Referee #2

Environmental monitoring is changing towards distributed measurements over large areas using wireless sensor networks since many years. The next logical step is to extend this technology to underground operation. The main aspects are related to the electromagnetic wave propagation of the radio, power supply for long term operation (and water proofness).

The strong point of this paper is that it provides a guided path to a low cost underground wireless sensor network using readily available components. It is a good description and the open source nature of this project is highly appreciated. Therefore is a great starter for anyone interested in this field of research and encourages others to become part of this project. I guess this is one of the main goals of this paper, therefore a significant achievement and worth to be published.

We want to thank the reviewer for the comments, which we believe helped us improve the manuscript significantly. Detailed answers are given below using blue font.

There are two aspects which lack a bit:

1.) Underground wireless sensor networks already have entered the commercial domain. The first systems appeared on the market for farmers and for irrigation control in municipalities. In some parts of Europe LoRaWAN (and NB-IoT narrow band internet of things) networks are nationwide available even offering underground connectivity at some places. E.g. Czech IoT companies offer IP68 rated underground wireless soil moisture sensing for farming, golf courses and municipal parks. A short reference to such systems may be helpful.

We searched online but didn’t find the references for the Czech IoT companies mentioned in the above comment. The only company providing fully buried wireless sensors we found is the Soil Scout (https://soilscout.com/solution/wireless-soil-moisture-sensor). Nevertheless, we added the suggested reference on the use of LoRaWAN networks by adding the following text to the manuscript.

“Yet, if a significantly larger number of nodes is required, it is recommended to use more complex solutions like the LoRa Wide Area Networking technology (LoRaWAN). The LoRaWAN is an open-source protocol that uses the LoRa protocol to enable communication between multiple nodes and hubs (also referred to as gateways), with additional benefits such as adaptive data rates that can reduce power consumption (Froiz-Míguez et al., 2020; Haxhibeqiri et al., 2018). There is also an emerging use of LoRaWAN solutions commercialized by private companies. Yet, they are still costly and, in most cases, target big end users, such as cities, and therefore, are less relevant for field-scale research. A review of the LoRaWAN technology is provided by Haxhibeqiri et al. (2018), and a more detailed focus on the limitations is provided by Adelantado et al. (2017)."

2.) The authors may comment on using their proprietary LoRa radio protocol versus the standard LoRaWAN protocol. I understand that they wanted to optimized the protocol and it may be simpler to implement, but LoRaWAN has some good points as well like adaptive datarate and multichannel reception. Adaptive datarate can help to save power consumption when being close to the gateway. Multichannel could be beneficial in case of multipath propagation. The authors may also comment on the choice of the frequency. Usually lower frequencies are better for penetration soil. Besides 433 MHz instead of 900 MHz in some countries even a frequency around 170 MHz can be used which allows for a much larger range. As far as I understood the authors change only power level. What about changing LoRa spreading factor? Please also specify your LoRa settings. It may be looked up on Github, but would be good to see it in the paper.

We revised the paragraph and added the suggested references as detailed in our answer to the previous comment.

We did not change the spreading factor; however, following the reviewer's comment, we agree that this should be another parameter to test in future work. To clarify this, we added the LoRa settings to the Materials and Methods section:

"During all scenarios, the default LoRa-Feather parameters were used (bandwidth = 125 kHz, coding rate = 4/5, spreading factor = 128 chips/symbol, and CRC on) – additional information regarding these parameters can be found in the readme file link embedded within the code on Github."

Some further comments:

One reviewer mentioned that power regulations may vary between regions. In Europe there are also some frequencies in the 868 MHz range allocated for higher power (27dBm, but bandwidth and duty cycle dependent). So in order to comply with regulations are very thorough look into the frequency band plan is required, especially if higher power levels are requested.

We added a new paragraph discussing power limitations imposed by local regulation.

"The chosen transmission power and radio band should also follow legal restrictions derived from local regulation. In Europe, for instance, the maximum approved transmission power is 14 dBm (for 433 MHz), compared to 30 dBm in the USA (915 MHz) (Fraga-Lamas et al., 2019; Froiz-Míguez et al., 2020; Haxhibeqiri et al., 2018). The results of our study show that even 5 dBm provided sufficient power for transmitting data from the underground node to the aboveground hub located at a horizontal distance of 2 m (**Fig. 3**). The relationship between transmission power, underground node depth, distance between an underground node and an aboveground hub, and soil texture is discussed in Hardie and Hoyle (2019). We note that the authors used a radio band of 433 MHz compared to 915 MHz used in this study, and therefore, some differences are expected; lower radio band frequency will result in lower radio propagation losses (i.e., larger range) (Froiz-Míguez et al., 2020). To the best of our knowledge, there is no published comparison between the two radio bands for LoRa-WUSN, thus we cannot conclude which of the two is preferable (e.g., in terms of RSSI or SNR). Another regulative limitation is the duty cycle for an on-air time. In Europe, it is 1 %, which means that for a 1 s LoRa transmission, this specific node cannot transmit during the following 99 s (Haxhibeqiri et al., 2018). The 0.3 s transmission duration presented in this study (**Table 2**) translates to a minimum interval time of 29.7 s before the subsequent transmission can be made."

I am a bit confused with the power levels mentioned. In the summary of hardware components the RFM95 module is mentioned. According to the manufacturers datasheet a maximum output power of 20 dBm is possible. Do you really get 23 dBm out of the module?

Regarding the maximum transmitting power, we found a discrepancy between the datasheet and the example code provided by the manufacturer – in the datasheet, it is 20 dBm and in the code it is 23 dBm. This was our mistake and we would like to thank the reviewer for pointing this out. The maximum transmitting power was changed to 20 dBm throughout the manuscript, figures, and code.

As already stated by another reviewer battery technology is important. Lithium thionyl chloride batteries are state of the art with extremely low self discharge and relatively low costs. The reviewer is using D-cells with less than 1% self discharge per year and 19 Ah. Double D cells with 35 Ah are also available (size of underground enclosure is usually not critical). Energy harvesting may be an option for unlimited lifetime but is still not mature enough and suffers from principle physical limits.

We revised this paragraph and added the potential use of other types of batteries as suggested by the two reviewers.

"In cases where extended battery life is needed, it is recommended to use battery technologies with lower self-discharge rates, such as non-rechargeable lithium-thionyl batteries with self-discharge rates lower than 1% per year. A comparison between different battery technologies is detailed in Callebaut et al. (2021). For instance, using a non-rechargeable lithium-thionyl battery with a ~7000 mAh is estimated to increase the underground battery's life threefold, resulting in 2-3 years of operation (according to the power consumption presented in **Table 2**)."

It may be a bit to deep in technical details, but please be careful when using the SDI-12 Arduino library with just the IO ports of the controller and not having an appropriate hardware interface according to the SDI-12 specification (see sdi-12.org). It may work, but may be out of specification.

We didn't encounter problems using SDI-12 Arduino library in our different systems. Nevertheless, we would like to thank the reviewer for providing these insights that we were not aware of. A link to this page was added to the code for cases where the end-user will want additional information related to SDI-12.

The authors discussed the range of their underground wireless system. I think there is still some demand for further research in modelling underground electromagnetic wave propagation, probably not within this paper but in future research.

We added this suggestion to the discussion.

"Different field settings may create additional complexity (Bogena et al., 2009), and there remains a need for further research in modelling and field validation of underground electromagnetic wave propagation, especially for clay soils in which soil moisture and bulk electrical conductivity are expected to be higher, thus reducing maximum communication range."