Empirical Evaluation of Wireless Underground-to-Underground Communication

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Abstract. Many applications for irrigation management and environment monitoring exploit buried sensors wired-connected to the soil surface for information retrieval. Wireless Underground Sensor Networks (WUSNs) is an emerging area of research that promises to provide communication capabilities to these sensors. To accomplish this, a reliable wireless underground communication channel is necessary, allowing the direct communication between the buried sensors without the help of an aboveground device. However, the significantly high attenuation caused by soil is the main challenge for the feasibility of WUSNs. Recent theoretical results highlight the potential of smaller attenuation rates with the use of smaller radio frequencies. In this work, experimental measurements are presented at the frequency of 433MHz, which show a good agreement with the theoretical studies. We observe that (a) a decrease of the frequency of the wireless signal implies a smaller soil attenuation rate, (b) the wireless underground communication channel presents a high level of temporal stability, and (c) the volumetric water content (VWC) of the soil is the most important factor to adversely affect the communication. The results show the potential feasibility of the WUSNs with the use of powerful RF transceivers at smaller frequencies (e.g., 300-500MHz band). We also propose a classification for wireless underground communication, defining and showing the differences between Subsoil and Topsoil WUSNs. To the best of our knowledge, this is the first work that reports experiment results for underground to underground communication using commodity sensor motes.

1 Introduction

Wireless Underground Sensor Networks (WUSNs), which consist of wireless sensors buried underground, are a natural extension of the wireless sensor network phenomenon and have been considered as a potential field that will enable a wide

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variety of novel applications that were not possible before [1]. The realization of wireless underground communication and networking techniques will lead to potential applications in the fields of *intelligent irrigation, border patrol, assisted navigation, sports field maintenance, intruder detection*, and *infrastructure monitoring.* This is possible by exploiting real-time soil condition information from a network of underground sensors and enabling localized interaction with the soil. In this paper, we focus on a promising application, where WUSNs can be used to provide real-time soil condition information for *intelligent irrigation* and can help maintain fields more efficiently according to the soil quality. As a result, the cost for maintaining a crop field can be significantly reduced through autonomously operating underground sensors.

Irrigation management is an *underground* application that has been deployed for more than 20 years [5]. In general, soil moisture sensors are buried at a 30-120cm depth [5], [6] and wired to an extension above the surface, which can be used for (1) manual collection of data, e.g, a person with a datalogger moves from sensor to sensor to download the data or (2) connection with a micro-controller which is responsible for sending the readings to a datalogger node, via wireless channel. The collected data is then used to assess the irrigation requirements of the field. The existing techniques, however, lack real-time information retrieval capabilities and are obtrusive for agriculture tasks on the field. A wireless underground sensor network, however, has the potential to help to reduce water application to the agricultural fields through measurement of soil moisture status to make better informed irrigation application (timing) decisions without obstructing with the field operations.

Despite its potential advantages, the realization of WUSN is challenging and several open research problems exist. The main challenge is the realization of efficient and reliable underground wireless communication between buried sensors. To this end, underground communication is one of the few fields where the environment has a significant and direct impact on the communication performance. More specifically, the changes in temperature, weather, soil moisture, soil composition, and depth directly impact the connectivity and communication success in underground settings. Hence, characterization of the wireless underground channel is essential for the proliferation of communication protocols for WUSNs.

In this paper, the results of field experiments for underground communication at the frequency of 433MHz using commodity sensor nodes is presented. Moreover, lessons learned from these experiments for the proliferation of efficient communication protocols for WUSNs are discussed. The results of the field experiments show a good agreement with the theoretical result [9] and confirms that the wireless underground channel (a) exhibits a two-path behavior at low burial depths, (b) presents a high degree of temporal stability compared to its air counterpart, and (c) is adversely affected by the volumetric water content (VWC) of the soil. Finally, the results show the potential feasibility of the WUSNs, especially with the use of more powerful RF transceivers at smaller frequencies, e.g., 300-500MHz band.

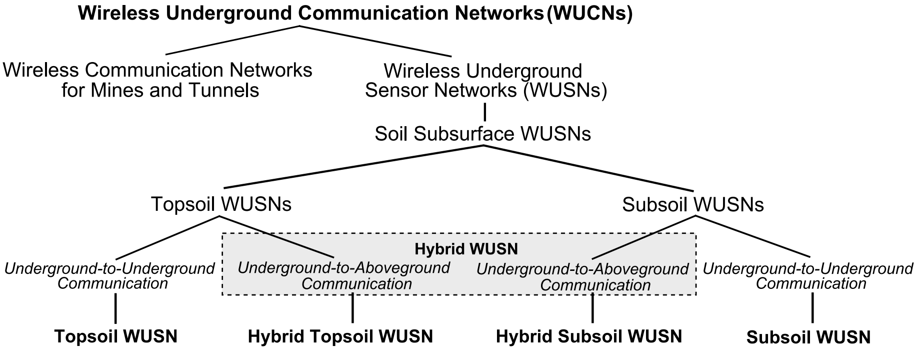


Fig. 1. Classification of wireless underground communication networks (WUCNs)

The rest of this paper is organized as follows: In Section 2, an overview on wireless underground communication networks (WUCN) is provided along with a classification of these networks and the related work. In Section 3, the testbed architecture for the experiments and the experimental methodology are described. The experiment results for the underground-to-underground communication are presented in Section 4. Finally, the lessons from the experiments and the future work is discussed in Section 5.

2 Background and Related Work

Wireless Underground Communication Networks (WUCNs) have been investigated in many context recently. Although a novel area, a detailed classification of these networks is necessary since several different scenarios, with very specific issues, are presented under the title *wireless underground communication* or, sometimes, *WUSNs*. In [1], two possible topologies for WUSNs are presented: the underground topology, where the majority of the nodes are buried, and the hybrid topology, where buried nodes coexist with some nodes deployed above ground. Based on this classification, we provide a detailed classification of WUCNs and present related work in this area.

2.1 Classification of Wireless Underground Communication Networks

As shown in Fig. 1, WUCNs can be mainly classified into two: wireless communication networks for mines and tunnels and wireless underground sensor networks (WUSNs). Based on this initial classification, it is important to note that there exist several solutions that focus on underground communication in mines and/or tunnels [4], [7], [10], [13]. In these work, although the network is located *underground*, the communication takes place *through the air*, i.e., through the underground voids. In this paper, however, we consider WUSNs, where sensor nodes are buried *underground* and communicate *through soil.*

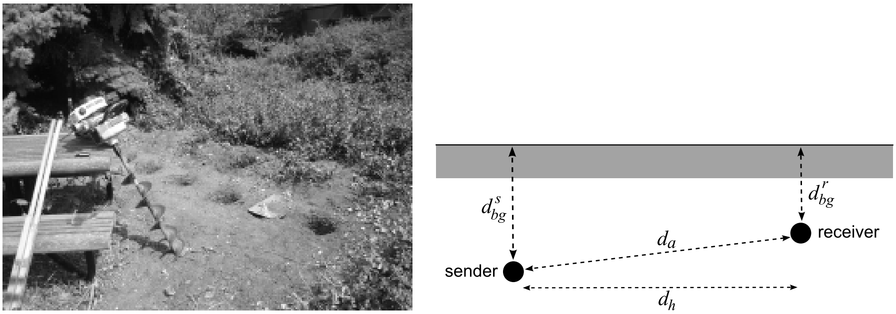
Although the sensors may be *buried* at different regions of the soil, WUSNs can also be classified into two based on the burial depth of the sensors. The recent research on agriculture, environment monitoring, and security mainly focuses on the *soil subsurface*, which is defined as the top few meters of the soil. Soil subsurface is classified into two regions [8]: (a) the *topsoil region*, which refers to the first 30cm of soil, or the root growth layer, whichever is shallower and (b) the *subsoil region*, which refers to the region below the topsoil, i.e., usually the 30-100cm region. Accordingly, as shown in Fig. 1, *Soil Subsurface WUSNs* can be classified as a function of the deployment region: *Topsoil WUSN*, if the WUSN is deployed in the *topsoil region*, or *Subsoil WUSN*, if deployed in the *subsoil region*. Moreover, these networks are further classified as *Hybrid WUSNs*, which include nodes that are deployed above the ground and the communication is highly dependent on the existence of the aboveground nodes. For Topsoil and Subsoil WUSNs, the majority of the communication flows in the underground-to-aboveground direction.

2.2 Related Work

The concept of WUSNs and the challenges related to the underground wireless channel have been introduced in [1]. The characteristics of extreme path loss caused by the soil attenuation and the water content are also highlighted. However, this analysis is limited to the 1.4-3GHz RF range. In [9], [2], we develop a theoretical model for the wireless underground communication and a set of simulated results for the 300-900MHz RF range are provided. However, experimental results have not been provided.

To date, very few WUSN experiments are found in the literature. Experiment results at the 2.4GHz frequency band are reported in [12], where the underground-to-underground communication is shown to be infeasible at this range. Instead, the results for underground-to-aboveground communication and vice-versa are provided. The burial depths for the presented experiments are 6cm and 13cm and a transmit power of 0dBm is used. Even with these small burial depths, the absence of results for underground-to-underground experiments points out the challenges of soil attenuation at the 2.4GHz band. In [16], experiment results at 2.4GHz band are also reported, where a burial depth of 9cm with a transmit power of +19dBm and a directional antenna with individual gain of 10dB is used. The experiments presented results related to only the underground-to-aboveground and aboveground-to-underground communication.

Experiments at the 869MHz band are explained in [14], where underground to aboveground communication is considered. In this work, a buried transmitter and an aboveground directional antenna is used for the experiments. Inter-node distances of more than 30m are reported, where different depths were used, i.e., 10-40cm. Also, different VWC are tested for different soil textures. The results from this work highlights that the use of a small frequency (869MHz) compared to 2.4 GHz can imply smaller soil attenuation and longer inter-node distances. The study focuses mainly on the metrics related to the efficiency of the customized directional antenna and the transmitter.



(a) Outdoor environment of the experiments

(b) Symbols used for distances in this document

Fig. 2. Symbols used for distances. Outdoor environment for the experiments.

It can be observed that the experiments in [12,16,14,19] focus on the *Topsoil WUSN* scenario, where underground to aboveground communication is considered. Also, some recent commercial products for golf field irrigation management [19], have been using a similar approach [16,14], where the node is buried very close to the surface, i.e., 5-15cm, a transmit power of $\geq$ 10dBm is used and underground to aboveground communication is considered.

Despite the potential applications of the existing work, underground to aboveground communication is not applicable for irrigation management. First, large crop fields prevent the use of direct communication, which has limited range. Moreover, frequent activities such as plowing performed on these fields require non-obstructive approaches, where aboveground relays are not feasible. Furthermore, plowing and similar mechanical activities occur exactly at the topsoil region, i.e., 0-30cm, where the soil composition is continuously affected. This requires higher burial depths in the root range of crops in the subsoil region, i.e., 40-100cm. These constraints call for subsoil WUSNs, where multi-hop communication is performed under the ground.

To the best of our knowledge, however, underground to underground communication has not been evaluated through experiments before. In this work, we present the first experimental results that focus mainly on *Subsoil WUSNs* and present guidelines for design of communication protocols for underground to underground communication. Certain results related to the *Topsoil WUSNs* are also presented.

3 Experiment Setup

The underground experiments were carried out in University of Nebraska-Lincoln City Campus on a field provided by the UNL Landscaping Services during August-November 2008 period. The analysis of the soil texture of the experiment site is shown in Table 1 according to laboratory analysis [20]. For the experiments, MICA2 nodes that operate at 433MHz are used [18]. This frequency

Table 1. Soil Analysis Report

Sample Depth	Organic Matter	Texture	%Sand	%Silt	%Clay
0-15cm	6.4	Loam	27	45	28
15-30cm	2.6	Clay Loam	31	40	29
30-45cm	1.5	Clay Loam	35	35	30

range has been theoretically shown to exhibit better propagation characteristics in [9]. The underground experiments were performed by digging 10 holes of 8 cm-diameter with depths varying from 70 to 100cm with an auger. A paper pipe with an attached Mica2 node is injected to each hole at different depths. The experiment site is shown in Fig. 2(a).

For the experiments, a software suite is developed to perform long duration experiments without frequent access to the underground motes. The software suite enables carrying out several experiments with various parameters without reprogramming the motes, which is a major challenge for underground settings. A Java/TinyOS 1.1x application, called S-GriT (Small Grid Testbed for WSN Experiments), is developed to allow many number of the nodes acting as *receivers*. The S-GriT allows configuration of multiple experiments with the following parameters: transmit power level, number of messages for the experiment, number of bytes per message, and delay between the transmission of each message. The nodes assume one of the three roles in the S-GriT application: (1) *Manager* is used by the operator to configure and start the experiments and also to retrieve the results from the receivers; (2) *Sender*, which is buried underground, receives configuration information from the Manager, via wireless channel; and (3) *Receiver* receives the test messages from the sender and prepares a *summary* containing the sequential number of each received message and the Received Signal Strength Indication (RSSI) level related to it, which is a measurement informed by the transceiver of the node and expresses the Received Signal Strength (RSS) of the signal. Consequently, the testbed experiments also stand as a proof-of-concept for underground data retrieval using commodity sensor nodes.

The experiment setup and the terminology used in representing the results are illustrated in Fig. 2(b), where d_{bg} is the burial depth of the node, d_h is the horizontal inter-node distance, and d_a is the actual inter-node distance. The superscripts s and r are also used to indicate sender and receiver. These values, as well as the transmit power, are varied to investigate the PER and RSS values of underground communication.

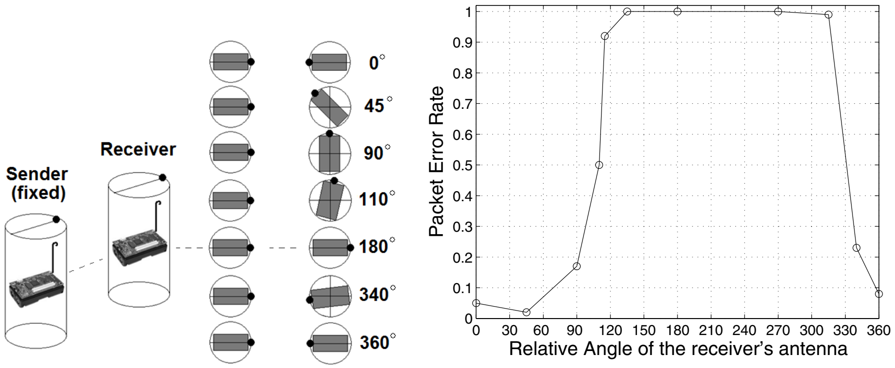
The experiments are conducted for four values of transmit power, i.e., -3dBm, 0dBm, +5dBm, and +10dBm. 30-byte packets are used with 100ms between each packet. Each experiment in this work is based on a set of 3 experiments with 350 messages or 2 experiments with 500 messages, which result in a total of 1000 packets. The number of packets correctly received by one or more receiver nodes are recorded along with the signal strength for each packet. Accordingly, the packet error rate (PER) and the RSS level from each receiver are collected. To prevent the effects of hardware failures of each individual Mica2 nodes, *qualification tests* have been performed before each experiment. Accordingly, *through-the-air* tests, which consists of 200 packets of 30 bytes, are performed to (1) determine compliant nodes and (2) confirm that the battery level of a node is above a safe limit. A node is labeled compliant with a given set of nodes if (1) its PER varies within 10% of the average PER calculated for the set of nodes and (2) its RSS average varies, at maximum, +/- 1 dBm from the average RSS for the set of nodes. The safe limit for the battery level has been determined as 2.5V. We observed that, in general, only 50% of the 11 nodes used were qualified for each experiment.

4 Experiment Results

The results are presented considering how some important parameters affect the wireless underground communication: the antenna orientation, the burial depth, the inter-node distance, and the soil moisture. Moreover, the temporal characteristics of the wireless underground communication channel are discussed.

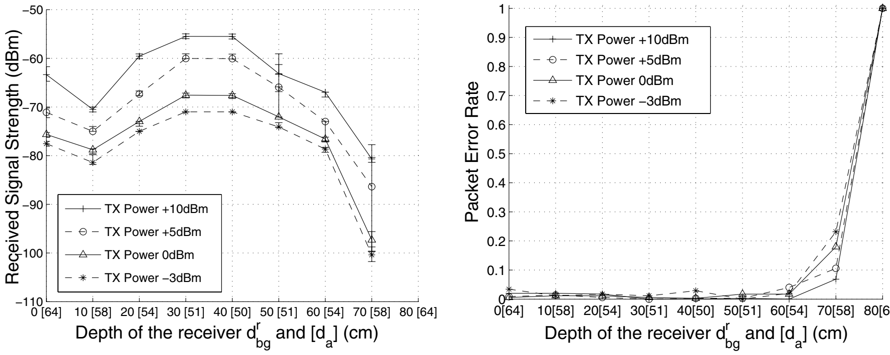
4.1 Antenna Orientation

Antenna orientation experiments were performed by placing a sender and a receiver at different angles as shown in Fig. 3(a) to provide guidelines for node deployment. The antenna of MICA2 is a standard one-quarter wavelength monopole antenna with 17cm-length, whose radiation pattern does not exhibit a perfect sphere and matches the dipole antenna model presented in [11]. The experiments were performed at a depth of d_{bg} = 40cm and at a distance of $d_a = d_h$ = 100cm between the sender and the receiver. In Fig. 3(b), the packet error rate (PER)



(a) Relative angles for the antenna. (b) PER vs. relative angle for the antenna.

Fig. 3. The schema used to test the effects of the antenna orientation for the underground-to-underground communication



(a) Received Signal Strength vs. depth of the receiver (d^r_{bg}) and actual inter-nodes distance d_a.

(b) Packet Error Rate vs. depth of the receiver (d^r_{bg}) and actual inter-nodes distance d_a.

Fig. 4. Effect of the reflected path from the ground surface. Sender buried with d^s_{bg}=40cm. Horizontal inter-node distance d_h=50cm. The depth of the receiver is varying from 0 to 80cm.

is shown as a function of the node orientation. It can be observed that when the relative angle varies from 90^o to 340^o, the PER increases and the orientation of a node has a significant impact on the communication success. If the antenna orientation is between 120^o and 300^o, virtually no communication is possible. Hence, during remaining experiments, only the 0^o orientation is used to eliminate the effect of antenna orientation. This result shows that the antenna orientation is an additional constraint to be considered for deployment of WUSNs, compared to traditional WSNs, especially for multi-hop underground networks, where communication range varies based on the antenna orientation.

4.2 Effects of Burial Depth

In this section, we discuss the effects of burial depth on the signal strength and PER. Accordingly, the horizontal inter-node distance between the sender and the receiver is fixed (d_h=50cm), the burial depth of the sender is also fixed (d^s_{bg}=40cm) and the depth of the receiver is varied from 10 to 100cm using different transmit power levels. In Fig. 4(a) and 4(b), the RSS and PER values are shown, respectively, as a function of the receiver depth. The actual distance, d_a, between the sender and the receiver is also indicated in parenthesis on the x-axis. Each line in the figures shows the results for different transmit power levels. In Fig. 4(a), the variance of the RSS is also shown along with the average values for each point.

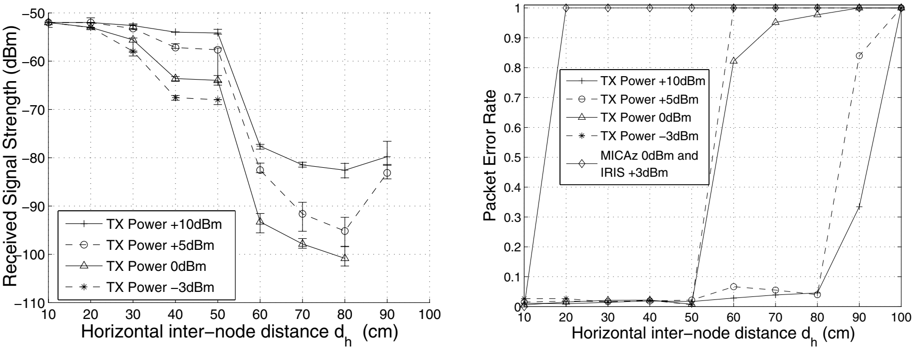
As shown in Fig.4(a), an increase in the actual inter-node distance, d_a, decreases the signal strength, as expected. The highest signal strength corresponds to the receiver depth of 30-40cm and the signal strength gradually decreases if the receiver burial depth is smaller than 30cm or higher than 40cm. One exception to this case is d^r_{bg} = 0cm, where the signal rays from above the ground impact the received signal strength positively and increase the RSS for each transmit power level. An important observation is the significant difference of RSS values at the same inter-node distances but at different burial depths. As an example, an additional attenuation of 20dB is observed for the same inter-node distance of d_a=58cm, when the receiver is buried at 70cm compared to the burial depth of 10cm. This behavior occurs mainly due to the reflection of RF signals from the soil surface, which positively affects the RSS when nodes are buried closer to the surface. This result validates the two-path channel model for the wireless underground channel proposed in [9,2].

It can be observed in Fig.4(b), that for the receiver burial depth of 70cm, the PER increases (0.1<PER<0.2) and an increase in burial depth to 80cm results in a communication loss. Note that this behavior occurs for all transmit power levels, highlighting that the burial depth plays an important role in the connectivity of the WUSN design. It can also be observed in Fig.4(a) that the RSS values have a very small variance for all depths and transmit power levels. Accordingly, for a given node deployment, the underground communication channel is very stable as long as the composition of the soil does not change. The only exception is the effects of varying VWC as will be discussed in Section 4.5.

4.3 Effects of Inter-node Distance

In this section, the effects of the inter-node distance on the signal strength and PER are highlighted. Accordingly, the burial depth of the sender and the receiver is fixed (d^s_{bg}=d^r_{bg}=40cm), and the inter-node distance is varied from 10 to 100cm using different transmit power levels. For completeness, the same experiment is repeated for MICAz and IRIS motes [18], with transmit power levels of 0dBm and +3dBm, respectively. In Fig. 5(a) and 5(b), the RSS and PER values are shown, respectively, as a function of the depth of the receiver for different transmit power levels. The variance of the RSS values are also shown. As shown in Fig. 5(b), the maximum inter-node distance is found to be between 80 and 90cm for transmit powers of +5 and +10dBm, and 50cm for -3 and 0dBm. For transmit power of -3 and 0dBm, when the inter-node distance varies from 60 to 70cm, the significant decrease of the signal strength can be observed in Fig. 5(a), which results in an abrupt PER increase as shown in Fig. 5(b). These results reveal the limitations of typical WSN nodes, such as the MICA2, considering the use of a low power transceiver (<+10dBm). In [2,9], it has been found that a path loss of about 30dB corresponds to an inter-node distance of 100cm, which is also observed in Fig.5(a), where attenuation of almost 30dB for an inter-node distance of 90cm is observed with transmit power of +10dBm.

The performance of the communication using MICAz (0dBm) and IRIS (+3dBm) for different burial depths and inter-node distances is shown in Table 2. The value, *Yes*, in the column, *Comm. success*, indicates that the communication is possible with a PER$\leq$ 97%. As shown in Table 2 and also in Fig. 5(b), the use of MICAz and IRIS, which operate at 2.4 GHz, is limited to an inter-node distance of 10cm for a burial depth d^s_{bg}=d^r_{bg}=40cm. This result also agrees with



(a) Received Signal Strength vs. horizontal inter-node distance (d_h).

(b) Packet Error Rate vs. horizontal inter-node distance (d_h).

Fig. 5. Maximum inter-node distance for underground-to-underground communication. Sender and receiver buried at depth=40cm (d^s_{bg}=d^r_{bg}=40cm). The inter-node distance d_h is varying from 10 to 100cm.

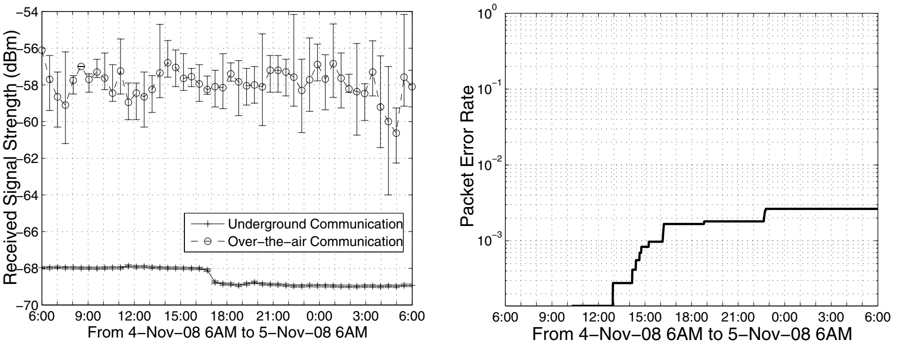
[12], which presented no communication for MICAz motes under similar conditions [12]. This experiment also proves that the use of a lower operating frequency of MICA2 (433MHz) exhibits better propagation characteristics than higher frequencies typically adopted for terrestrial sensor nodes such as 2.4 GHz (MICAz and IRIS). Finally, the results validate our recent theoretical studies that highlight the need for lower operating frequencies for the feasibility of WUSNs [2], [9].

4.4 Temporal Characteristics

In this section, the temporal characteristics of the wireless underground channel are investigated. Accordingly, a 24-hour experiment is performed by fixing the horizontal inter-node distance between the sender and the receiver (d_h=50cm), the burial depth of the sender and the receiver (d^s_{bg}=d^s_{bg}=40cm), and the transmit power at +10dBm. For comparison, the same experiment is repeated

Table 2. Underground-to-underground communication using MICAz and IRIS motes

Mote	**Burial depth (d^s_{bg}=d^r_{bg})**	**Inter-node dist.(d_h)**	**Comm. success**
MICAz	10 – 40cm	10cm	Yes
MICAz	10cm	20cm	Yes
MICAz	10cm	≥ 30cm	No
MICAz	20 – 40cm	≥ 20cm	No
IRIS	10 – 40cm	10cm	Yes
IRIS	10 – 20cm	20cm	Yes
IRIS	10 – 20cm	≥ 30cm	No
IRIS	30 – 40cm	≥ 20cm	No



(a) Received Signal Strength vs. Time. Comparison between underground and over-the-air wireless communication.

(b) Historical evolution of PER over the Time (PER <1% for all 24h period)

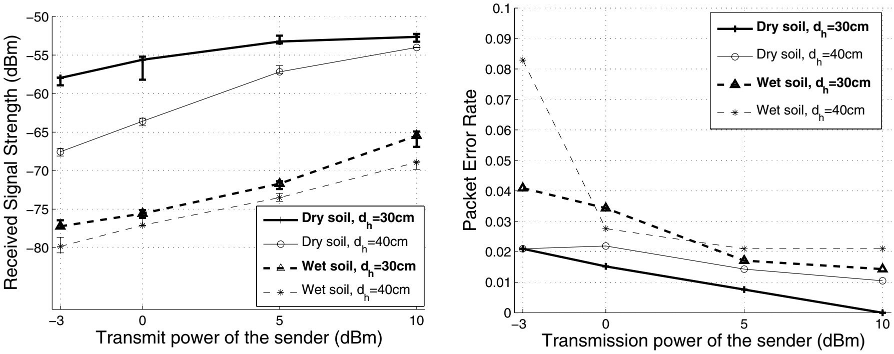
Fig. 6. Period of 24h: RSS and historical evolution of PER. Sender and receiver buried with (d^s_{bg}=d^r_{bg}=40cm). Horizontal inter-node distance d_h=50cm. Transmit power=+10dBm.

over-the-air in an indoor environment with an inter-node distance of 5m and a transmit power of +10dBm. In Fig. 6(a) and 6(b), the RSS and PER values are shown, respectively, as a function of time. Each data point shows the average of 30 minutes of RSS or PER information, which corresponds to 150 packets. In Fig. 6(a), the confidence intervals of the RSS is also shown along with the average values for each point as well as the results of the over-the-air experiments. In Fig. 6(b), the temporal evolution of the cumulative PER is shown for underground communication.

As shown in Fig. 6(a), the maximum variation of the signal strength is only 1 dB. No precipitation event was registered during the period and only a 8^{o}C variation is observed on the temperature during the experiment [21]. Compared to the over-the-air communication, where both the average and the variance of the RSS vary significantly with time, underground wireless channel exhibits a stable characteristic with time. As shown in Fig.6(b), during the same period of time, PER is always smaller than 0.5% with a small variance. This result agrees with the model for wireless underground channel proposed in [2,9], which points out the high stability of the wireless underground channel. The temporal stability has important impacts in the design of routing and topology control protocols for WUSNs.

4.5 Effects of Soil Moisture

In this section, the effects of the volumetric water content (VWC) on the signal strength and PER are discussed. Accordingly, the burial depth of the sender and the receiver is fixed (d^s_{bg}=d^r_{bg}=40cm), two different inter-node distances (d_h=30cm and 40cm) are used in conjunction with two different VWC levels (dry and wet soil), and the transmit power is varied. The *dry soil* experiments refer



(a) Comparison of the Received Signal Strength with dry and wet soil scenarios

(b) Comparison of the PER with dry and wet soil scenarios

Fig. 7. Effect of the VWC over the wireless underground-to-underground communication. Sender and receiver buried at d^s_{bg}=d^r_{bg}=40cm, 2 inter-node distances: d_h=30cm and d_h=40cm. Varying transmit power of the sender.

to tests realized on Oct 20th, 2008, a sunny day, and the *wet soil* experiments were performed on Oct 22nd, 2008, a rainy day, when 2.5 inches of precipitation was recorded [21]. Based on the *oven drying method* [15], the different VWCs are measured to be 11% for dry soil 18% for wet soil, which corresponds to an increase of almost 60%in VWC. In Fig. 7(a) and 7(b), the RSS and PER values are shown, respectively, as a function of the transmit power level of the sender. Each line in the figures shows the results for different VWC and inter-node distances.

As shown in Fig. 7(a), for high VWC, i.e., wet soil, the attenuation increases by 12 to 20dB compared to dry soil. The Fig. 7(b) also reveals that the increase of VWC implies higher PER. We can also observe, from the Figs. 7(a) and 7(b), that the negative effect of the VWC over the quality of the communication is reduced when the transmit power is increased. Therefore, for a scenario where the natural or artificial irrigation is expected to occur, the design of the WUSN protocols should carefully consider the variation of the VWC of the soil. For instance, the communication protocol may consider the soil moisture measurements of a physical region to make informed routing decision or even consider to temporarily raise the transmit power of some of the nodes in order to decrease the adverse effects of VWC.

5 Conclusion

In this work, we propose a classification of wireless underground communication networks and present experiment results for underground-to-underground communication for subsoil WUSNs. To the best of our knowledge, this is the first work that provides insight to communication through soil using commodity sensor nodes.

The experiment results reveal the feasibility of using commodity sensor motes for WUSNs as well as their limitations. Accordingly, we have shown that the orientation of the underground nodes plays an important role in the connectivity of WUSNs. Moreover, the experiment results show that the burial depth is important for the WUSN design due to the effects of reflected rays from the underground-air interface at the surface. In addition, the wireless underground channel has been found to exhibit extreme temporal stability, which is important in the design of routing and topology control protocols. Furthermore, it is observed that for a given deployment and soil composition, there is a minimum transmit power for which the underground-to-underground communication has the same reliability compared to cases where higher transmit power levels are used. Finally, the direct influence of soil moisture on the communication success is shown and it was observed that this influence can be decreased using higher transmit power levels. These observations agree well with our channel model in [2,9], however, a detailed validation of the proposed model is out of the scope of this paper. These valuable insight to the underground communication provides several guidelines for the development of communication protocols and power management schemes for WUSNs. Since the soil moisture significantly affects the communication success, this information should be effectively integrated to the design of these protocols.

In addition to the characteristics of wireless underground communication, the limitations of the commodity sensor nodes for WUSNs are also observed as a result of these experiments. It can be observed that for this specific Subsoil WSUN scenario, the inter-node distance was smaller than 1m. In terms of signal attenuation, this corresponds to roughly a 1:20 attenuation rate compared to *through-the-air* communication in an outdoor environment [3]. Consequently, a new generation of nodes with more powerful transceivers and/or more efficient antennas are required for the actual deployment of WUSN applications. We expect that the use of higher transmit power levels will provide higher communication ranges with still acceptable energy efficiencies as shown in [2,9] through simulations. However, considering that this approach implies higher energy consumption, we also expect the use of hybrid architectures with aboveground nodes to decrease energy consumption.

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