UNDERGROUND WIRELESS COMMUNICATION AND WAKE-UP AT 125KHZ

Alain Jansen
University of Twente
The Netherlands
g.a.a.jansen@student.utwente.nl

ABSTRACT

Wireless Underground Sensor Networks (WUSNs) have applications in, for example, environment and infrastructure monitoring. Typically used high-frequency radio waves for communication between nodes do not penetrate soil well, which results in a short communication range. On the other hand, low frequency signal suffer from much less signal loss in soil. Magnetic Induction communication, which uses low frequency signals, is a promising technique that could be used to meet the range requirements for Wireless Sensor Network Applications. Power conservation is also a design challenge for WUSNs. Previous work suggests that Wake-Up receivers can significantly increase battery life. Multiple experiments have been conducted to find the maximum communication distance in aboveground and underground conditions. All the tests have been performed by using the same transmitter and Wake-Up receiver that operate at 125 kHz. The results of the experiments showed that the maximum communication distance was roughly the same in air and underground. The found maximum distance was 6 m, but this distance could likely be improved. Hence, the technique looks promising for WUSN applications.

Keywords

Underground Communication, Wireless, Low Frequency, Magnetic Induction, Wake-Up, Wireless Underground Sensor Network

1. INTRODUCTION

Wireless Sensor Networks (WSNs) have a plethora of applications, performing tasks like monitoring, tracking and controlling. Two critical aspects of WSNs are their longevity and reliability [3]. When lots of sensor nodes are deployed, it would be undesirable to have to change the batteries of a device when it runs out of energy. Thus, the nodes should be energy efficient. Furthermore, when a node senses something, the measurements should reach the desired location, rendering them useless otherwise. This means the connection between nodes should be reliable. The aspect of reliability that is of interest for this paper is the communication distance while still having a stable connection.

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One sub category of WSNs are Wireless Underground Sensor Networks (WUSNs). As the name implies, sensor nodes are deployed underground, for example in soil, mines or caves. One application of WUSNs is environmental monitoring, with monitoring soil conditions as an example. WUSNs could also have applications in infrastructure monitoring. For instance, they could be used to monitor the condition of pipelines. [1].

As discussed earlier, key aspects of typical WSNs are longevity and reliability/communication distance. However, due to the underground conditions, typically used Electromagnetic (EM) waves with high frequencies cannot be used. This is because they suffer from very high loss in high density materials [1] such as soil.

As for the longevity, changing the battery nodes is already undesirable in terrestrial sensor networks. When the nodes are buried underground, recharging or replacing the power supply of nodes will be more difficult because it is harder to reach the nodes. Another problem is that the radios of WUSN devices typically have to be stronger than those found in terrestrial ones due to the very lossy underground channel. This means that more power will be consumed when transmitting data when compared to many existing low energy communication options.

1.1 Related work

1.1.1 Communication

Current research regarding the underground communication mostly focuses on EM waves and Magnetic Induction (MI). The majority of research has been done about the use of EM waves, mostly in the frequency range of MHz and higher signals. One major disadvantage of EM waves is that HF waves (having a frequency of more than 3 MHz) are bad at penetrating soil. This is because HF waves suffer from high attenuation in soil compared to in air. On the other hand, Low Frequency (LF) signals (having a frequency of 299 kHz and lower) suffer from less attenuation in underground conditions than HF signals, which makes them a better choice for WUSNs.

LF waves are typically used for so called ground wave communication. LF waves have a long wavelength (more than 1 km), which means they can diffract over obstacles and allows them to follow the contours of the earth. Paper [9] goes into more detail about this.

However, LF EM waves also come with some downsides. Generally speaking, the lower the used frequency, the larger the antenna should be [1]. As an illustration of this, antennae typically have a size that is a fraction of the wavelength. A 125 kHz wave has a wavelength of approximately 2400 meters. Thus, when making an antenna using 1/4 of the wavelength, the antenna size is 600 meters.

Another disadvantage of using EM waves is the problem of multi-path fading [4]. Multi-path fading occurs when nodes are buried close to the surface. If a node sends out a signal it can be reflected by the ground surface. There will be a direct signal path between the two nodes and a path that follows the wave that was bounced off the surface. The waves following these paths could interfere, leading to a decrease in the communication range.

Finally, even if LF EM waves suffer less from attenuation in soil compared to HF waves, they still do suffer more from signal loss underground than in the air.

As for MI, the used antennae are (small) coils. The transmitter coil is used to generate a magnetic field. This field will induce some voltage in the receiving node and can be used to communicate data. MI communication has some advantages over EM communication, namely somewhat constant dynamic channel conditions and a small antenna size in comparison to EM. This is because underground mediums (mainly soil and water) have comparable magnetic field attenuation to air [8]. Carrier signals of different frequencies (125 kHz and 13.56 MHz) have been tested. These tests did show that lower frequencies also perform better than higher frequencies when using MI communication [5]. Furthermore, the problem of multi-path fading should not occur when using MI communication [8].

1.1.2 Power conservation

For power conservation, there has been some research on power scavenging techniques. These techniques include harvesting energy from tremors or radio waves [7]. However, the authors remarked that further research is required for the use of such techniques.

Energy could also be conserved by making use of smart topology or networking schemes [1]. One example of such a scheme would be making use of so-called Wake-Up receivers [2]. By using a combination of Wake-Up receivers and a matching network topology, energy can be conserved. It is particularly useful for periodic or query-based applications, which is the typical application domain for WUSNs.

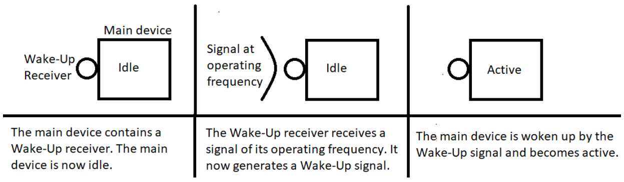


Figure 1. Schematic overview of Wake-Up mechanics.

Figure 1 shows how a Wake-Up scheme works on a very basic level. The main device is idle/on standby and a Wake-Up receiver is attached to it. By means of passive (powered by the received signal) or active (using a battery) Wake-Up, the main device will get a Wake-Up signal that it should turn its main radio on again. This Wake-Up signal will be generated when a signal of a certain desired frequency arrives. To filter out noise, a Wake-Up pattern could be used. This means that the signal from the transmitter contains a bit-pattern that corresponds with the Wake-Up pattern of the receiver. The receiver will only generate a Wake-Up signal if the two patterns are the same.

1.2 Problem statement and suggested solutions

HF signals suffer from a high signal loss in underground conditions. To alleviate this, LF signals could be used. To keep the antenna size down and have constant channel conditions, MI communication techniques should be used.

Furthermore, energy consumption is a major topic for WUSNs. Energy conservation using Wake-Up receivers has not yet been tested extensively in underground conditions. Assuming a Wake-Up scheme would save energy, it should be looked at how long the communication distance is when using a Wake-Up receiver. The main problem here is that typical Wake-Up receivers have a very small antenna which limits the communication range.

1.3 Research questions

- Wireless sensor devices should have a long lifespan because it is undesirable to have to change the battery. One solution to increase the battery life of a sensor device could be to use a Wake-Up mechanic.

  Could low frequency (125 kHz) signals be used to notify a device to Wake-Up in underground conditions?

- Typically used high frequency signals do not penetrate soil well, which results in a high loss of signal and a very limited communication range.

  What communication distance can be achieved by using 125 kHz signals for communication and a Wake-Up receiver as the receiver node?

- There exist RFID- and Wake-Up Devices which operate at 125 kHz.

  Could these existing devices, possibly with some modifications, be used as devices for a WUSN?

2. GENERAL TESTING SET-UP

Before delving into the tools used, a quick overview of the general idea behind the test set-ups is in order.

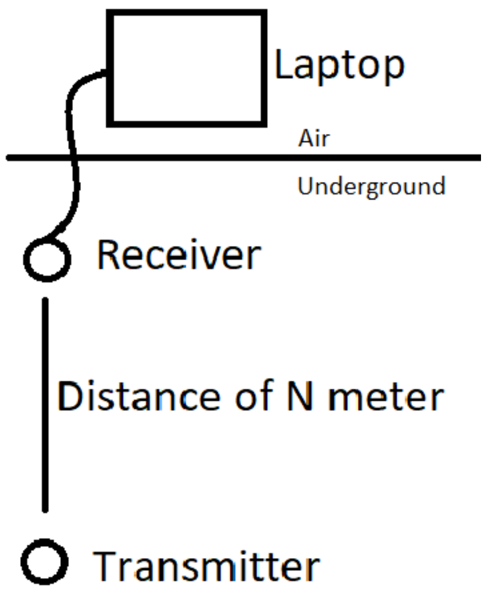


Figure 2. General overview of the testing set-ups.

Figure 2 shows the general idea behind the testing set-ups that will be discussed later. The set-up contains a receiver node, a transmitter node and a certain distance between them (N meters). In the case of underground testing, the receiver and transmitter nodes both are underground while the laptop is aboveground.

The most important aspect to measure is the Received Signal Strength Indicator (RSSI). The RSSI value represents the strength of the signal when it reaches the receiver. The main aspects that influence this value are the distance between the transmitter and the receiver, as well as how they are oriented towards one another.

The receiver that is used can output the RSSI value. Specifically for the used board (the AS3933 Demoboard), the value is based on the voltage that is induced in an antenna. Generally speaking, the closer the nodes are together the stronger the signal is, which means the induced voltage will be higher. The RSSI value ranges between 0 and 31, with 0 being no induced voltage (and thus no received signal) and 31 being the maximum amount of induced voltage. These values are stored in the registers of the board. According to the documentation of the AS3933 Demoboard, the following formula can be used to calculated the induced voltage in an antenna from the RSSI value:

$Vref = 80 \quad \mu Vrms$

$Vin = Vref * 10^{\frac{RSSI}{10}}$

Were Vin is also in Vrms (Root-mean-square voltage).

To be able to record the RSSI values measured during testing, the receiver node will be connected to a laptop by cable.

3. TOOLS

3.1 Receiver side

3.1.1 AS3933 Demoboard

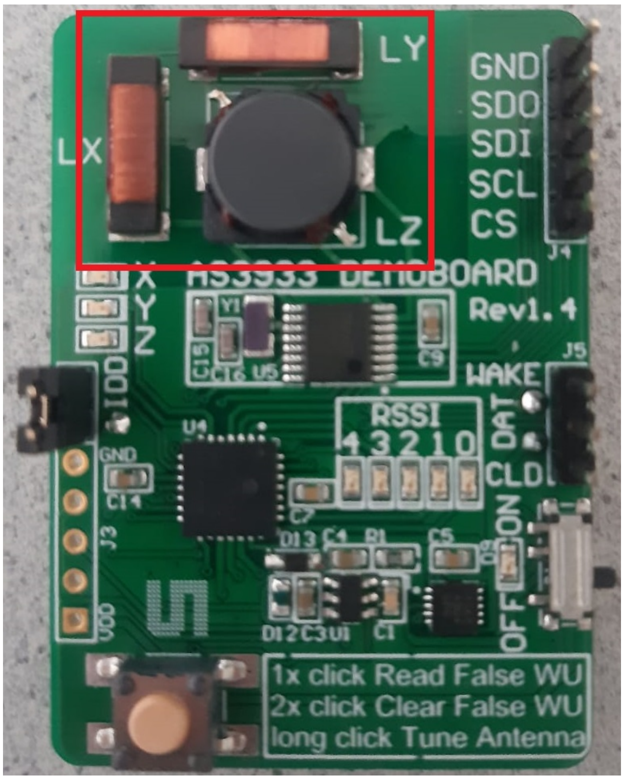


Figure 3. The AS3933 Demoboard.

Figure 3 shows a picture of the AS3933 Demoboard. This board acts as the receiver node and is a Wake-Up receiver. It is a 3-channel receiver, which means it has three different antennae to receive signals. The location of the three antennae is shown in the red box. The main advantage of this is that the alignment between the transmitter and receiver matters less. The transmitter can be aligned to any one of the antennae of the board. The three antennae are tuned to receive signals of approximately 125 kHz.

The Demoboard can also output the RSSI value. What this value consists of has already been discussed in section 2.

The main reason this board was chosen, is the fact that it is a Wake-Up receiver. By using a Wake-Up receiver as the receiving node, both the first and second sub-questions can be answered. As long as the Wake-Up receiver receives a signal, it can generate a Wake-Up signal.

The current consumption of this board while receiving a signal was measured to be 1.9 mA. This value is a bit higher in reality because the measurement was performed by using a multimeter, which has an internal resistance. The author of paper [6] also measured the energy consumption of the AS3933 Demoboard and reported a value of 2.2 mA while the board was receiving data. Taking the the current consumption of the most important components of the Demoboard into account, the current consumption when the system is idle should be 42.74 μA[6].

3.1.2 Software

The AS3933 Demoboard also comes with a piece of software named AS39x EvalSW. This software can be used to change certain settings of the Demoboard and the transmitter, such as disabling certain receiving channels or changing the sensitivity. During the experiments, the default settings have been used.

The most important feature of the software for the experiments is that it can read the register values of the AS3933 Demoboard. Therefore it can be used to extract the RSSI values.

Another program that must be used is screen recording software to make a recording of the output of the registers. During the experiments, the capture function of the Windows 10 Xbox Game Bar has been used, but any screen recording software should suffice.

3.1.3 Laptop

A laptop is used to run the software. It can be connected to the AS3933 Demoboard by means of a Mini-USB cable.

3.1.4 Packaging

Because the Demoboard will also be used underground, it has to be packaged to prevent it from being damaged by the underground conditions (soil and moisture). For this purpose, a plastic takeout box has been used as shown in figure 4. A little hole has been made in the box to put the Mini-USB cable through. To ensure the soil does not enter the box, the hole has been sealed off with tape.

3.2 Transmitter side

3.2.1 125 kHz Wake-up Transmitter Board

Figure 5 shows a picture of the transmitter board. It can send a Wake-Up signal, periodically emit a Wake-up signal, or send a Wake-Up signal followed by a continuous stream of dummy data. All these signals have a frequency of 125 kHz. The AS3933 Demoboard clears its registers quickly after it has received something. Thus reading the

Figure 4. Packaging of the receiver.

register values based on the Wake-Up signals is unreliable. It will most likely result in a list containing only RSSI values of zero. Therefore the mode where it continuously sends data has been used.

The current consumption while transmitting was measured to be 56 mA. This value is higher in reality because the measurement was done using a multimeter, as was the case with the AS3933 Demoboard. While not transmitting anything, the current consumption was measured 25 mA. The consumption could likely be lowered since the board does contain some unnecessary features and is not yet directly connected to a Wake-Up receiver.

One other downside is that this board cannot communicate directly with another device by cable. This means this board cannot be used to create a more complete device (transceiver).

Figure 5. The transmitter board.

3.2.2 *Battery*

Normally, the transmitter board uses an adapter plugged into a power outlet. This is obviously not an option in underground conditions. Hence, an external power source had to be made. The adapter normally outputs 9v and around 2A. A battery pack with 8 AA batteries and a 9v regulator have been chosen to get the same power output as the adapter.

3.2.3 *Transmitter packaging*

The transmitter also has to be protected from underground conditions. The packaging shown in figure 6 is made up of different plastic parts and contains a hook so it can be retrieved easier.

Figure 6. The packaging of the transmitter.

4. METHODOLOGY

In section 2 the idea behind the general test set-up has been discussed. In the next subsection, multiple test set-ups will be discussed. Even if the set-ups are different, how the measurements should be performed and how the results should be extracted remain the same. The main goal of the experiments is to see how far the signal will reach and to see how stable the signal is.

4.1 Preparation and set-ups

For each experiment, it must be ensured the transmitter is in data transmission (Pattern+Data as shown on the board) mode before burying the transmitter. This ensures that the transmitter will constantly send data to the receiver. It is only then that the registers of the receiver are constantly updated with RSSI values.

Experiment 1 and 3 have been conducted both aboveground/in air and underground. The main difference between these scenarios is that for the underground scenario, both the transmitter and receiver are placed underground. When testing in air, everything was aboveground.

Appendix A contains photos of some of the test set-ups.

4.1.1 *Experiment 1*

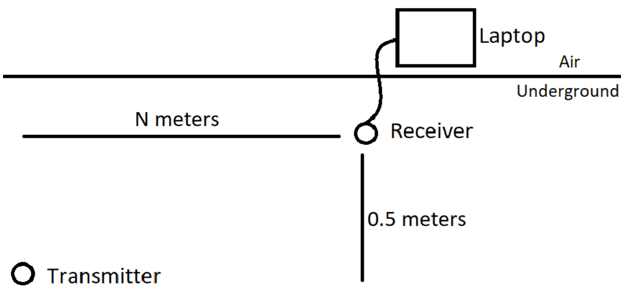


Figure 7. Schematic overview of the first experiment.

Figure 7 shows a schematic overview of the set-up for the first experiment. The transmitter is buried 0.5 m lower than the receiver. The horizontal distance between them starts at 1 m and will be incremented by 0.5 m for each distance to be measured by moving the receiver further away. From these distances, the actual distance between the devices can be calculated using Pythagoras' theorem.

For the aboveground scenario, the transmitter was placed on the ground and the receiver was placed on a plastic object to create a vertical distance of 0.5 m between the receiver and the transmitter.

The main goal of this experiment was to test if the system performs similarly in air and underground. It is expected that they perform similarly.

Figure 8. Orientation of the devices.

Figure 8 shows how the devices are orientated towards one another.

4.1.2 *Experiment 2*

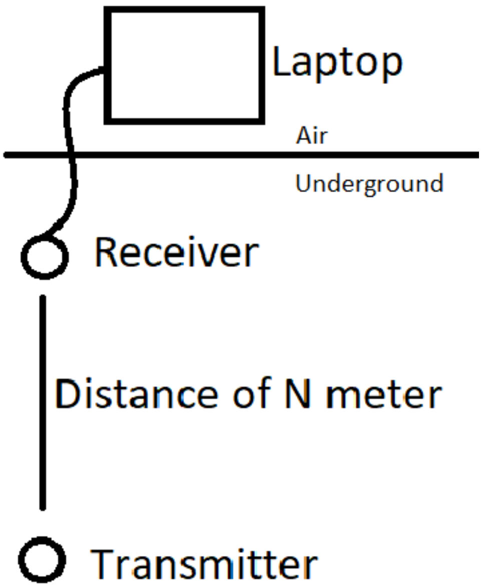


Figure 9. Schematic overview of the second experiment.

In this experiment, the receiver is placed directly above the transmitter, as illustrated in figure 9. The devices are oriented the same as shown in figure 8, but now with the devices aligned vertically. Because of trouble digging deeper than 1.2 m, two measurements have been done for this scenario, with respectively a distance of 0.5 m and 0.9 m between the nodes. This test has only been conducted in underground conditions.

The main goal of this experiment was to see if a better antenna alignment would lead to a higher RSSI values. The expectation is that the RSSI value at a distance of 0.9 m is bigger than the RSSI value found at around 1 m in experiment 1.

4.1.3 *Experiment 3*

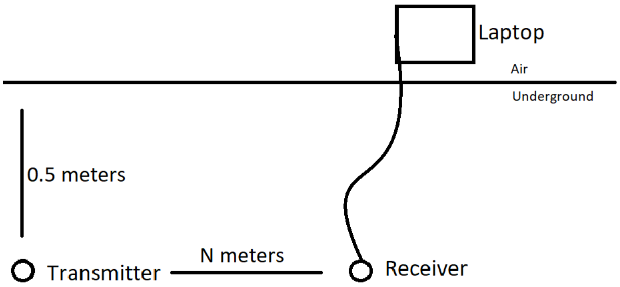


Figure 10. Schematic overview of the third experiment.

For the third experiment, the receiver and the transmitter had both been buried at the same depth of 0.5 m, as can be seen in figure 10. The idea behind this is that the maximum achievable communication distance will be greater than the one in experiment 1 due to better antenna alignment.

Once again, there is a horizontal distance between the two nodes. This distance starts at 2 m and is incremented by 1 m for each distance to be measured by moving the receiver further away.

Figure 11. Orientation of devices for third experiment.

Figure 11 shows the orientation of the devices for this experiment. Note that the orientation for this experiment is practically the same as the orientation in the second experiment. This is because the core of the coil of the transmitter directly points at one of the coils of the receiver.

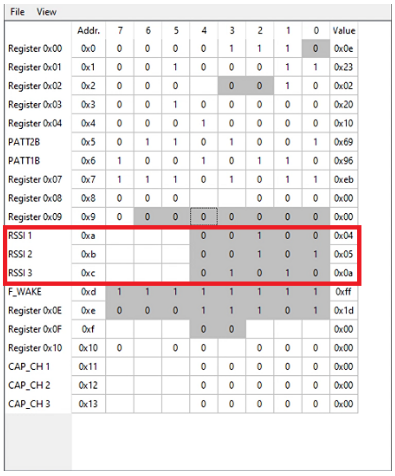
For the aboveground scenario, both devices were placed on a plastic object at 0.5 m above the ground.

The main goal of this experiment was to see how the system performs compared to experiment 1 and how much distance could be gained with better antenna alignment.

The expectation of this experiment is that it should be able to achieve a communication distance of a few more meters than in experiment 1.

4.2 Performing the measurements

After the devices have been buried/placed according to the proper set-up, the measurements can start. The "read register" screen in the AS39x EvalSW software can be used to read the register values. Figure 12 shows what the output screen looks like. The register values that are interesting for these experiments are indicated by the red box.


File View

	Addr.	7	6	5	4	3	2	1	0	Value
Register 0x00	0x0	0	0	0	0	1	1	1	0	0x0e
Register 0x01	0x1	0	0	1	0	0	0	1	1	0x23
Register 0x02	0x2	0	0	0		0	0	1	0	0x02
Register 0x03	0x3	0	0	1	0	0	0	0	0	0x20
Register 0x04	0x4	0	0	0	1	0	0	0	0	0x10
PATT2B	0x5	0	1	1	0	1	0	0	1	0x69
PATT1B	0x6	1	0	0	1	0	1	1	0	0x96
Register 0x07	0x7	1	1	1	0	1	0	1	1	0xeb
Register 0x08	0x8	0	0	0			0	0	0	0x00
Register 0x09	0x9	0	0	0	0	0	0	0	0	0x00
RSSI 1	0xa				0	0	1	0	0	0x04
RSSI 2	0xb				0	0	1	0	1	0x05
RSSI 3	0xc				0	1	0	1	0	0x0a
F_WAKE	0xd	1	1	1	1	1	1	1	1	0xff
Register 0x0E	0xe	0	0	0	1	1	1	0	1	0x1d
Register 0x0F	0xf				0	0				0x00
Register 0x10	0x10	0		0	0		0	0	0	0x00
CAP_CH 1	0x11				0	0	0	0	0	0x00
CAP_CH 2	0x12				0	0	0	0	0	0x00
CAP_CH 3	0x13				0	0	0	0	0	0x00

Figure 12. Register values screen.

For getting new register values, the screen has to be manually refreshed. 40 - 55 measurements have been taken for each measurement scenario. To be able to extract the values from the video later on, it should be ensured that the page is refreshed at a constant pace (for example, every second).

4.3 Extracting the results

Sometimes there is no difference in register values between two measurements. If that is the case, there is no clear indication that the values have been updated. This is why the constant pace of refreshing is important: to ensure most of the data can be extracted even if the screen does not show change.

Only the measurements of the antenna with the highest RSSI values have been extracted for further processing, because this is the antenna that is best aligned with the transmitter. This antenna remained the same between measurement scenarios (for instance, between 1 m and 2 m distance). This is not the case between experiments, because of the change in orientation between the devices.

The RSSI values recorded by the system are either binary or hexadecimal values and should afterwards be converted to decimal values for easier processing.

The data is used to evaluate two aspects: the average RSSI value (not containing measurements with a value of zero) and the percentage of measurements that had a value of zero. The average gives a good indication of how strong the signal is (when there is a signal). The percentage of zero measurements should give an indication about how stable the signal is.

5. RESULTS

In this section, graphs that compare the RSSI values and the percentage of zero measurements will be presented. The RSSI value graph show how the RSSI changes over distance. The zero measurement graphs show what percentage of the measurements for that distance had a value of zero.

5.1 Experiment 1

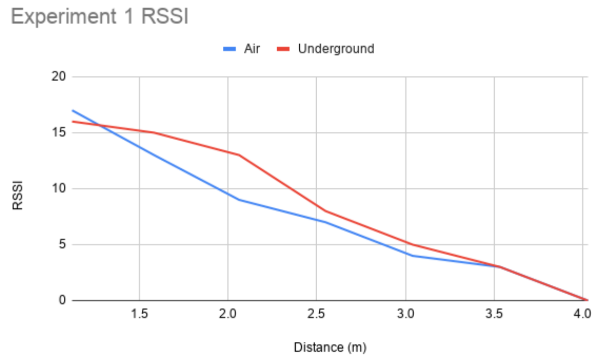


Figure 13. RSSI over distance.

Figure 17 shows how the RSSI changed over the distance. The further away the nodes were from each other, the lower the RSSI values became. It is worth noting that the signal is lost between 3.5 and 4 meters for both the air and the ground scenario.

Figure 14. The percentage of zero measurements over all measurements. The air scenario had 40 measurements, the ground scenario 55.

Figure 14 shows the percentage of measurements with a value of zero for each distance. The air scenario was stable with around 10-15 percent of the measurements resulting in zero, the underground scenario was more over the place ranging between 3-30 percent.

5.2 Experiment 2

Because of trouble digging deep, only two measurements have been performed for the vertical scenario, and only underground. This test mainly served to see if better antenna alignment led to higher RSSI values by comparing the results of experiments 1 and 2. For a distance of 0.5 m between the transmitter and receiver, the RSSI value was 23. For 0.9 meters between the transmitter and receiver the value was 20.

5.3 Experiment 3

The results for this experiment are reported in the same way as the results for experiment 1.

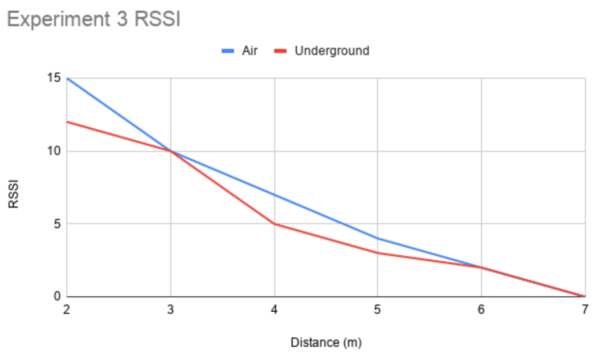


Figure 15. RSSI over distance.

The most important thing to note in figure 15 is that the signal is lost somewhere between 6 and 7 meters for both the air and underground conditions. Overall, the signal strength in the ground seems to be a bit weaker than the signal strength in air.

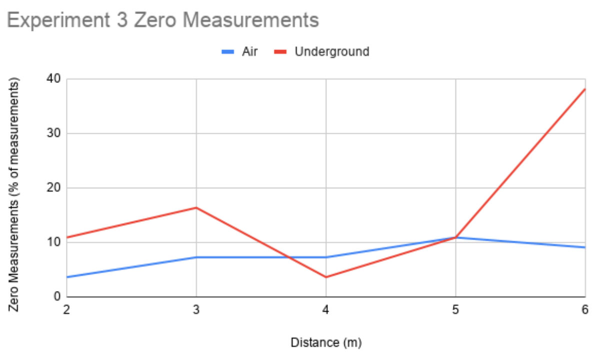


Figure 16. The percentage of zero measurements over all measurements for that distance. Both the air and the underground scenario had 55 measurements.

As for the zero measurements graph for experiment 3 as shown in figure 16, the air condition is once again somewhat stable. However, nearly 40 percent of the underground measurements had a value of zero at a distance of 6 m.

6. DISCUSSION

With the transmitter using the actual adapter hooked up to a power outlet, the maximum communication distance was between 7 - 8 meters. These values serve as a sort of reference value. If the maximum distance found for one of the experiments was lower than that, the cause should be identified.

The humidity of the soil has not been taken into account because there was not enough time and difference in weather between testing days to be able to draw concrete conclusions as to how it affects the results. The soil content was pretty constant between the testing days. The volumetric water content ranged between 0.2 and 0.35 on both days depending on the depth of the sensor. Furthermore, as discussed in section 1.1.1, the soil composition should not have much effect on the results.

6.1 Experiment 1

The maximum communication distance was a meager 3.5 m. This is not enough for actual operation in a WUSN. The nice take-away from this experiment however, was that the underground scenario actually performed similar to the air scenario. As for the signal stability, it seems that the signal is more stable in air conditions because the percentage of zero measurement stayed approximately the same.

6.2 Experiment 2

The main takeaway from experiment 2 is that the reported RSSI value at 0.9 m was equal to 20, quite a bit higher than the RSSI value of 16 measured at 1.1 m (actual diagonal distance, not the horizontal distance) in experiment 1. This led to the hypothesis that better antenna alignment (meaning the alignment as shown in fig 11) would lead to quite an improvement in terms of distance that could be covered.

6.3 Experiment 3

The hypothesis presented in subsection 6.2 is indeed proven true by the results of experiment 3, where the maximum reading distance in underground conditions was 6 m compared to the 4.5 m of experiment 1. However, when looking at the amount of measurements with value zero at 6 m, it can be seen that the signal is very unstable. From this it seems that if the system operates very near maximum distance, the signal becomes very unstable before it is lost entirely. So the actual operating distance is a bit less than 6 m, unless a smart data transmission protocol is used to compensate for the packet loss.

When comparing the performance of the air and underground conditions for experiment 3, the air scenario seemed to perform slightly better. This could have two causes: the antenna alignment was still not optimal during the underground tests or air conditions simply are better for the signal propagation than underground conditions. While it is true that the antenna alignment was more difficult and less verifiable in underground conditions, the other cause cannot be completely disregarded. Even if the signal underground performs worse because the conditions in air are better, the loss is not that great and should not be more than 0.5 m.

The stability of the signal at 6 m was also better in air conditions. This indicates that the maximum distance is a little bit further away than 6 m in air, while the signal got very unstable at 6 m when underground.

Finally, a maximum distance of 6 m is still not close to the reported maximum distance of 7 - 8 meters. While the cause of this has not been formally tested yet, some informal tests have been conducted that have possibly identified the cause. The distance of 7 - 8 m was found when using the adapter as a power source for the transmitter. There were two main differences between the tests: the adapter test used the nodes without packaging and, obviously, used a different power source. The packaging was tested and did not seem to be the problem. The system using batteries reported the same RSSI values in air with and without the nodes packaged. Thus, the cause probably lies with the power source. The voltage was the same for the adapter and the battery pack. Thus the supplied power was unlikely to be the cause. When putting the transmitter in its packaging, the battery pack is directly in contact with the transmitter board. Some short tests in air have been conducted where the battery was moved further away from the transmitter board. They show that the maximum distance increases to around 7 m, which is close to the reference value. It thus seems likely that the battery pack somehow interfered with the signal, but more formal tests have to be conducted to be sure of this behaviour.

7. CONCLUSION

To conclude, a Wake-Up scheme could work for underground conditions. WUSNs typically do not have to report very often, so the use of a Wake-Up scheme will lead to a longer battery life. As long as the Wake-Up receiver can receive a signal, it can generate a Wake-Up signal. Its suitability is thus bounded by the maximum communication distance that can be reached. During the tests, a maximum of slightly below 6 m was found. When taking the cause into account, it could likely be increased to be closer to 7 m if the battery pack was moved away further from the transmitter node.

As for the suitability of these specific devices for deployment in a WUSN, modifications would have to be made. The transmitter node cannot be directly connected to the Wake-Up receiver board. But even if it is not feasible with these specific devices without (very heavy) modifications, the technology and principles can be combined. However, further research is required to see if the energy consumption for the receiver and transmitter can be reduced if they are idle.

Up to a distance of 6 m, the devices perform very similarly in the air and underground. If one would use different devices using the same principles as the AS3933 devices, but with a longer communication distance in air, it seems likely that the communication distance will also increase when underground. One example would be using a Wake-Up receiver with larger coils, since this would likely increase the maximum communication distance. Paper [8] also suggests a so-called Wave Guide System, where there are coils in between the nodes that acts as relays to increase the communication distance.

Communication using 125 kHz signals in underground conditions seems promising. The signal does not seem to suffer from much loss in underground conditions, but with these specific devices the distance was limited to 6 m. However, this range could likely be increased by some of the aforementioned methods.

8. REFERENCES

[1] I. F. Akyildiz and E. P. Stuntebeck. Wireless underground sensor networks: Research challenges. *Ad Hoc Networks*, 4(6):669–686, 11 2006.

[2] I. Demirkol, C. Ersoy, and E. Onur. Wake-up receivers for wireless sensor networks: Benefits and challenges - [Accepted from open call]. *IEEE Wireless Communications*, 16(4):88–96, 8 2009.

[3] U. Farooq. Wireless Sensor Network Challenges and Solutions Android Operating System Architecture View project Wireless Sensor Network Challenges and Solutions.

[4] L. Li, M. C. Vuran, and I. F. Akyildiz. Characteristics of Underground Channel for Wireless Underground Sensor Networks. *The 6th Annual Mediterranean Ad Hoc Networking WorkShop*, (September):92–99, 2007.

[5] C. Mc Caffrey, J. Hakli, M. Hirvonen, I. Huhtinen, K. Nummila, and T. Lehikoinen. Magnetically coupled wireless communication for buried environmental sensor. In *12th International Conference on Environment and Electrical Engineering, EEEIC 2013*, pages 341–345, 2013.

[6] M. A. Rahman and M. A. R. Tajudeen. General Wake-Up Radio Module for Ism Band. pages 31–32, 2017.

[7] U. Raza and A. Salam. On-Site and External Energy Harvesting in Underground Wireless. *Electronics*, 9(4):681, 4 2020.

[8] Z. Sun and I. F. Akyildiz. Magnetic induction communications for wireless underground sensor networks. *IEEE Transactions on Antennas and Propagation*, 58(7):2426–2435, 7 2010.

[9] L. Zhou, X. Xi, J. Liu, and N. Yu. LF ground-wave propagation over irregular terrain. *IEEE Transactions on Antennas and Propagation*, 59(4):1254–1260, 2011.

APPENDIX

A. PHOTOS OF THE EXPERIMENT

Figure 17. Hole for the transmitter for experiment 1 and 2.

Figure 18. Photo of the set-up for experiment 1. The red box indicates the position of the transmitter, the blue box the position of the receiver. Normally the receiver is buried a bit deeper, but for illustrative purposes that is not the case here.

Figure 19. Photo of the set-up for the test in air for experiment 3. The measuring tape was removed during testing.

Figure 20. Hole for the transmitter for experiment 3.