LETTERS

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Experiment Measurements for Packet Reception Rate in Wireless Underground Sensor Networks

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***Abstract*— A Wireless Underground Sensor Network (WUSN) is a network of wireless sensor devices in which all sensor devices are deployed completely underground (network sinks or any devices specifically for relay between sensors and a sink may be aboveground). These networks can be utilized to monitor the underground environment, especially soil conditions and aboveground events, such as the presence of people or animals. This paper measures the path loss exponent and packet reception rate for underground environment using test bed experiment work. The signal strength of the signal propagation is measured underground and aboveground.**

***Index Terms*— Signal Strength, Path Loss Exponent, Packet Reception Rate**

I. INTRODUCTION

The richness of existing and potential applications from commercial agriculture and geology to security and navigation has stimulated significant attention to their capabilities for monitoring various underground conditions. A Wireless Underground Sensor Network (WUSN) is defined as a network of wireless sensor devices in which all sensor devices are deployed completely underground (network sinks or any devices specifically for relay between sensors and a sink may be aboveground). These networks can be utilized to monitor the underground environment, especially soil conditions such as water and mineral content or the presence of toxic substances, as well as certain aboveground events, such as the presence of people or animals overhead which can be determined with the use of pressure sensors [1].

Since WUSN devices are completely self-contained within the underground environment, they must be able to communicate through soil and rock using a buried antenna. Unfortunately the underground is a challenging environment for wireless communication. Radio waves experience high levels of attenuation due to absorption by soil, rock, and water in the underground. Signal losses are highly dependent on numerous soil properties such as soil makeup (sand, silt, or clay) and density, and can change dramatically with time (e.g. increased soil water content after a rainfall) and space (soil properties change dramatically over short distances

The unique nature of the physical layer in WUSNs is what makes communication amongst underground wireless sensor networks such an interesting research topic. Wireless communication with electromagnetic waves through a dense medium such as soil or rock experiences high levels of attenuation due to absorption of the signal. Overall, the underground wireless channel for electromagnetic waves can be characterized by extreme signal loss, multi-path effects due to the inhomogeneous nature of soil, noise due to electrical ground currents, extended black-out periods after a rainfall due to wet soil [1].

The amount of signal loss when propagating through soil or rock is dependent upon the properties of the material. Any water in the soil produces significant amounts of attenuation which increase as the water content of the soil increases. The effect of water on the signal is dependent on the frequency being used however. Higher frequencies will be more affected than will lower ones. In general, lower frequencies will experience less attenuation when propagating through the ground. Other soil factors which affect attenuation of electromagnetic signal propagating through the ground include density, particle size and temperature.

This paper calculates the path loss exponent for underground environment using test bed experiment work. The test bed measures the signal strength of the signal propagation underground and aboveground. 100 samples of the signal strength readings were recorded for four different orientations (north, south, east and west) of the receiver and the average of these 100 readings will be used as the signal strength at that point in each orientation. In order to solve the problem of the variation of signal strength, the average value and the curve-fitting of the data recorded were used. The results show that the proposed path loss exponent can be used for many underground applications such as sports field turf management, landscape management and underground infrastructure monitoring. In addition, this paper measures Packet Reception Rate (PRR) for underground environment using test bed experiment work. The test bed measures the signal strength of the signal propagation underground and aboveground.

The remaining parts of this paper are organized as follows: Section II will present related work. PRR model will be described in Section III and Section IV will conclude the paper.

II. RELATED WORK

The main challenge in WUSN area is the realization of efficient and reliable underground links to establish multiple hops underground and efficiently disseminate data for seamless operation. To this end, the propagation characteristics of electromagnetic (EM) waves in soil prevent a straightforward characterization of underground wireless channel. First, EM waves encounter much higher attenuation in soil compared to air, which severely hampers the communication quality. As an example, efficient communication between sensor nodes above and below ground is shown to be possible only at the distance of 0:5m when the 2:4 GHz frequency is used [2].. Moreover, the surface of the ground causes reflection as well as refraction, which prevents simple ray models characterize the underground channel accurately. In addition, multi-path fading is another important factor in underground communication, where unpredictable obstacles in soil such as rocks and roots of trees make EM waves being refracted and scattered. Since underground communication and networking are primarily limited by the wireless channel capabilities, these challenges caused by underground channel should be carefully considered for the design of WUSN.

Stuntebeck et al. examined the packet error rate and the received signal strength of received packets for a communication link between two underground sensors and between an underground sensor and an aboveground sensor [2]. They found that the communication between two underground sensors nodes at the same depth is impossible. Hence, they focus on communication between one underground sensor node and one aboveground. However, authors in [2] did not measure the path loss exponent which is useful to predict the signal propagation.

There has been some work focusing on the electromagnetic (EM) wave propagation through soil and rock for ground-penetrating radars [3, 4, 5, and 6]. In [3], a review of the principles of the surface-penetrating radar is provided. More specifically, an overview of the empirical attenuation and relative permittivity values of various materials, including soil, at 100MHz is presented. In [4], it has been shown that the soil composition has significant effects on the Ground Penetrating Radar (GPR) detection of landmines. Furthermore, in [5], the electromagnetic field principles of a vertical electric dipole in a conducting half-space over the frequency range from 1 to 10 MHz are analyzed. Similarly, in [6], communication through soil is regarded as an electromagnetic wave transfer through the transmission line and microwave analysis methods are exploited to provide a propagation model. The results of this work focus on the frequency range of 1-2 GHz. Although significant insight in EM wave propagation through soil can be gathered from these works, none of the existing work provides a complete characterization of underground communication. More specifically, neither the channel characteristics nor the multi-path effects due to obstacles in soil have been analyzed before.

III. PRR MODEL

The PRR is approximated as the probability of successfully receiving a packet between two neighbour nodes (Zuniga & Krishnamachari, 2004). If PRR is high that means the link quality is high and vice versa. In this work, the physical layer is based on the IEEE 802.15.4/Zigbee RF transceiver that has a frequency of 2.4 GHz with O-QPSK modulation. It is based on a chip rate Rc of 2000 kc/s, a bit rate Rb of 250 kb/s and a codebook of M=16 symbols. The PRR uses the link layer model derived in IEEE 802.15.4 Standard [7 and 8] as:

$$PRR = \left[1 - \left(\frac{8}{15}\right)\left(\frac{1}{16}\right) \sum_{j=2}^{16} (-1)^j \binom{16}{j} \exp\left(20\gamma(d) \left(\frac{1}{j} - 1 \right) \right) \right]^{176} \quad (1)$$

where γ(d) is Signal to Noise Ratio (SNR) and it can be calculated by IEEE 802.15.4 Standard as:

$$SNR = \gamma(d) = P_t - PL(d) - S_r \quad (2)$$

where P_t is the transmitted power in dBm (maximum is 0 dBm for TelosB), S_r is the receiver's sensitivity in dBm (-90 - -94dBm for TelosB) [9]. *PL(d)* is the path loss model which can be calculated as:

$$PL(d) = PL(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_\sigma \quad (3)$$

where d is the transmitter-receiver distance, *PL(d0)* is the path loss at the reference distance d0 (1 m), n is the path loss exponent and *Xσ* is a zero-mean Gaussian distributed random variable in (dB) with standard deviation *σ* (dB).

A. Path Loss Exponent Determination

The PRR test bed measured the signal strength of the underground signal propagation in the field of University Technology Malaysia (UTM). It consists of a sink and four TelsoB radio sensor nodes. The sink is a laptop with TelosB attached in the USB port. It is placed in the centre of WUSN as shown in Figure 1. In this figure, the radio sensor nodes are distributed in different orientations (north, south, east and west) and different depths (0cm - 20cm). TelosB consists of low power transceiver based on CC2420 ChipCon chip [9] that employs IEEE 802.15.4 physical and MAC layers specifications.

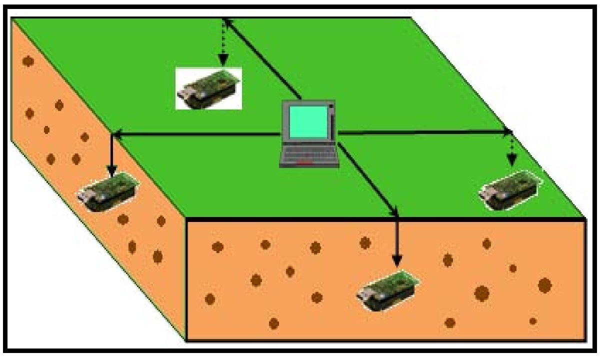
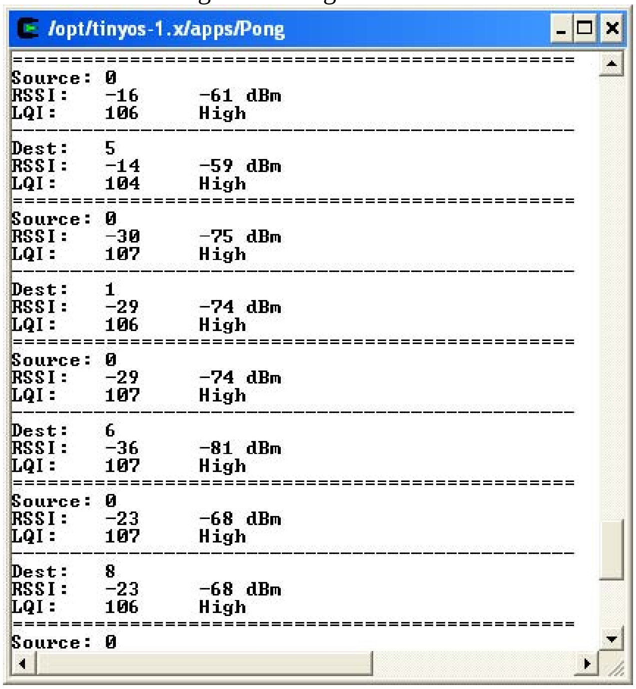


Figure 1: WUSN model

The experiment was conducted at a coverage radius between 1- 10 m and three levels of depth (0, 10 and 20 cm) in the underground. At each specified point, 100 samples of the signal strength readings were recorded for each point and the average was used. Then the average of four different orientations was used in the same level of underground depth. Figure 2 shows the result of program that collects signal strength in the sink node.



```
=================================================
Source: 0
RSSI:    -16      -61 dBm
LQI:     106      High
-------------------------------------------------
Dest:    5
RSSI:    -14      -59 dBm
LQI:     104      High
=================================================
Source: 0
RSSI:    -30      -75 dBm
LQI:     107      High
-------------------------------------------------
Dest:    1
RSSI:    -29      -74 dBm
LQI:     106      High
=================================================
Source: 0
RSSI:    -29      -74 dBm
LQI:     107      High
-------------------------------------------------
Dest:    6
RSSI:    -36      -81 dBm
LQI:     107      High
=================================================
Source: 0
RSSI:    -23      -68 dBm
LQI:     107      High
-------------------------------------------------
Dest:    8
RSSI:    -23      -68 dBm
LQI:     106      High
=================================================
Source: 0
```

Figure 2: Asymmetric Signal Strength Reading

As can be seen in Figure 2, the signal strength between two sensor nodes is measured based on asymmetric link which means the signal strength reading is measured in both side of communication link.

Figure 3 illustrates the signal strength varies with logarithm of distance. It shows the variation due the orientation of the receiver with the three levels of underground depth. The results show a signal strength variation up to 14dBm between 0cm and 20cm depth of the underground at the same distance far from the sink.

In order to calculate the path loss exponent, the curve-fitting of the data recorded for each depth was calculated. The curve-fitting line of the average value is calculated based on minimized total error R^2 as follows [10]:

$$R^2 = \sum_{i=1}^{m} (y_i - (ax_i + b))^2 \tag{4}$$

where Yi is PL(d , a is 10n, b is PL(d0) when compared to equation (3). The condition for R2 to be a minimum is that:

$$\frac{\partial(R^2)}{\partial a} = 0 \text{ and } \frac{\partial(R^2)}{\partial b} = 0 \tag{5}$$

However, b is constant in equation (4) and is equal to 51.5, 60 and 65 for 0cm, 10cm and 20cm underground depth respectively. In this test bed, d0 = 1m so we do not need partial derivatives for b. From equations (4) and (5), we have:

$$\frac{\partial(R^2)}{\partial a} = -2\sum_{i=1}^{m} [y_i - b + ax_i)]x_i = 0 \tag{6}$$

Equation (6) is simplified to become:

$$a = \frac{\sum_{i=1}^{m} xy - b\sum_{i=1}^{m} x}{\sum_{i=1}^{m} x^2} \tag{7}$$

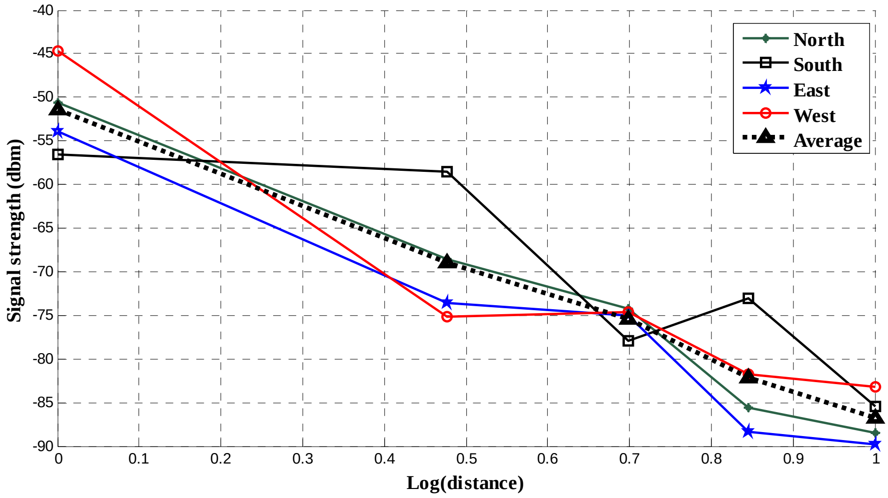
From the test bed and MATLAB calculation, the values of n are 3, 3.1 and 3.3 for 0cm, 10cm and 20cm underground depth respectively as derived from equation (7).

B. PRR Determination

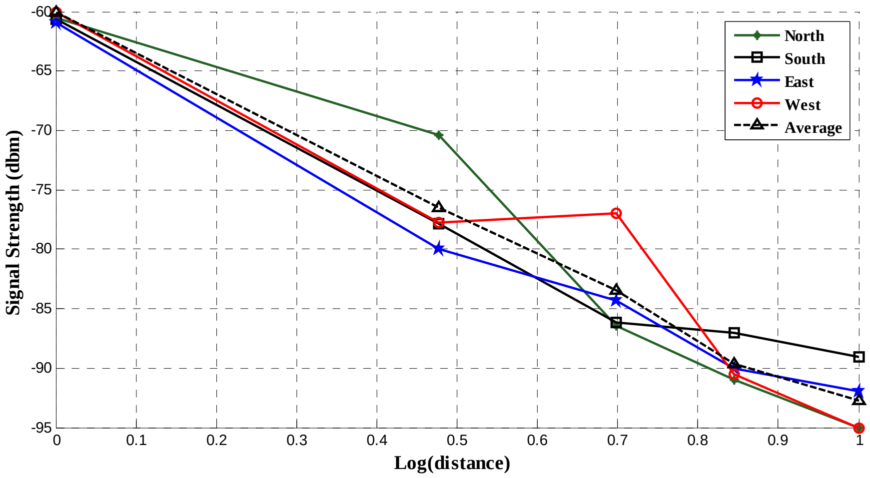
The above section shows the calculation of path loss exponent which can be used to substitute in equation (1) to get PL(d). Hence, SNR can be calculated based on Pt which is 0 dbm and Sr which is between -90 – -94 dbm. Figure 4 shows the result for three underground test beds. In this figure, the test bed with touch ground experiences highest PRR compared to the underground test beds. This is mainly due to EM waves do not propagate well in underground due to absorption by soil, rock, and water which causes signal losses. Figure 4 also shows that PRR is decreased when the depth of sensor nodes is increased. This is primarily due to the signal attenuation.

IV. CONCLUSION

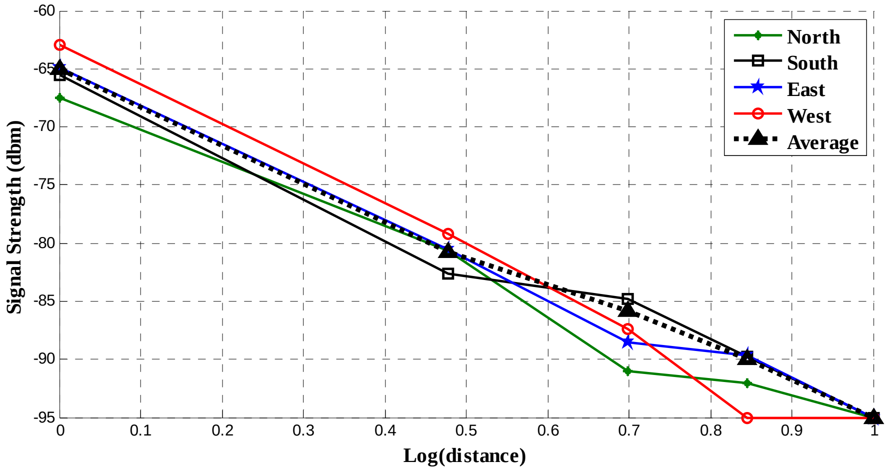
Overall, the results of these experiments demonstrate that existing wireless sensor network solutions have limited applicability for wireless underground sensor networks. Reliable communication between an underground and a surface node was only achievable over a range of 5m; even with the underground node placed at a relatively shallow depth of 20 cm. In addition, PRR can be enhanced when the sensor node placed at shallow depth of maximum 10 cm using the CC2420 transceiver.


-40
-45
-50
-55
-60
-65
-70
-75
-80
-85
-90
Signal strength (dbm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Log(distance)
North
South
East
West
Average

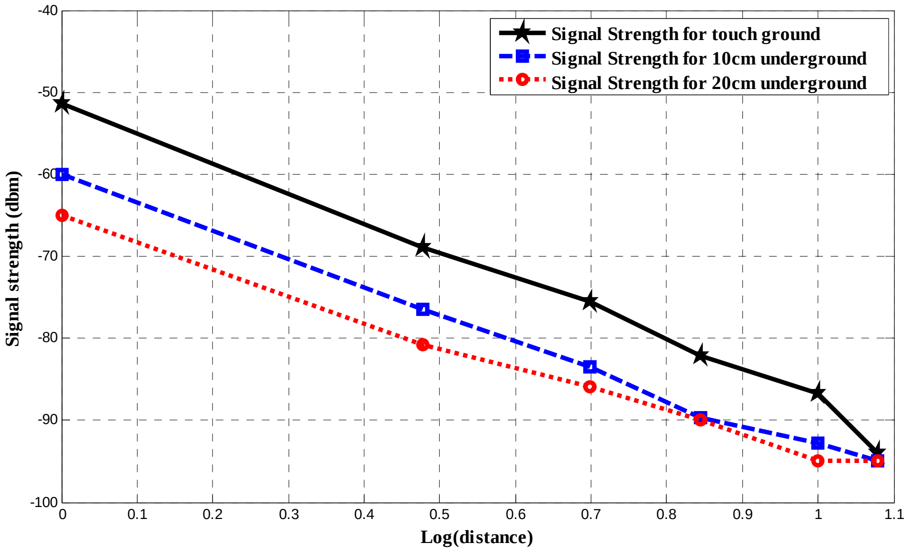
a)


-60
-65
-70
-75
-80
-85
-90
-95
Signal Strength (dbm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Log(distance)
North
South
East
West
Average

(b)


-60
-65
-70
-75
-80
-85
-90
-95
Signal Strength (dbm)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Log(distance)
North
South
East
West
Average

(c)



(d)

Figure 3: Variation of Signal Strength for WUSN (a) 0cm; (b) 10cm; (c) 20cm and (d) Average.

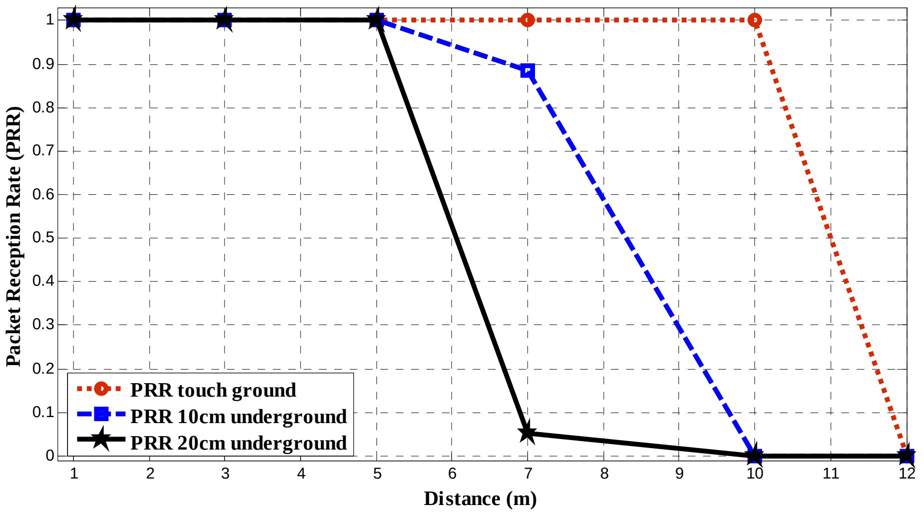


Figure 4: PRR for WUSN

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REFERENCES

[1] Akyildiz & Stuntebeck, E, (2006), Underground wireless sensor networks: research challenges. Ad Hoc Networks (Elsevier), June 2006, 669-686.

[2] Stuntebeck, E., Pompili, D., Melodia, T. (2006). Underground Wireless Sensor Networks Using Commodity Terrestrial Motes, poster presentation at IEEE SECON 2006, September 2006

[3] Daniels, D. J. (1996). Surface-Penetrating Radar. Electronics & Communication Engineering Journal, vol. 8, no. 4, pp. 165 - 182, Aug. 1996.

[4] Miller, T. W., Brian Borchers, Jan M.H. Hendrickx, Sung-Ho Hong, Louis W. Dekker, and Coen J. Ritsema. (2002). Effects of soil physical properties on GPR for landmine detection. in Fifth International Symposium on Technology and the Mine Problem, April 2002.

[5] Wait, J. and Fuller, J. (1971). On radio propagation through earth.Antennas and propagation. IEEE Trans. Antennas and Propagation, vol. 19, no. 6, pp. 796-798, November 1971.

[6] Weldon, T. P. and Rathore, A.Y. (1999). Wave propagation model and simulations for landmine detection.. Tech. rep., Univ. of N. Carolina at Charlotte, 1999.

[7] Zuniga, M. and Krishnamachari, B. (2004). Analyzing the Transitional Region in Low Power Wireless Links, Sensor and Ad Hoc Communications and Networks, IEEE SECON 2004, 1st Annual IEEE Communications Society Conference, 2004. Pages: 517 - 526.

[8] IEEE 802.15.4 Standard. (2003) Part 15.4: Wireless medium access control (MAC) and physical layer (PHY) specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs), IEEE Standard for Information Technology, IEEE-SA Standards Board, 2003.

[9] Chipcon. (2005). CC2420 low power radio transceiver, http://www.chipcon.com.

[10] Faires, J. D. and Burden, R. (2003). Numerical Methods. Robert W. Pirtle, USA 2003, pp. 344-345