MoleNet: A New Sensor Node for Underground Monitoring

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***Abstract*—This paper introduces a new platform called the MoleNet, for wireless underground sensor networks (WUSNs). The MoleNet is specially designed for a reforestation project in Cameroon, but serves also any other underground monitoring purposes. Due to the distinctive nature of the underground channel, most commercial platforms are not feasible for this environment. The underground environment unlike the terrestrial one is not easily accessible after the deployment of a sensor network. Energy harvesting is also not a feasible option, and hence the lifetime of the deployed network needs to be enhanced to reduce the operational and maintenance cost. In this paper we focus on the design and evaluation of the MoleNet platform on the single node level. We present our energy optimization approach and investigate the challenges associated with underground communication.**

I. Introduction

Wireless underground communication presents new challenges for the researchers. The channel characteristics in wireless underground sensor networks (WUSNs) are quite unique that does not allow the usage of communication devices and standards developed for terrestrial networks. MoleNet [1] is designed specially for an underground environment.

The development of the MoleNet platform is a cooperation between the Sustainable Communication Networks group at the University of Bremen in Germany and the ReviTec [1], [2] project from the Centre of Environmental Research and Sustainable Technology (UFT) at the University of Bremen. The aim of the ReviTec project is to revitalize the soil by reforestation. The project site presents a challenge as its soil is extremely dry. The particles in dry soil become hydrophobic and hence they do not absorb much water. Even when it rains the gravity drains a large portion of water into the ground and the soil does not hold the water for a longer period of time. Most of the plants cannot withstand the dehydration stress and hence no plant grows in such areas. In order to address this dilemma, old coffee bags filled with soil and seeds are used in order to preserve more water during rainy periods. The structure of coffee bags allow the roots of the plants to grow into the soil below. In order to measure the effectiveness of the coffee bags, constant monitoring of the water content below the placed coffee bags is required.

Soils are a three dimensional complexity with high variability in space and time. In the context of the rehabilitation of degraded sites with the ReviTec approach, monitoring of soil parameters, particularly temperature and water content are mandatory to document the restoration process and to adjust the measure, if necessary. Soil degradation is prominent in rural areas. The sites often are remote from settlements and vandalism is frequent. Also farm and wild animals can harm the sensors and data loggers. The advantages of a wireless underground sensor network are numerous, including avoidance of vandalism by man and animals (buried nodes), no disturbance of the site by accessing and excavating the instruments and not to forget the possibility of monitoring sites in no-go areas affected by terrorism, as experienced in many regions of Sub-Sahara-Africa, including our research sites in Northern Cameroon (Maroua region). The MoleNet sensor nodes assist the water content monitoring at the project site with least physical interruption.

Fig. 1: Our MoleNet platform on the field.

In this paper, we focus on the design and evaluation of our new MoleNet platform at the single node level. More concretely, we present:

1) A rigorous requirements analysis for underground sensor nodes for long-term monitoring
2) The design and implementation of our MoleNet platform
3) The evaluation of the MoleNet platform

This paper continues as follows: In Section II, we present an overview of some related works in the area of WUSN. In Section III, we discuss the properties of soil and the challenges

[1]Thanks to Prof. G.-P. Picco for the idea of the name of our platform!

it presents for wireless underground communication. In Section IV, we briefly discuss the requirements for our application of WUSN. In Section V, we discuss the hardware design of MoleNet. Section VI presents the results of our experiments at the University of Bremen and at ReviTec project site in Ngaoundere, Cameroon. Section VII sketches our future work, and finally Section VIII summarizes the paper.

II. Related Work

There is substantial research going on in different areas of Wireless Underground Sensor Networks (WUSNs). In some applications e.g. predicting landslides [3], detection of volcano activities [4] and precision horticulture [5], the sensors are buried under ground but the antennas of the sensor nodes are planted above the ground, hence the exchange of information is similar to the terrestrial communication. In some other implementations e.g. soil water content monitoring in golf course in [6] uses two soil moisture sensors for volumetric water content monitoring. The wireless sensor nodes are buried under the ground but the information is sent directly to the infrastructure wireless sensor node above the ground. The above ground sensor node then relays the information to the distant sink using multiple above ground sensor nodes. The focus of these implementations is only on underground to above ground (UG2AG) communication. Such a scenario is known as hybrid WUSN as it uses combination of underground and aboveground wireless sensor nodes.

In some other experiments possibilities of underground communication are explored, e.g. [7] used Crossbow MiCAZ nodes for wireless underground communication. The Crossbow MiCaZ nodes operate at 2.4 GHz and were buried at depths between 0 and 13 cm. A maximum transmission power of 0dbm was used for communication. The setup was not able to achieve any underground to underground (UG2UG) communication. The experiments also pointed out that UG2AG and AG2UG links are asymmetric because air and soil have different dielectric properties. An UG2AG communication range of only 7m was achieved. SoilNet from [8] is build for soil water content monitoring. Zigbee radios operating at 2.4GHz are used for communication between different sensor nodes. The experiment also used a hybrid approach to increase the communication range between sensor nodes. The experiments inspected that communication range is highly affected by operating frequency and water content in the soil. In [9], MICA2 nodes operating at 433 MHz are used for underground communication. The experiment investigated UG2UG communication with variable depths of 70 to 100cm. The effects of antenna orientation on the signal strength are also inspected. The PER increases drastically if the relative angle between sender and receiver becomes greater than 90 degrees. The MICA2 nodes achieved an UG2UG communication range of 80cm to 90cm for +5 and 10 dBm transmit powers for a fixed depth of 40cm.

In [10] and [11] the authors discussed different aspects of underground communication. A complete analytical model incorporating the physical properties of soil is presented. They discussed that the communication between underground sensor nodes highly depends on their depth. If the sensor nodes are burried close to the surface then the receiver can exploit the multipath propagation. However if the nodes are burried beyond a certain level then the receiver will only receive the direct path signal. 300MHz to 900MHz is the most suitable frequency band for underground communicaton. The degradation in the performance of underground communication with increase in volumetric water content (VWC) is also discussed.

The focus of most of the experiments and applications in WUSN is to establish a reliable communication between underground and aboveground sensor nodes. However, as the requirements analysis in the Section IV-A will show, we need the complete network to be underground and only very few nodes aboveground (the sink).

III. Characteristics of Soil

Soils are usually composed of three types of particles, i.e. sand, silt and clay. The proportion of these particles determine the specific type of soil. Soils that are a mixture of all three particles are called loams [12]. Depending upon the structure of the soil, there are pores amongst different particles of the soil. These pores determine the porosity of the soil. The volume and weight of soil is not only dependent on sand, silt and clay but also on the amount of water and air immersed in these pores. Different particles hold different amount of water depending on their size i.e. particles of sand has fairly large size as compared to clay particles. Due to variable sizes, Different particles in soil exhibit Different humidity values with same amount of volumetric water content (VWC). Therefore humidity is not a very reliable parameter to model the water content in a given soil type. The amount of water in soil is therefore measured as VWC quantity.

A. EM Wave Propagation Through Soil

The propagation of electromagnetic waves through any material highly depends on its dielectric properties. The dielectric properties of soil are not uniform as concentration of soil particles yield different dielectric constants. Different particle in the soil hold different amount of water hence the dielectric properites of a specific soil highly depends on the proportion of different particles, the volumetric water content and the frequency of operation [13]. Dry soil is much more feasible for the propagation of electromagnetic waves than wet soil. Different particles and obstacles in the soil also cause reflection and scattering of electromagnetic waves. Due to the difference in the dielectric properties of soil and air, the authors in [14] also figured out that the communication from UG2AG is much more viable than communication from AG2UG .

B. Underground Channel Classification

The underground region for communication can be classified into two regions, i.e. topsoil and subsoil region. A region till 30cm of depth is classified as topsoil while the region beyond 30cm is classified as subsoil region. The communication

in topsoil region is found to be much more feasible than in the subsoil region, since the communication in topsoil takes advantage of multipaths [11]. On the other hand sometimes the deployment in the topsoil region is not feasible as agricultural activities can damage the sensor nodes.
Keeping in view of all the challenges of the underground channel, a detailed analysis of all the hindrances is required. The next section highlights the most important aspects concerning the overall design of an underground sensor network.

IV. Requirement Analysis

The development of MoleNet is part of an agricultural/reforestation research project at Revitec site in Ngaoundere, Cameroon. The project site presents its own challenges and requirements. To the best of our knowledge, there is no other application that solely relies on UG2UG communication. As explained in Section II, most of the applications use hybrid WUSN while in some other scenarios UG2UG communication experiments are carried out only for research purposes. This section will discuss in detail the following requirements for this project.

A. WUSN Topology

Since the ReviTec project site is quite remote and isolated place, therefore all the sensor nodes must be buried in the ground to avoid any theft. A secure place above the ground is also required for the deployment of the base station. Because of the mentioned constraints, the deployment of a hybrid WUSN is not an option for this project. The one advantage with the project site is that it will not receive any ploughing or similar activity, therefore the MoleNet nodes can be buried in the topsoil region.

B. Sensors

The main aim of the project is to monitor VWC at different locations of the project site but VWC sensors are quite expensive. 5TM soil moisture and temperature sensor [15] from Decagon Devices is mostly used for measuring VWC and it costs around 180 euros. Therefore interfacing them at every node is not a feasible solution. An alternate solution is to equip few sensor nodes with VWC sensors while all the other nodes can be equipped with temperature and humidity sensors. The temperature and humidity sensors can also help in vague estimation of the water content. The location of sensor nodes with VWC sensors must be selected carefully in order to have a better overall model of the VWC over the whole site.

C. ISM Band

As investigated in [11], most feasible frequency band for underground communication is 300-900MHz. The transceivers that are normally available in this range are 433MHz and 868MHz transceivers. Both these frequencies belong to the ISM band in Europe but only 433MHz frequency is available in Africa. The maximum power for different frequencies in this band is regulated by Electronic Communication Committee (ECC) in Europe. ECC allows a maximum transmission power of 10dBm with less than 10% duty cycling for 433MHz frequency. Similarly for the 868MHz frequency, a maximum power transmission of 14dBm is allowed with less than 1% duty cycling[16]. For research purposes, the performance of both frequencies is investigated.

D. Lifetime

The most important parameter for wireless sensor networks is their lifetime. For WUSN this parameter becomes even more significant as there is no option of energy harvesting for the underground sensor nodes. Therefore underground sensor nodes require much better utilization of resources than any other application. Since the base station will be above the ground an energy harvester like solar panel can be used to increase its lifetime.
The average reforestation monitoring period is 5-6 years. Therefore the sensor nodes must have a life time more that the complete reforestation period. Reactive sampling like [17] can be used to reduce continuous sampling of data. The frequency of sampling must be increased only when there are significant changes in the VWC. The sensor nodes must be equipped with sufficient memory to store more frequent samples when a reliable link to the base station is not available.

E. Weather Conditions

The weather conditions bring new hindrances for underground to underground communication. As investigated in [11], moist soil is not very feasible for the propagation of electromagnetic waves. So during rainy weather conditions the sensor nodes must ensure the delivery of data to the sink or in worst case scenario, maintain the database locally and transfer it to the sink when the channel becomes appropriate for communication. Figure 2 shows a comparison of the precipitation rate in Ngaoundere, Cameroon and Bremen, Germany. The graph shows that overall precipitation rate for a specific month is less for Bremen but the span of rain is spread over the whole year. Whereas in Ngaoundere there is almost no rain for 5 months. The structure of soil in Ngaoundere also does not hold water for very long time. The channel characteristics will not remain static over a long period of time. Once the plantation will start growing, the plants and their roots will further deteriorate the communication channel between different nodes. Hence the deployed network is required to be very robust and able to handle extreme channel fluctuations over large periods of time.

F. Remote Data Accumulation

Since the project site is quite remote, it is not convenient to visit the site frequently for data gathering. Therefore base station must be equipped with GSM or GPRS communication capabilities for the remote access of data. The base station must also be equipped with camera in order to monitor the growth of vegetation corresponding to the VWC. The base station can exploit the energy harvesting techniques i.e. solar panel to enhance its lifetime.

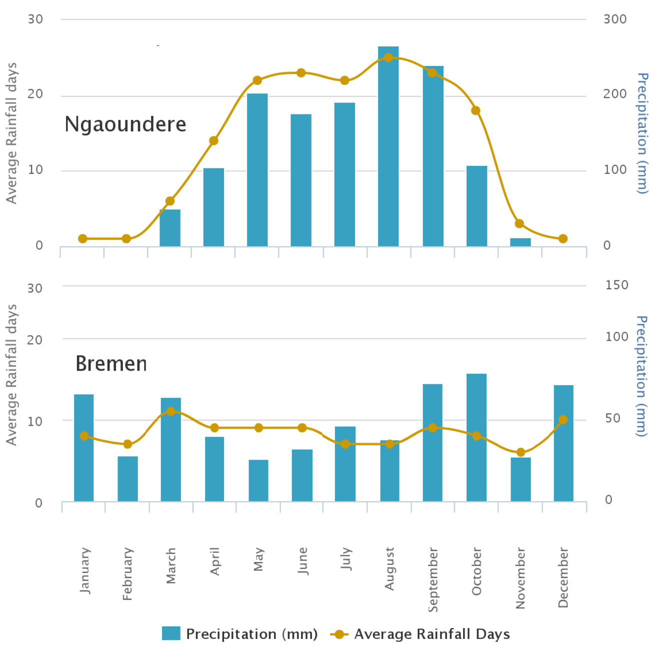


Fig. 2: Average Rainfall comparison in Ngaoundere, Cameroon and Bremen, Germany from 2000 to 2012 [18].

G. Low Cost Sensor Node

The project is carried out in a country where electronic components are not easily available. Furthermore, cost of the sensor nodes must be very low as they will be deployed in a huge field (one of our ReviTec sites is 30 hectares).

Keeping in view of all the constraints, MoleNet is designed to meet most of the requirements. Next section will highlight the different modules of the MoleNet sensor node.

V. MoleNet

The MoleNet is aimed to be designed with least number of components to reduce the overall power consumption of the sensor node. Extensive testing of various components has led us to the final design. Figure 3 shows a top view of the MoleNet platform.

MoleNet is powered by an Atmel ATmega 328p running at 8MHz, which is programmable with a serial or an ISP programmer. Atmega 328p has 32KiB of Flash program memory, 2KiB of Ram and 1KiB of EEPROM memory [19]. 1KiB of EEPROM memory is not enough to store the data locally when the channel is not feasible for communication. Therefore an external EEPROM of 512KiB is integrated in the MoleNet. A 434MHz transceiver is interfaced in the final version for wireless communication. The MoleNet is also equipped with real-time clock (RTC) that not only maintains the time locally but also helps the MoleNet to remain in deep sleep mode for most of the time. The RTC wakes up the MoleNet once every hour in the current configuration. The MoleNet senses the data, transmits it to the sink and goes back into the deep sleep mode.

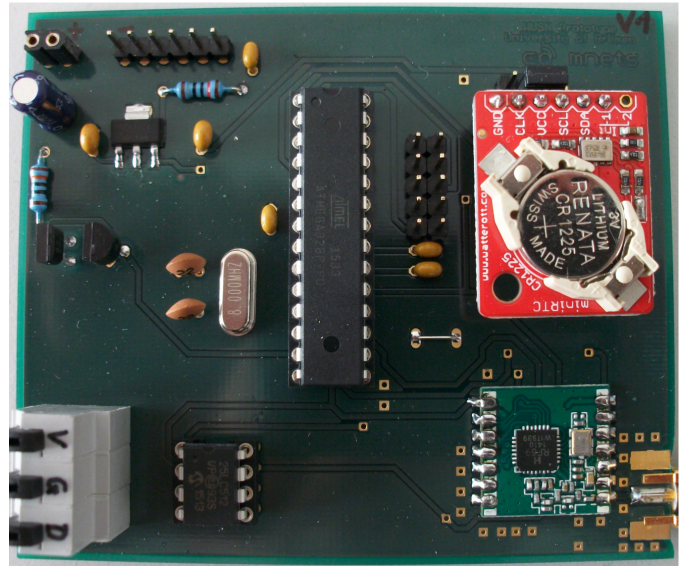


Fig. 3: Top view of MoleNet.

MoleNet provides multiple analog and digital interfaces for different sensors. A terminal provides an easy possibility to connect a sensor to the board. This sensor can be supplied with the board's operating voltage (3.3V) or by the battery and is switched on and off by the microcontroller. The sensor's data line is connected either to the hardware serial port of the microcontroller or one of the digital I/Os.

For the ease of assembly, maintenance and availability of components from the deployed country, the MoleNet is designed using almost only electronic parts in through-hole-technology (tht). The compatibility to the Arduino/Genuino platform allows extending and programming MoleNet using the Arduino IDE and the huge amount of libraries provided by the community.

A. Transceiver

Since 2.4Ghz frequency is not feasible for underground communication, transceivers operating in the range of 300MHz to 900MHz were evaluated only. Multiple transceivers RFM69W, RFM22B and RFM69CW were tested for the MoleNet sensor node. RFM22B 434MHz transceiver and RFM69CW have same characteristics except RFM22B has maximum 20dBm transmit power as compared to 13dBm of RFM69CW transceiver. RFM69W and RFM69CW transceivers module use FSK, GFSK, MSK, GMSK and OOK for modulation while RFM22B only uses FSK, GFSK, and OOK for modulation. All the transceivers use Serial Peripheral Interface (SPI) for communication with the micro-controller. The experiment is performed using a spectrum analyzer in the lab environment. First the performance of 868MHz RFM69W transceiver was evaluated for different antennas. The transmitters were placed at a distance of 0.5m from the receiver antenna for both 434MHz and 868MHz transceivers. The measurements were performed using the max hold function of

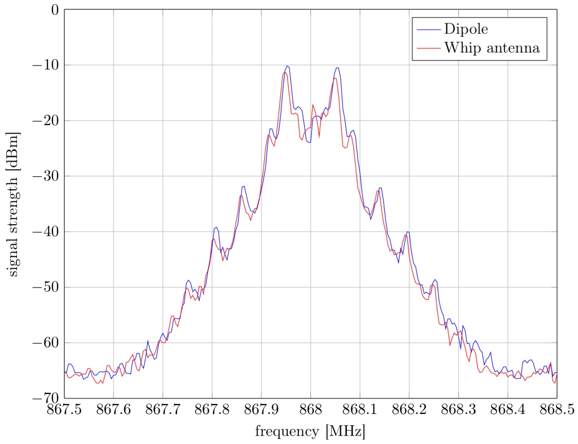


Fig. 4: 868MHz RFM69CW transceiver RSS at transmission power of 13dBm

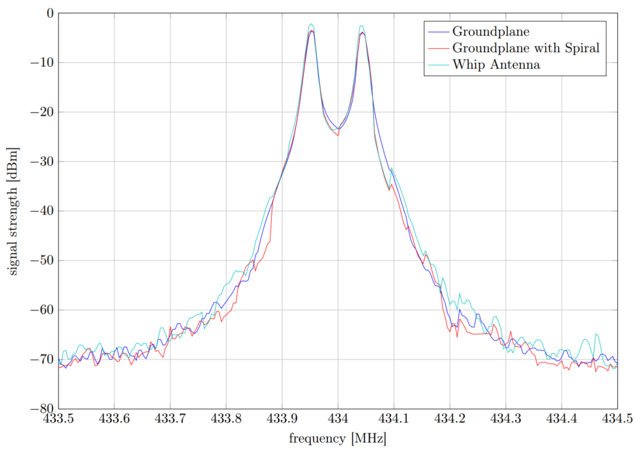


Fig. 5: 434MHz RFM22B transceiver RSS at transmission power of 17dBm

the spectrum analyzer with measurement time of 30s. Figure 4 shows the received signal strength corresponding to RFM69W 868MHz transceiver for a transmit power of 13 dBm. Dipole antenna performed slightly better than the Whip antenna for the 868MHz RFM69CW transceiver.

The 434MHz RFM22B transceiver is then used to measure the received signal strength for different antenna designs. A transmission power of 17dBm is used for the experiment. Figure 5 shows the received signal strength (RSS) for the 434MHz RFM22B transceiver. Transceiver with the whip antenna performs better than the groundplane and groundplane with spiral antenna. Keeping in consideration that the transmit power for both experiments were different, still the 434MHz transceiver showed better received signal strength compared to 868MHz transceiver. Transceivers for both frequencies were later used for underground communication experiments.

B. Energy Consumption

The design of MoleNet is an optimized version of Arduino clone Wattuino Pro Mini. The standard design of Arduino clone Wattuino included power indicator LED. The removal of this LED reduced the power consumption in deep sleep

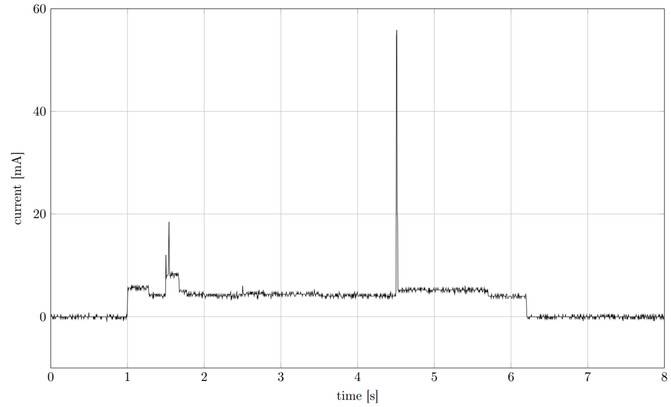


Fig. 6: Power consumption of MoleNet during one active cycle.

```
       0123 4567 8901 2345 6789 0123 4567 8901
      ------------------------------------------
 0    |   'D'    |   YEAR    |   '/'    |  MONTH  |
 4    |   '/'    |   DAY     |   ' '    |   't'   |
 8    |   HOUR   |   ':'     | MINUTE   |   ' '   |
12    |    'W'   | W_CHAR_1| W_CHAR_2| W_CHAR_3|
16    | W_CHAR_4|   ' '     |   'T'    | W_CHAR_1|
20    | T_CHAR_2| T_CHAR_3| T_CHAR_4|   ' '   |
24    | CHKSUM   |   ' '     | SUCCESS |   ' '   |
28    |   ' '    |   ' '     |--------------------
      ---------------------
```

Fig. 7: The packet structure of MoleNet.

mode from 11.7mW to 900μW. The standard Arduino clone Wattuino also uses an inefficient voltage regulator. This regulator is also replaced by a power efficient MCP1703 regulator. This replacement further improved the power consumption from 900μW to 146μW in deep sleep mode.

MoleNet is kept in deep sleep mode for more than 99% of the time to save energy. The RTC wakes up MoleNet from deep sleep for sensing and transmission of data. Figure 6 shows the power consumption during one active cycle. The first peak corresponds to the sensor measurement and the second peak to the transmission of the sensor data to the receiver. After the transmission of data, the microcontroller again goes to deep sleep mode. The estimated lifetime of MoleNet is 5.77 years with sensing and transmission frequency of once every hour for a battery of 2000mAh.

C. Application

The MoleNet sensor node can be programmed using Arduino IDE. The libraries of the transceivers used in MoleNet are provided by the manufacturer and are available on github [20]. The maximum length of one packet is limited by the library to 61 bytes and is depicted in Figure 7.

The values `YEAR`, `MONTH`, `DAY`, `HOUR`, `MINUTE`, `CHKSUM` and `SUCCESS` are stored as unsigned 8 bit integer. The values starting with `W_CHAR` (water content) and `T_CHAR` (temperature) are the sensor raw values and used as characters. `CHKSUM` is the checksum from the sensor. `SUCCESS` indicates if the reading and the transmission was successful.

D. Cost

The project site requires dense deployment of the nodes. Most of the commercial wireless sensor nodes cost more than 90 euros. Therefore cost of the designed sensor node is strived to be as low as possible. Table I shows the cost of individual components and total cost of MoleNet, which is below 50 euros. The cost may further be reduced when the nodes are manufactured in large quantity.

Components	**Cost**
Micocontroller	€2.85
RFM69CW	€4.35
EEPROM	€2.15
RTC	€10.00
Antenna	€6.27
Res, Cap, etc.	€5.00
PCB	€15.35
Total	**€45.97**

TABLE I: Cost of MoleNet sensor node.

The MoleNet sensor node supporting both 434Mhz and 868MHz transceivers is then used for various UG2UG and UG2AG experiments. The next section highlights the main results from those experiments.

VI. Experimental Results

Before the actual deployment at the Revitec site, different experiments were performed at the University of Bremen using the MoleNet sensor node. The general testing environment is presented in Figure 8 and is situated outside of our campus, on a large free field with minimum interference. The soil at the experiment field is a mixture of sand and clay with almost equal proportion of both particles. An area of 3m x 3m was cleared from vegetation to monitor the UG2AG communication for different depths. The receiver antenna FLEXI-SMA90-433, that is attached to a spectrum analyzer through 7m long N-type connector RG214U cable is kept at a height of 65cm from the ground. The depth of sensor node, as well as the distance between the sensor node and the receiving antenna were varied.

Four types of experiments were performed to evaluate the performance of the MoleNet sensor Node. First the 434MHZ transceiver was used with the MoleNet to evaluate UG2AG communication for fixed and variable depths of the underground sensor node. Then the 868MHz transceiver is used to evaluate UG2AG communication for fixed depth of underground sensor node. At last the 434MHz transceiver was used to discover the range of reliable UG2UG communication.

A. UG2AG communication, 20cm depth, 434MHz

First the MoleNet sensor node was buried at a depth of 20cm. The aboveground receiver was placed at a distance of 1.5m above the ground. The receiving MoleNet was connected to the laptop to monitor the packet error rate (PER) and received signal strength (RSS) of incoming packets. The above ground receiver node was then moved away from the transmitter to determine the range of reliable communication. In nearly dry soil a communication range of 80m was achieved. Figure 9a shows the packet loss rate for dry soil. Until 79m there were no packet losses but after 81m packet loss rate increased drastically. Figure 9b shows the RSS for the receiver from 80 to 84m. Although the packet loss rate increased after 80m but received signal strength of the packets after 80m remained consistent. The same experiment was then carried out in moist soil, where the communication range was reduced to 40m.

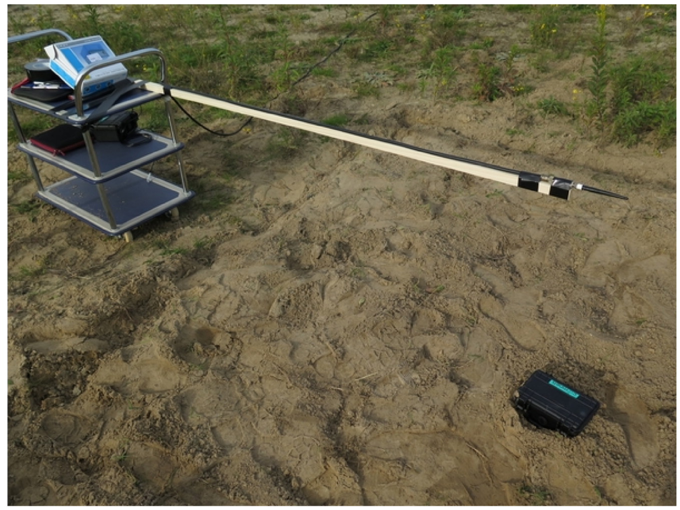


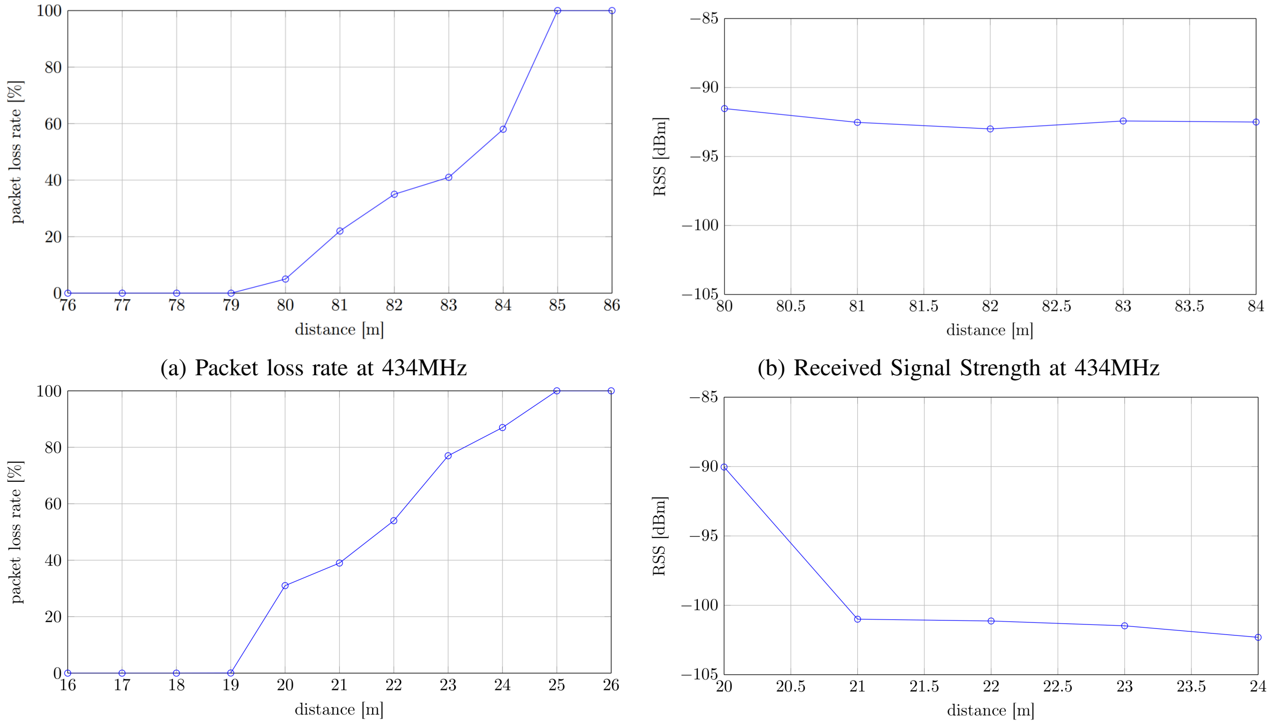
Fig. 8: UG2AG experimental setup, near University of Bremen

B. UG2AG communication, 20cm depth, 868MHz

The same experiment was then performed using the MoleNet sensor node with 868MHZ transceiver. The reliable communication range achieved by 868MHz transceiver was only 20m in dry soil. Figure 9c shows the packet loss rate for 868MHz transceiver. Until 19m the communication was reliable between the transmitter and receiver but after 20m there was significant increase in packet loss rate. Figure 9d shows the received signal strength of 868MHZ transceiver. In contrast to 434MHz transceiver, the received signal strength of the packets outside reliable communication range also degraded drastically. These results dictate that 868MHz transceiver is not appropriate for underground communication. Therefore the 868MHz transceiver was not further used for any experiments.

C. UG2AG communication, variable depths, 434MHz

Then UG2AG communication was analyzed for different depths of the underground sensor node. The depth of the underground sensor node is increased in steps of 10cm. Figure 10 shows the respective received signal strength for different depths. The experiments were performed at multiple locations for cross validation of the results. Ideally the received signal strength should decrease with increasing depth but at some instances RSS increased slightly with increasing depth. As investigated in [11], The reason for this behavior can



(a) Packet loss rate at 434MHz

(b) Received Signal Strength at 434MHz

(c) Packet loss rate at 868MHz

(d) Received Signal Strength at 868MHz

Fig. 9: UG2AG experiments at 433 MHz (top) and 868 MHz (bottom).

be multipath propagation, the behavior that is much more prominent in topsoil region.

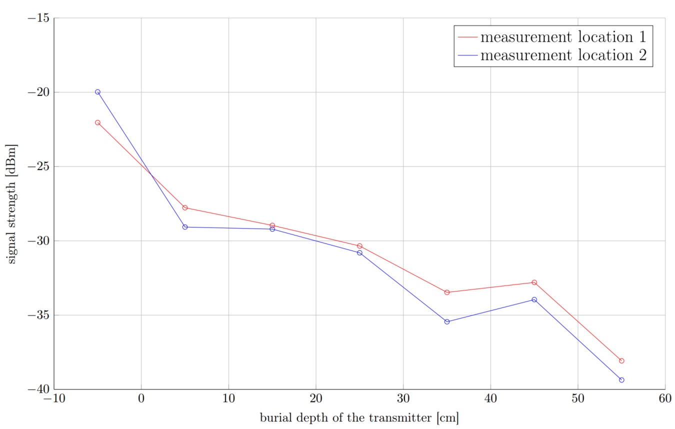


Fig. 10: Received Signal Strength at 433MHz

D. UG2UG communication, 20cm depth, 434MHz transceiver

Finally MoleNet with 434MHz transceiver was used to find the maximum range of reliable UG2UG communication. Both the MoleNet sensor nodes, the transmitter and the receiver were buried in a depth of 20cm at a distance of 10m from each other. There was no communication between the two sensor nodes at a distance of 10m. First, the distance between the two nodes was reduced in steps of 1m. Both the sensor nodes started to communicate at a distance of 8m with the holes opened from the top. Once the holes were covered there was no communication at 8m. The distance was then reduced by 0.5m. There was a reliable communication (less than 5% loss) between the two sensor nodes at a distance of 7.5m even when the holes were covered from the top.

E. Experiment Results from Ngaoundere, Cameroon

The final version of MoleNet sensor node was also tested at the ReviTec project site in Ngaoundere, Cameroon. Figure 11 shows the MoleNet sensor Node before being buried at the ReviTec site. The MoleNet was buried in a depth of 13cm. The MoleNet remained buried at the site for five days and the results were gathered by the above ground MoleNet sensor node in a nearby building. There were several rain showers during the deployment period of five days at the ReviTec site. The MoleNet sensor node managed to operate successfully during that period.

The values of VWC were recorded for five days. Figure 12 shows the readings of VWC during that period. The graph shows an increase in VWC of the soil on 10th of April at 14:00. That was the time when it started raining at the ReviTec site. There were few light showers of rain on 11th of April and on 12th of April it rained very heavily at the ReviTec project Site. The graph also shows an abrupt increase in the VWC on 12th of April at 14:00. As discussed in Section I, the soil at the ReviTec site does not hold the water for very long time. Therefore the VWC also started falling rapidly.

The experiments have shown that the MoleNet can operate successfully in an underground environment.

Fig. 11: MoleNet after being buried for 5 days at the ReviTec site in Ngaoundere, Cameroon

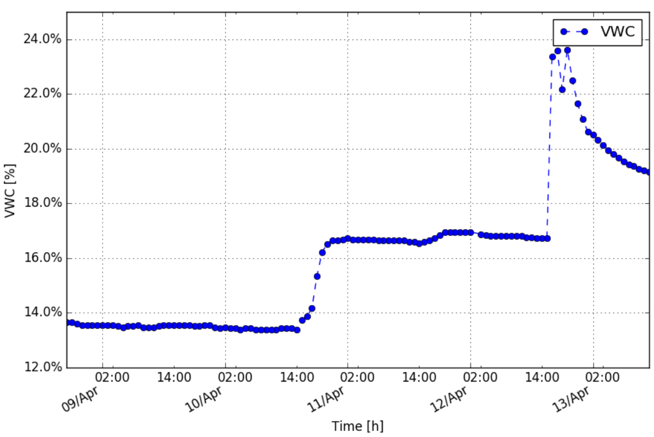


Fig. 12: Volumetric water content readings from the ReviTec site in Ngaoundere, Cameroon

VII. Future Work

In the next phase MoleNet will be used to deploy a complete network of underground sensor nodes, including a sophisticated base station. The focus of research will be to maintain a reliable underground sensor network that can operate in different weather conditions and have an increased lifetime. Techniques like reactive and adaptive sampling will be adapted to further increase the lifetime of the MoleNet sensor node and the whole network. A testbed will be created near the University of Bremen to further investigate the challenges of multi-hop routing in wireless underground sensor networks.

VIII. Conclusion

In this paper we presented our design of a new underground sensor node, called MoleNet. We have shown to reduce the energy consumption of the node dramatically in deep sleep mode and have investigated various transmission frequencies and antenna designs. Best results were observed with a 434 MHz transceiver and a whip antenna, achieving a range of over 80m UG2AG communication and a 7.5m range in a UG2UG communication, both at 20 cm depths. Our hardware and software is open source and available under github[2].

These results show that UG2UG communication at acceptable distances is possible and thus also the deployment of very long-lived, fully underground sensor networks. Our next step is develop and deploy the complete network.

References

[1] "Revitec project." [Online]. Available: http://www.revitec.de

[2] R. Kesel, H. Koehler, and W. Heyser, "A modular approach of ecological restoration to combat degradation and desertification," *SER-Newsl. 1–2.*

[3] A. Sheth, K. Tejaswi, P. Mehta, C. Parekh, R. Bansal, S. Merchant, T. Singh, U. B. Desai, C. A. Thekkath, and K. Toyama, "Senslide: A sensor network based landslide prediction system," in *Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems*. New York, NY, USA: ACM, 2005, pp. 280–281.

[4] G. Werner-Allen, K. Lorincz, M. Welsh, O. Marcillo, J. Johnson, M. Ruiz, and J. Lees, "Deploying a wireless sensor network on an active volcano," *IEEE Internet Computing*, vol. 10, no. 2, Mar. 2006.

[5] J. L. Riquelmea, F. Sotoa, J. Suardiaza, P. Sáncheza, A. Iborraa, and J. Vera, "Wireless sensor networks for precision horticulture in southern spain," *Elsevier Comp. and Electr. in Agriculture*, vol. 68, no. 1, 2009.

[6] C. J. Ritsema, H. Kuipers, L. Kleiboer, E. van den Elsen, K. Oostindie, J. G. Wesseling, J.-W. Wolthuis, and P. Havinga, "A new wireless underground network system for continuous monitoring of soil water contents," *Water resources research*, vol. 45, no. 4, 2009.

[7] E. P. Stuntebeck, D. Pompili, and T. Melodia, "Wireless underground sensor networks using commodity terrestrial motes," in *2nd IEEE Workshop on Wireless Mesh Networks*, 2006.

[8] H. R. Bogena, J. A. Huisman, H. Meier, and A. Weuthen, "Hybrid Wireless Underground Sensor Networks: Quantification of Signal Attenuation in Soil," *Vadose zone journal*, vol. 8, pp. 755 – 761, 2009.

[9] A. R. Silva and M. C. Vuran, "Empirical evaluation of wireless underground-to-underground communication in wireless underground sensor networks," in *Proceedings of the 5th IEEE International Conference on Distributed Computing in Sensor Systems*, 2009, pp. 231–244.

[10] M. C. Vuran and A. R. Silva, *Communication Through Soil in Wireless Underground Sensor Networks – Theory and Practice*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 309–347.

[11] I. F. Akyildiz, Z. Sun, and M. C. Vuran, "Signal propagation techniques for wireless underground communication networks," *Phys. Commun.*, vol. 2, no. 3, pp. 167–183, Sep. 2009.

[12] "Soil properties." [Online]. Available: http://sciencelearn.org.nz

[13] P. Hoekstra and A. Delaney, "Dielectric properties of soils at uhf and microwave frequencies," *Journal of Geophysical Research*, vol. 79, no. 11, pp. 1699–1708, 1974. [Online]. Available: http://dx.doi.org/10.1029/JB079i011p01699

[14] A. R. Silva and M. C. Vuran, "Development of a testbed for wireless underground sensor networks," *EURASIP J. Wirel. Commun. Netw.*, vol. 2010, pp. 9:1–9:12, Apr. 2010.

[15] "5tm vwc sensor." [Online]. Available: https://www.decagon.com/

[16] "Ti: Ism-band and short range device regulatory compliance overview." [Online]. Available: http://www.ti.com/

[17] R. Cardell-Oliver, M. Kranz, K. Smettem, and K. Mayer, "A reactive soil moisture sensor network: Design and field evaluation," *IJDSN*, vol. 1, no. 2, pp. 149–162, 2005.

[18] "World weather online." [Online]. Available: http://www.worldweatheronline.com/

[19] "Atmel atmega328p." [Online]. Available: http://www.atmel.com/

[20] "Transceiver arduino library." [Online]. Available: https://github.com/lowpowerlab/rfm69

[2]https://github.com/ComNets-Bremen/WUSN