Experiment Measurements of RSSI for Wireless Underground Sensor Network in Soil

Yu Xiaoqing, Zhang Zenglin, Han Wenting

Abstract—**Wireless underground sensor network (WUSN) consists of wireless devices that can be exploited below the ground surface. These devices are buried completely under dense soil. Thus electromagnetic wave transmits only through the soil medium. In this paper, the relationship among radio frequency signal propagation characteristics of AG-UG, UG-AG and UG-UG communication mode under wireless channel and node burial depth, horizontal inter-nodes distance and soil water content was studied with 240MHz, 433MHz and 868MHz carrier frequency. The experiment demonstrated that the model goodness of fit R^2 in AG-UG and UG-AG communication, the maximum is 0.997, the minimum is 0.910. Model goodness of fit R^2 in UG-UG communication, the maximum is 0.970, the minimum is 0.866. Besides, three-dimensional surface of RSSI was built and the model verification experiment was conducted through SPASS software. In the AG-UG and UG-AG communication, root mean square error is in the range of 0.729-3.198 dBm. In the UG-UG communication, root means square error is in the range of 3.238-6.553 dBm. Validation results showed that the model could better predict the received signal strength from different communication.**

Index Terms—**Communication, experiments, RSSI, soil, Wireless sensor networks**

I. INTRODUCTION

For agricultural regional scattered, topography changes, different environmental conditions, rapid, accurate and effective collect method of crop growth environment variable information is one of the primary problems to solve in the agricultural environment information technology research [1-3]. The emergence and application of wireless sensor network technology are the main technical method to solve this problem. As a new information collection method, wireless underground sensor network is very different from that of traditional wireless sensor network, whose electromagnetic wave propagates in a soil medium between sensor nodes and the propagation characteristics are decided by soil properties. When a signal propagates within soil medium, it may be reflected, diffracted, and scattered [4-6].

Wireless underground sensor network is that the WUSN sensor equipment with wireless transceiver module buried completely in certain soil depth, sensor module perceives the data and sends data through the wireless mode. Many sensor nodes consist of a sensor network in the soil and complete automatically the entire process of data perception, collection [7]. The WUSN has many advantages, such as strong concealment, ease of deployment, timeliness of the data, reliability, large covering range, ease of upgrade, etc.

In the following section, we briefly discuss related work on the application using the wireless underground sensor networks technology. In Section 3, the experiment materials and methods are described. The experimental results for the AG-UG, UG-AG and UG-UG communication in the soil is presented in Section4. Finally, summary and future plan for continuation of this work are discussed in Section 5.

II. RELATED WORK

The concept of Wireless underground sensor network was introduced in wireless communication lab at the Georgia Institute of Technology in 2006. Wireless underground sensor networks have been investigated in many contexts recently, but research reports of wireless underground sensor networks in agricultural application are few.

I.F.Akyildiz put forward the concept of WUSN for the first time and analyzed path loss of the underground wireless channel under the different soil composition. Besides, the key issues that should be considered were put forward in the wireless underground sensor network communication architecture and WUSN design [8]. M.C.Vuran studied the channel model of electromagnetic wave transmission in soil, analyzed path loss, bit error rate, maximum transmission distance, water content test error of electromagnetic wave multipath transmission, etc under the main influence factors such as the soil composition, soil volumetric water content and node burial depth, node distance and sensor frequency [9]. A.R.Silva studied the effect of antenna bandwidth of wireless sensor network node at 433 MHz frequency, the buried depth of nodes in the soil 15cm and 35cm, and water content of the soil 9.5% and 37.3% on communication between aboveground node and underground node [10]. J.R.Coen developed the near surface wireless underground sensor networks system used for golf course which included acquisition nodes, sink nodes, relay nodes and a gateway node. The gateway node controlled data storage and transmission of the sink node, could connect with computer or GPRS module through the RS232 interface. Like sink node, gateway node could be remotely controlled through DDI [11]. H.R.Bogena researched wireless signal attenuation of ZigBee wireless transceiver module by using soil column

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in different soil types and the water content [12]. L.Li designed the architecture for wireless underground sensor network system in Beijing university of posts and telecommunications, studied the electromagnetic wave propagation in the underground soil, underground channel model, the effect of soil electrical characteristics on network performance and wireless underground sensor network node layout, and conducted simulation analyzes through mathematical simulation software MATLAB [13]. In addition to applications in agriculture, wireless underground sensor network can also be used for underwater monitoring and geological coal seam communication, be utilized for transport, tunnel safety, volcanic activity, earthquake, military and other fields underground information monitoring [14-16].

At present, wireless sensor network in the agricultural application belongs to the terrestrial wireless sensor network [17,18], which connect the sensor to the read data transceiver equipment on the ground through the cable in order to avoid the sensor network communicates in the underground soil. Study on wireless underground sensor network is in the stage of experimental research and has not formed relatively perfect theory system and the technical system. A series of research by researchers at home and abroad on the underground wireless channel characteristics can provide the necessary basis for wireless underground sensor network planning and deployment and further research. But the impact on the wireless underground sensor network signal transmission is different because of different soil complex environment, soil composition, compactness and water content. Therefore, the stability and reliability of wireless signal propagation need to be further researched according to the specific soil environment. Literature shows [19] that it only can communicate in the soil surface depth when 2.4 GHz frequency terrestrial wireless sensor network node is directly used in wireless underground sensor network, but it is not feasible when but node is buried under the magnetism of soil for the information acquisition of magnetism soil in the actual. Comprehensive considering the effect of signal attenuation and antenna size, it is necessary to conduct experiment for hundred MHz frequency wireless underground sensor network channel to prove the influence of different factors on the signal strength and bit error rate in the soil environment, which provides a certain foundation for wireless underground sensor network node layout with high stability and reliability and the construction of network system.

III. Materials and methods

A. Experiment materials

This research adopts the developed wireless underground sensor network node and sink node. Sink node is the same as underground node, but no sensor, which connects to the computer by 232 or 485 interface. The processor module of node adopts 16-bit MSP430 single chip microcomputer as main controller chip. Soil water content sensor XR61-TDR2, work voltage is 4-6.5 VDC, electrical current is 28-30 mA, output voltage is 0-2.5 VDC, the voltage signal is converted into a digital signal by A/D conversion transmitted to the processor module. The RF module is H8410, 8-24 VDC wide voltages, the maximum transmit power 20 dBm, sensitivity of -120 dBm, transmission rate 2400-57600 bps. The antenna of a sensor node is a standard one-quarter wavelength monopole antenna with 50 Ω impedance, SMA interface, and GFSK modulation mode. Node is sealed by engineering plastic shell, and made waterproof processing using 704 sealants. WUSN node picture is presented in Fig.1. The WUSN electromagnetic wave signal attenuation is tested through a spectrum analyzer that is Agilent N9912A type handheld RF spectrum analyzer, frequency range from 100 KHz to 6 GHz.

A.Unsealed sensor node B.sealed sensor node
Fig.1. Picture of wireless underground sensor network node

The experimental tests were conducted in the laboratory of the Research Institute of Water-saving Agriculture of Arid Regions of China in the Northwest Agriculture and Forestry University. The experiments soil is obtained from the construction site below 30cm-40cm deep in the Research Institute, 2mm sieves after drying. Soil box of long 5 m, width and height 1 m is made. Soil can be ranked based on particle size and the variations of sand, silt and clay content. Sandy soil produced the least amount of attenuation, while clay soil produced the most. During the experiment, soil medium was assumed as a homogeneous medium, and the surrounding temperature was maintained at a range of 20-24 ℃ throughout the experiment. The basic physical property index of the soil sample is given in Table 1.

TABLE I
THE BASIC PHYSICAL PROPERTY INDEX OF THE SOIL SAMPLE

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

B. Experiment design

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 aboveground 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 (AG-UG), underground-aboveground (UG-AG) and underground-underground (UG-UG) communication. The diagram of the communication structure is shown in Fig.2.

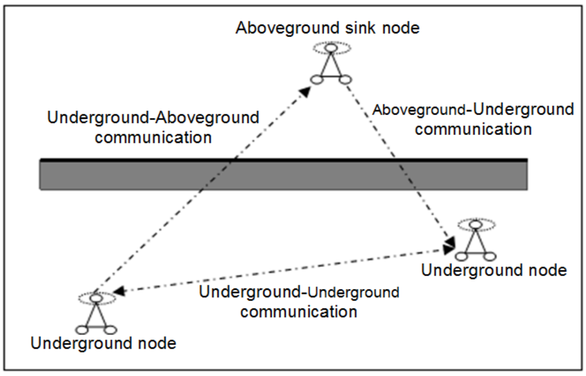


Fig.2. Structure of communication in WUSN

In the soil WUSN communication, node burial depth, soil water content and horizontal inter-nodes distance have a certain diffraction, scattering and direct influence on the wireless signal transmission. Communication quality is part of the important indexes to measure wireless underground sensor network communication performance. Received signal strength index (RSSI) is tested under different communication ways by changing nod burial depth, soil water content and horizontal inter-nodes distance to make evaluation on the communication quality of the wireless underground sensor network system.

C. *Experiment method*

Node RF frequency, node burial depth, soil water content and horizontal inter-nodes distance are the main influence factors on wireless underground sensor network communication. WUSN node frequencies are 3 power frequencies within the scope of hundred MHZ, 240 MHz, 433 MHz and 868 MHz. In AG-UG, UG-AG and UG-UG communication, node transmission power is 1 dBm, 11 dBm and 20 dBm, respectively.

AG-UG and UG-AG Communication

In the wireless underground sensor network AG-UG and UG-AG communication, sink node is deployed on the ground surface that is perpendicular to underground node, underground node burial depth changes every 10 cm within 10 cm to 100 cm, soil water content in the range of 5% to 30%, a total 6 levels, the influence characteristics of node burial depth and soil water content on received signal strength are measured in AG-UG and UG-AG communication. AG-UG and UG-AG communication test model is shown in Fig.3.

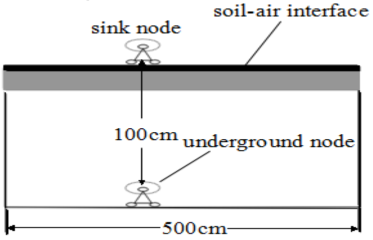


Fig.3. Testing model of AG-UG and UG-AG communication

UG -UG Communication

In the actual wireless underground sensor network communication, it not only exists communication between the sink node and underground node, communication between underground nodes is essential, and is particular important, underground communication test model is shown in Fig.4. In UG-UG communication, transmitting node and the receiving node burial depth are fixed 40 cm, soil water content changes from 5% to 30%, 6 levels, the horizontal inter-nodes distance changes from 100 cm to 1000 cm, 10 levels, the influence characteristics of horizontal inter-nodes distance and soil water content on received signal strength are measured in UG-UG communication.

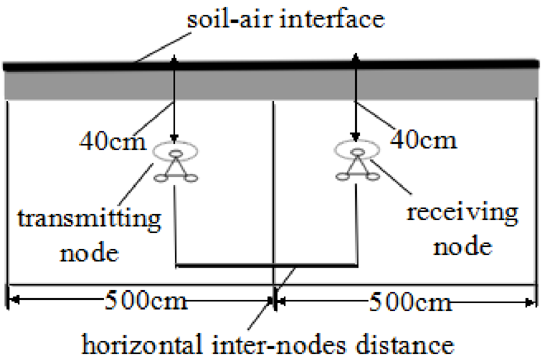


Fig.4. Testing model of underground communication

RSSI Measurement

Received power as a function of transmitted signal, path loss and antenna gain at the receiver end is given from Friis Equation (1) [20,21]:

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

Where P_r is the receiver power, P_t is the transmitter power, G_t and G_r 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 and 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, $L_p= L_0+L_s$, Ls is extra path loss caused by soil when electromagnetic wave propagate in the soil medium. The spectrum analyzer is used to test WUSN electromagnetic wave signal attenuation, namely the received signal strength RSSI value in the experiment.

IV. EXPERIMENT AND RESULTS

A. *AG-UG and UG-AG communication*

Received Signal Strength Analysis

When sink node is deployed on the ground surface that is perpendicular to underground node, node frequency are 240 MHz, 433 MHz and 868 MHz, underground node burial depth changes every 10 cm within 10 cm to 100 cm, soil water content in the range of 5% to 30%, a total 6 levels, the influence of node burial depth and soil water content on received signal strength are measured in AG-UG and UG-AG communication, which are shown in Fig.5 and Fig.6, respectively.

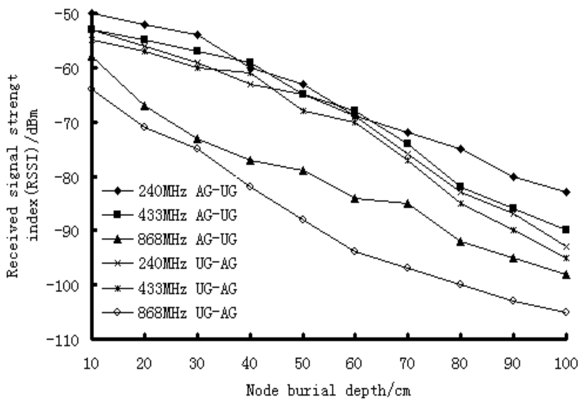


Fig.5. Effects of node burial depth on received signal strength

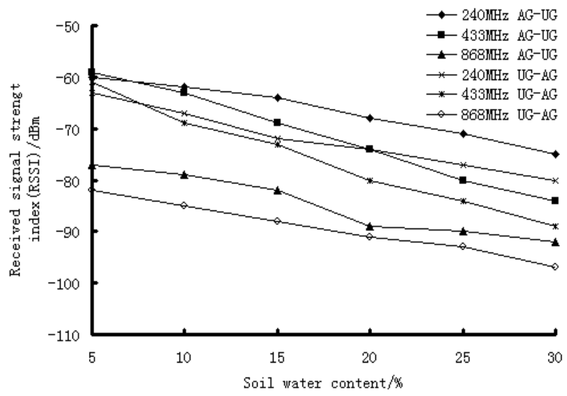


Fig.6. Effects of soil water content on received signal strength

It can be shown in Fig.5 that the RSSI linearly decrease with the increase of node frequency and node burial depth. In the AG-UG communication, RSSI of 433 MHz nodes is relatively strongest when node burial depth at 40cm and 60cm. In the UG-AG communication, received signal strength of the node with 433 MHz frequencies is the largest when node burial depth at 40cm. RSSI are greater than -100 dBm when node frequency is 240 MHz and 433 MHz frequency. WUSN node frequency is 868 MHz. RSSI is lower than -100 dBm when underground node burial depth is more than 80cm, which RSSI reduces by 2 dBm to 10 dBm than AG-UG communication.

It can be shown from Fig.6, that RSSI is almost equal when the node frequency is 240 MHz and 433 MHz under soil water content is less than 10% in the AG-UG communication. With the increase of soil water content, RSSI linearly decreases and changes within the range of -60 dBm to -80 dBm. When node frequency is 868 MHz, RSSI obviously decreases, and sharply falls about 10 dBm when the water content is greater than 15%. RSSI reduces in the gradual status when soil water content in the range of 20% to 30%. In the UG-AG communication, the RSSI of 240 MHz frequency and 433 MHz frequency are similar when soil water content is less than 15%. RSSI linearly decreases with the increase of soil water content and changes within the range of -60 dBm to -90 dBm. When the node frequency is 868 MHz, RSSI changes from -82 dBm to -97 dBm that is smaller than other frequency, and reduces by about 5 dBm than AG-UG communication.

The effect of node burial depth and soil water content on the received signal strength under three frequencies in AG-UG and UG-AG communication is made regression analysis through Matlab, goodness of fit is shown in Table 2 and Table 3, respectively.

TABLE II
R^2 IN THE EFFECT OF NODE BURIAL DEPTH ON RSSI

Node frequency/MHz	Communication mode	R^2
240	AG-UG	0.992
240	UG-AG	0.975
433	AG-UG	0.968
433	UG-AG	0.910
868	AG-UG	0.973
868	UG-AG	0.971

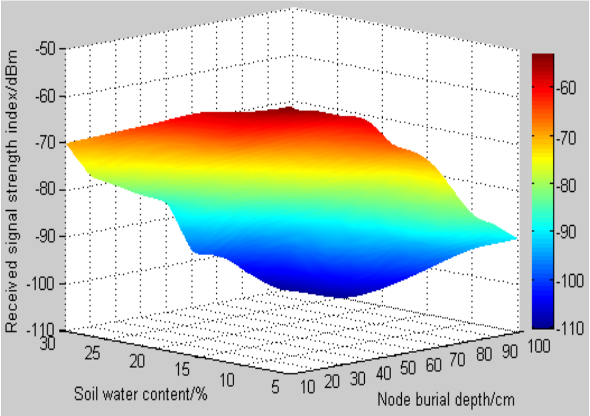
TABLE III
R^2 IN THE EFFECT OF SOIL WATER CONTENT ON RSSI

Node frequency/MHz	Communication mode	R^2
240	AG-UG	0.983
240	UG-AG	0.984
433	AG-UG	0.997
433	UG-AG	0.990
868	AG-UG	0.950
868	UG-AG	0.995

It can be seen from Table 2 and Table 3, that the maximum R^2 is 0.997 and the minimum R^2 is 0.910 in 12 RSSI model goodness of fit.

3D model and verification

433 MHz frequency at WUSN node communication frequency, three-dimensional curved surface model of the effect of burial depth and soil water content on RSSI is built through Matlab in AG-UG and UG-AG communication, as shown in Fig.7 and Fig.8, respectively. In addition, the fitting model and the goodness of fit of received signal strength are obtained through the Matlab binary quadratic fitting.



Note: RSSI changed with the color, the area of deep red meaning RSSI>-70dBm, the area of deep blue meaning RSSI<-100dBm.
Fig.7. Curved surface of RSSI in AG-UG communication

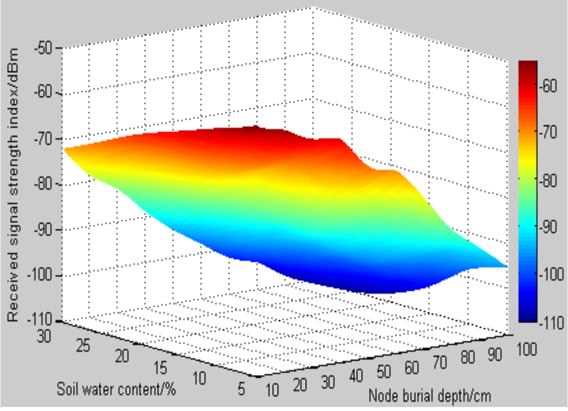


Fig.8. Curved surface of RSSI in UG-AG communication

It can be included from Fig.7, that the deeper the underground node burial depth, the greater the soil water content, the smaller the RSSI in the AG-UG communication. RSSI is greater than -105 dBm when soil water content is below 20%. When soil water content is more than 20% and underground node burial depth is in the range of 10cm to 90cm, RSSI are greater than -100 dBm. The effect of node burial depth and soil water content on RSSI in the AG-UG communication is analyzed through Matlab. Relationship is established in Equation (4). It has a binary quadratic relationship, goodness-of-fit R^2 is higher, of 0.987.

$$R_{ss} = -43.5622 - 0.2722N_d - 0.7695S_v - 0.0016N_d^2 - 0.0011N_dS_v - 0.0029{S_v}^2 \qquad (4)$$
$$R^2 = 0.987$$

where R_{ss} is the received signal strength index, dBm; N_d is node burial depth, cm; S_v is soil water content, %。

It can be shown from Fig.8 that RSSI is greater than -100 dBm when soil water content is below 20% in the UG-AG communication. When soil water content is more than 20%, RSSI reaches the minimum value - 110 dBm at the maximum node burial depth. In the UG-AG communication, the biggest underground node burial depths are different under different soil water content. Compared with AG-UG communication, RSSI reduces by 2 dBm to 5 dBm at the same as soil water content. The effect of node burial depth and soil water content on RSSI in the UG-AG communication is analyzed through Matlab. Relationship is established in Equation (5). It has a binary quadratic relationship, goodness-of-fit R^2 is higher, of 0.987.

$$R_{ss} = -38.1378 - 0.5136N_d - 1.4867S_v - 0.0003N_d^2 - 0.0010N_dS_v - 0.0161{S_v}^2 \qquad (5)$$
$$R^2 = 0.987$$

where R_{ss} is the received signal strength index, dBm; N_d is node burial depth, cm; S_v is soil water content, %。

In order to assess AG-UG and UG-AG communication model, goodness of fit R^2 and root mean square error RMSE that can better reflect the data fluctuation are analyzed through using SPASS software, as shown in Table 4.

It can be shown from Table 4, that goodness of fit R^2 between model calculation results and actual measured values is the minimum 0.954 when soil water content is 10% in the AG-UG communication, the maximum is 0.992 when soil water content is 25%. RMSE is 1.415 dBm~3.198 dBm. In the UG-AG communication, goodness of fit R^2 between model calculation results and actual measured values is the minimum 0.963 when soil water content is 5% in the AG-UG communication, the maximum is 0.998 when soil water content is 20%. RMSE is 0.729 dBm~2.906 dBm.

The results show that the received signal strength of the actual measured values and model calculation results has a smaller difference. The model has a good forecast for received signal strength of different soil water content and different node burial depth of AG-UG and UG-AG communication.

TABLE IV
R^2 AND ROOT-MEAN-SQUARE ERROR BETWEEN MEASURED AND COMPUTED

Soil water content/%	Communication mode	R^2	RMSE/dBm
5	AG-UG	0.968	2.571
5	UG-AG	0.963	2.906
10	AG-UG	0.954	3.198
10	UG-AG	0.995	1.072
15	AG-UG	0.983	1.872
15	UG-AG	0.984	1.966
20	AG-UG	0.985	1.987
20	UG-AG	0.998	0.729
25	AG-UG	0.992	1.415
25	UG-AG	0.994	1.223
30	AG-UG	0.979	2.139
30	UG-AG	0.979	1.987

B. *UG-UG communication*

Received Signal Strength Analysis

In UG-UG communication, node frequency are 240 MHz, 433 MHz and 868 MHz, transmitting node and the receiving node burial depth are fixed 40 cm, the horizontal inter-nodes distance changes from 100 cm to 1000 cm, 10 levels, soil water content changes from 5% to 30%, 6 levels, the effect of horizontal inter-nodes distance and soil water content on received signal strength RSSI are measured in UG-UG communication, which are shown in Fig.9 and Fig.10, respectively.

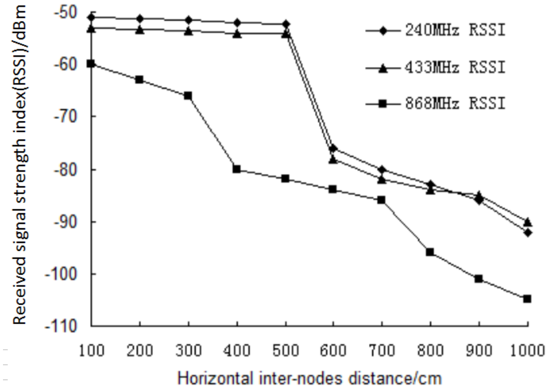


Fig.9. Effects of horizontal inter-nodes distance on RSSI

As shown in Fig.9, the WUSN node frequency are 240 MHz and 433 MHz, the RSSI is very strong and smoothly changes in the range -50 dBm to -55 dBm when horizontal inter-nodes distance is less than 500cm. RSSI greatly reduces to about 80 dBm when the horizontal inter-nodes distance increases to 600cm. With the increase of horizontal inter-nodes distance, the RSSI gradually decreases and the reduce amplitude becomes slower. WUSN node frequency is 868 MHz. RSSI reduces 10 dBm when horizontal inter-nodes distance is less than 300cm. When horizontal inter-nodes distance is in the range of 400cm to 700cm, RSSI smoothly changes from -80 dBm to -85 dBm. RSSI continues to fall to about -105 dBm when horizontal inter-nodes distance is more than 700cm.

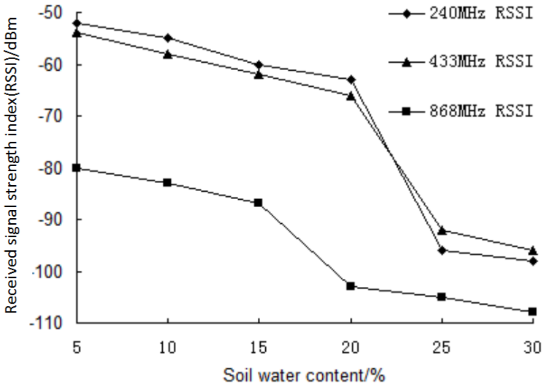


Fig.10. Effects of soil water content on RSSI

It can be shown in Fig.10, the horizontal inter-nodes distance keeps 50cm, the higher the soil water content, the lower the RSSI in the same node frequency. When the frequencies are 240 MHz and 433 MHz, the RSSI reduces and is not less than -66 dBm when soil water content is below 20%. RSSI sharply falls to about -95 dBm when soil water content increases to 25%. After that, the RSSI variation is not obvious, but the RSSI of 240 MHz is less than 433 MHz frequency and is higher than -100 dBm. When the frequency is 868 MHz, RSSI is in the range of -80 dBm to -108 dBm and different from other frequencies. Compared with 240 MHz and 433 MHz, the RSSI reduces by about 10 dBm to 30 dBm.

The effect of horizontal inter-nodes distance and soil water content on the received signal strength under three frequencies in UG-UG communication is made regression analysis through Matlab. Goodness of fit is shown in Table 5.

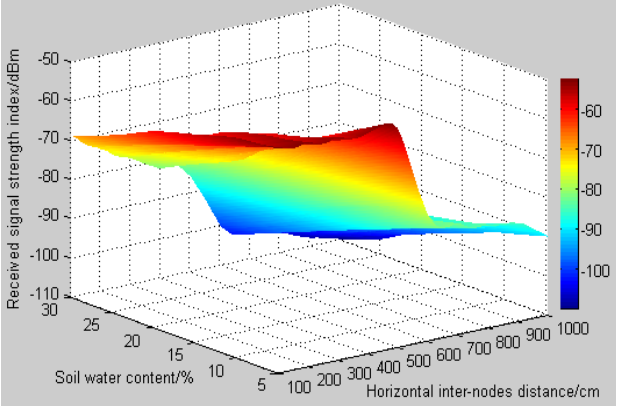
TABLE V
R^2 IN THE EFFECT OF HORIZONTAL INTER-NODES DISTANCE ON RSSI

Node frequency/MHz	Horizontal inter-nodes distance R^2	Soil water content R^2
240	0.894	0.903
433	0.866	0.932
868	0.970	0.923

It can be seen from Table 5, that the maximum R^2 is 0.970 and the minimum R^2 is 0.866 in 6 RSSI model goodness of fit.

3D model Analysis

Through received signal strength test analysis in the UG-UG communications, RSSI are almost uniform in 433 MHz and 240 MHz frequency communications, and 433 MHz frequency RSSI value is bigger under a certain horizontal inter-nodes distance and soil water content. 433 MHz frequency at WUSN node communication frequency, three-dimensional curved surface model of the effect of horizontal inter-nodes distance and soil water content on RSSI is built through Matlab in UG-UG communication, as shown in Fig.11. In addition, the fitting model and the goodness of fit of received signal strength are obtained through the Matlab binary quadratic fitting.



Note: RSSI changed with the color, the area of deep red meaning RSSI>-70dBm, the area of deep blue meaning RSSI<-100dBm.
Fig.11. Curved surface of RSSI in UG-UG communication

It can be shown from Fig.11 that RSSI decreases with the increase of horizontal inter-nodes distance and soil water content. When the soil water content reaches 20%, RSSI value reaches -100 dBm at the horizontal inter-nodes distance 1000cm. RSSI is -100 dBm when soil water content increase to 25% and the horizontal inter-nodes distance is 800cm. With the horizontal distance between the nodes, the RSSI continuously decreases, till the minimum -105 dBm. RSSI reaches -100 dBm when soil water content is the maximum 30% and the horizontal inter-nodes distance is 600cm, and gradually decreases to the minimum -110 dBm with the increase of horizontal inter-nodes distance, the reduce amplitude of 2 dBm to 3 dBm.

The effect of horizontal inter-nodes distance and soil water content on RSSI in the UG-UG communication is analyzed through Matlab. Relationship is established in Equation (6). It has a binary quadratic relationship. Goodness-of-fit R^2 is higher, of 0.945.

$$R_{ss} = -37.8433 - 0.0502H_s - 0.5746S_v - 0.0103S_v^2 \quad (6)$$

$$R^2 = 0.945$$

where R_{ss} is the received signal strength, dBm; H_s is the horizontal inter-nodes distance, cm; S_v is soil water content, %。

In order to assess UG-UG communication model, goodness of fit R^2 and root means square error RMSE that can better reflect the data fluctuation is analyzed through using SPASS software, as shown in Table 6.

It can be shown from Table 6, that goodness of fit R^2 between model calculation results and actual measured values is the minimum 0.854 when soil water content is 5% in the UG-UG communication, the maximum is 0.960 when soil water content is 30%. RMSE is 3.238 dBm~6.553 dBm.

The results show that the received signal strength of the actual measured values and model calculation results has a smaller difference. The model has a good forecast for received signal strength of different soil water content and different horizontal inter-nodes distance in UG-UG communication.

TABLE VI
R^2 AND ROOT-MEAN-SQUARE ERROR BETWEEN MEASURED AND COMPUTED

Soil water content/%	R^2	RMSE/dBm
5	0854	6.553
10	0.932	4.390
15	0.939	4.063
20	0.955	3.463
25	0.950	3.708
30	0.960	3.238

Verification Analysis

To verify received signal strength RSSI attenuation prediction model of UG-UG communications, test is conducted under the 433 MHz frequency and soil water content 10%. The RSSI attenuation model is shown in Equation (7), and the verification results as shown in Fig.12 .

$$R_{ss} = -45.483 - 4.7614 N_d - 0.0189 N_d^2 \qquad (7)$$

$$R^2 = 0.988$$

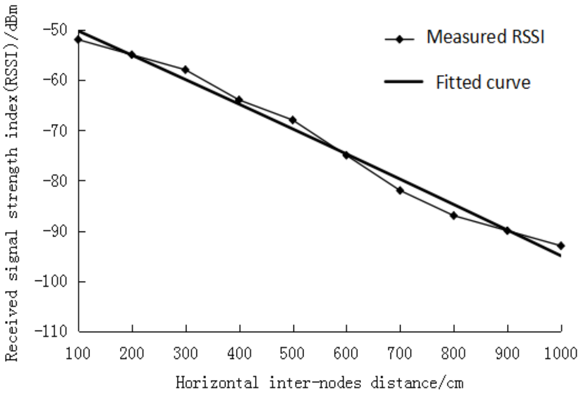


Fig.12 Comparison between computed and measured RSSI

Results show that the RSSI disparity is very small between measured and computed received signal strength. The model can predict well received signal strength when soil water content is certain and horizontal inter-nodes distance is different in UG-UG communication.

To be able to evaluate the UG-UG communication prediction model, the SPASS software was used to analyze the goodness-of-fit R^2 and the RMS, which can reflect data fluctuation better, as shown in Table 7.

TABLE VII
R^2 AND ROOT-MEAN-SQUARE ERROR BETWEEN MEASURED AND COMPUTED DATA AT DIFFERENT SOIL WATER CONTENT IN UG-UG COMMUNICATION

Soil water content/%	R^2	RMSE/dBm
5	0854	6.553
10	0.932	4.390
15	0.939	4.063
20	0.955	3.463
25	0.950	3.708
30	0.960	3.238

It can be seen from Table 8 that the goodness-of-fit R^2 is 0.854 of soil water content 5% between the model calculation results and the actual measured values. When the soil water content is 30%, it is the maximum 0.960. RMSE at 3.238~6.553dBm.

V. DISCUSSION

For understanding wireless underground sensor network performance in the soil, wireless signal propagation and the relationship between wireless signal and influencing factors were studied under the 240 MHz, 433 MHz and 868 MHz frequency, such as node burial depth, horizontal inter-nodes distance and soil water content. The received signal strength and bit error rate data were obtained and carried out statistical analysis.

Wireless underground sensor network transmission in the soil has a direct relationship with and frequency, node burial depth, horizontal inter-nodes distance and soil water content, the greater node frequency, the poor communication performance. RSSI of 433 MHz nodes is the relative strongest in AG-UG and UG-AG communication when node burial depth changes from 40cm to 60cm. RSSI decreases with the increase of node burial depth and soil water content in AG-UG and UG-AG communication. In the UG-UG communication, the RSSI is very strong and smoothly changes from -50 dBm to -55 dBm when the node frequency are 240 MHz and 433 MHz and horizontal inter-nodes distance is less than 500cm. When soil water content is more than 25%, RSSI of 240 MHz is less than 433 MHz frequency.

Compared to that in air, the underground communication exhibits significant challenges for the development of wireless underground sensor networks. Among these challenges, the attenuation caused by the soil is the most important aspect of underground communication and has to be completely characterized. Through experiments, it is shown that in the zone of hundreds MHz frequency band, the RSSI can be limited to a degree by supporting feasible communication.

VI. CONCLUSION

In this work, we propose an advanced network, a hybrid wireless sensor network for agriculture to improve the accuracy of current agricultural information collection system. The experimental design and results of AG-UG, UG-AG and UG-UG communication were presented in this paper. The experimental 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 communication.

Despite their potential, the proliferation of WUSN has been delayed by the unique challenges of the underground environment. Some of these challenges are related to the communication involving an underground node and an aboveground device. The experimental results reveal the feasibility of using hundreds MHz frequency sensor motes for WUSN. Moreover, the experimental results show that the burial depth is important for the WUSN tests due to the effects of reflected rays from the underground-air interface at the surface. In addition, we have shown that the inter-node distance plays an important role in the communication of WUSN. Finally, the direct influence of volumetric water content of the soil on the communication success is shown. From above experiments, we could conclude that:

(1) It was found that the carrier frequency was one of the important factors affecting underground RF transmission. Nodes with 433MHz 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.

(2) RSSI of UG-AG communication reduces 2 dBm to 10 dBm than AG-UG communication in the effect of node burial depth on communication. The effect of soil water content on communication, RSSI of UG-AG communication reduces about 5 dBm than AG-UG communication.

(3) RSSI model goodness of fit is established through Matlab simulation under three frequencies, the maximum R^2 is 0.997, the minimum R^2 is 0.910. Besides, the three-dimensional curved surface of RSSI variation is established under 433 MHz in AG-UG and UG-AG communication, and the model is verified through SPASS software, the minimum R^2 is 0.954, the maximum R^2 is 0.998, root mean square error RMSE is 0.729 ~ 3.198 dBm.

(4) In the UG-UG communication, the RSSI model goodness of fit is established through Matlab simulation under three frequencies, the maximum R^2 is 0.970, and the minimum R^2 is 0.866. Besides, the three-dimensional curved surface of RSSI variation is established under 433 MHz in UG-UG communication, and the model is verified through SPASS software, the minimum R^2 is 0.854, the maximum R^2 is 0.960, root mean square error RMSE is 3.238 ~ 6.553 dBm.

This paper does not make a network validation test and consider other environmental factors because of the particularity of the soil environment and the limitation of wireless underground sensor network node, but the test results are in accordance with the basic theoretical research. These studies will provide the basic support for further research and the building of wireless underground sensor network system.

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