

# TESTING GROUND CONDITIONS FOR EFFECTIVE BURIED SENSOR WIRELESS LORAWAN SIGNAL TRANSMISSION

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### ABSTRACT:

Long-range, low-power, wide-area network modulation technique (LoRa) is already used in a variety of fields, such as agriculture and healthcare, to reliably transmit a small amount of data above ground. Research measuring the reliability and signal strength of LoRa devices underground, however, is rare. The purpose of this study is to test the signal strength from LoRa devices in a variety of shallow-depth, underground conditions. The experiments are divided into two parts. The first experiment tries to determine the relationship between signal strength and device depth underground. The second experiment tries to determine the relationship between signal strength and soil moisture content. The experimental results are compared with the Modified-Friis model and CRIM-Fresnel model. The results show a decreasing trend in signal strength with increasing depth. The signal strength of LoRa devices in clay is weaker than in sand. However, soil moisture experiments demonstrate that as the soil moisture in sand increases the signal strengthens. In clay, as the soil moisture increases the signal weakens.

## 1. INTRODUCTION

Long-range, low-power, radio modulation technique (LoRa) provides reliable and secure transmission of data over the air (Augustin et al., 2016). LoRa is being used for sensor communication in Internet of Things (IoT) applications for smart cities, agriculture, and the medical industry. LoRaWAN is a networking protocol built on top of LoRa and used by millions of devices connected to aboveground networks (Wixted et al., 2016). However, evaluation of their shallow underground performance in geotechnical and geomatic engineering applications remains relatively unexplored (Hardie and Hoyle, 2019). Here, we assess the ability to collect data from sensors that communicate via LoRaWAN but may become buried when situated close to ground. An example of such scenario is land survey marks equipped with LoRaWAN that may become shallowly buried by accident or on purpose.

Monitoring is essential in large construction projects. Monitoring equipment usually operates in the field in relatively poor meteorological conditions and challenging geographical environments. LoRaWAN needs to be robust in such conditions when used for remote data collection from field sensors. Measuring the reliability of LoRa devices that are deliberately or accidentally shallowly buried in topsoil is important to set a baseline for underground performance, without which informed decisions about deployment and management of the technology cannot be made. Here, we evaluate LoRa signal strength under different depth and soil conditions and provide data supporting the deployment of LoRa technology when a sensor may be buried underground.

We report on two experimental conditions: (1) experimental establishment of the relationship between received signal strength and depth in three types of soil; and (2) experimental establishment of the relationship between received signal strength and

soil moisture content. Results are compared with the two main electromagnetic signal attenuation models – the Modified-Friis model and the CRIM-Fresnel model (Abdollahi and Sadeghioon, 2019). As expected, the results show a decreasing trend in signal strength with increasing depth. The received signal strength of LoRa devices in clay is weaker than in sand. Unexpectedly, in the soil moisture experiments, sand environments show an increase in signal strength with increasing soil moisture. An increase in soil moisture in clay environments resulted in a tendency to decrease signal strength.

## 2. BACKGROUND

Few research papers investigate radio frequency (RF) path loss in underground wireless data transmissions (Sadeghioon et al., 2017; Abdollahi and Sadeghioon, 2019), especially using LoRa and particularly in underground-to-above-ground environments (UG2AG). Where LoRa is studied in UG2AG environments, the experiments were performed in mixed soil environments (Hardie and Hoyle, 2019).

We fill the gap in pure soil experiments for LoRa signal strength monitoring and comparison. A pure soil approach enables more accurate monitoring and comparison of the LoRa signal in different soil conditions. To make our experiment more accurate and avoid any external interference to the signal, we use previous experimental models for reference. This method provides theoretical models and results prediction for our experiment.

The experimental model proposed by Abdollahi and Sadeghioon (2019) is adopted. It describes the discrepancies between the measurements of signal attenuation within different mixed soil laboratory testing environments and the estimation values from two theoretical electromagnetic (EM) signal attenuation models: modified-Friis (Li et al., 2007) derived from the Friis (Friis, 1946) model to accommodate for signal spread under

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soil, and the Complex Refractive Index Model-Fresnel (CRIM-Fresnel) (Bogena et al., 2009; Sambo et al., 2019). Although the EM frequencies and technology targeted by Abdorahimi and Sadeghioon (2019) were not LoRa sensors and gateways, their method for avoiding signal interference from within the experiment, as well as estimation of EM signal attenuation, can be used for reference.

Two main models are applicable for EM signal propagation in soil: the Modified-Friis Model and the CRIM-Fresnel model.

### 2.1 Modified-Friis model

The Modified-Friis model for total power received equation (Friis, 1946) employed by Abdorahimi and Sadeghioon (2019) provides a theoretical background on EM signal propagation in soil using, as input, the magnetic permeability of the soil. The modification leads to the exclusion of the free-air component, suited for our experiment:

$$P_r = P_t + G_r + G_t - P_L \quad (1)$$

where  $P_r$  = transmission received power  
 $P_t$  = transmission power from sensor  
 $G_t, G_r$  = sensor and receiver gain  
 $P_L$  = total path loss

Total path loss equation is (Li et al., 2007):

$$P_L = 6.45 + 20\log(d) + 20\log(\beta) + 8.69d\alpha \quad (2)$$

where  $d$  = distance between sensor and receiver  
 $\beta$  = phase shifting coefficient  
 $\alpha$  = signal attenuation coefficient

The phase shifting and signal attenuation coefficient are calculated as:

$$\beta = \omega \sqrt{\frac{\mu\epsilon'}{2} \left( \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} + 1 \right)} \quad (3)$$

$$\alpha = \omega \sqrt{\frac{\mu\epsilon'}{2} \left( \sqrt{1 + \left(\frac{\epsilon''}{\epsilon'}\right)^2} - 1 \right)} \quad (4)$$

where  $\omega = 2\pi f$ , where  $f$  is the signal frequency  
 $\mu$  = magnetic permeability of the soil  
 $\epsilon'$  = real part of the dielectric permittivity  
 $\epsilon''$  = imaginary part of the dielectric permittivity

### 2.2 CRIM-Fresnel model

The CRIM-Fresnel model (Abdorahimi and Sadeghioon, 2019) determining the total attenuation of the signal underground (Bogena et al., 2009) is defined as:

$$A_{tot} = a_{CRIM} \left( \frac{dB}{m} \right) * d(m) + R_c \quad (5)$$

where  $a_{CRIM}$  = soil attenuation coefficient  
 $d$  = the distance between sensor and receiver  
 $R_c$  = the signal attenuation from reflection

The equations of attenuation coefficient ( $a_{CRIM}$ ) and the attenuation due to the reflection ( $R_c$ ) are given below:

$$a_{CRIM} = 8.68 \frac{60\pi (2\pi f \epsilon_0 \epsilon'' + \sigma)}{\sqrt{\frac{\epsilon'}{2} \left( 1 + \sqrt{1 + \left(\frac{\epsilon'' + \frac{\sigma}{2\pi f \epsilon_0}}{\epsilon'}\right)^2} \right)}} \quad (6)$$

$$R_c = 10 \log \left( \frac{2R}{1+R} \right) \quad (7)$$

$$R = \left( \frac{1 - \sqrt{\epsilon'}}{1 + \sqrt{\epsilon'}} \right)^2 \quad (8)$$

where  $\epsilon$  is the complex dielectric permittivity of the soil  
 $\sigma$  represents the bulk electrical conductivity of soil

### 2.3 Method to avoid external interference to the signal from the study

The wireless underground sensor network (WUSN) of radio frequency (RF) transmissions is challenged by the high attenuation of the EM signal in soil (Abdorahimi and Sadeghioon, 2019). Underground signals travel through soils with a high density or high moisture content and non-homogenous soil mixture, affecting the isotropy of signal propagation (e.g., through discontinuities and boundaries), both of which will make the signal decrease sharply. Abdorahimi and Sadeghioon (2019) illustrated that signal attenuation is mainly affected by reflection, refraction, diffraction, absorption, scattering of the EM wave and traveling in free space. This informs our experimental setup, following the recommendations enabling to ensure the reliability of measurements:

- Use a container made of aluminum, rather than plastic as the sample mold to avoid environmental electromagnetic interference (EMI) contamination that could adversely affect readings;
- Compact the soil sample by rammer to limit the volume of air in soil, and thus avoid environmental interference to the signal;
- Use a cylindrical shape container for ensuring maximum contact between the compaction rammer and soil surface at the edges of the container and avoid environmental interferences to the signal;
- Use different soils (clay, sand and silt) with different moisture contents (10%, 20% and 30%) tested in different depths for the reliability of the experiment;
- Minimize the time delay between measurements at each depth to avoid changes in soil condition and homogeneity; and

- Reduce the effect of the container acting as a wave guide by earthing the container to the ground and thus cancel eddy current effects that may generate on the wall of the container.

## 2.4 Results prediction from study

According to Abdorahimi and Sadeghioon (2019)'s experimental results, matching the theoretical models, no matter what kind of soil composition, the signal attenuation increases with the increase in distance between sensor and receiver. Furthermore, under constant soil moisture conditions, the signal attenuation in high clay content soil will increase more than signal attenuation in high sand content soil. This is because high clay content has more bound water and a higher bulk density, which adversely effects the transmission of the signal at distance.

In the same soil composition and distance condition, the signal attenuation will decrease with the increase of soil moisture content because water, as a semi-transparent medium for electromagnetic radiation, will reflect, transmit and absorb electromagnetic radiation.

## 2.5 Recommended method to reduce external interference to the signal from literature review

There are five main factors affecting signal transmission regardless of soil properties:

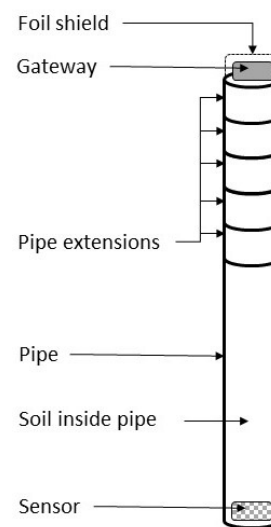
- Reflection. Reflection is when a wave bounces off something. It is the behavior of electromagnetic signals when they hit a reflective surface, such as metal, and bounce away, in a different direction than they were travelling prior to hitting the surface. Repeated reflective behavior, caused by hitting the same reflective surface or multiple reflective surfaces, interferes with the reception of the signal and can lead to a weakened signal. (Cook, 2015)
- Refraction. Refraction is when a wave is bent upon entering mediums with different speeds, such as from air to water. The refraction caused by different mediums is measured as a refractive index. Too much refraction between transmitter and receiver can reduce speed and capacity. (Cook, 2015)
- Diffraction. Diffraction is when a wave goes around an obstacle, such as a hill. Obstacles can create an area, known as shadow zones, of reduced intensity and altered direction of waves. (Cook, 2015)
- Scattering. Scattering is when a wave is sent in multiple, unpredictable directions. This happens when it meets irregular mediums and materials and can lead to signal strength and integrity reduction. (Cook, 2015)
- Absorption. Absorption is when a wave is captured and converted into heat by the material it is trying to pass through. This affect occurs when a medium's molecules can not move as fast as the incoming wave. Absorption rates vary between materials. (Cook, 2015)

Therefore, to avoid interference and increased signal strength caused by these four factors, it is recommended that tinfoil be wrapped around the gateway receiver on all sides, except for the side that is in direct line with the transmitter, to ensure that only

the signal from the transmitter is received and to increase signal strength by reflection and refraction of signal. Sheley (2022) noted tinfoil is a suitable metal for this purpose as it blocks radio frequency waves effectively, it can conduct electricity to form a Faraday cage, and it is inexpensive and readily available.

## 3. METHODOLOGY

Assuming a straight-line travel of electromagnetic waves, the experiment is designed using pipes of differing lengths to simulate different depths of sensor burial. A LoRa gateway (receiver) is placed at one extremity of the pipe, while a LoRa sensor (transmitter) is placed at the other end (Figure 1).



**Figure 1.** Experimental setup to evaluate the effects of variation in soil depth, moisture and type on signal strength (not to scale).

Three experiments were designed to test signal strength under a variety of different soil type and moisture content environments. A pilot experiment determined how to minimise the influence of the signal from the surrounding environment on the signal strength measurements (i.e., shielding of the apparatus). Two main experiments assessed the impact of the changing experimental conditions on signal strength: the variation in sensor depth and soil types; and the variation of gravimetric moisture content in these same soil types.

### 3.1 Equipment

The soil depths tested in the experiment are 20cm, 40cm, 60cm, 80cm, 100cm, 120cm, 140cm, 160cm. A Holman 3m PVC DWV pipe with a diameter of 100mm is divided into two 20cm, one 60cm and two 100cm sections with handsaw. Holman Industries 100mm DWV PVC Coupling Slips are prepared to connect the pipe sections so the target length can be reached. The gateway used in the experiment is Model RAK7258. It is set up to connect to The Things Network (TTN) (The Things Industries, 2016), so that the signal strength reported by the gateway can be read and collected. The type of sensor used in the experiment is Oyster-LoRaWan-915 from Digital Matters and it operates at 915MHz in the 900MHz band.

After the gateway and sensor are set up, a ground test at South Melbourne Beach was carried out to test the connectivity between

gateway and sensors. The test was also done to find the maximum signal depth of the sensor.

Other equipment used in the experiment include sieve, soil moisture sensor (model ECOWITT WH0291), tin foil, shovel, ruler, scale, saw, gloves, face masks, rammer, bucket and soil mixer.

### 3.2 Soil preparation

Dry sand and dry clay is sourced from the Geotechnical, Soil and Water Laboratory at Melbourne University.

Soil moisture content is calculated using the equation:

$$p = \frac{m_w}{m_s} \quad (9)$$

where  $m_w$  = the mass of water  
 $m_s$  = the mass of dry soil

With the equation, the soil moisture content can be controlled by calculating the mass of water and dry soil. Then the dry soil and water are added together and mixed with a soil mixer. Mixtures of soil with moisture content of 10%, 20% and 30% are prepared. A soil moisture sensor is used to verify the soil moisture content.

### 3.3 Data Collection

The signal strength, measured as the received signal strength index (RSSI) of the sensor signal at the gateway is read from the TTN website. RSSI is a measure of the power presented in the received signal in dBm (Farahani, 2011). The higher the value of RSSI, the stronger the signal strength. We collected 11 data points at each depth and report the mean value of RSSI.

### 3.4 Pilot experiment-test the usage of tinfoil

As discussed previously, the gateway only receives the best signal from the sensor. It does not matter which direction it came from. However, as signals travelling through the pipe are the subject of this experiment, foil is used to conceal external signals ensuring signals through the pipe are the strongest signals. The experimental setup is placed in a bucket for the collection of soil after the experiment. This is also applied to the main experiments.

The experiment setup is shown in Figure 2. The sensor and the gateway are located at opposing ends of a 100cm-long pipe, which is filled with dry sand. Four scenarios are tested using these setups:

1. No foil at either end;
2. Foil at gateway end only;
3. Foil at sensor end only; and
4. Foil at both ends.

When covering only one end of the pipe with foil, only the area that is exposed to air is covered with foil. Foil is not used inside sections of pipe.

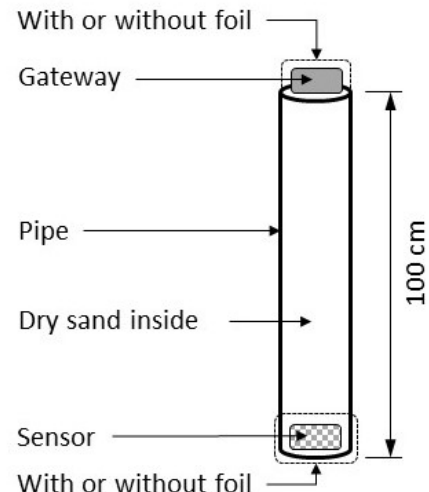


Figure 2. Experimental setup for pre-experiment

As found in the literature review, increasing soil depth decreases signal strength. In these tests, the only signal barrier from the sensor to the gateway is the soil in the pipe. Therefore, it is determined that the test with the worst result will be used in the actual experiment, as it is expected that the signal has travelled through soil within the pipe to the gateway. This is discovered to happen in the scenario where only the gateway end has foil around it.

## 4. EXPERIMENTS

### 4.1 Experiment 1: Soil Depth

To test the effect of soil depth on signal strength, a sensor is placed at one end of the pipe and gateway at the other end. Soil fills the space between them. The setup is shown in Figure 1. Increments of 20cm, from 20cm to 160cm, is tested to determine the trend of signal strength with increasing depth. After eleven data points at each depth, soil is removed from the pipe, and weighed on a scale to determine the density of soil for this trial.

### 4.2 Experiment 2: Soil Moisture

The soil moisture experiment setup is the same as it is in Experiment 1: Soil Depth. However, this time depth is fixed at 40cm, and water is introduced to the soil. A soil moisture sensor is used to test the soil moisture content before beginning the experiment. The experiment procedure is then the same as Experiment 1.

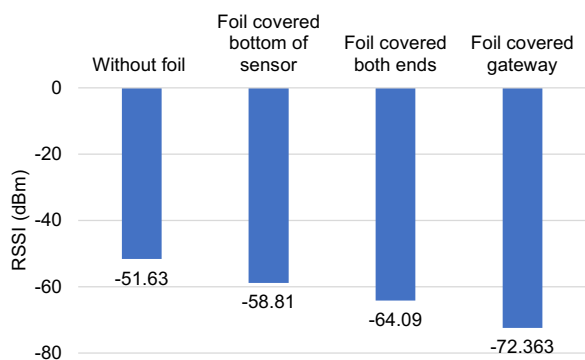
## 5. RESULTS

### 5.1 Pilot experiment

The preliminary test results indicate that the scenarios with a foil cover on the gateway result in the lowest measured RSSI, which validates our expectation (Figure 3).

### 5.2 Main experiment

The results show overall trends that the signal strength is decreasing with increasing depth of both soil types tested. However, the signal strength increases at a soil depth between 20cm



**Figure 3.** Signal strength of Oyster AU 915 with different foil cover scenarios at a depth of 100cm

and 40cm. There is an increase of signal strength for the sensor in sand between the 1m and 1.2m depth. For the sensor in clay there is also an increase of signal between 80cm and 1m.

In sand, the signal strength increases monotonically with the increase of moisture content. However, the signal strength for the clay did not increase monotonically with moisture content (Figure 7). It shows an upturn from 20% soil moisture to 30% soil moisture.

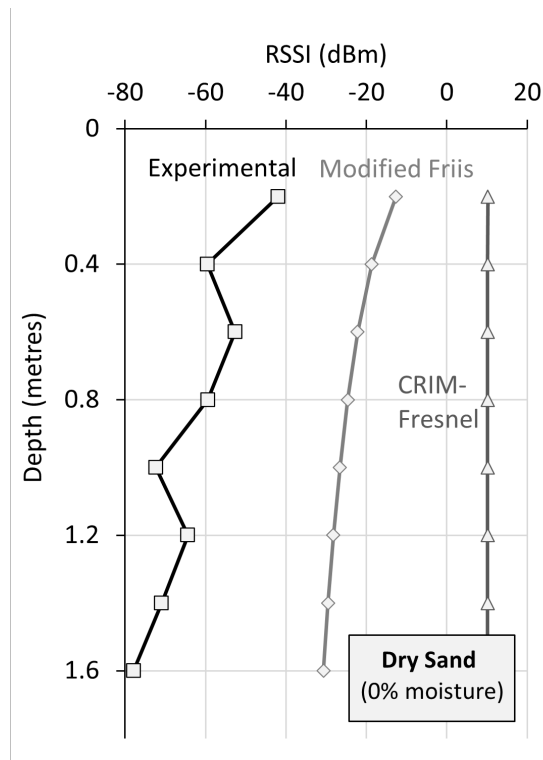
## 6. DISCUSSION

From the experimental results, it is proven that LoRa signal can maintain a communication channel even at a vertical depth of 1.6m. It was hypothesised that signals in clay would be weaker than those in sand. However, the experimental result indicates that this relationship is not consistent with variable depth or moisture content.

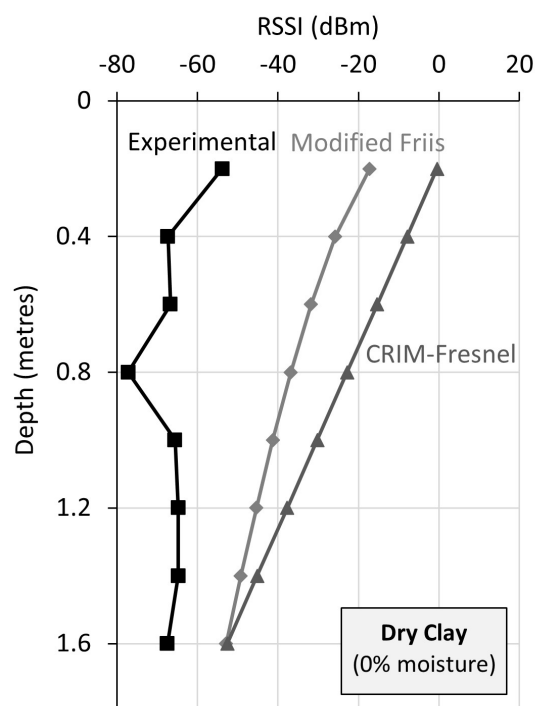
### 6.1 Comparison with theoretical models

Figures 4 and 5 show that signal strength decreases with depth for both sand and clay. This trend is also reported in a paper by Shaibu et al. (2019). Their test results show that as soil becomes finer, signal strength becomes weaker. Our results showing actual RSSI in sand do not align with the predictions of the Modified Friis and CRIM-Fresnel models. In clay, however, there is a higher correlation with both models; the Modified Friis model being the most accurate.

One reason to explain this trend is that magnetic and electrical properties of the soil affect signal strength (Utsi, 2017). As explained above, both the Modified-Friis model and the CRIM-Fresnel model have taken the electromagnetic property into considerations. The Modified-Friis model uses the magnetic permeability, whereas the CRIM-Fresnel model uses the dielectric permittivity and bulk electrical conductivity. These variables are properties of magnetic and electrical properties respectively. The value of electrical conductivity increases from sand to clay. This is in reference to the CRIM-Fresnel model equations; with increasing electrical conductivity signal attenuation increases Bogena et al. (2009) (Smith and Doran, 1997). An experiment by Ahmed et al. (2019) demonstrates electrical conductivity and magnetic permeability have a directly proportion relationship. This means that magnetic permeability will also increase, which increases total path loss in Modified-Friis model. Both models



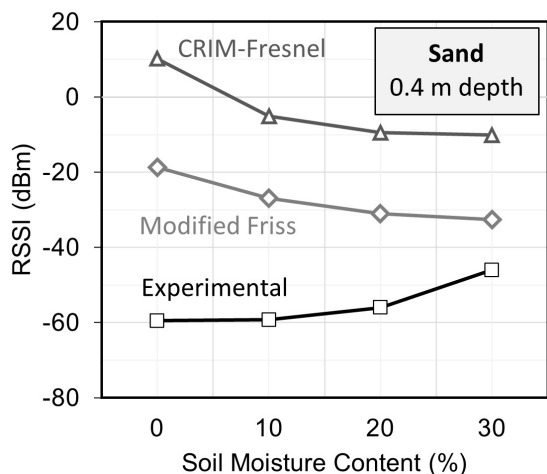
**Figure 4.** LoRa signal strength in dry sand at depths 0.2 to 1.6 metres



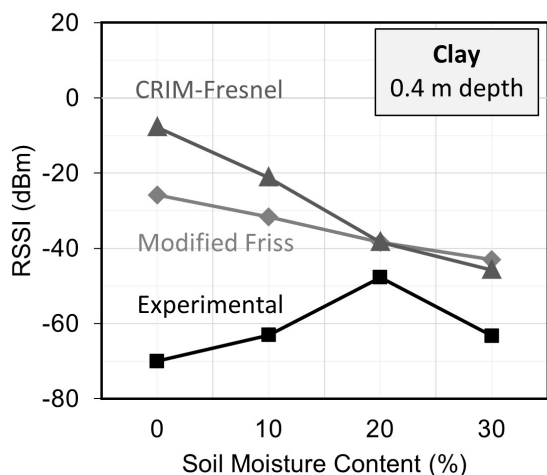
**Figure 5.** LoRa signal strength in dry clay at depths 0.2 to 1.6 metres

predict, with increasing magnetic and electrical properties, signal attenuation will increase. This prediction was present in the laboratory results gathered.

In the experiment of Abdorahimi and Sadeghioon (2019), with increasing soil moisture content, signal attenuation rate decreased. Their results match our lab-based results, but contradict theoretical models (Figures 6 and 7). Increasing the electrical conductivity of soil should increase signal attenuation, resulting in a weaker received signal strength. It is uncertain why we observe the LoRa signal increase with soil moisture.



**Figure 6.** LoRa signal strength in sand with different moisture content at depth of 0.4m



**Figure 7.** LoRa signal strength in clay with different moisture content at depth of 0.4m

## 6.2 Limitations

Despite the experiment being conducted in the laboratory, there are still many uncontrollable variables and limitations that can affect the accuracy of the result for intended applications. These limitations include:

1. Inability to precisely control sensor frequency;
2. Inability to completely remove air from soil;
3. Inability to maintain uniform soil moisture throughout the soil;

Sensor frequency is a factor that affects the signal strength of electromagnetic waves. As shown in Equation 2 and its components, the frequency of the sensor affects the free space path

loss: the higher the frequency, the more the signals are attenuated. The experiment should also show this trend within the same depth data group. However, no obvious relationship is discovered between different frequencies and signal strength. As explained previously, foil is wrapped around the exterior of the gateway to avoid receiving signals other than the ones coming through the soil. Despite this measure, it cannot be guaranteed that the distance travelled by each signal is the same.

To improve this observation, more experimental data will be required and random errors, such as differences in travelling distance, can be reduced by taking an average value. This can also be improved by having a programmable LoRa frequency sensor. With such a sensor, the signal frequency can be controlled, further reducing possible errors.

Inability to completely remove air from soil has an impact on the experiment. Due to the limited amount of data collected, random errors, such as air in soil, will greatly affect the results' accuracy and precision. As the density of the same type of soil is different every time it means that content of air within the soil varies in each of the test. This variation causes inconsistency of signal travelling through soil, which results in the soil penetration distance being less than what is labelled at each experiment. Also, as explained above, the radio waves received in this experiment may not have travelled the same distance or via the same path. Therefore, with different paths, the distance travelled in air will also be different. This will also affect the signal strength.

This experiment could be improved by using a hydraulic compressor with a head of the same radius as the inner tube radius. Soil restrains, such as a cap, could be applied at the sensor end of the pipe. Using the volume function, and the specified density of soil, a set amount of soil should be prepared. To achieve high uniform density of the soil, the compressor should be used every 20cm.

By controlling the density of the soil, random errors of the experiment should reduce. However, it should be noted that soil moisture experiments always require additional soil space for water. Therefore, compressing soil to its dry bulk density in the depth experiments will cause the results to be incomparable to the soil moisture experiments. Therefore, it is recommended that the density is controlled at a level that can incorporate water content of at least 30% soil moisture.

The inability to maintain uniform soil moisture throughout the experiment is another limiting factor. Soil moisture is measured using gravimetric soil moisture content. Our soil moisture tests show that sand had a relatively smaller range of soil moisture values for each experiment compared to clay, suggesting that the values collected from soil moisture experiments in sand had higher accuracy. However, after the experiment, a large amount of water was collected at the bottom of the tube; the higher the soil moisture, the more water is collected. This implies a migration of moisture during the experiment and suggest that the soil moisture was not evenly distributed.

## 6.3 Future work

The experiment will be further developed to acquire more reliable results showing signal performance in different soil type and conditions. The current data was collected at a single setup per depth or soil moisture level, with eleven data measurements

per level. To further remove random errors and make the experiment robust, additional measurements are recommended across combinations of soil type, depth and soil moisture content.

A sensitivity analysis should be conducted to assess effects of different factors on signal interference, to determine the range of environments the technology can be applied to. The laboratory results are a baseline, where the signal strength may not fully reflect real application performance, e.g., due to additional environmental interference from machinery, moving obstacles (such as people, cars and weather conditions). Therefore, field experiments are recommended to obtain values that better represent real deployment scenarios.

## 7. CONCLUSION

Based on our two experiments, we observed a decreasing trend in signal strength as sensor burial depth increases, with clay showing greater signal loss than sand. This depth experiment then validates the theoretical predictions of the Modified-Friis and CRIM-Fresnel models, and shows that under dry soil conditions (i.e., soil moisture 0%), signal strength adequate for data transmission can be detected up to a depth of 1.6m. The results show LoRa is suitable for monitoring shallowly buried sensors in geospatial applications.

This is meaningful for applications where a sensor has been shallowly buried underground (intentionally or accidentally) but is still able to transmit a signal with a packet of data from an underground sensor to a receiver above ground. The LoRa device could be collecting, for example, data from an accelerometer to relay valuable information about the movement of the device after an avalanche, an earthquake or construction collapse. The LoRa transmitter can be attached to sensors measuring light, sound, moisture, position and other environmental characteristics.

If the sensors are equipped with a transceiver (allowing them to receive messages as well as send messages), the sensor may receive messages at their underground location from a transmitter above ground initiating commands for the device to perform actions, such as turning on or off a motor (e.g., for a water pump) or switching on or off a light.

Interestingly, some of our soil moisture experiments show a result contradicting the theoretical model. Sand shows an increase in signal strength with increasing soil moisture, while the signal strength in clay decreases with increased soil moisture beyond a certain threshold. Since theoretical models suggest signal strength will follow a decreasing pattern when soil moisture is increased, it is unclear whether this experimental trend is attributable to experimental uncertainties.

Yet, even in environments of significant moisture, signal strength sufficient to transmit data is detected. This supports the use of LoRaWAN, possibly following more comprehensive field tests, in remote geospatial monitoring situations where a sensor may be intentionally or unintentionally shallowly buried.

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