The International Society of Precision Agriculture presents the
16th International Conference on
Precision Agriculture
21–24 July 2024 | Manhattan, Kansas USA

Optimizing the Connectivity of Wireless Underground Sensor Networks

Mingqiang Han[1], **Naiqian Zhang**[1], **Paul Armstrong**[2]

[1]Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, KS, USA

[2]USDA Agricultural Research Service, Manhattan, KS, USA

A paper from the Proceedings of the
16th International Conference on Precision Agriculture
21-24 July 2024
Manhattan, Kansas, United States

Abstract.

Advancements in the Internet of Things (IoT) have driven the development of Wireless Underground Sensor Networks (WUSNs), promising significant applications in environmental monitoring and precision agriculture. However, the practical implementation of WUSNs faces considerable challenges due to the complex underground environment. This study addresses these challenges by evaluating the performance of different wireless technologies for WUSNs and developing a path loss prediction model to better understand underground channel characteristics. Specifically, we focus on the Underground-to-Aboveground communication link and propose a signal propagation model that accounts for the layered nature of soil profiles, providing a more detailed perspective on signal propagation loss. Experiments were conducted at different locations with three transceivers buried at depths of 10, 20, 30, 40, and 50 cm, with 300 packets transmitted at each depth to assess transmission performance. This study enhances the understanding of underground communication, demonstrating that effective communication is achievable up to a depth of 50 cm. Results indicated that the SX1262 consistently exhibited the lowest average path loss across different depths and soil types, showing resilience to varying soil properties and a slower increase in path loss with depth. The proposed model offers a more accurate method for predicting path loss, contributing to the reliability and efficiency of WUSNs. These findings have significant implications for improving WUSN applications and advancing the field of wireless communication in challenging underground environments.

Keywords.
Wireless Underground Sensor Networks, Path Loss Prediction, Soil Dielectric Properties, Performance Analysis

---

The authors are solely responsible for the content of this paper, which is not a refereed publication. Citation of this work should state that it is from the Proceedings of the 16th International Conference on Precision Agriculture. EXAMPLE: Last Name, A. B. & Coauthor, C. D. (2024). Title of paper. In Proceedings of the 16th International Conference on Precision Agriculture (unpaginated, online). Monticello, IL: International Society of Precision Agriculture.

Introduction

Recent advancements in the IoT have given rise to the sub-field of WUSNs. This innovative field finds applications in environmental monitoring and precision agriculture, such as autonomous irrigation systems. Despite the numerous potential benefits of WUSNs, several challenges must be addressed to enable their practical implementation. WUSNs involve embedding sensors beneath the Earth's surface, which introduces unique challenges due to the complex underground environment. The primary medium for electromagnetic wave propagation in WUSNs is soil, which is significantly denser than air, leading to higher signal attenuation. Additionally, the presence of tree roots, rocks, clay particles, and other subterranean objects can cause signal reflections and refractions. Soil properties such as texture, moisture, and density further influence wave propagation, resulting in variable signal losses over space and time. Another critical factor affecting WUSN performance is burial depth. To avoid disturbances from plowing and other mechanical activities, sensors need to be buried at depths greater than 30 cm. However, deeper burial depths increase signal attenuation. Therefore, a thorough understanding of the wireless underground channel characteristics is essential to ensure reliable and efficient communication between buried sensors. The objectives of this study are twofold: 1) to assess the performance of different wireless technologies for use in WUSNs, and 2) to develop a path loss prediction model to better understand the underground channel characteristics.

Link Budget Models for WUSN systems

The signal propagation link budget in soil can be computed using the following equation:

$$P_r = P_t + G_r + G_t - L_t \tag{1}$$

where P_r is the received signal power, P_t is the transmitted signal power, G_r is the receiver antenna gain, G_t is the transmitter antenna gain, L_t represents the total path loss, combining the path loss in the air with the additional attenuation in the soil. The path loss in the air can be calculated using the free-space loss formula.

WUSNs feature three types of communication links based on the locations of transmitters and receivers: Underground-to-Underground (UG2UG), Underground-to-Aboveground (UG2AG), and Aboveground-to-Underground (AG2UG) links. This study focuses on the UG2AG link to understand the attenuation caused by soil. For this link, the loss related to soil is composed of two components: the absorption loss within the soil and the refraction loss at the soil-air boundary.

Several models have been developed to predict path loss for the UG2AG link. The Modified Friis model (Sun et al., 2011) accounts for changes in both wavelength and amplitude when signals propagate through soil compared to air. The loss at the boundary is a function of the soil's dielectric constant. Another similar approach was proposed by Dong et al., (2013), which neglects the loss due to wave refraction because the signal travels perpendicularly from a higher density medium (soil) to a lower density one (air). The WUSN-PLM model (Wohwe Sambo et al., 2020) estimates path loss by segmenting the burial depth into two categories: topsoil and subsoil regions. This segmentation is due to the significant reflection effects at the topsoil level, attributed to its proximity to the ground surface.

Observing the large deviation between the predicted path loss using these models and actual measurements, this study proposes a new method for prediction. Considering that soil profiles are commonly layered rather than uniform, a multi-layer signal propagation model was proposed. This model assesses signal propagation loss between different layers of soil, providing a detailed perspective on how soil influences signal propagation.

Experiments and Results

To assess the performance of UG2AG transmission, we selected three transceivers: the STEVAL-FKI915V1 based on the S2LP platform, suitable for Sigfox applications; the SX1262, designed for sub-GHz LoRa applications; and the SX1280, suitable for 2.4 GHz LoRa applications. The S2LP, SX1262, and SX1280 were initialized with operating frequencies of 868 MHz, 915 MHz, and 2400 MHz, respectively, to investigate the impact of frequency allocation on underground communication links. The receiver was positioned above ground at a height of 1.5 meters and maintained a horizontal distance of 2 meters from the transmitter's burial location. Once the transmitter was placed underground, we meticulously returned the excavated soil to its original depth to simulate natural conditions accurately.

The experiments were conducted at different locations to facilitate a comparative analysis of the impact of various soil properties on wireless transmission. Each transmitter was installed at five depths: 10, 20, 30, 40, and 50 cm. At every depth, we transmitted 300 packets, each containing a 12-byte payload. For each received packet, we recorded the power levels and Signal-to-Noise Ratio (SNR) to assess the transmission performance.

The path loss of the tested transceivers under different burial depths at two locations is shown in Figure 1. Among the tested transceivers, the SX1262 consistently exhibited the lowest average path loss across different depths and locations. It demonstrated remarkable resilience in diverse soil types and moisture levels, with a slower increase in path loss as the burial distance increased. The Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used to assess the performance of prediction models by comparing the measured path loss across all locations with their predicted values. The proposed model achieved RMSE and MAE values significantly lower than those of other models.

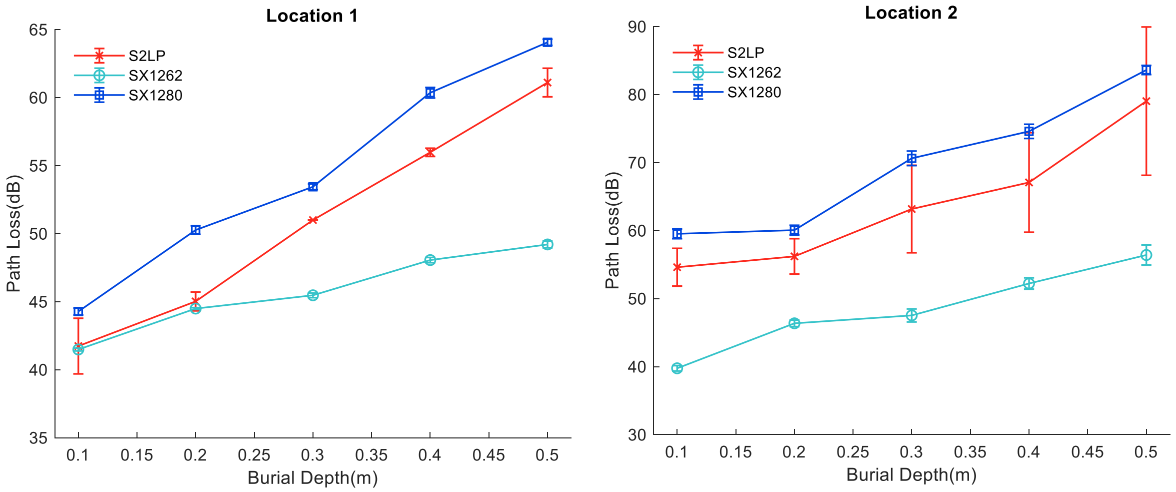

Fig 1. The average path loss and its standard deviation for transceivers tested at two locations with burial depths ranging from 10 to 50 cm.

Conclusion

This study provides a deeper understanding of the challenges in underground communication by introducing a theoretical framework for better signal propagation modeling and empirically validating this model under real-world conditions. This study demonstrates that effective underground communication is achievable up to a depth of 50 cm. Among the transceivers tested, the SX1262, utilizing LoRa modulation, exhibited superior performance in soil environments. The effectiveness of WUSNs is highly influenced by soil moisture, with received packets containing errors and exhibiting higher path loss in locations with higher moisture levels. Regarding path loss prediction, the proposed model proved to be more effective at predicting signal transmission in soil compared to existing models. The findings from this study significantly contribute to the field of wireless communication, particularly in enhancing the reliability and efficiency of WUSNs.

References

Dong, X., Vuran, M. C., & Irmak, S. (2013). Autonomous precision agriculture through integration of wireless underground sensor networks with center pivot irrigation systems. *Ad Hoc Networks*, *11*(7), 1975–1987. https://doi.org/10.1016/j.adhoc.2012.06.012

Sun, Z., Akyildiz, I. F., & Hancke, G. P. (2011). Dynamic Connectivity in Wireless Underground Sensor Networks. *IEEE Transactions on Wireless Communications*, *10*(12), 4334–4344. https://doi.org/10.1109/TWC.2011.093011.110632

Wohwe Sambo, D., Forster, A., Yenke, B. O., Sarr, I., Gueye, B., & Dayang, P. (2020). Wireless Underground Sensor Networks Path Loss Model for Precision Agriculture (WUSN-PLM). *IEEE Sensors Journal*, *20*(10), 5298–5313. https://doi.org/10.1109/JSEN.2020.2968351