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ELECTROMAGNETIC WAVE PROPAGATION IN SOIL FOR WIRELESS UNDERGROUND SENSOR NETWORKS

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Abstract—Wireless underground sensor networks (WUSN) consist of wireless devices that operate below the ground surface. These devices are buried completely under dense soil, thus electromagnetic wave transmits only through soil medium. However, the high attenuation that caused by soil is the main challenge for the electromagnetic wave transmission for WUSN. In this study, architecture of wireless underground sensor network communication was established. The experimental measurements were conducted using WUSN sensor nodes at three different carrier frequencies, respectively. Received signal strength and packet error rate were examined for communication links between the sensor nodes. The test results showed that carrier frequency was one of the main factors that affected electromagnetic wave propagation in the soil medium. It was concluded that the burial depth of the sensor nodes, horizontal inter-node distance, and soil volumetric water content have significant impacts on the signal strength and packet error rate during the electromagnetic wave propagation within a WUSN.

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1. INTRODUCTION

Wireless underground sensor networks (WUSN) utilize sensor technology, embedded technology, network technology, wireless communication technology, distributed intelligent information processing technology, etc. [1, 2]. Sensor network uses systematic development approaches to realize miniaturization, integration, multifunction, systematization, network, especially to achieve extreme low power consumption design for the sensor network.

The core of wireless communication is the transmission of electromagnetic energy. The propagation of electromagnetic wave in wireless underground sensor network (WUSN) is very different from that of traditional wireless sensor network (WSN). In wireless underground sensor network, sensor nodes are buried in soil. Electromagnetic wave propagates in soil medium between sensor nodes, and propagation characteristics are decided by soil properties. Soil is a light dense medium compared to the air, which produces great absorption and attenuation to the electromagnetic wave [3–8]. Wireless underground sensor networks have been investigated in many contexts recently. The concept of WUSN and the challenges related to the underground wireless channel have been discussed in [9–14].

In [15], the propagation situation of electromagnetic waves in the soil, underground channel model, electrical characteristics of soil and deployed solutions of wireless underground sensor networks nodes were described. Transmission parameters of electromagnetic wave and energy losses were analyzed using a mathematical simulation software at a carrier frequency of 400 MHz. The sensor was buried at a depth of 0.5 m. The horizontal distance between sensor nodes was 1 m. The soil was carefully evaluated with a conductivity of 0.1 and a dielectric constant of 10. Moreover, the volumetric water content of the soil changed from 5% to 30%, and the proportion of sand and clay soil was also different.

In [16], the near surface wireless underground sensor networks system used for golf course was developed which included acquisition nodes, sink nodes and a gateway node. Each acquisition node consisted of a soil moisture sensor, a controller, a wireless transceiver (Nordic Company NRF905) with a carrier frequency of 868 MHz, an antenna, a memory unit and a battery power module. It could be connected with several moisture sensors. The sink node was the same as the acquisition nodes but with no sensors connected. The sink nodes collected the data from the acquisition nodes, communicated with other sink nodes if needed, and transmitted the data to the gateway node.

In [17], Silva and Vuran studied the impact factors of the communication performance for terrestrial nodes and underground nodes, including antenna bandwidth of WSN nodes at 433 MHz frequency, burial depth of nodes in the soil (15 cm and 35 cm), and water content of the soil (volumetric water content was 9.5% and 37.3%, respectively). The field experiment showed that the ultra-wideband antenna could increase the communication range by more than 350% compared to the original antennas. Volumetric water content increased from 9.5% to 37.3% leading to 70% drop of transmission distance. When nodes buried depth were changed from 35 cm to 15 cm, the transmission distance of the signal for the terrestrial nodes to underground nodes (downlink transmission) increased three times, but the transmission distance of the signal for the underground nodes to terrestrial nodes (uplink transmission) only increased by 0.4.

Sheth et al. buried wireless sensors with a tension induction module at a depth of 25 cm on a mountain to predict landslide [18]. Martinez et al. introduced a system with a sensor placed under ice to test the ice parameter [19]. The system did not really construct wireless underground sensor network, but used separation way of induction module and data transceiver. Allen et al. developed a sensor network to monitor volcanic activity. Although the node was buried under volcanic soil, the antenna of wireless RF module was exposed in the air [20].

In summary, wireless underground sensor network is a relatively new area which still needs more studies to understand the propagation performance of RF signals. This paper reports the progress on a development of wireless underground sensor network for soil property evaluation and the field experiments to identify significant impact factors on underground RF propagation.

2. MATERIALS AND METHODS

2.1. Measurement Principles

According to Peplinski principle, the value of the complex propagation constant of the RF signal in soil was given in Equation (1)

$$\gamma = \alpha + j\beta,$$
$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}, \quad \beta = \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right]} \tag{1}$$

where $\omega = 2\pi f$ was the angular frequency, μ , the magnetic permeability, and ε' and ε'' are the real and imaginary parts of the dielectric constant, respectively.

Equation (1) shows that the complex propagation constant of the RF signal in soil is dependent upon the carrier frequency, composition of soil, and soil volumetric water content. Consequently, the signal attenuation would also vary with these parameters. Hence, a series of experimental tests were designed to evaluate the impact of these parameters on the RF signal propagation in soil.

2.2. Wireless Underground Sensor Nodes

Wireless underground sensor nodes (Sensor Node) were developed with an adjustable carrier frequency of 240 MHz, 433 MHz and 868 MHz. Each sensor node consisted of a sensor module, a processor module, a wireless communication module and a power supply module. The sensor module included a soil moisture sensor, FDS100 (Shenzhen, China). The processor module included a microcontroller, MSP430 (Texas Instrument, Texas, USA) that featured with a low power consumption. The wireless communication module consisted of a wireless transceiver, H8410 (Shenzhen, China) that could be set with three different carrier frequencies. The power node was formed with two high performance batteries (1.5 Voltage). Each sensor node used a standard monopole omni-directional antenna with quarter-wave, GFSK modulation mode and a maximum transmitted power of 100 mW. The antenna was placed in the vertical direction. Fig. 1 shows the developed sensor nodes.

(a) (b)

Figure 1. Wireless underground sensor node. (a) The unsealed sensor node. (b) The sealed sensor node.

2.3. Soil Medium

The lab tests were carried out in the laboratory of the Research Institute of Water-saving Agriculture of Arid Regions of China in the Northwest Agriculture and Forestry University. Since the soil composition directly affected the attenuation of RF signal, the soil samples were carefully prepared. Soil could be classified based on particle size and the variations of sand, silt and clay content. Sandy soils produced the least amount of attenuation, while clay soils produced the most. During the experiment, soil medium was assumed as a homogeneous one. Using the pipette method and Stokes' law [21], the soil medium had a clay content of 11.32%, silt content of 61.26%, and sand content of 27.42%. The surrounding temperature was kept at a range of 20–24°C throughout the experiment.

2.4. WUSN Communication Test Setup

Wireless underground sensor nodes, a transmission node and a receiving node were buried in soil. The burial depth of sensor nodes was defined as the distance from the node antenna position to the ground surface. During the experiment, the transmission node was fixed at a specific burial depth (d_s). The receiving node was buried at different depths during the tests. Fig. 2 shows the defined distances related to the WUSN experiment. The actual inter-node distance was defined as the distance between the transmission node and receiving node (d_a). The horizontal inter-node distance, d_h, was the horizontal projection of the actual-node distance. The horizontal inter-node distance remained unchanged during the tests. When the burial depth of the receiving node was changed, the actual inter-node distance would change accordingly.

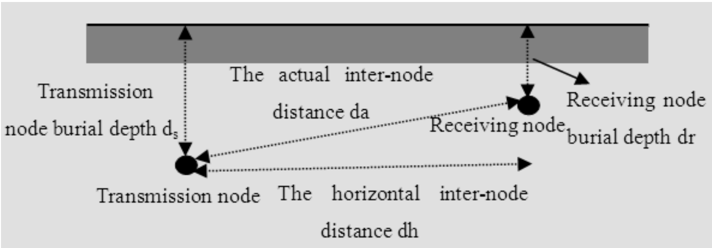


Figure 2. Distances defined in the tests of the wireless underground communication.

The received signal strength (RSS) was measured at the receiving node through the measurements of transmitted power and signal loss using a spectrum analyzer (DSA1000A, Agilent, California, USA). It was measured at various carrier frequencies, horizontal inter-node actual distances, and soil volumetric water contents. At each specific test, RSS was measured 30 times, and the average value was used to represent the RSS for the test. Packet error rate (PER) was the ratio, in percentage, of the number of test packets sent by the transmittance node but not successfully received by the receiver node to the number of total packets sent by the transmittance node.

2.5. Effects of Node Burial Depth

The signal output power of the transmission node was set at 20 dBm. The transmittance node was buried at a depth (d_s) of 40 cm. The receiving node was buried at varied depths of 10 cm to 100 cm with an increment of 10 cm. The horizontal inter-ode distance (d_h) was fixed at 50 cm. The soil was kept dry. The effects of the node burial depth on the received signal strength and the error rate were measured at three carrier frequencies, 240 MHz, 433 MHz, and 868 MHz, respectively.

2.6. Effects of the Horizontal Inter-node Distance

In the wireless underground sensor network, the horizontal inter-node distance between the transmission and receiving nodes was very important to ensure good communication. The influence of the horizontal inter-node distance on the received signal strength and the error rate needed to be considered. During this test, the soil was kept dry, the transmission power at 20 dBm, and the node burial depths for both transmission and receiving nodes were fixed at 40 cm. The horizontal inter-node distance (d_h) could change in the range of 10 cm–100 cm with an increment of 10 cm. The effects of the horizontal inter-node distance on the received signal strength and error rate were measured at three carrier frequencies, 240 MHz, 433 MHz, and 868 MHz, respectively.

2.7. Effects of the Soil Volumetric Water Content

In WUSN, RF wave completely propagated in soil medium. Soil volumetric water content was the main factor that influenced communication. The soil samples with different water contents were made through mixing water and soil by a blender according to a required proportion. The error was kept below 7%. The transmit power was set at 20 dBm. The node burial depths for both transmittance and receiving nodes were fixed at 40 cm. The horizontal inter-node distance (d_h) was set at 40 cm. The soil volumetric water content was changed in the range of 5% to 30%. The effects of the soil water content on the received signal strength and error rate were measured at three carrier frequencies, 240 MHz, 433 MHz, and 868 MHz, respectively.

The test results would be summarized and analyzed statistically to find significant impact factors on the RF propagation in soil.

3. RESULTS AND DISCUSSION

3.1. Effects of Node Burial Depth

Figure 3 shows variations on the received signal strength and error rate values with different node burial depths and carrier frequencies, respectively.

As shown in Fig. 3(a), the received signal strength decreased with the increase of carrier frequency. When the node burial depth of the receiving node was changed in a range of 30 cm–50 cm, the received signal strength remained at the highest level with relatively small changes. The received signal strength was the highest at about −53 dBm, when the carrier frequency was 433 MHz. When the node buried depth was smaller than 30 cm or between 50 cm and 70 cm, the node received signal strength with a carrier frequencies of 240 MHz and 433 MHz were very similar, but it decreased significantly with 868 MHz frequency. When the node buried depth $d_r > 50$ cm, the node received signal strength decreased dramatically for all three carrier frequencies. When the receiving node was buried under the ground surface at 0 cm, the received signal strength became large because the reflection of RF wave through the ground surface was reflected back which increased the received signal strength. Fig. 3(a) also shows that additional signal attenuates 13 dBm–18 dBm in receiving node burial depth 70 cm compared with node burial depth 10 cm at the same node distance 58 cm. Due to the reflection of ground surface, electromagnetic wave causes the increase of receiving signal strength

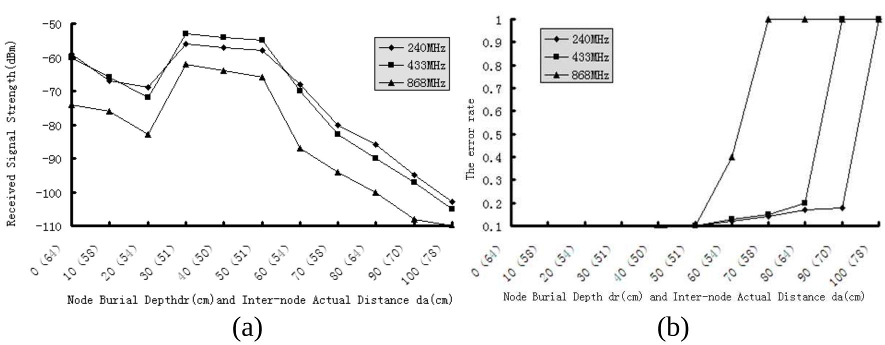


Figure 3. Effects of node burial depth. (a) Tests for the received signal strength. (b) Tests for the error rate.

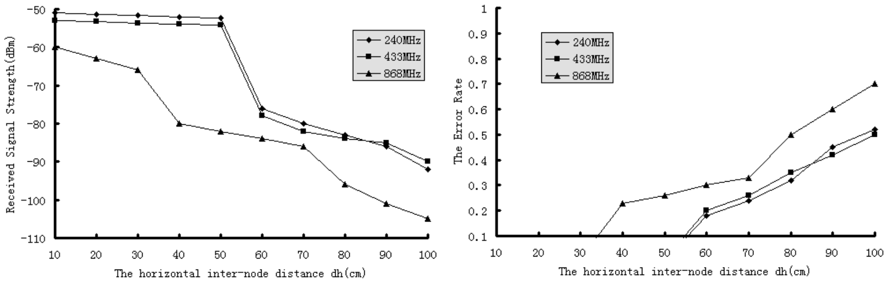
when WUSN node burial depth was smaller.

Figure 3(b) shows that carrier frequency was one of the main factors that influenced RF propagation in the soil medium. The high carrier frequency led to high error rate and made the communication unfeasible. It could also be found from Fig. 3(b) that at the carrier frequency of 240 MHz, the error rate was almost zero when the receiving node burial depth was less than 50 cm. When the receiving node burial depth was larger than 50 cm and less than 90 cm, i.e., the node actual distance was less than 70 cm, the error rate was less than 18%. The error rate increased rapidly to 100% when the receiving node burial depth was larger than 90 cm. When the receiving node burial depth was less than 50 cm and using the carrier frequency of 433 MHz, the error rate was close to zero. When the receiving node burial depth was larger than 50 cm and less than 80 cm, the error rate was slightly increased and kept at less than 20%. However, it was quickly increased to 100% when the node burial depth continuously increased, which seriously influenced communication. Similarly, when the receiving node burial depth was less than 50 cm and using the carrier frequency of 868 MHz, the error rate was close to zero. When the receiving node burial depth was increased to 60 cm, the error rate was suddenly increased to 40%, and to 70 cm, the error rate was increased to 100%. Communication between the nodes could not be achieved.

3.2. Effects of the Horizontal Inter-node Distance

Figures 4(a) and 4(b) show the received signal strength and error rate values, respectively, as a function of the horizontal inter-node distance.

In WUSN, the change of the horizontal inter-node distance seriously affected the received signal strength when both transmission and receiving nodes were buried at a depth of 40 cm. In Fig. 4(a), the received signal strength was very strong in the range of −50 dBm to −55 dBm when the carrier frequency was 240 MHz and 433 MHz, and the horizontal inter-node distance $d_h < 50$ cm. When the horizontal inter-node distance was increased to 60 cm, the received signal strength was suddenly reduced to about −80 dBm. Then, the received signal strength was also slowly reduced with the increases of the horizontal inter-node distance. When 85 cm $< d_h <$ 100 cm, the received signal strength of the 433 MHz node was greater than the 240 MHz node. Hence, when the horizontal inter-node distance in a range of 100 cm, the inter-node communication was well maintained in the soil medium. When the carrier frequency was increased to 868 MHz and the horizontal inter-node distance changed in a range of $d_h < 30$ cm, the received signal strength was reduced about 10 dBm.



(a) (b)

Figure 4. Effects of the horizontal inter-node distance. (a) Tests for the received signal strength. (b) Tests for the error rate.

The received signal strength was suddenly reduced about 15 dBm when the horizontal inter-node distance was increased to 40 cm. The received signal strength was gradually changed in a range of -80 dBm to -85 dBm when the horizontal inter-node distance was $40\,\text{cm} < d_h < 70\,\text{cm}$. The change gradient of the received signal strength in $80\,\text{cm} < d_h < 90\,\text{cm}$ was very similar to that in $30\,\text{cm} < d_h < 40\,\text{cm}$. The received signal strength continued to decline from -96 dBm to -105 dBm with the increase of the horizontal inter-node distance, which affected the communication of underground inter-nodes.

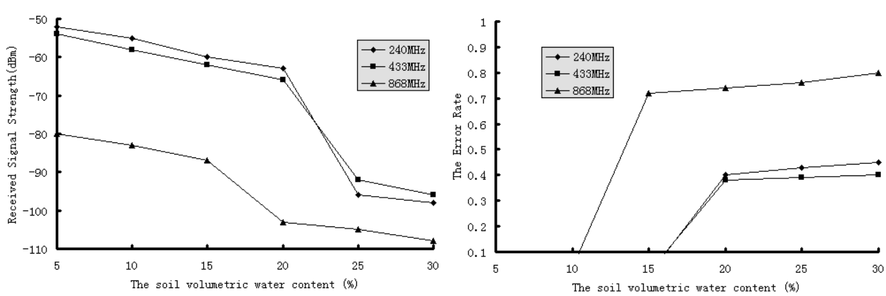
Figure 4(b) shows that the error rate could be neglected when the horizontal inter-node distance $d_h < 55\,\text{cm}$ for the nodes with a carrier frequency of 240 MHz or 433 MHz. The error rate was gradually changed with the increase of d_h. It was slightly higher for the 240 MHz node than that of 433 MHz node when the horizontal inter-node distance was $85\,\text{cm} < d_h < 100\,\text{cm}$. For 240 MHz and 433 MHz nodes, the error rate was gradually increased with the increase of the horizontal inter-node distance, but the biggest error rate was less than 50%. For the 868 MHz node, the error was close to zero when the horizontal inter-node distance was in a range of $d_h < 35\,\text{cm}$. When the horizontal inter-node distance was increased to 40 cm, the error rate reached more than 20%. The error rate was then changed linearly in the range between 20% and 30% when d_h was less than 70 cm. When the horizontal inter-node distance was $70\,\text{cm} < d_h < 100\,\text{cm}$, the error rate was increased from 30% to 70%.

3.3. Effects of the Soil Volumetric Water Content

Figures 5(a) and 4(b) show the received signal strength and error rate values, respectively, as a function of the soil volumetric water content.

The influence of different soil volumetric water contents on the communication was very obvious for different carrier frequencies. Fig. 5(a) shows that the higher was the soil volumetric water content, the lower was the received signal strength when the sensor nodes were buried at a depth of 40 cm with the horizontal inter-node distance at 40 cm. Specifically, when soil volumetric water content was below 20% and the carrier frequencies were 240 MHz and 433 MHz, the received signal strength was reduced very little in amplitude with the increase of soil volumetric water content and was not more than −66 dBm node. The received signal strength sharply fell to about −95 dBm when soil volumetric water content continued to increase to 25%. Changes of the received signal strength was not obvious for the nodes at 240 MHz and 433 MHz when the soil volumetric water content was changed between 25% and 30%. But, the received signal strength for 240 MHz frequency node was less than that of the 433 MHz frequency node. Both of them were larger than −100 dBm. At 868 MHz, the received signal strength was very different from that of the other node frequency. There is little change for the received signal strength between −80 dBm to −85 dBm when soil volumetric water content was less than 15%. When soil volumetric water content was increased to 20%, the received signal strength sharply fell to −103 dBm. After that, the received signal strength continued to decrease with the increase of soil volumetric water content. The decreasing rate of the amplitude was very small. When soil volumetric water content was 30%, the received signal strength reached minimum −108 dBm. Overall, the received signal strength was reduced about 10 dBm–30 dBm compared with the 240 MHz and 433 MHz frequency node.

Figure 5(b) shows that the error rate could be neglected when the node frequency was 240 MHz or 433 MHz and soil volumetric water



(a) (b)

Figure 5. Effects of the soil volumetric water content. (a) Tests for the received signal strength. (b) Tests for the error rate.

content less than 16%. As shown in Fig. 5(b), the received signal strength was sharply reduced when soil volumetric water content was increased to 20%, and the error rate was sharply increased to 40%. The error rate was increased about 5%, when soil volumetric water content continued to increase from 20% to 30%. At this time, 240 MHz frequency node produced slightly higher error rate than 433 MHz node. Obviously, the error rate of the 868 MHz frequency node was higher than the other nodes. When the soil volumetric water content was lower than 10%, the error rate was extremely low. The error rate was sharply increased to 70% when soil volumetric water content was increased to 15%. When the soil volumetric water content continued to increase, the error rate remained relative stable.

4. CONCLUSIONS

In this study, underground communication characteristics of wireless underground sensor networks were investigated. The experiment design and results are presented in this paper. The experiment results reveal the feasibility of RF wave transmission in the soil medium for wireless underground sensor networks and show some influence factors on underground communication are consistent with Equation (1). It was found that the carrier frequency was one of the important factors affecting underground RF transmission. The nodes with 433 MHz carrier frequency showed the best performance in the underground communication experiments. The experiment results also show that the node burial depth was important due to the effects of reflected waves from the underground-air interface at the surface. The burial depth of 50 cm was the best for communication. The horizontal inter-node distance played an important role in the underground-underground communication. The direct influence of the soil volumetric water content on the communication was observed in the experiment. The results revealed that the received signal strength decreased more than 10 dBm when the soil volumetric water content increased by 5%. Since the soil volumetric water content significantly affects the communication, this information should be effectively integrated to the design of underground communication protocols.

In addition to the transmission characteristics of RF waver in underground environment, it was also observed that soil medium generated more attenuation than air for electromagnetic waves. Consequently, new generation of nodes with more powerful transceivers would be required for reliable implementation of wireless underground sensor network.

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