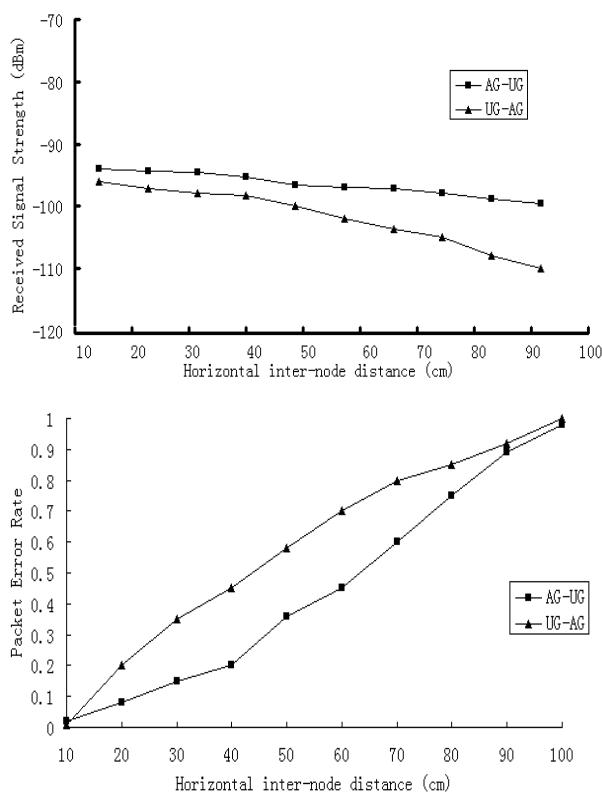


Fig. 4 Effect of volumetric water content levels 30% on the WUSN communication

It can be concluded from Fig.3 and Fig.4, that the received signal strength decreases 7 dB when the volumetric water content level changes from 10% to 30% in both underground-to-aboveground and aboveground-to-underground communication. Moreover, the soil water content has the negative effect on WUSN communication, which can be reduced when the horizontal inter-node distance increase. In addition, we can also conclude, that the soil volumetric water content has also important effect on the packet error rate. In the soil water content level is 10%, we can seen from Fig.3, that the error rate of underground-to-aboveground communication is higher than aboveground-to-underground communication when the horizontal inter-node distance is less than 70 cm.

Then, the result is opposite. When the soil water content is 30%, the error rate of underground-to-aboveground communication is higher than aboveground-to-underground communication in the all of inter-node distance. In all, the soil water content has a significant influence on the quality of WUSN communication.

V. CONCLUSION

In this work, we propose the characteristics of aboveground-to-underground and underground-to-aboveground communication in the WUSN and present experiment and results of WUSN communication in some factors. The experiment results reveal the feasibility of Mica2 sensor node in the WUSN communication. It can be concluded the effect of the node burial depth, the inter-node distance and the soil volumetric water content on the communication. The soil volumetric water content is an important effect factor in the WUSN communication, we can conclude that a 20% increase in the soil water content decreases the communication range by more than 70%. In addition, it can be seen that it is about 1:20 attenuation rate in the WUSN communication compared to air communication.

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REFERENCES

- [1] M. C. Vuran, and I. F. Akyildiz, "Channel model and analysis for wireless underground sensor networks in soil medium," *Physical Communication*, 2010, 245-254, <http://dx.doi:10.1016/j.phycom.2010.07.001>.
- [2] I. F. Akyildiz, and E. P. Stuntebeck, "Wireless underground sensor networks: Research challenges," *Ad Hoc Networks*, 2006, (4):669-686, <http://dx.doi:10.1016/j.adhoc.2006.04.003>.
- [3] A. R. Silva, and M. C. Vuran, "Communication with above devices in wireless underground sensor networks: a empirical study," *Communications (ICC)*, 2010 IEEE International Conference Proceedings, IEEE Communication Society, Cape Town, 23-27, <http://dx.doi:10.1109/ICC.2010.5502315>.
- [4] L. Li, M. C. Vuran, I. F. Akyildiz, "Characteristics of Underground Channel for Wireless Underground Sensor Networks," *The Sixth Annual Mediterranean Ad Hoc Networking Workshop*, 2007(6):12-15.
- [5] Z. Sun, and I. F. Akyildiz, "Channel Modeling of Wireless Networks in Tunnels," in Proc. IEEE Globecom 2008, New Orleans, USA, November 2008, <http://dx.doi:10.1109/GLOCOM.2008.ECP.38>.
- [6] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless Sensor Networks: A Survey," *Computer Networks*, 2002, 38(4):393-422, [http://dx.doi.org/10.1016/S1389-1286\(01\)00302-4](http://dx.doi.org/10.1016/S1389-1286(01)00302-4).

- [7] J. Tiusanen, "Attenuation of a Soil Scout radio signal," *Biosystems Engineering*, 2005, 90(2):127-133, <http://dx.doi.org/10.1016/j.biosystemseng.2004.10.013>.
- [8] J. Carle, D. SimPlot-Ryl, "Energy Efficient Area Monitoring by Sensor Networks," *IEEE Computer Magazine*, February 2004, 37(2):40-46, <http://dx.doi.org/10.1109/MC.2004.1266294>.
- [9] C. J. Ritsema, H. Kuipers, and L. Cleiboer, "A new wireless underground network system for continuous monitoring of soil water contents," *Water resources research*, 2009, 45(36):36-44, <http://dx.doi.org/10.1029/2008WR007071>.
- [10] S. Irmak, and D. Z. Haman, "Performance of Watermark Granular Matrix Sensor in Sandy Soils," *Applied Engineering in Agriculture*, 2001, 6(17):787-795.
- [11] O. Green, E. S. Nadimi, and V. Blanes, "Monitoring and modeling temperature variations inside silage stacks using novel wireless sensor networks," *Computers and Electronics in Agriculture*, 2009, 69(1):149-157, <http://dx.doi.org/10.1016/j.compag.2009.07.021>.
- [12] Y. Kima, Y. M. Yang, and W. S. Kang, "On the Design of Beacon based Wireless Sensor Network for Agricultural Emergency Monitoring Systems," *Computer Standards & Interfaces*, 2011, 33(4):32-39, <http://dx.doi.org/10.1016/j.csi.2011.05.004>.
- [13] G. W. Allen, K. Lorincz, M. Ruiz, and O. Marcillo, "Deploying A Wireless Sensor Network on An Active Volcano," *IEEE Internet Computing*, 2006, 10(2):18-25, <http://dx.doi.org/10.1109/MIC.2006.26>.
- [14] J. A. Lopez, F. Soto, and J. Suardiaz, "Wireless sensor networks for precision horticulture in Southern Spain," *Computers and Electronics in Agriculture*, 2009, 68(3):25-35, <http://dx.doi.org/10.1016/j.compag.2009.04.006>.
- [15] L. Li, and X. M. Wen, "Energy Efficient Optimization of Clustering Algorithm in Wireless Sensor Network," *Journal of electronics & information technology*, 2008, 30(4):966-969.
- [16] H. R. Bogena, J. A. Huismana, H. Meierb, U. Rosenbaum, and A. Weuthena, "Hybrid wireless underground sensor networks: Quantification of signal attenuation in soil," *Vadose Zone Journal*, 8(3):755 - 761, August 2009, <http://dx.doi.org/10.2136/vzj2008.0138>.
- [17] P. Berman, G. Calinescu, C. Shah, and A. Zelikovsky, "Power efficient Monitoring Management in Sensor Networks," *Proceedings of IEEE Wireless Communication and Networking Conference(WCNC04)*, Ailanta, USA, 2004, <http://dx.doi.org/10.1109/WCNC.2004.1311452>.
- [18] A. Chehri, P. Fortier, and P. M. Tardif, "Application of Ad-hoc sensor networks for localization in underground mines," in *Proc. Wireless and Microwave Technology Conference 2006 (WAMICON '06)*, Florida, USA, December 2006, <http://dx.doi.org/10.1109/WAMICON.2006.351901>.
- [19] E. Shih, S. H. Cho, N. Ickes, R. Min, A. Sinha, A. Wang, et al, "Physical Layer Driven Protocol and Algorithm Design for Energy-Efficient Wireless Sensor Networks," *Proceedings of 2001 ACM MOBICOM*, Rome, Italy, July 2001:272-286, <http://dx.doi.org/10.1145/381677.381703>.
- [20] D. Xin, and M. C. Vuran, "Spatio-temporal Soil Moisture Measurement with Wireless Underground Sensor Networks," *Ad Hoc Networking Workshop*, 2010, <http://dx.doi.org/10.1109/MEDHOCNET.2010.5546861>.
- [21] Z. Abrams, A. Goel, S. Plotkin, "Set K-Cover Algorithms for Energy Efficient Monitoring in Wireless Sensor Networks," *Proceedings of the 3rd International Conference on Information Processing in Sensor Networks (IPSN04)*, Berkeley, California, USA, 2004, <http://dx.doi.org/10.1145/984622.984684>.
- [22] A. Sheth, K. Tejaswi, P. Mehta, C. Parekh, R. Bansal, and S. Merchant "Senslide:A Sensor Network Based Landslide Prediction System," *Proceedings of Sensys ' 05-The 3rd International Conference on Embedded Networked Sensor Systems*, 2005:280-281, <http://dx.doi.org/10.1145/1098918.1098954>.
- [23] Land and Water Development Division, FAO Organization of the United Nations, "Topsoil Characterization for Sustainable Land Management," in *Proc. Rome: Food and Agricultural Organization*, Rome, Italy, October 1998.
- [24] Crossbow Mica2, MicaZ, and IRIS motes, <http://www.xbow.com>.



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