Evaluation of LoRa technology in 433-MHz and 868-MHz for underground to aboveground data transmission

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Abstract

The development of Wireless Underground Sensor Networks (WUSNs) is currently receiving significant attention to collect data underground all along the year without impacting aboveground activities. Although the opportunities are promising for sectors as agriculture and environment monitoring, the task is particularly challenging as the radio waves are significantly more attenuated in the soil in comparison with in the air. In addition, the communication ranges are highly impacted by some operating and environmental conditions as the soil moisture, its composition and compaction as well as the burial depth of the nodes. In this paper, we developed two sets of nodes operating at 433 MHz and 868 MHz based on the LoRa technology which is the physical layer of the Low Power Wide Area Network LoRaWAN and initially developed for aboveground IoT applications. We successively tested these nodes in real conditions on underground to aboveground (UG2AG) data transmissions and with various operating conditions and radio parameters. First results highlighted the interest of the 868 MHz radio modules tuned at the maximal allowed transmit power in Europe (+14 dBm/25 mW), in comparison with the 433 MHz radio modules (+10 dBm/10 mW). Next results enabled to point out the importance of the inclination of the receiving antenna but also the impact of the burial depth of the emitting node, as well as the interest to place the emitting antenna directly in contact with the soil. The best configuration enabled to reach UG2AG ranges of more than 275 meters long with low depth buried nodes (15 to 30 cm), that clearly enables to envision agriculture and environment monitoring applications based on such radio modules.

Keywords: Wireless Underground Sensor Networks, IoUT, LoRa technology, environmental monitoring, precision agriculture.

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1 Introduction

In the coming years, Wireless Underground Sensor Networks (WUSNs) are expected to play a major role in the environment monitoring and real time decision making (Sardar et al., 2019, Sambo et al., 2020). The applications range from smart irrigation and precision farming to minimize water losses and optimize the use of agricultural resources (Silva and Vuran, 2010) to the detection of pesticide residues in soil near rivers (Akyildiz and Stuntebeck, 2006) and early population warning against risks of landslides (Ferreira et al, 2019). Other potential applications are underground infrastructure monitoring (e.g. pipes, storage tanks), sport field monitoring and detection of people or vehicles aboveground (Zaman and Forster, 2018). These applications are based on the development of nodes composed of sensors, radio communication devices and antennas, all buried at a few dozens of centimeters deep to collect data directly from the underground environment (e.g. moisture, temperature, salinity, vibrations) without impacting the aboveground activities and all along the year. The interest to conceal the nodes underground is also to protect them from potential damages caused by humans, animals and machines (Huang et al., 2020). The data collected in the field are next transferred to the cloud, leading to the new paradigm of Internet of Underground Things (IoUT) (Saeed and al., 2019, Salam and Raza, 2020).

As depicted on Figure 1, three communination links, called underground to underground (UG2UG), underground to aboveground (UG2AG) and aboveground to underground (AG2UG), are possible in a wireless underground sensor network (Silva et al., 2014). The establishment of the communication between the different nodes is however challenging as the radio electromagnetic waves are significantly more attenuated in the soil in comparison with in the air (20-300 times worse) (Da Silva et al., 2014). In particular, the UG2UG link is difficult to obtain, the communication ranges reported in the literature being generally lower than a few meters. Moreover, compared with in the air, many environmental factors affect the inter-node communication distance in a WUSN, especially the Volumetric Water Content (VWC) or soil moisture which drastically attenuates the propagation of the radio signals underground (Bogena et al., 2009). In UG2UG, the strength of the received signals can decrease of several dozens of decibel-milliwatts on wet soil compared to a dry soil (Vuran and Silva, 2009). The composition of the soil, i.e. the percentage of sand, silt and clay (Foth, 1990), impacts also indirectly the inter-node connectivity with greater or lesser water holding capacity. The topology of the terrain is also an important point to be considered to adequately place the nodes in the field, as well as the burial depth (i.e. the distance between the antenna and the surface) which impacts the strength of the received signal for the UG2AG/AG2UG links (Sambo et al., 2020), but also for the UG2UG links which are affected by the reflection of the radio waves by ground surface (Vuran and Silva, 2010). The roots of plants and trees as well as the stage of vegetation aboveground can also impact the UG2AG/AG2UG communications (Vuran and Silva, 2009). Several work aim to characterize, modelize and simulate the propagation of radio waves in soil face to such varying environmental conditions (Vuran and Akyildiz, 2010, Silva et al., 2015).

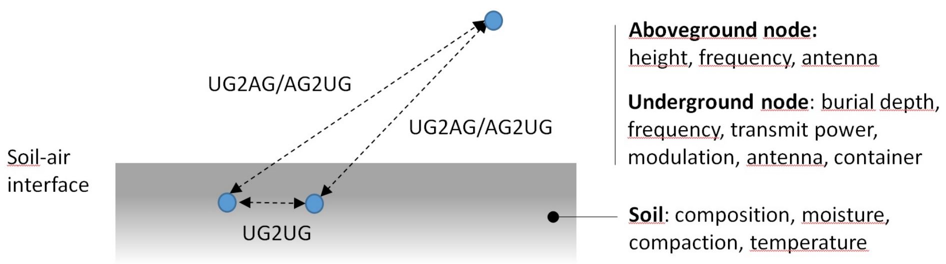


Figure 1: Communication links in WUSN and main inluencing factors

The choice of the operating frequency for the radio transceivers is also essential as the attenuation in soil increases with the frequency value. Several studies highlighted however that the 300-900 MHz frequency band is particularly relevant for WUSNs as it leads to higher communication ranges compared for example with the 2.4 GHz (Silva et al., 2015) and it enables to use reasonable sizes of antennas (a quarter of the signal wavelength). The antennas can be directly in contact with the soil or inside a container, and of different types (e.g. monopoles or dipoles antennas) (Tiusanen, 2009, Salam et al., 2019). The maximum transmit power is limited by the regulations in the country where the WUSNs are deployed. A compromise has also to be found between the transmit power and energy consumption of the buried nodes to obtain run times ideally for several months or years without battery replacement.

In Europe, the 433.05-434.79 MHz and 863-870 MHz are licence free bands particularly relevant to develop WUSNs. They are already used for IoT applications by the Low Power Wide Area Networks (LPWANs), as SigFox, NB-IoT and LoRaWAN, for sending small data packages over long distances with low energy consumption on battery powered nodes. With its open protocol, the interest of LoRaWAN (LoRa Alliance, 2018) is its physical layer, the LoRa technology, developed in 2014 by the French start-up company Cycleo and today managed by Semtech. This technology is based on a Chirp Spread Spectrum (CSS) modulation technique, which encodes information using frequency chirps having a linear variation of frequency over time (Augustin et al., 2016). In the air, this modulation leads to a certain immunity against interferences and multi-paths (Staniec and Kowal, 2018). Several LoRa radio modules are today off the shelf at 433 MHz and 868MHz. In the regard of European regulations, 433 MHz transmissions are allowed at +10 dBm/10 mW whereas 868 MHz transmissions are allowed at +14 dBm/25 mW for the specific 868.0-868.6 MHz frequency band. In addition to the operating frequency and transmit power, several parameters can be configured on the LoRa radio modules, in particular the spreading factor (SF), the coding rate (CR) and the bandwith (BW), see (Augustin et al., 2016). A compromise has to be found between these parameters: high SF values lead to high sensitivity and long communication range to the detriment of airtime and thus energy consumption. High CR values lead to increase the robustness of transmission to the detriment of the airtime and thus also energy consumption. High BW values lead to high data rate and short airtime, but low sensitivity (Zorbas et al., 2018).

In the literature, still very few work have investigated the performance of LoRa communication for WUSNs in real conditions. In (Hardie and Hoyle., 2019), LoRa nodes operating at 433 MHz are buried in the soil from 15 to 30 cm deep with different combinations of LoRa parameters. The obtained transmission distances UG2AG with a transmit power of +25 dBm in SF 12 in relatively dry soil were about 100-200 m, depending on the chosen configuration and soil composition. This work highlighted the difficulty to reach more than a few meters in UG2UG that leads to question the interest of this link in an agricultural context. The issue of power consumption for the buried node is also pointed out. In (Ebi et al., 2019), the radio transmission performances in LoRa and LoRaWAN are evaluated at 868 MHz to monitor an underground infracstructure. They highlighted the interest to first use the LoRa technology for the UG2AG communication, in order to obtain reliable packet delivery, to next use the LoRaWAN protocol for the aboveground communications. In (Lin et al., 2019), the link quality of the UG2AG LoRa communication is investigated, in particular with respect to the burial depth and the internode distance. No packet loss was observed if the RX node is located at the vicinity of the TX node, even at the maximum burial depth (0.8 m). This was also the case with an internode distance of 50 m when TX nodes are buried at 0.4 m. For Tx nodes buried more deeply (0.6 m and 0.8 m), the packet loss increased progressively with the internode distance to be total at respectively 28 m and 22 m. In (Gineprini et al., 2020), less than one percent of the transmitted packets was lost with an UG2AG communication link composed of 27 m aboveground and from 0.1 m to 0.5 m underground. In (Di Renzone et al., 2021), the performances of data transmission in LoRaWAN for different soil compositions was studied for depths up to 0.5 m. The packet loss was below 2 % whatever the soil composition with the gateway placed at 15 m. In (Wu et al., 2019), a simulator was developed to study the impact of soil moisture and burial depth on a LoRaWAN network with a centre frequency ranging from 915 to 928 MHz in New Zealand.

Although UG2UG links are difficult to establish, the UG2AG links with a star topology can be sufficient for numerous applications. This is the case for example of sensors and nodes deployed underground with aboveground collector and repeater nodes. The UG2AG link must however be robust and well-designed. The objective of this paper is to first compare the performance of LoRa technology at both 433 MHz and 868 MHz frequency bands for this UG2AG link and next establish an adequate configuration, in particular in terms of burial depht, inclination of the receiving antenna and contact of the emitting antenna with the soil, with the aim to develop future environmental and agricultural monitoring applications. For that, the nodes were built from commercial components. The maximum transmit powers authorized in Europe for each of the frequency bands were used. The experiments were carried out with a spreading factor (SF) ranging from 7 to 12 to highlight the impact of this parameter on the attainable communication range. The impact of the soil moisture on the UG2AG communication range was first studied to determine the preferred choice for the frequency band for the UG2AG link. Next, the impacts of the burial depth, the inclination of the receiving antenna and the way to bury the emitting antenna were investigated, as well as the analysis of the packet loss.

2 Experimental setup

2.1 Presentation

The experimentations reported in this paper follow the scheme presented on Figure 2.

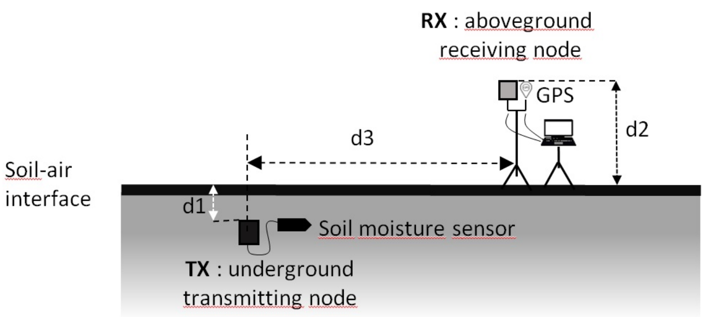
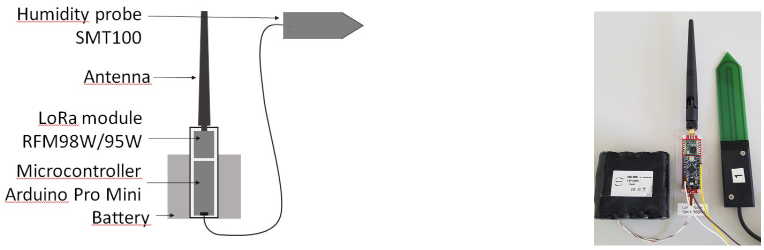


Figure 2: Experimental setup

A soil moisture sensor is buried at the deep d_1 in an open field. This sensor is connected to an underground node TX transmitting periodically the data of the probe (humidity, temperature, dielectric permittivity) in LoRa to a receiving node RX located aboveground at the height d_2 and a varying distance d_3: the RX node is moved until the UG2AG link is disrupted. The data frame are recorded on a computer which is connected to a GPS to georeference the successive positions. First experiments use a set of TX and RX nodes operating at 433 MHz, and second experiments use a set of TX and RX nodes operating at 868 MHz. The power of the radio transmitters are tuned to the maximum value allowed by the European regulations, respectively +10 dBm/10 mW and +14 dBm/ 25mW. On a periodic basis (every 12 s), the TX node picks up the measured values from the sensor and sends a set of six frames with the LoRa parameter SF going from 7 to 12. The RX node waits several minutes on a position enabling to receive several sets of six frames. These experimentations are repeated with different soil moistures, burial depths, RX antenna inclinations and with the TX antenna directly in contact with the soil or inside a PVC container.

2.2 Materials

A first set of TX and RX nodes is built with RFM98W radio modules operating at 433 MHz. A second set uses RFM95W radio modules operating at 868 MHz. These radio modules are manufactured by HopeRF and include the SX1276 transceiver from Semtech with the LoRa technology. The TX nodes, see Figure 3, are composed of a microprocessor ATmega328 running at 8 MHz installed on an Arduino Pro Mini board and a radio module RFM98W/95W with a quarter wave whip antenna (RF FLEXI-SMA90-433, 2 dBi gain, 16.2 cm at 433 MHz and RF FLEXI-SMA-868, 2 dBi gain, 13.6 cm at 868 MHz). The radiation pattern of these antennas is maximum at perpendicular to the whip and close to zero at the end. They will be vertically oriented in the experiments. The TX node is powered with a 3.6 V/8800 mAh Lithium-Ion battery, and connected to a Truebner SMT100 probe. The RX nodes, see Figure 4, are composed of a microprocessor ATmega328 running at 8 MHz installed on an Arduino Pro Mini board and a radio module RFM98W/95W with a quarter wave whip antenna (Siretta Delta 12A, 3 dBi gain, 13 cm at 433 MHz and Taoglas TI.18.3113, 3.2 dBi gain, 39 cm at 868 MHz). The supply of the RX node is delivered by the USB port of the computer on which it is connected.



(a) (b)

Figure 3: Transmitter node TX: a) Sectional drawing b) Battery, node and moisture probe

(a) (b) (c)

Figure 4: Receiver node RX: a) Principle scheme, b) Node, c) GPS (u-blox C94-m8p)

2.3 Software development

The Arduino Pro Mini boards of the TX nodes are programmed to configure the parameters of the radio module LoRa (frequency, transmit power, spreading factor SF, coding rate CR, bandwith BW) and periodically transmit the data frame presented on Table 1.

Table 1: Data frame (15 bytes) sent by the TX node to the RX node

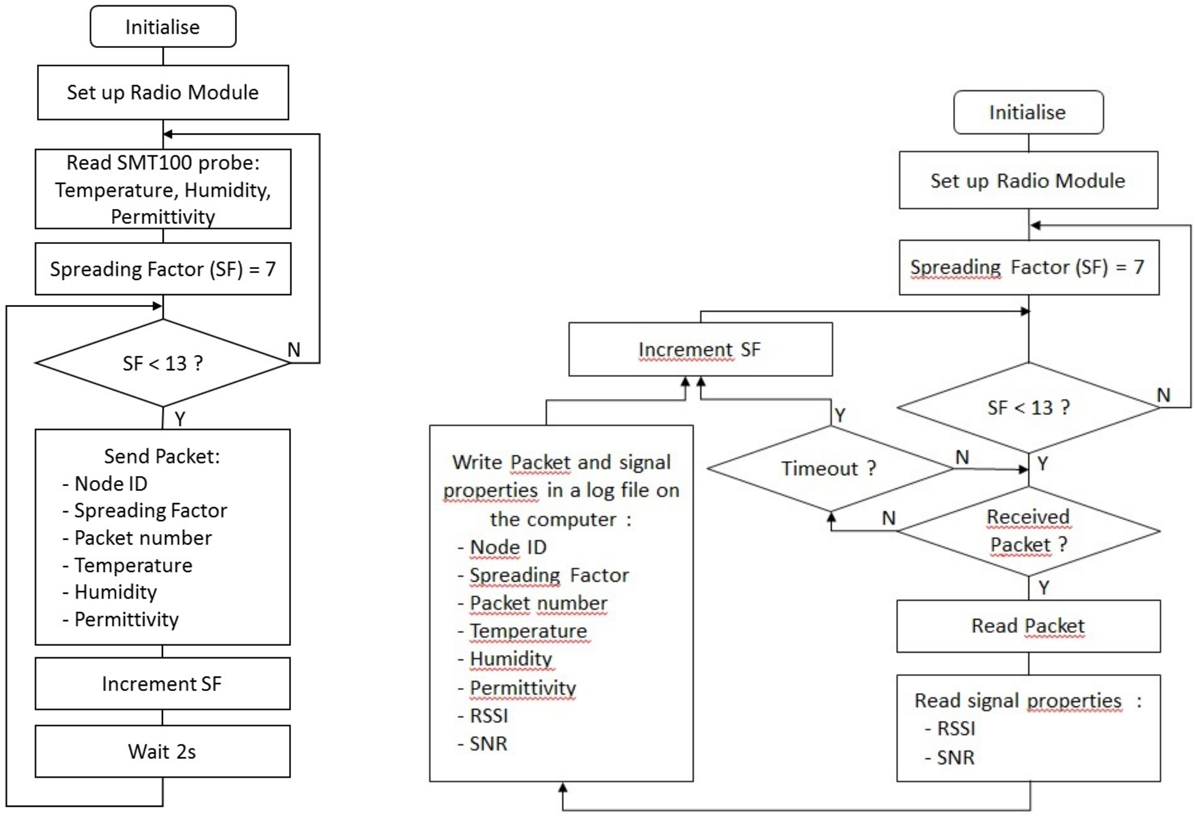
Name	**Description**
Node ID	Node identifiant
SF	Spreading factor (varying from 7 to 12)
Counter	Number of the frame
Permittivity	Data of the sensor SMT100
Humidity	Data of the sensor SMT100
Temperature	Data of the sensor SMT100

Different values for the spreading factor SF are used in order to experimentally quantify its impact on the communication range. Theorically, the higher it is, more the range increases but to the detriment of the data rate as the signal is transmitted over a longer period of time, see Table 2, but also to the detriment of the energy consumption as the radio communication is longer. At each cycle, the TX node reads the data of the SMT100 probe and successively transmits six frames with a spreading factor SF varying from 7 to 12, see the diagram of the TX program on Figure 5a. The output power is constant and tuned at +10 dBm for the 433 MHz node and +14 dBm for the 868 MHz node. The coding rate CR is equal to 4/5 and the bandwidth BW is tuned to 125 KHz.

Table 2: Transmit time of a frame of 15 bytes with respect to the SF value. BW = 125 KHz, CR = 4/5. Values given by the application "LoRa Modem Calculator Tool" from Semtech.

Spreading factor	**RF transmit time (ms)**	**SNR required (dB)**
SF=12	933.9	-20
SF=11	466.9	-17.5
SF=10	299.0	-15
SF=9	149.5	-12.5
SF=8	74.8	-10
SF=7	45.6	-7.5

The RX node waits for data from the TX node. To establish a communication, the value of the spreading factor SF must be identical for both the TX and RX nodes. The RX node is initialized at SF=7 and scans until the reception of a frame, see the diagram of the RX program on Figure 5b. At each received frame, the RX node reads the values RSSI (Received Signal Strength Indication) and SNR (Signal-to-noise Ratio) which qualify the RF signal. It concatenates then the received frame of the TX node and the values of the RF signals to next send this frame to the computer, see Table 3. On the computer, a program in Python reads the data frames and stores them in a dated file with the GPS position. These data are next processed and analysed using Matlab software.



(a) (b)

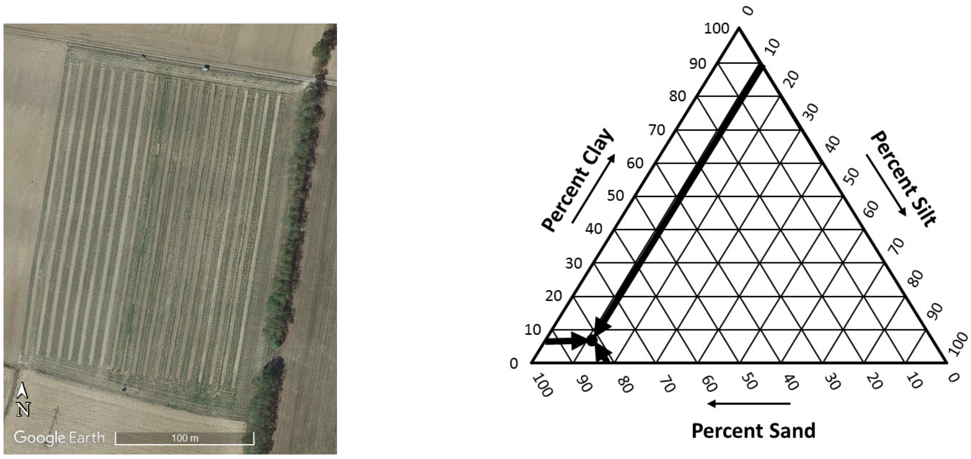
Figure 5: Diagrams of the program in the: (a) TX node, (b) RX node

Table 3: Data frame sent by the RX node to the computer

Name	Description
Node ID	Node identifiant
SF	Spreading factor detected
Counter	Number of the frame
Permittivity	Data of the sensor SMT100
Humidity	Data of the sensor SMT100
Temperature	Data of the sensor SMT100
RSSI	Received Signal Strength Indication
SNR	Signal-to-noise Ratio

3 Experimentations

The experiments were carried out at the experimental field of INRAe (French National Research Institute for Agriculture, Food and Environment) presented on Figure 6. This field of 3.8 hectares is an open environment, flat without obstacles. At low depth, the composition of the soil is 81.6 % of sand (72.3 % of fine sand and 9.3 % of coarse sand), 11.3 % of silt (7.1 % of fine silt and 4.2 % of coarse silt) and 7.1 % of clay. The weather conditions were low temperatures (respectively 7.6 °C and 8.7 °C) with cloudy sky.



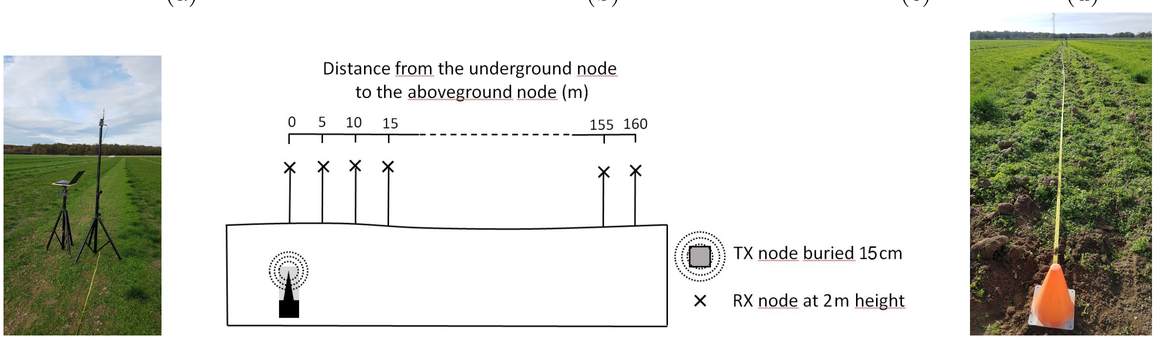
(a) (b)

Figure 6: Experimental field: (a) Google Earth © Digital Globe, 46°20'22.35"N, 3°25'44.28"E, 280m (b) Soil texture triangle based on the Unites States Department of Agriculture (USDA) classification

3.1 Tests with different soil moistures

A PVC tube of 8 cm diameter is buried on the field with the moisture probe on the side, see Figures 7a and b. It is next covered with soil and compacted. A first set of experiments uses a set of TX and RX nodes operating at 433 MHz. A second set of experiments uses nodes operating at 868 MHz. Two different soil moistures (10 % and 22 %) are investigated. For each experiment, the TX node is installed inside the tube at about $d_1 = 15$ cm deep. The RX node is positionned on a tripod at $d_2 = 2$ m height, see Figures 7c, 7d, 7e, and is straightly moved with steps of 5 m, see Figures 7f anf 7g.

(a) (b) (c) (d)



(e) (f) 2 (g)

Figure 7: Testbed: (a,b) The TX node is buried with the probe at 15 cm depth, (c,d,e) The RX node is installed on a tripod at 2 m height, (f,g) Steps of 5 m are carried out.

In the first set of experiments, the soil moisture is measured by the probe at 10.3 %, the soil relative permittivity at 6.0 and the soil temperature at 9.4 °C. The results are presented on the left part of Figure 8: at each inter-node distance RX-TX, the SF graphics highlight if the UG2AG link was successfully established or not for a spreading factor SF varying from 7 to 12. Clearly, the set of nodes operating at 868 MHz reached longer distance (170 m) than with the set at 433 MHz (125 m). These distances were reached by configuring a high spreading factor (SF 12) for the LoRa modules, that enables a high sensitivity and communication range to the detriment of the airtime and high energy consumption. We can observe that until 90 m, the UG2AG link at 868 MHz is maintained for all the SF values, whereas only 55 m for the UG2AG link at 433 MHz. Therefore, although the 433 MHz is theorically more relevant to obtain longer communication range compared with the 868 MHz, the possibility to tune higher the power transmit at 868 MHz (+14 dBm for the 868 MHz and +10 dBm for the 433 MHz in line with the regulations) reverses the results. The values RSSI (Received Signal Strength Indication) and SNR (Signal-to-Noise Ratio) of the RX node decrease slowly with respect to the internode distance. They are however clearly higher at 868 MHz than at 433 MHz enabling to maintain the communication at a longer distance, despite more variations at 868 MHz.

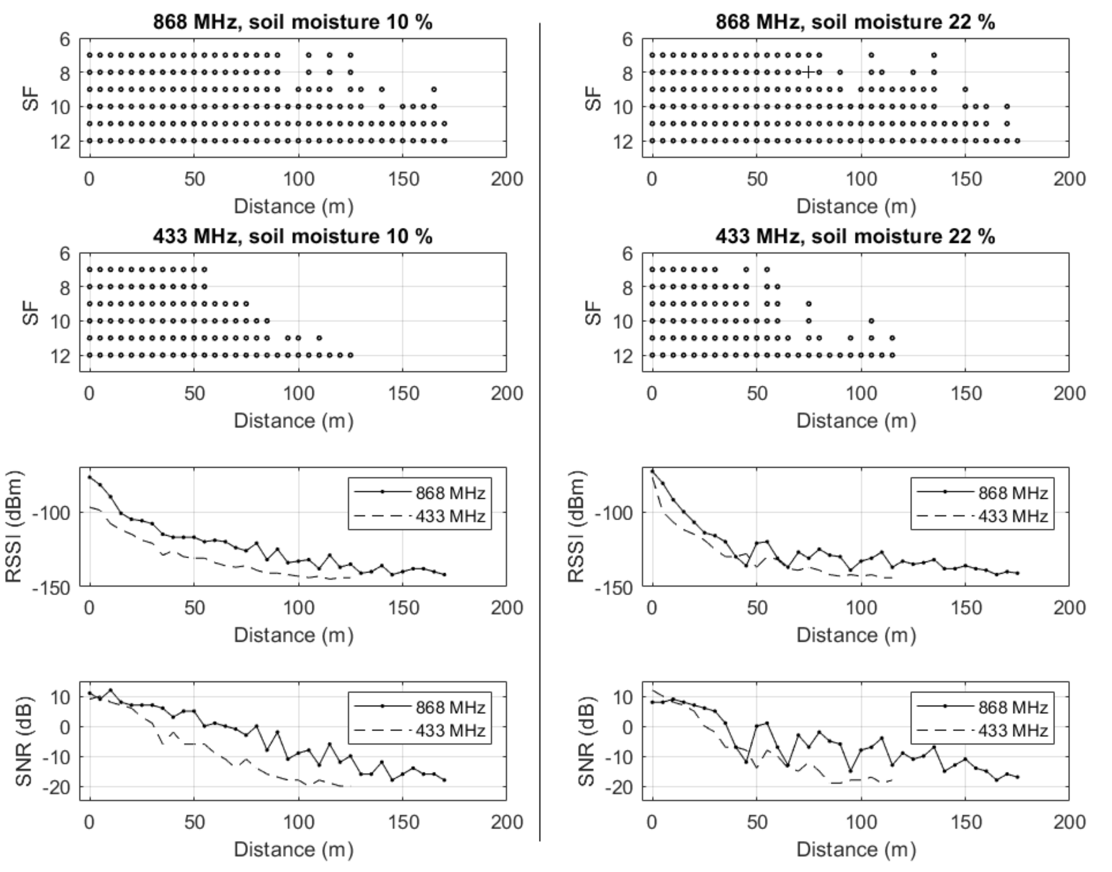


Figure 8: Measurements on the UG2AG link obtained with a soil moisture of respectively 10 % (left part) and 22 % (right part)

In the second set of experiments, the soil moisture and permittivity were doubled in comparison with the first experiments (soil moisture 22.8 % and relative permittivity 12.2). The soil temperature was at 11.9 °C. The results are presented on the right part of Figure 8. We can observe that the maximal internode distance with the set of nodes at 868 MHz is slightly affected by the higher soil moisture, leading to communications until 175 m. Moreover, until 80 m, the communications are always possible with all the SF values. The set of nodes at 433 MHz is however more impacted by the higher soil moisture: the maximal internode distance is slighly reduced (from 125 m to 115 m) but the communications are only possible with high SF values, and that from the distance 70 m. The RSSI and SNR values are however more stable at 433 MHz than at 868 MHz which have more variations.

For these tests, we can also notice that the minimal RSSI value for the RX node is measured at -144 dBm, that is close to the sensitivity given in the datasheet of the SX1276 component (-148 dBm). These experiments highlight the importance of this parameter in the choice of the radio component. By comparison, the sensitivity of the first LoRa transceiver SX1272 from Semtech was -137 dBm. In addition, these experiments highlight that as the communication signal is less attenuated at 868 MHz than at 433 MHz, a lower SF can be used to reach the same distance (e.g. at 100 m and soil moisture 22.8 %, the TX node at 868 MHz can use a SF=9 whereas the TX node at 433 MHz has to use a SF=12). That enables to reduce the transmit time (this time is divided by six from SF=12 to SF=9, see the previously presented Table 2), and therefore limit the energy consumption of the TX node.

3.2 Tests with the same transmit power (10 mW)

The previous tests were carried out with TX nodes in line with the European regulations, i.e. +14 dBm/25 mW at 868 MHz and +10 dBm/10 mW for the 433 MHz, meaning a difference of 4 dBm. To compare the performances with the same transmit power, the transmit power of the 868 MHz TX node was decreased at +10 dBm/10 mW. The results are presented on Figure 9.

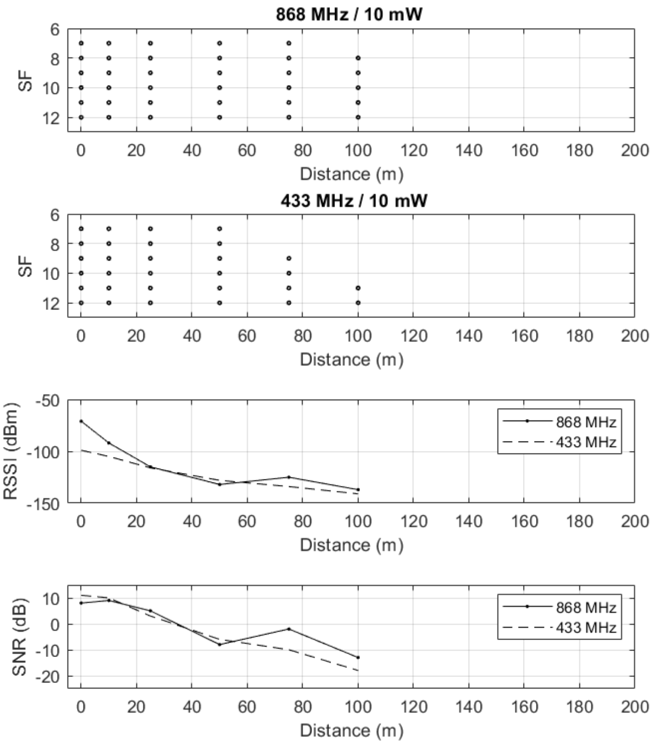


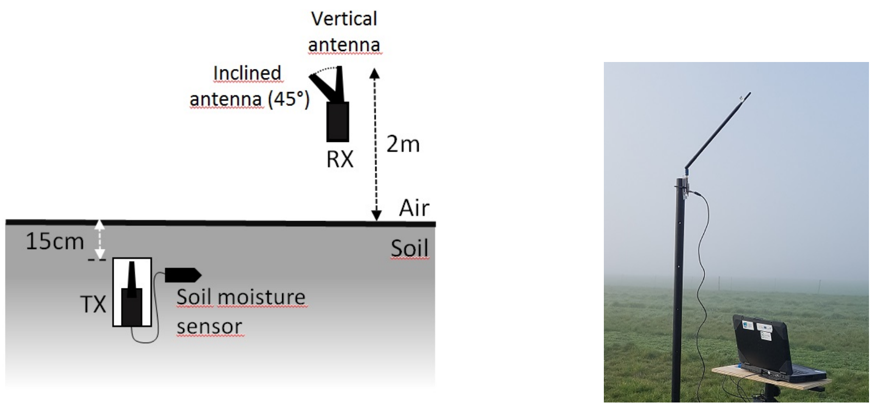
Figure 9: Same transmit power

We can observe that, even with the same transmit power, the communication at 868 MHz is less attenuated than at 433 MHz (e.g. at the distance of 100 m, the signal is received at 868 MHZ with SF=8 and SNR=-13 dB whereas at 433 MHz the signal is received with SF=11 and SNR=-18 dB).

Face to such results, we decided to continue the investigations on the UG2AG communication link using exclusively the 868 MHz frequency band. We investigated different configurations for the deployment of the nodes which can impact the communication range. The following section addresses the impact of the inclination of the RX antenna on the communication range.

3.3 Tests with different RX antenna inclinations

The objective is here to study the impact of the inclination of the RX antenna on the communication range, see Figures 10a and 10b. Preliminary tests enabled to select two relevant inclinations of the RX antenna for the field experiments, i.e. a vertical RX antenna and an inclined RX antenna at 45°. The RX antenna is pointed towards the buried TX node. As previously, the TX node is placed in a PVC tube and buried at 15 cm deep. The RX node is placed at 2 m above the soil. The experimental conditions were permittivity 9.0, humidity 16.85 %, temperature 6.8 °C.



(a) (b)

Figure 10: a) Experimental setup, b) Inclination of the Rx antenna pointed toward the TX node

The results are presented on Figure 11. They highlight that the inclination of the RX antenna enables to maintain the communications with low SF (e.g. at 250 m, SF=9 when the RX antenna is inclined, and SF=12 when the RX antenna is vertical) and significantly reduce the attenuation of the signal: the RSSI signal is about 10 to 15 dBm higher when the RX antenna is inclined in comparison when the RX antenna is vertical. The SNR signal remains moreover positive on a distance largely superior when the RX antenna is inclined (positive until 150 m) in comparison when the RX antenna is vertical (positive until 50 m).

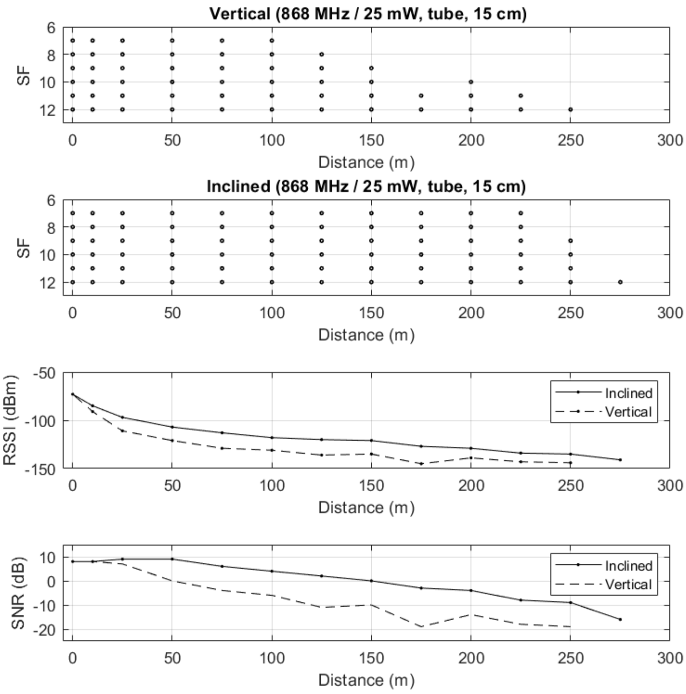


Figure 11: Tests with a vertical and inclined (45°) RX antenna

3.4 Tests with different burial depths for the TX node

After have highlighted the interest of the 868 MHz frequency band and the inclination of the RX antenna, the objective of the following experimentations were to evaluate the impact of the depth of the buried node on the UG2AG communication. For that, two burial depths were considered, respectively 15 cm and 30 cm as depicted on Figure 12. The RX node is still placed at 2 m above the soil, and the measurements are carried out successively with a vertical RX antenna and an inclined RX antenna. The experimental conditions were permittivity 12.45, humidity 23.36 %, temperature 8.7 °C. The results are presented on Figure 13.

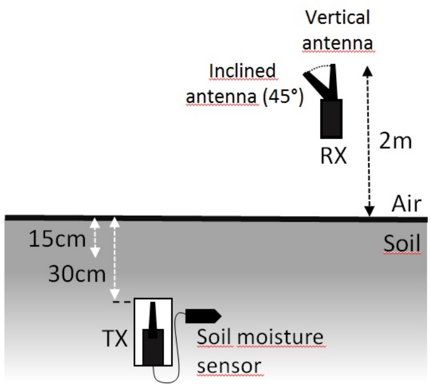


Figure 12: Experimental setup

When the RX antenna is vertical, the communication range was 250 m when the TX node is at 15 cm deep. At 30 cm deep, the range is reduced to 175 m. The values of RSSI and SNR are however similars until 175 m, but when the TX node is at 15 cm, the RSSI signal is maintained

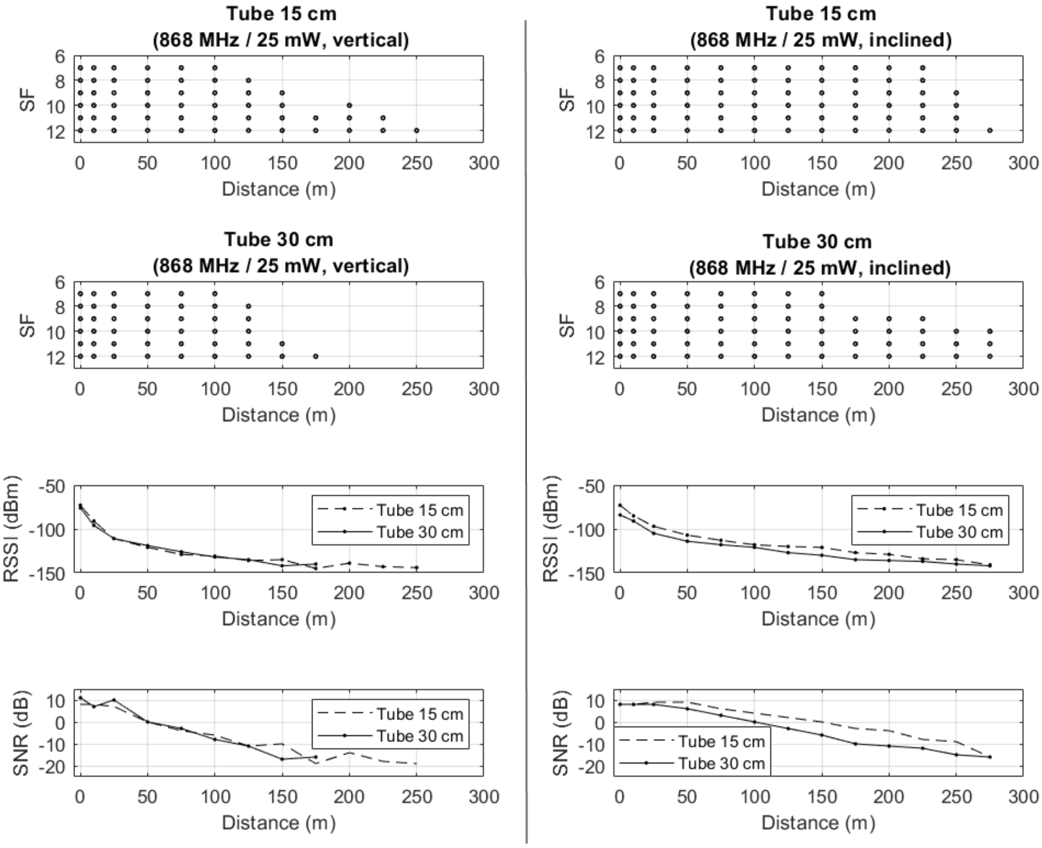
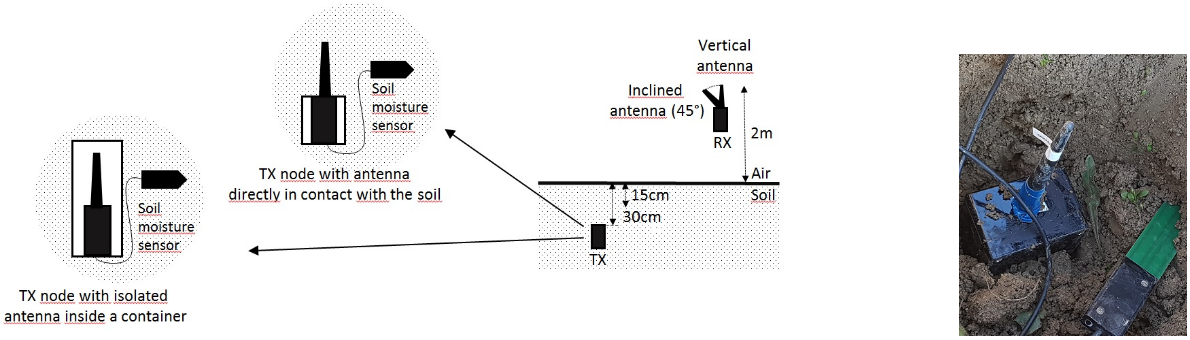


Figure 13: Measurements on the UG2AG link obtained with a burial depth of respectively 15 cm and 30 cm with a vertical RX antenna (left part) and inclined RX antenna (right part)

about -142 dBm until 250 m. When the RX antenna is inclined, the RSSI signal decreases of about 7dBm when the TX node is at 30cm deep in comparison with 15 cm. The SNR signal is positive until 100 m for the TX node at 30 cm deep, and until 150 m for the TX node at 15 cm deep (in comparison, the SNR signal is only positive until 50 m for the two burial depths when the Rx antenna is vertical). These results highlight the negative impact on the UG2AG link of the burial depht. However, the performances remain acceptable, even at 30 cm deep, that enables to envision environmental and agricultural monitoring applications.

3.5 Tests with the Tx antenna inside a container (PVC tube) or directly in contact with soil

In all the experimentations presented in the previous sections, the TX antenna was located inside a PVC tube of 8 mm diameter. However, in order to check if this container had an impact on the quality of the communication, some comparative tests were carried out with the TX antenna directly in contact with the soil and the TX antenna in the PVC tube, see the principle scheme and materials on Figure 14. For each of these two configurations, the measurements were carried out with respectively 15 cm and 30 cm burial depths, and with respectively a vertical and inclined RX antenna. The experimental conditions were permittivity 12.45, humidity 23.36 %, temperature 8.7 °C. Figures 15 and 16 present the results, and Tables 4 and 5 highlight particular points.



(a) (b)

Figure 14: a) Experimental setup b) TX antenna directly in contact with the soil

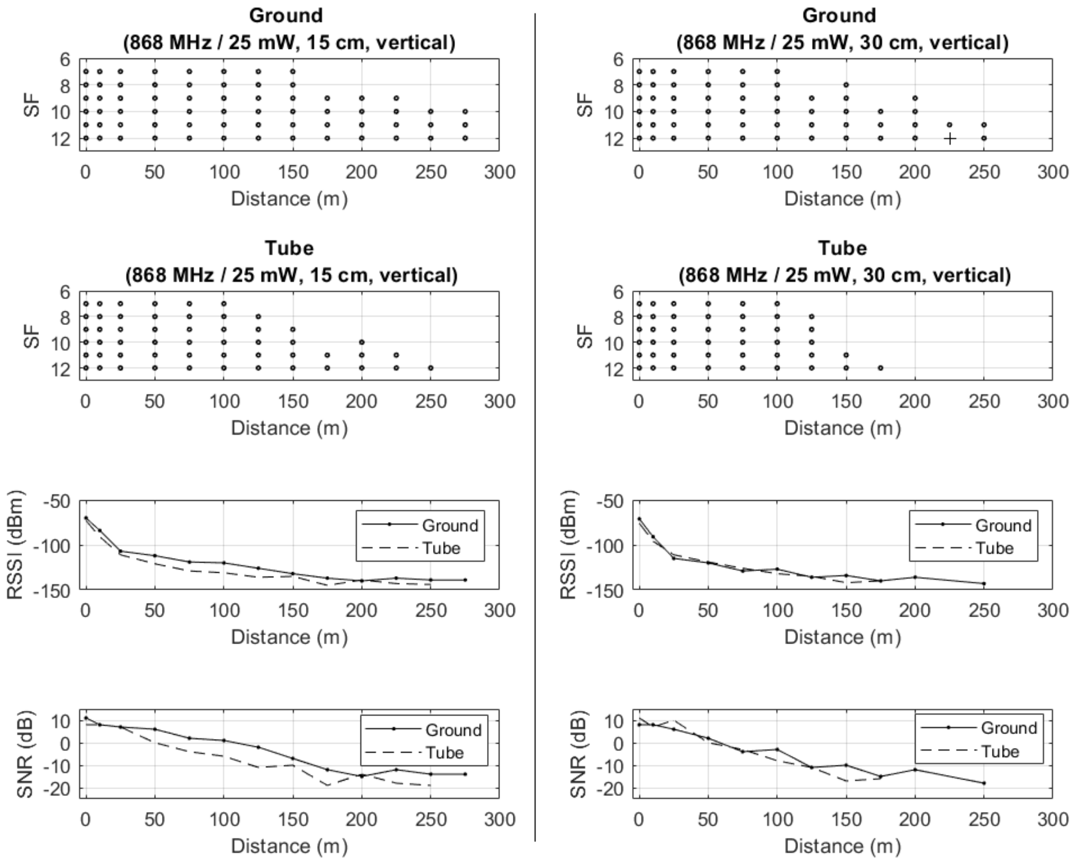


Figure 15: With vertical RX antenna

Table 4: Vertical RX antenna: RSSI and SNR values

		150 m		250 m	
		RSSI (dBm)	SNR (dB)	RSSI (dBm)	SNR (dB)
15 cm	Ground	-132	-7	-139	-14
15 cm	Tube	-135	-10	-144	-19
30 cm	Ground	-134	-10	-	-
30 cm	Tube	-142	-17	-	-

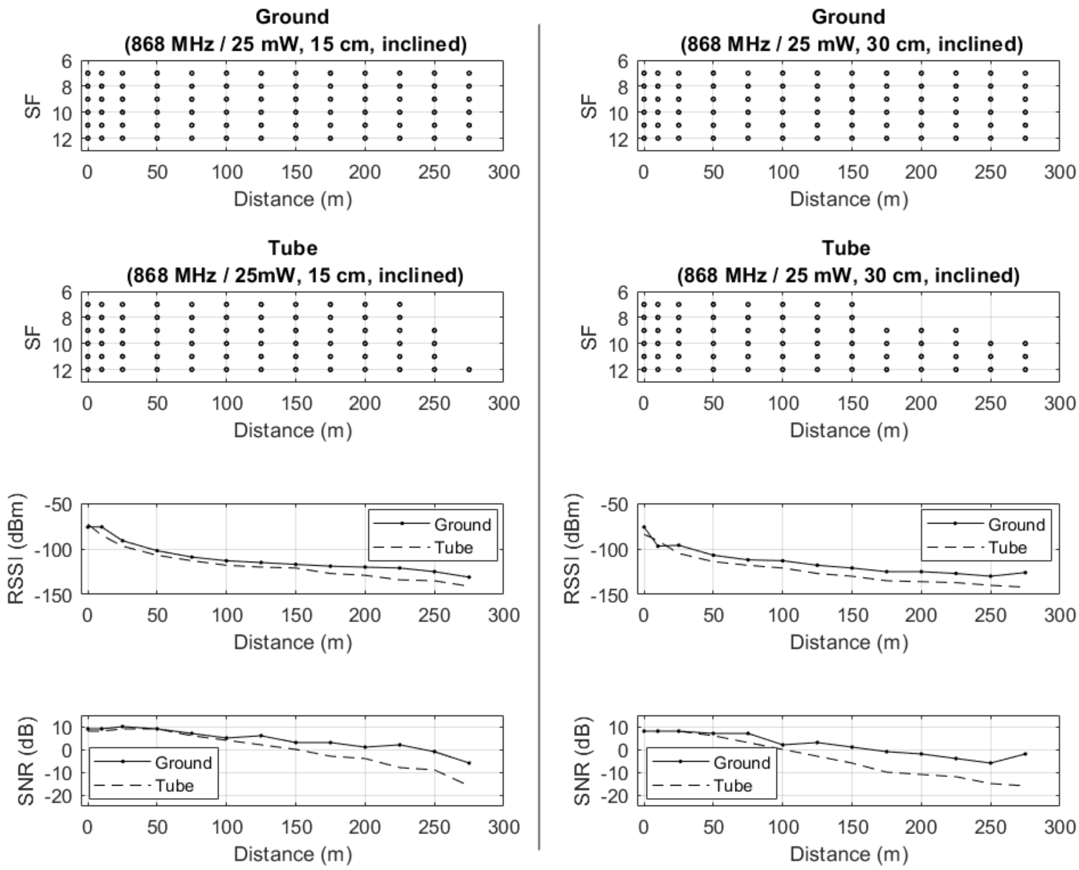


Figure 16: With inclined RX antenna

Table 5: Inclined RX antenna (45°): RSSI and SNR values

		150 m		250 m	
		RSSI (dBm)	SNR (dB)	RSSI (dBm)	SNR (dB)
15 cm	Ground	-117	3	-125	-1
15 cm	Tube	-121	0	-136	-10
30 cm	Ground	-120	2	-130	-6
30 cm	Tube	-130	-6	-140	-15

The RX antenna was vertical in Table 4, and inclined in Table 5. In the two Tables, the results are given for the inter-node distances of respectively 150 m and 250 m. In Table 4, at 150 m, the RSSI value decrease of 3 dBm at 15 cm deep when the TX antenna is placed on the PVC tube (from -132 to -135 dBm), and 8 dBm at 30 cm deep. At 250 m, the RSSI signal is attenuated of 5 dBm at 15 cm deep, and no communication is possible at 30 cm deep. In Table 5, it appears clearly that the RSSI and SNR values are improved when the RX antenna is inclined. In particular, at 150 m, the SNR value remains positive when the RX antenna is directly in contact with the soil at 15 cm and 30 cm.

These results highlight clearly the negative impact of the PVC container on the communication. The performances are better when the TX antenna is directly in contact with the soil with RSSI signals about 10 dBm higher. Moreover, when the RX antenna is inclined and the burial depth is 15 cm with the TX antenna in contact with the soil (see the right part of Figure 16), this configuration enables to emit with SF=7 whatever the distance, leading to a short transmit time and energy consumption. The atteinable communication range with this configuration was 275 m. However, the limit of the communication range was not reached and longer distance could certainly be attainable. In fact, at 275 m, we reached the limit of the experimental field. However, such distance is already suited to develop monitoring applications based on UG2AG communications.

3.6 Reliability of data transmission

The packet delivery ratio (PDR), i.e. the ratio between the number of received packets (R) to the total number of sent packets (S), is an indicator of the reliability of the communication, see (1).

$$PDR(\%) = \frac{R}{S}.100 \tag{1}$$

Experimentations were carried out to determine this ratio at each SF for internode distances going from 50 m to 200 m, see Table 6. The TX node was buried at 15 cm depth with the antenna directly in contact with the soil, and the RX node was located 2 m above the ground with a vertical RX antenna. At each SF, the TX node sends 100 packets and the number of received packets by the RX node was measured as well as the RSSI value.

Table 6: Packet delivery ratio at different SF and RSSI values. Experimental conditions are 868MHz / 25mW, burial depth 15 cm, TX antenna in contact with the soil, vertical RX antenna, soil moisture 17 %

RSSI Internode distance	-115 dBm 50 m	-120 dBm 100 m	-130 dBm 150 m	-135 dBm 200 m
SF=7	99 %	100 %	9 %	0 %
SF=8	99 %	99 %	30 %	0 %
SF=9	100 %	97 %	90 %	37 %
SF=10	99 %	97 %	100 %	42 %
SF=11	100 %	100 %	100 %	90 %
SF=12	99 %	100 %	100 %	100 %

The results highlight that for RSSI values up to -120 dBm, that corresponds to an internode distance of 100 m, less than 3 % of packets were lost and the value of SF has little impact. However, from RSSI values below -130 dBm, the value of SF significantly impacts the quality of the link. At SF=7 and -130 dBm, only 9 % of the packets transmitted were received in comparison to 100 % at SF=12. At -135 dBm, no packet was received at SF=7 and still 100 % at SF=12.

4 Discussion and conclusions

This paper addresses the issue of the communication range of an UG2AG link in a WUSN to serve as basis for future applications in agriculture and environment monitoring. Based on the LoRa technology, two sets of nodes at 433 MHz and 868 MHz were built and tested in real conditions, i.e. an open field with sandy soil composition, soil moisture of 10 % and 22 %, and burial depht of the nodes at 15 cm and 30 cm. The interest of the 868 MHz radio modules at the maximal allowed transmit power in Europe (+14 dBm/25 mW) was first clearly highlighted with results more relevant in comparison to the 433 MHz frequency at +10 dBm/10 mW. Next, completed with a TX antenna directly placed in contact with the soil, as it was shown that a PVC container significantly attenuates the communication signal, and with an inclined RX antenna at 45° pointed toward the buried node, UG2AG communication ranges of more than 275 meters long were reached. At this distance, the LoRa parameter SF can moreover be maintained at a low value enabling to limit the energy consumption of the buried TX node. The benefit to place the TX antenna directy in contact with the soil and incline the RX antenna is highlighted in the Table 7 which is the synthesis of the results at the internode distance of 100 m.

Table 7: Synthesis of results at 868 MHz / 25 mW, internode distance: 100 m

	RX antenna	Straight				Inclined			
	TX antenna	Inside tube		Soil contact		Inside tube		Soil contact	
	Burial depth (cm)	15	30	15	30	15	30	15	30
SF=7	RSSI (dBm)	-131	-132	-122	-129	-117	-123	-112	-115
	SNR (dB)	-7	-9	0	-6	4	-1	7	5
SF=8	RSSI (dBm)	-131	-132	-119	-131	-117	-123	-112	-115
	SNR (dB)	-7	-9	0	-7	4	-1	8	6
SF=9	RSSI (dBm)	-131	-133	-119	-129	-117	-124	-112	-115
	SNR (dB)	-7	-11	0	-6	5	-1	7	7
SF=10	RSSI (dBm)	-132	-132	-119	-129	-116	-121	-112	-114
	SNR (dB)	-7	-9	1	-6	4	0	7	7
SF=11	RSSI (dBm)	-131	-131	-120	-129	-117	-121	-112	-115
	SNR (dB)	-6	-7	1	-5	5	0	8	7
SF=12	RSSI (dBm)	-131	-132	-120	-129	-118	-121	-112	-115
	SNR (dB)	-6	-9	1	-5	4	0	8	7

Although these results are already relevant to envision the deployment of such nodes in the field, several improvements could be considered in future work. First, it will be necessary to deploy several TX buried nodes in the field during several seasons to study the behavior and reliability of the communications over different weather conditions and vegetation cover. Moreover, it could be interesting to adapt some parameters of the nodes, as well as the layout of the RX node in the field. In particular, the SF parameter could be tuned with respect to the soil moisture measured by the probe (e.g. low value in dry soil and high value in wet soil). Another way could be to modify the SF value with respect to the RSSI and SNR values measured by the RX node as with the adaptive data rate (ADR) in the LoRaWAN protocol (Li et al., 2018). This approach requires however to implement the AG2UG link and define listening windows for the RX node. During our experiments, we have also observed the benefit for the communication range to orientate the antenna of the RX node towards the TX node. In case of several TX nodes disseminated in the field or a mobile RX node embedded on a vehicle, an approach could be to actuate the orientation of the RX antenna to control and maintain this direction during inter-node communications, e.g. from the knowledge of the GPS coordinates. This approach requires however some memory capacities of the TX nodes and bi-directionnal communications with adequate strategies. Another point that could be considered is to investigate the robustness of the UG2AG communication face to the potential presence of interferences. In fact, the experimentations reported in this paper were performed in relatively interference-free areas, i.e. without active transmitters in the immediate vicinity with the same frequency range. Most of the time, this is the case in the considered applications (agriculture and monitoring of natural environments). However, although LoRa is a robust technology which possesses a remarkable immunity to multipath and interferences, in particular when small bandwidths and high spreading factors are used, the presence of interferences in more disturbed environmenst could be studied, with the possibility to adapt both the channel frequency and the coding rate. Finally, other frequency bands could also be advantageously investigated in the WUSN, as the 869.4 - 869.65 MHz which allows transmit powers of 500mW, that means twenty times higher than the transmit power used in this paper. This band is not part of the LPWAN (Low Power Wide Area Networks) and is thus not suited for monitoring applications as it would involve a high energy consumption for the TX buried node, but it could be used as an alternative to send alert messages requiring reliable communications.

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