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Wireless Sensor Network Communication Using Electromagnetic Waves at Radio Frequency 433 MHz

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Abstract

Wireless sensor network has the advantage of being low-cost, easily deployed and of good mobility. Wireless underground sensor network (WUSN) consists 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. In this paper, the application research of the wireless underground sensor network is described. Experimental measurements of the signal strength and error rate are presented at the frequency of 433MHz, which show a good agreement with the theoretical studies. The results show the burial depth of the sensor nodes, the horizontal inter-node distance, and the soil volumetric water content have significant impacts on the signal strength and packet error rate during the electromagnetic wave propagation within a WUSN.

***Keywords**: Wireless sensor networks, electromagnetic wave, communication, transmission, soil*

1. Introduction

A wireless sensor network consists of sensors used to monitor physical or environmental phenomena such as humidity, temperature, sound, pressure or motion and cooperatively pass the data through the network of sensors to a main location (Lopez etal.,2009;Aqeel etal.,2011;Carle and SimPlot-Ryl,2004;Berman etal.,2004;Xin and Mehmet,2010;Sheth, Tejaswi, and Mehta,2005). Wireless underground sensor network is very different from that of traditional wireless sensor network, which electromagnetic wave propagates in soil medium between sensor nodes and the propagation characteristics are decided by soil properties (Akyildiz and Stuntebeck 2006). When a signal propagates within a medium, it may be reflected, diffracted, and scattered (Akyildiz, Sun, and Vuran, 2009; Sun and Akyildiz, 2008). Each effect occurs to a different extent in various media, depending on factors such as wavelength and intensity of the wave, thickness and physical composition of the medium.

Wireless underground sensor network is that the WUSN sensor equipment with wireless transceiver module buried completely in certain soil depth, sensor module percepts the data and send data through the wireless mode. Many sensor nodes consist of sensor network in the soil and complete automatically the entire process of data perception, collection (Yu etal.,2013;Akyildiz etal.,2002;Green, Nadimi, and Blanes,2009;Kima etal.,2011;Shih etal.,2001). The WUSN has many advantages, such as strong concealment, easy of deployment, timeliness of the data, reliability, large covering range, easy of upgrade, *etc* (Akyildiz and Stuntebeck,2006).

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2. Related Work

Wireless underground sensor networks have been investigated in many contexts recently, but research reports of wireless underground sensor networks in agricultural application are little. The concept of WUSN and the challenges related to the underground wireless channel have been introduced in (Akyildiz and Stuntebeck, 2006).

In (Coen, Henk, and Leon,2009), 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 with a carrier frequency of 868 MHz, an antenna, a memory unit and a battery power module. It could connect with several moisture sensors. In (Bogena etal.,2009), wireless signal attenuation of ZigBee wireless transceiver module of the 2.44 GHz frequency was researched by using soil column in different soil types and the water content. In (Li and Wen,2008), 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. In (Silva and Vuran,2010), the impact factors of the communication performance were studied for terrestrial nodes and underground nodes, including antenna bandwidth of WSN nodes at 433 MHz frequency, the buried depth of nodes in the soil and water content of the soil.

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.

3. Materials and Methods

Measurement Principles:

The signal propagation in soil depends on the path loss in soil. Received power as a function of transmitted signal, path loss and antenna gain at the receiver end is given from Friis equation as shown in Equation (1) (Stuber, 2001)

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - L_0(dB) \quad (1)$$

Where P_t is the transmitter power, G_t and Gr are the gains of the transmitter and receiver antenna, L_0 is the path loss of electromagnetic wave propagation in free space. The path loss is shown in Equation (2).

$$L_0(dB) = 32.4 + 20\log(d) + 20\log(f) \quad (2)$$

Where d is the distance between transmitting and receiving nodes, measured in meters. f is node operating frequency, the unit is MHz. Electromagnetic wave propagate in the soil, a correction factor should be increased in Friis equation to express influence of the soil medium on electromagnetic wave propagation loss. As a result, the receiving node as the received signal energy is expressed in Equation (3).

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - L_p(dB) \quad (3)$$

Where, $L_p = L_0 + L_s$, L_s is extra path loss caused by soil when electromagnetic wave propagate in soil medium. Compared with the air, electromagnetic wave propagation rate will decrease according to the operating frequency, and different band can cause the signal distortion. S_0 the extra path loss L_s caused by soil can be expressed in Equation (4):

$$L_s(dB) = L_{s1}(dB) + L_\alpha(dB) \quad (4)$$

where, L_{s1} is attenuation loss due to the difference of the wavelength λ_1 of electromagnetic wave signal in soil, compared to the wavelength λ_0 in free space, and L_α

is the transmission loss caused by attenuation with attenuation constant α, L_{s1}=20log(λ_0/λ_1)。

Considering that the wavelength in the soil propagation is $\lambda_1=2\pi/\beta$, in the free space is λ_0=c/f, where β is the phase shifting constant, c=3×10^8m/s, f is the operating frequency, the L_{s1} and L_α can be represented as follows:

$$L_{s1}(dB) = 154 - 20\log(f) + 20\log(\beta) \tag{5}$$

$$L_\alpha(dB) = 8.69\alpha d \tag{6}$$

Given that the path loss in free space is $L_0=20\log(4\pi d/\lambda_0)$, the path loss L_p of an electromagnetic wave in soil is in Equation (7):

$$L_p(dB) = 6.4 + 20\log(d) + 20\log(\beta) + 8.69\alpha d \tag{7}$$

where the distance d is given in meters, the attenuation constant α is in 1/m and the phase shifting constant β is in radian/m. Note that the path loss L_p depends on the attenuation constant α and the phase shifting constant β. The values of these parameters depend on the dielectric properties of soil.

The Peplinski principle governs the value of the complex propagation constant of the electromagnetic wave in soil, which is given as γ=α+jβ with

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]} \quad (8) \qquad \beta = \omega\sqrt{\frac{\mu\varepsilon'}{2}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}+1\right]} \quad (9)$$

Where ω=2πf is the angular frequency, is the magnetic permeability, and ε' and ε'' are the real and imaginary parts of the dielectric constant, respectively. Consequently, the path loss in soil is dependent on the complex propagation constant.

Experiment Setup:

The experiment 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. During the experiment, soil medium was assumed as a homogeneous medium, and the surrounding temperature was kept at a range of 20-24℃ throughout the experiment. Using the pipette method and the Stokes' law (Li and Qi,2001), the soil medium had a clay content of 11.32%, the silt content of 61.26%, and the sand content of 27.42%. The basic physical property index of the soil sample is shown in table 1.

Table 1. The Basic Physical Property Index of the Soil Sample

Soil type	Particle-sized fractions (%)		
	Sand (2～0.02 mm)	Silt (0.02～0.002 mm)	Clay (<0.002 mm)
Silty loam	27.42	61.26	11.32

In the wireless underground sensor network communication, the sensor nodes are deployed mainly in the underground soil, but it still need to communicate with the ground node to implement the data collection, management and relay, *etc*. Therefore, there are three different kinds of WUSN communication mode based on the transmitting node and the receiving node are deployed on the aboveground or underground in the soil, the aboveground-underground communication, underground-aboveground and underground-underground communication. The diagram of communication structure is shown in Figure 1.

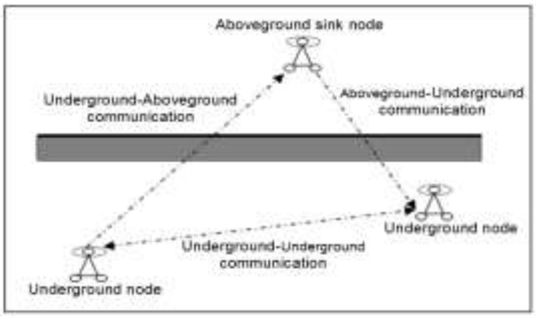

Figure 1. Structure of Communication in WUSN

4. Results and Discussion

The aboveground-underground communication:

The aboveground node is deployed on the ground surface that is perpendicular to the underground node, the change of the underground node burial depth and soil moisture content has much effect on the wireless underground sensor network transmission in the WUSN aboveground-underground communication. When the underground node burial depth and soil moisture content change at the same time, received signal strength changes in the range of -53dBm to -110dBm, is shown in Figure 2.

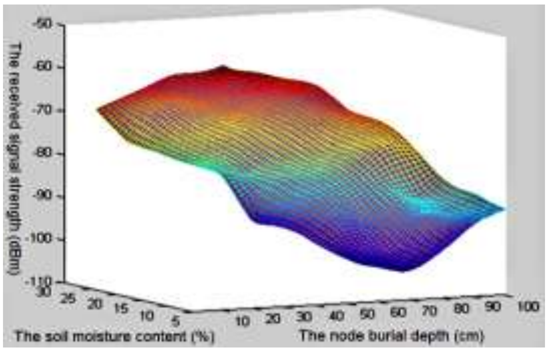

Figure 2. Effects of Received Signal Strength in Aboveground-Underground Communication

It can be included in Figure 2, that the deeper the underground node burial depth, the higher the soil moisture content, received signal strength in the communication is relatively weaker. When soil moisture content is below 20% and node burial depth changes from 10cm to 100cm, WUSN aboveground-underground communication is feasible, and received signal strength is higher than -105 dBm. When soil moisture content increased to more than 20%, the node burial depth changes in the range of 10cm to 90cm, the received signal strength is greater than -100 dBm, wireless underground sensor networks aboveground-underground communication is good. The analysis is carried on through Matlab, relationship is established in Equation (10).

$$R_{ss} = -43.5622 - 0.2722N_d - 0.7695S_v - 0.0016N_d^2 - 0.0011N_dS_v - 0.0029S_v^2 \quad (10)$$

$$R^2 = 0.9870$$

Where R_{ss} is the received signal strength, dBm ; N_d is the underground node burial depth, cm ; S_v is the soil moisture content, %。It can be seen from the Equation (10), the changes of the node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the received signal strength R_{ss} in the aboveground-underground communication, goodness-of-fit R^2 is higher.

When the aboveground node is deployed on the ground surface that is perpendicular to the underground node, the change of the underground node burial depth and soil moisture content has much effect on the bit error rate in the WUSN aboveground-underground communication. The bit error rate is shown in Figure 3.

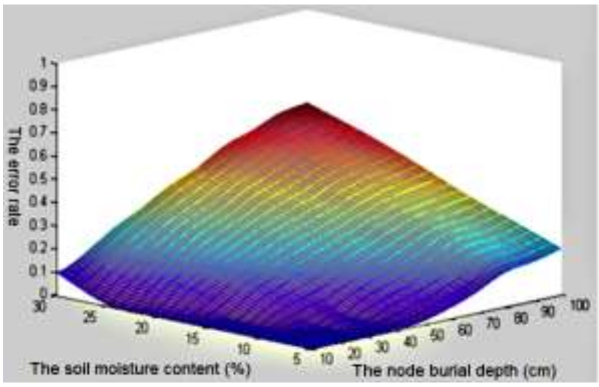

Figure 3. Effects of Packet Error Rate in Aboveground-Underground Communication

From Figure 3, we can conclude that the deeper the underground node burial depth, the higher the soil moisture content, bit error rate in the communication is relatively weaker. Bit error rate increases with the increase of node burial depth and soil moisture content increase, and the maximum is less than 60%. The analysis is carried on through Matlab, relationship is established in Equation (11).

$$E_r = -0.1353 - 0.0032N_d - 0.0054S_v - 0.0001N_d S_v \quad (11)$$
$$R^2 = 0.9821$$

Where E_r is the bit error rate；N_d is the underground node burial depth, cm；S_v is the soil moisture content, %。It can be seen from the Equation (11), the changes of the node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the error rate E_r in the aboveground-underground communication, goodness-of-fit R^2 is higher.

The underground-aboveground communication:

In the wireless underground sensor network communication, underground-aboveground communication is one of the most important communications. In the process of underground-aboveground communication test, wireless underground sensor network node RF frequency is 433 MHz, the aboveground node is deployed on the ground surface that is perpendicular to the underground node, and the change of the received signal strength and the bit error rate are analyzed. The effect of Wireless underground sensor network underground node burial depth and soil moisture content on the received signal strength is shown in Figure 4.

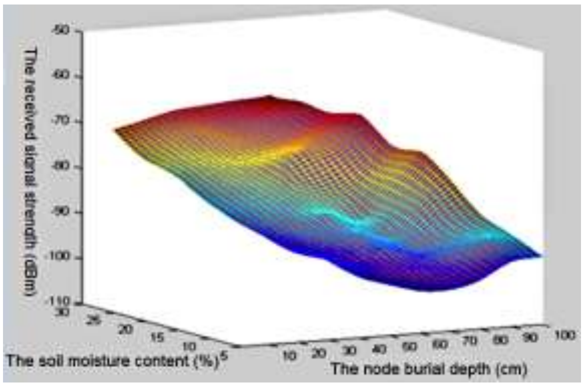

Figure 4. Effects of Received Signal Strength in Underground-Aboveground Communication

It can be included in Figure 4, that the received signal strength changes from -55dBm to -110dBm in the WUSN underground-aboveground communication when the aboveground node is deployed on the ground surface that is perpendicular to the underground node. When soil moisture content is below 20%, the received signal strength is higher than -100 dBm. When soil moisture content increased to more than 20%, the received signal strength achieves the minimum -110 dBm in the maximum underground node burial depth. Under the same soil moisture, the received signal strength decreases by about 2 dBm to 5 dBm in the WUSN underground-aboveground communication compared with the aboveground-underground communication in the same condition. The analysis is carried on through Matlab, relationship is established in Equation (12).

$$R_{ss} = -38.1378 - 0.5136N_d - 1.4867S_v - 0.0003N_d^2 - 0.0010N_dS_v - 0.0161S_v^{\ 2} \quad (12)$$

$$R^2 = 0.9869$$

It can be seen from the Equation (12), the changes of the node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the received signal strength R_{ss} in the underground-aboveground communication, goodness-of-fit R^2 is higher.

Figure 5 reflects the change of bit error rate in the wireless underground sensor network underground-aboveground communication under the underground node burial depth and soil moisture content change circumstances.

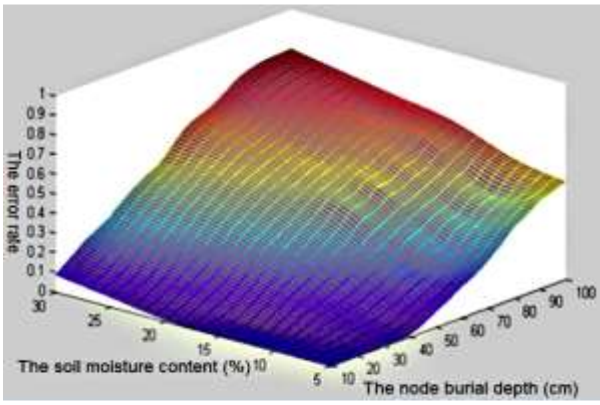

Figure 5. Effects of Packet Error Rate in Underground-Aboveground Communication

From Figure 5, we can conclude that underground node burial depth and soil moisture content change within the biggest scope, the bit error rate is under 80% in the WUSN underground-aboveground communication, the communication is good. The bit error rate is less than 70% when node burial depth is less than 80 cm, soil moisture content changes within the scope of 5% to 30%. With the increases of node burial depth, the bit error rate increases, but the maximum error rate is less than 80%. In addition, when the soil moisture content is less than 20%, the node burial depth changes from10 cm to 100 cm , bit error rate is still less than 70%. With the increases of soil moisture content, the bit error rate also increases slightly. Compared with the aboveground-underground communication in the same condition, the bit error rate is greater in the WUSN underground-aboveground communication and increases by about 20% to 30%. The analysis is carried on through Matlab, relationship is established in Equation (13).

$$E_r = -0.2289 - 0.0060N_d - 0.0010S_v - 0.0001N_dS_v - 0.0001{S_v}^2 \quad R^2 = 0.9703 \tag{13}$$

It can be seen from the Equation (13), the changes of the node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the error rate E_r in the underground-aboveground communication, goodness-of-fit R^2 is higher.

The underground-underground communication:

To investigate the effects of burial depth and water moisture content on the received signal strength and bit error rate, the horizontal inter-node distance between the sender and the receiver is fixed 50 cm. In the communication between underground nodes, the sender node is fixed depth 40 cm, the receiver node varies from 10 cm to 100 cm. Moreover, the range of the soil moisture content is 5% to 30%. In Figure 6 and Figure 7, the received signal strength and bit error rate values are shown, respectively.

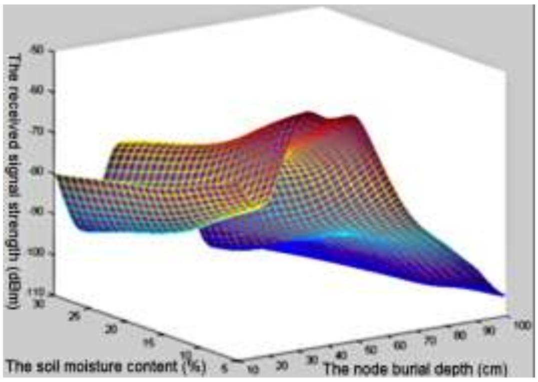

Figure 6. Tests for the Received Signal Strength. The Underground Node Is Varied From 10cm to 100cm

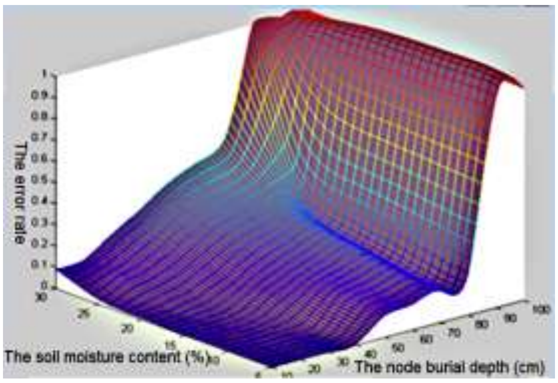

Figure 7. Tests for Bit Error Rates. The Underground Received Node Is Varied From 10cm to 100 cm

It can be observed in Figure 6, that received signal strength gradually reduced with the increase of the receiver node depth when WUSN sender node buried depth keeps in depth 40 cm. When receiver node burial depth changes from 30 cm to 50 cm, received signal strength reaches maximum. Received signal strength gradually increases when receiver node buried depth is less than 30 cm and change to 10 cm, received signal strength gradually decreases when receiver node buried depth is more than 50 cm.

In addition, we can conclude that soil moisture content is less than 30%, the minimum received signal strength is higher than -110 dBm. The received signal strength reaches the minimum when the soil moisture content is 30%. With the increase of soil volumetric water content interval 5%, received signal strength reduces 2 dBm to 10 dBm when the receiver node burial depth below 80 cm. The decrease extent of the received signal strength becomes small when receiver node buried depth is higher than 80 cm, average 1 dBm. The effect of the receiver node burial depth and the soil moisture content is analyzed through Matlab, relationship is established in Equation (14).

$$R_{ss} = -53.8017 + 0.2083N_d - 1.8269S_v - 0.0065N_d^2 + 0.0048N_dS_v + 0.0231S_v^{\ 2} \quad (14)$$
$$R^2 = 0.814$$

It can be seen from the Equation (14), the changes of the receiver node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the received signal strength R_{ss} in the underground-underground communication, goodness-of-fit R^2 is higher.

It can be included in Figure 7, that WUSN node electromagnetic wave communication produces the error rate in the underground soil that increases with the increase of soil moisture content. When the soil moisture content changes in the rang of 5% to 30% and receiver node burial depth 10 cm to 70 cm, the highest error rate is no more than 50%. The error rate increases with the increase of soil moisture content, when the receiver node burial depth 80 cm and soil moisture content changes from 5% to 25%, the maximum error rate is about 40%. The effect of the receiver node burial depth and the soil moisture content is analyzed through Matlab, relationship is established in Equation 15.

$$E_r = 0.1313 - 0.0098N_d - 0.0101S_v + 0.0002N_d^{\ 2} + 0.0005S_v^{\ 2} \quad (15)$$
$$R^2 = 0.8845$$

It can be seen from the Equation (15), the changes of the node burial depth N_d and soil moisture content S_v have binary quadratic relationship on the error rate E_r in the underground-underground communication, goodness-of-fit R^2 is higher.

In the test of underground-underground communication, the sensor node RF frequency uses 433 MHz, sender and receiver nodes burial depth are fixed 40 cm, soil moisture content changes in the range of 5% to 30%, the change range of horizontal inter-node distance is 10 cm to 100 cm. The effects of horizontal inter-nodes distance and soil moisture content on received signal strength and the error rate are measured, as shown in Figure 8 and Figure 9.

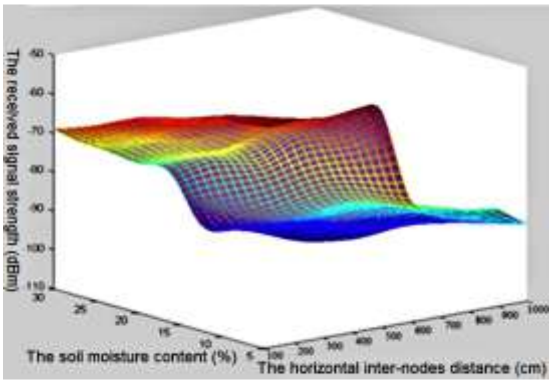

Figure 8. Tests for the Received Signal Strength. The Horizontal Inter-Nodes Distance Varies From 10cm to 100 cm

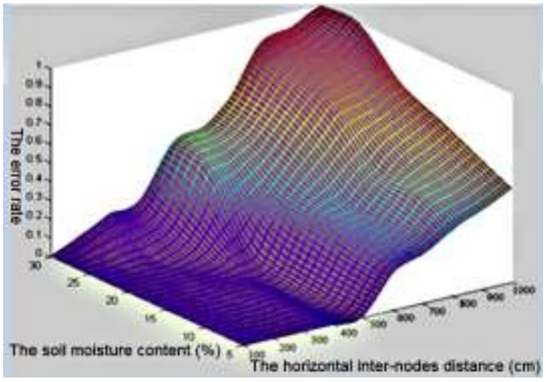

Figure 9. Tests for Packet Error Rates. The Horizontal Inter-Nodes Distance Is Varied From 10 cm to 100 cm

It can be showed in Figure 8, when the horizontal inter-nodes distance changes in range of 10 cm to 100 cm and soil moisture content is less than 25%, the minimum received signal strength is not less than -100 dBm. The received signal strength gradually decreases with the increase of the horizontal inter-nodes distance when the soil moisture content is 25%, the minimum value is about -105 dBm. When soil moisture content increases continually to 30%, the received signal strength reduces and reaches minimum, about -110 dBm. The effect of the horizontal inter-nodes distance and the soil moisture content is analyzed through Matlab, relationship is established in Equation (16).

$$R_{ss} = -37.8433 - 0.0502H_s - 0.5746S_v - 0.0103{S_v}^2 \qquad (16)$$
$$R^2 = 0.9449$$

It can be seen from the Equation (16), the changes of he horizontal inter-nodes distance H_s and soil moisture content S_v have binary quadratic relationship on the received signal strength R_{ss} in the underground-underground communication, goodness-of-fit R^2 is higher.

We can include from Figure 9, the error rate increases gradually when the soil moisture content is less than 25% and the horizontal inter-nodes distance changes in the range of 10 cm to 100 cm. At the maximum horizontal inter-nodes distance, the error rate increase extent is almost equal to 10%, but the highest error rate is no more than 80%. When soil moisture content is more than 25%, the error rate reaches 100% in the maximum horizontal inter-nodes distance. The effect of the horizontal inter-nodes distance and the soil moisture content is analyzed through Matlab, relationship is established in Equation (17).

$$E_r = 0.0346 - 0.0003H_s - 0.0113S_v + 0.0003{S_v}^2 \qquad (17)$$
$$R^2 = 0.9630$$

It can be seen from the Equation (17), the changes of the horizontal inter-nodes distance H_s and soil moisture content S_v have binary quadratic relationship on the error rate E_r in the underground-underground communication, goodness-of-fit R^2 is higher.

In a word, the node burial depth, the horizontal inter-nodes distance and the soil moisture content have a great impact on the received signal strength and bit error rate of the aboveground-underground, underground-aboveground and underground-underground communication.

5. Conclusions

In this work, we propose the characteristics of aboveground-underground, underground-aboveground and underground-underground communication in the WUSN. The experiment design and results were presented in this paper. The experiment results revealed the feasibility of RF wave transmission in the soil medium for wireless underground sensor networks and showed the effect of some influence factors on underground communication. From above experiments, we could conclude that:

(1) In the WUSN aboveground-underground communication, the received signal strength changes through binary quadratic relationship in the range of -53 dBm to -110 dBm when node burial depth and soil moisture content change, and the error rate is less than 60%.

(2) The received signal strength changes through binary quadratic relationship in the range of -55 dBm to -110 dBm when node burial depth and soil moisture content change in the underground-aboveground communication, and the error rate is not more than 80%. Compared with the aboveground-underground communication, the received signal strength decreases by about 2 dBm to 5 dBm in the underground-aboveground communication.

(3) In the underground-underground communication, the received signal strength decreases with the increase of soil moisture content when node burial depth and soil moisture content change, and has the relationship of binary quadratic with node burial depth and soil moisture content. When the soil moisture content is 20%, 25%, 30% and the horizontal inter-nodes distance is 1000 cm, 1000 cm, 600 cm, respectively, the received signal strength achieves -100 dBm. The received signal strength and the error rate change through binary quadratic relationship with the change of the horizontal inter-nodes distance and soil moisture content.

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