Survey on Transmission Performance for Soil Wireless Sensor Network Signal in Different Communication

X.Q. Yu, Z.L. Zhang, and W.T. Han

***Abstract*—To explore WUSN (Wireless Underground Sensor Network, WUSN) signal transmission characteristics in the soil, this paper focused on wireless network signal transmission attenuation under the 433MHz channel when it was three communication modes. By changing the underground node burial depth, horizontal inter-nodes distance and soil water content, the value of received signal strength and the packet error rate were measured in three kinds of communication modes under different sink node layout, respectively, and the experiment results were analyzed. The results show that received signal strength is weaker and the packet error rate is higher in UG-AG communication than AG-UG communication. In the underground to underground communication, the received signal strength decreases with increases of horizontal inter-nodes distance when the horizontal inter-nodes distance is larger than 600cm, and the amplitude of reduction is 2 dBm to 3dBm. The signal attenuation models under the 433MHz channel were established through the data fitting analysis, respectively, goodness-of-fit R^2 is higher. The study on wireless underground sensor network signal transmission characteristics in soil provides the technical support for building of wireless underground sensor network system in the soil.**

***Index Terms*—Wireless sensor networks, transmission characteristics, packet error rate, soil water content**

I. Introduction

Soil environmental parameter information is a space fusion multiple interconnected three-dimensional network information, the information perception, processing, integration and application are the main content of agricultural environment information technology research [1,2]. Due to agricultural geographical dispersion, topography changes, different environmental conditions characteristics [3], multidimensional, network, accurate, rapid and effective method for crop growth environment variable information collection is one of the primary problems to solve in the agricultural environment information technology research. The emergence and application of wireless sensor network technology [4-6] are the main technology to solve the problem.

At present, soil environmental information wireless sensor network belongs to the interrestrial wireless sensor network system, which usually connects the sensor to the read data transceiver equipment on the ground with a cable way, to avoid the sensor network communication in the underground soil. These sensor devices are exposed on the ground not only influence farming, wireless transmitting and receiving function of the wireless sensor node is also affected by serious geography and climate natural factors [7]. Based on these shortcomings, a wireless underground sensor network (Wireless Underground Sensor Network, WUSN) provides a new method for monitoring underground information data and has become the direction of the agricultural environment monitoring technology research. WUSN makes wireless data transceiver module equipment completely are buried in soil, and send data through wireless way after the induction module sensing data. The WUSN has many advantages, such as strong concealment, easy of deployment, timeliness of the data, reliability, large covering range, easy of upgrade, etc [8-10].

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

II. Related Work

Research reports of wireless underground sensor networks in agricultural application are few. The concept of Wireless underground sensor network was introduced by I.F. Akyildiz in wireless communication lab at the Georgia Institute of Technology in 2006 [11]. L.Li designed the architecture for wireless underground sensor network system, 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 [12]. H.R.Bogena researched wireless signal attenuation of

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X. Q. Yu was with the North University of China, Taiyuan, Shanxi 030051 China. (e-mail: yuxiaoqing115@gmail.com).

Z. L. Zhang is with the Northwest A & F University, yangling, Shaanxi 712100 China. (corresponding author to provide phone: +86-18834905777;e-mail: zhangzenglin115@gmail.com).

W. T. Han is with the Northwest A & F University, yangling, Shaanxi 712100 China. (e-mail: wentinghan200@126.com).

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ZigBee wireless transceiver module by using soil column in different soil types and the water content [13]. 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 [14]. A.R.Silva applied wireless sensor network node with 433 MHz frequency full wave antenna and the center shaft type sprinkler for maize precision irrigation, and analyzed the influence of the ground cover, corn canopy and sprinkler rotational speed on the information received [15]. M.C.Vuran found that many factors had great influence on soil water content acquisition signal distortion degree, such as rainfall and storm weather conditions, soil compactness and vegetation cover degree, wireless underground sensor network topology structure, sampling time and sampling density, etc [16]. In addition to applications in agriculture, wireless underground sensor network can also be used for underwater monitoring and geological coal seam communication, be used for transport, tunnel safety, volcanic activity, earthquake, military and other fields underground information monitoring [17,18].

Agricultural environmental information wireless underground sensor network monitoring at home and abroad is started to research in recent years, it is in the stage of basic experimental research at present and has not yet formed perfect theory system and technical system. The propagation properties of an electromagnetic wave in the soil are not only needed to study in soil wireless underground sensor network. The transmission properties of electromagnetic waves in the soil and air interface are also needed to study [19]. Signal transmission paths of inter-nodes have the aboveground to underground (AG-UG), underground to aboveground (UG-AG) and underground to underground (UG-UG). In the paper, the received signal strength (Received Signal Strength, RSS) and packet error rate (Packet Error Rate, PER) are seen as an index to measure signal attenuation situation [20]. The effect of node burial depth, horizontal inter-nodes distance and the soil water content on received signal strength and packet error rate are studied under 433 MHz RF frequency in AG-UG, UG-AG and UG-UG communication, in order to lay a certain foundation for wireless underground sensor network node deployment method and network system building.

III. Materials and methods

A. Experiment environment

The experimental 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. The experiments soil is obtained from the construction site below 30cm-40cm deep in the Research Institute, 2 mm sieves after drying. 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 kept at a range of 20-24 ℃ . 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. Wireless underground sensor network node

Wireless underground sensor network node consists of the sensor module, the processor module, wireless communication module and power supply module [21]. 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 water proof processing using 704 sealant. WUSN node picture is presented in Fig.1.

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

C. Experiment method

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 and keeps 1 m high on the ground and 20 m horizontal distance with underground node, transmission power is -1 dBm and 11 dBm, respectively. In the through-the-earth communication, 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 and packet error rate are measured. The through-the-earth communication test model is shown in Fig.2.

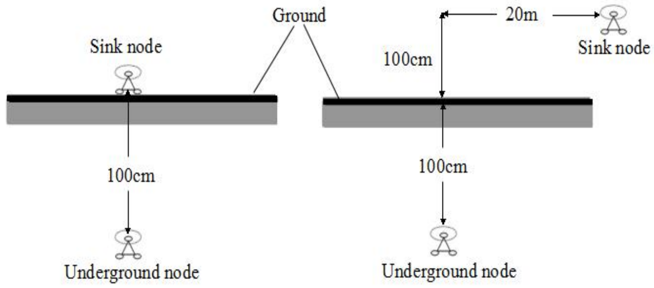


Fig.2 Testing model of through-the-earth communication

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.3. In UG-UG communication, transmission power is 20 dBm. In the effect of node burial depth and soil water content on received signal strength and packet error rate, transmitting node burial depth is fixed 40 cm, the horizontal inter-nodes distance is fixed 50 cm, the receiving node burial depth changes from 10 cm to 100 cm, 10 levels, soil water content changes from 5% to 30%, 6 levels. In the effect of horizontal inter-nodes distance and soil water content on received signal strength and packet error rate, 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.

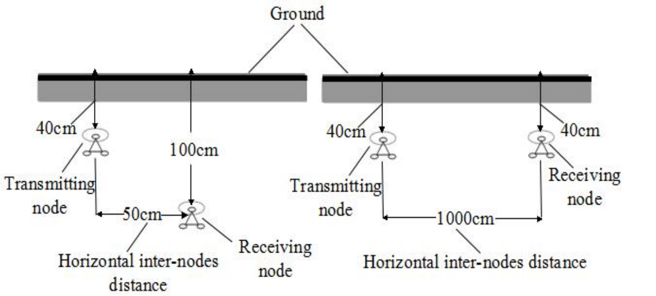


Fig.3 Testing model of underground communication

The WUSN electromagnetic wave signal attenuation is test through spectrum analyzer that is agilent N9912A type handheld RF spectrum analyzer, frequency range from 100 KHz to 6 GHz. In the process of packet error rate calculation, 30 bytes data packets are sent every 1s, 300 messages every three experiment, a total 900 data receiving packets, correct or error of receiving packets are been documented.

IV. The Electromagnetic Wave Loss Model

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) [22-24]:

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

Where P_r is the receiver power, P_t is the transmitter power, G_t and 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, Ls is extra path loss caused by soil when electromagnetic wave propagate in soil medium. The spectrum analyzer is used to test WUSN electromagnetic wave signal attenuation, namely the received signal strength and packet error rate value in the experiment. Binary regression model fitting using Matlab is conducted for data processing in UG-UG communication, and regression model fitting using the following different function model is conducted for data processing in through-the earth communication, the letters represent different numerical constants values:

Linear model: $y = ax + b$ (4)

Logarithm model: $y = a_0 \ln(x) + b_0$ (5)

Quadratic polynomial model:

$$y = a_1 x^2 + a_1' x + b_1 \quad (6)$$

Cubic polynomial model:

$$y = a_2 x^3 + a_2' x^2 + a_2'' x + b_2 \quad (7)$$

V. Experiment and Results

In wireless underground sensor network communication, WUSN node frequency is 433 MHz. In AG-UG and UG-AG through-the-earth communication, the changes of received signal strength and packet error rate of the electromagnetic wave transmission in the soil under different underground node burial depth and soil water content are analyzed when sink node is deployed on the ground surface that is perpendicular to underground node and keeps 1 m high on the ground and 20 m horizontal distance with underground node. In the UG-UG communication, the effect of underground receiving node burial depth, soil water content and horizontal inter-nodes distance on received signal strength and packet error rate are measured.

A. The effect of node burial depth on through-the-earth communication

when sink node is deployed on the ground surface that is perpendicular to underground node and keeps 1 m high on the ground and 20 m horizontal distance with underground node, underground node burial depth changes every 10 cm within 10 cm to 100 cm, the influence of node burial depth on received signal strength and packet error rate are measured in AG-UG and UG-AG communication, which are shown in Fig.4 and Fig.5, respectively.

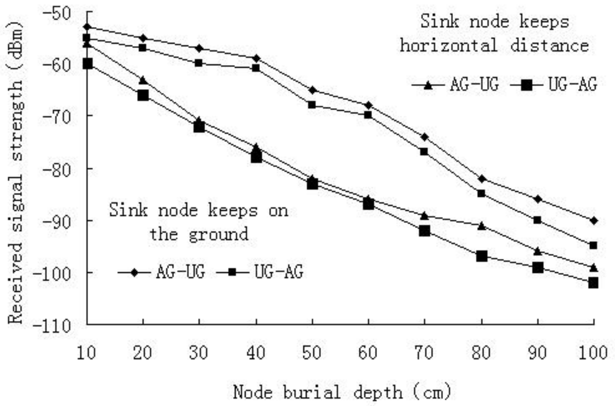


Fig.4 Effects of node burial depth on received signal strength

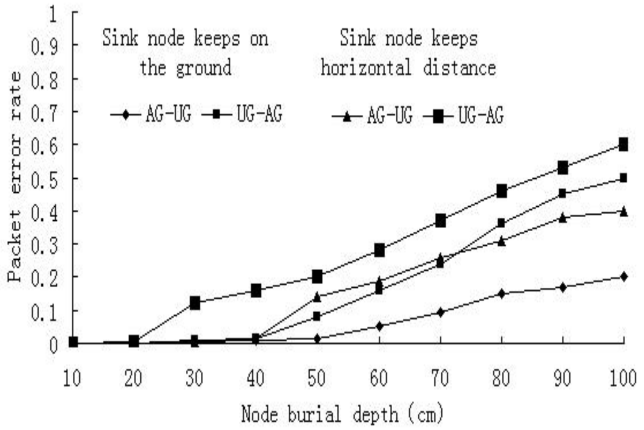


Fig.5 Effects of node burial depth on packet error rate

It can be shown in Fig.4 and Fig.5 that the deeper node burial depth. The weaker received signal strength and the higher the packet error rate. Received signal strength is weaker and the packet error rate is higher in UG-AG communication than AG-UG communication under the same conditions of sink node deployment. When sink node is deployed on the ground surface, received signal strength reduces by about 5 dBm and packet error rate increases by 30% in UG-AG communication than AG-UG communication, the minimum received signal strength is -95 dBm, the maximum error rate is 50%. When sink node keeps horizontal distance, received signal strength reduces by 7 dBm-9 dBm and packet error rate increases by 10%-20% in AG-UG and UG-AG communication. Packet error rate is smaller in AG-UG communication than error rate value of the sink node is deployed on the ground surface and the maximum is less than 60% when the node burial depth is more than 70 cm.

B. The effect of soil water content on through-the-earth communication

when sink node is deployed on the ground surface that is perpendicular to underground node and keeps 1 m high on the ground and 20 m horizontal distance with underground node, underground node burial depth is fixed 50 cm, soil water content changes from 5% to 30%, 6 levels, the effect of soil water content on received signal strength and packet error rate are measured, which are shown in Fig. 6 and Fig.7, respectively.

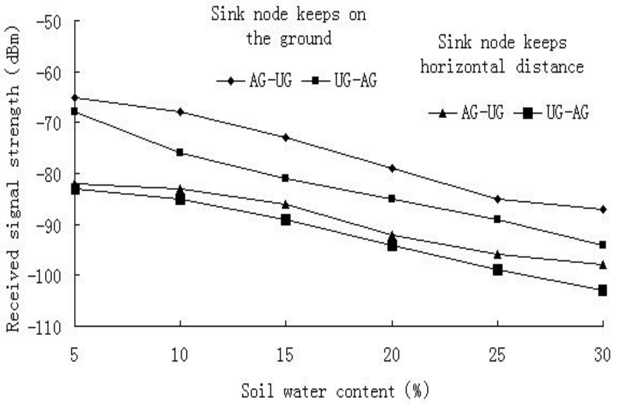


Fig.6: Effects of soil water content on received signal strength

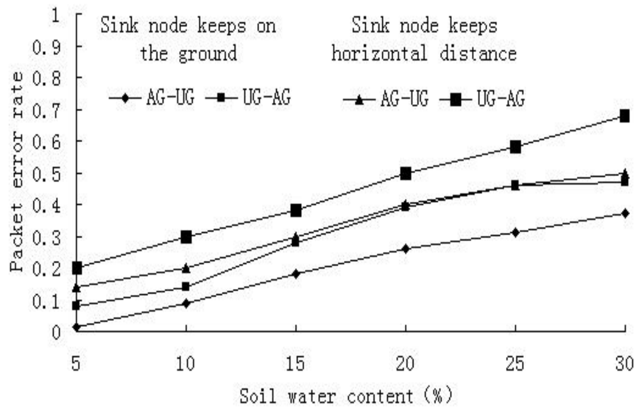


Fig.7: Effects of soil water content on the packet error rate

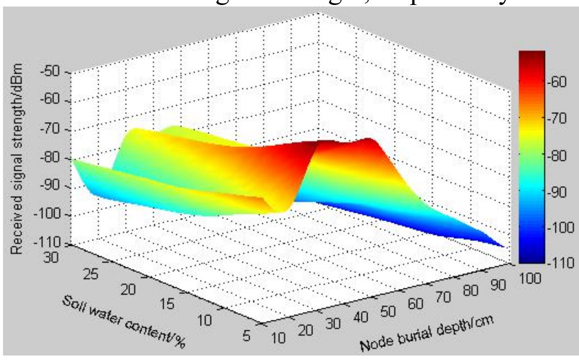
It can be shown in Fig.6 and Fig.7 that received signal strength decreases and packet error rate increases with the increase of soil water content, almost a linear change. When sink node is deployed on the ground surface, received signal strength reduces by about 7 dBm and packet error rate increases by 10% in UG-AG communication than AG-UG communication, the minimum received signal strength is -94 dBm, the maximum error rate is less than 50%. When sink node keeps horizontal distance, received signal strength decreases by 9 dBm-11 dBm and packet error rate increases by 10%-20% in AG-UG and UG-AG communication. Packet error rate is nearly the same in AG-UG communication and error rate value of the sink node is deployed on the ground surface and the maximum is less than 70% when soil water content is between 15% and 25%. Therefore, received signal strength is less and packet error rate is higher in UG-AG communication than AG-UG communication when the sink node is deployed in the same condition.

C. UG-UG communication

In wireless underground sensor network UG-UG communication, nodes are completely buried in the underground soil, the communication media is the soil that is completely different from air transmission medium, and is also completely different from AG-UG communication and UG-AG communication.

The effect of node burial depth and soil water content

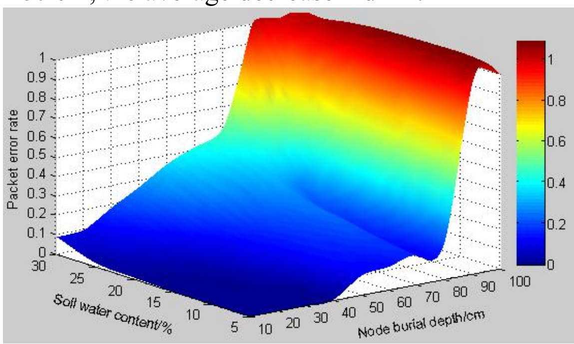
In UG-UG communication, transmitting node burial depth is fixed 40 cm, the horizontal inter-nodes distance fixed 50 cm, the receiving node burial depth changes from 10 cm to 100 cm, 10 levels, soil water content changes from 5% to 30%, 6 levels, the effect of node burial depth and soil water content on received signal strength and packet error rate are measured in UG-UG communication, which are shown in Fig.8 and Fig.9, respectively.



Note: RSS changed withe the color, the area of deep red meaning RSS>-70dBm, the area of deep blue meaning RSS<-100dBm.
Fig.8 Curved surface of received signal strength under node burial depth and soil water content in UG-UG communication

As shown in Fig.8, received signal strength decreases gradually with the increase of the actual distance between transmitting node and receiving node, namely the receiving node burial depth. Received signal strength shows normal distribution and reaches the maximum when receiving node burial depth is the scope of 30 cm to 50 cm. In soil surface communication, the received signal strength increases due to the reflection wave of electromagnetic wave through the ground and reflected back increases transmitting node energy. Therefore, different receiving node burial depth leads to received signal strength is not the same in UG-UG communication at the same the actual distance between nodes and horizontal inter-nodes distance.

Received signal strength reaches the minimum and the minimum value is more than -110 dBm, when soil water content is the maximum 30%. When soil water content changes in range of 5% to 30% and the receiving node burial depth is less than 80 cm, received signal strength decreases averagely 2 dBm to 10 dBm. Received signal strength decreases continuously and the amplitude decreases when the receiving node burial depth is more than 80 cm, the average decrease 1 dBm.

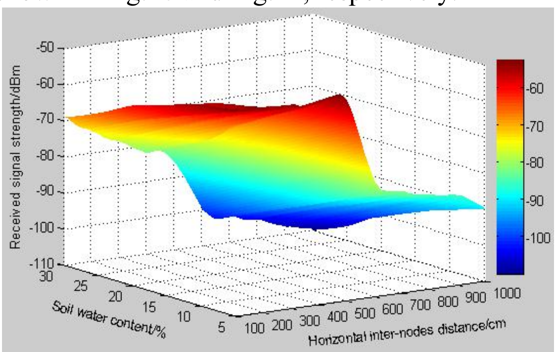


Note: PER changed withe the color, the area of deep red meaning PER>0.8, the area of deep blue meaning PER<0.1.
Fig.9 Curved surface of packet error rate under node burial depth and soil water content in UG-UG communication

It can be seen from the Fig.9, packet error rate increases dramatically to the maximum 100% UG-UG communication when the soil water content changes from 5% to 25% and the receiving node burial depth at 90 cm. When soil water content is the maximum 30% and the receiving node burial depth increases from 80 cm to 100 cm, error rate is also increases rapidly to the maximum. At the same receiving node burial depth, packet error rate increases with the increase of soil water content, the maximum amplitude is 15%. When soil water content changes in the range of 5% to 30% and the receiving node burial depth changes from 10 cm to 70 cm, packet error rate increases with the increase of soil water content and the maximum error rate is less than 50%.

The effect of horizontal inter-nodes distance and soil water content

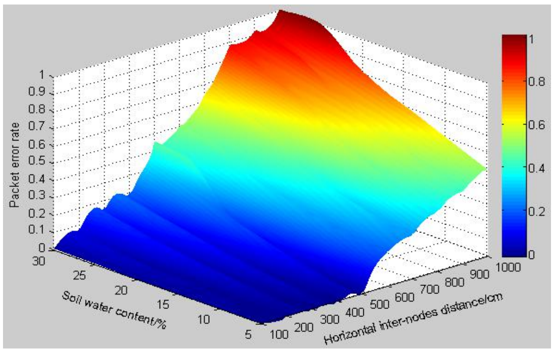
In UG-UG communication, transmitting node and the receiving node burial depth are fixed 40 cm, the horizontal inter-nodes distance changes from 100 cm to 1000 cm, 10 levels, soil water content changes from 5% to 30%, 6 levels, the effect of horizontal inter-nodes distance and soil water content on received signal strength and packet error rate are measured in UG-UG communication, which are shown in Fig.10 and Fig.11, respectively.



Note: RSS changed with the color, the area of deep red meaning RSS>-70dBm, the area of deep blue meaning RSS<-100dBm.
Fig.10 Curved surface of received signal strength under horizontal inter-nodes distance and soil water content in UG-UG communication

It can be shown in Fig.10, that received signal strength decreases with the increase of horizontal inter-nodes distance and soil water content. When the soil water content is 20%, received signal strength value reaches -100 dBm in horizontal inter-nodes distance 1000 cm. The received signal strength is -100 dBm when soil water content increases to 25% and the horizontal inter-nodes distance is 800 cm. With the increase of horizontal inter-nodes distance, the received signal strength decreases continuously to the minimum -105 dBm. When soil water content is the maximum 30% and the horizontal inter-nodes distance is 600 cm, received signal strength achieves -100 dBm and decreases gradually with the increase of horizontal inter-nodes distance, the amplitude is 2 dBm to 3 dBm, to the minimum -110 dBm.

It can be seen from the Fig.11, the packet error rate increases gradually with the increase of horizontal inter-nodes distance when soil water content is less than 25%. At the maximum horizontal inter-nodes distance, the packet error rate changes with the change of soil water content and increase rate nearly equal to 10%, the maximum is less than 80%. the error rate has risen sharply about 20% to 30%, when soil moisture content changes in range of 5% to 20% and the horizontal inter-nodes distance is 600 cm. When soil water content is more than 25% and the horizontal inter-nodes distance is 500 cm, error rate rise amplitude increases about 30%, and it also gradually changes to the maximum with the gradual increase of horizontal inter-nodes distance.



Note: PER changed withe the color, the area of deep red meaning PER>0.8, the area of deep blue meaning PER<0.1.

Fig.11 Curved surface of packet error rate under horizontal inter-nodes distance and soil water content in UG-UG communication

D. *The fitting model*

In three kinds of wireless underground sensor network communication mode, the best model of received signal strength and packet error rate are obtained under different conditions through curve fitting processing of received signal strength and error rate value. In AG-UG and UG-AG data processing, different functions are used to make regression fitting model, and the best model is concluded through Matlab binary regression in UG-UG communication.

Through-the-earth communication model

In the wireless underground sensor network through-the-earth communication experiment, the effect of node burial depth and soil water content on received signal strength and packet error rate is made model fitting under 4 kinds of sink node deployment and communication mode, the important indicator is the goodness of fit R^2. Goodness of fit is statistical analysis indicator of the relationship degree between theoretical calculated values and measured values, it illustrates the relationship is more close if the value is more close to 1.

When sink node is deployed on the ground surface that is perpendicular to underground node and keeps 1 m high on the ground and 20 m horizontal distance with underground node in AG-UG and UG-AG communication, they are called sink node horizontal distance 0 m and 20 m. The effect model goodness of fit R^2 of node burial depth and soil water content on received signal strength are shown in Table 2 and Table 3.

TABLE II
R^2 IN THE EFFECT OF NODE BURIAL DEPTH ON RECEIVED SIGNAL STRENGTH

Sink node horizontal distance/m	Communication mode	Linear	Logarithmic	Quadratic	Compound
0	AG-UG	0.968	0.789	0.990	0.995
0	UG-AG	0.963	0.780	0.992	0.994
20	AG-UG	0.968	0.975	0.996	0.998
20	UG-AG	0.986	0.953	0.999	1

Through comparing goodness of fit of received signal strength change curve under the sink node horizontal distance and communication mode, cubic polynomial R^2 value is the maximum in 4 kinds of model processing and shows related degree is the better, which indicates that the attenuation of the received signal strength with node burial depth towards similar with the corresponding curve trend. Cubic polynomial expressions are in 4 kinds of fitting:

$$\begin{cases} y = 0.0497x^3 - 1.0857x^2 + 2.3192x - 54.9 \\ y = 0.0344x^3 - 0.8817x^2 + 1.4324x - 56.133 \\ y = -0.0375x^3 + 0.9254x^2 - 10.84x - 45.567 \\ y = 0.0107x^3 + 0.0396x^2 - 6.2892x - 53.767 \end{cases} \quad (8)$$

TABLE III
R^2 IN THE EFFECT OF SOIL WATER CONTENT ON RECEIVED SIGNAL STRENGTH

Sink node horizontal distance/m	Communication mode	Linear	Logarithmic	Quadratic	Compound
0	AG-UG	0.984	0.909	0.984	0.999
0	UG-AG	0.983	0.980	0.993	1
20	AG-UG	0.964	0.852	0.968	0.998
20	UG-AG	0.987	0.874	0.994	1

Cubic polynomial R^2 value is the maximum in 4 kinds of model processing of the effect of soil water content on received signal strength and R^2 is 1 in UG-AG communication. Cubic polynomial expressions are in 4 kinds of fitting:

$$\begin{cases} y = 0.3056x^3 - 3.1905x^2 + 4.7897x - 67 \\ y = -0.213x^3 + 2.5754x^2 - 14.069x - 56.333 \\ y = 0.3241x^3 - 3.5635x^2 + 7.8267x - 86.667 \\ y = 0.1667x^3 - 2x^2 + 2.8333x - 84 \end{cases} \quad (9)$$

The effect model goodness of fit R^2 of node burial depth and soil water content on packet error rate are shown in Table 4 and Table 5.

TABLE IV
R^2 IN THE EFFECT OF NODE BURIAL DEPTH ON PACKET ERROR RATE

Sink node horizontal distance/m	Communication mode	Linear	Logarithmic	Quadratic	Compound
0	AG-UG	0.884	0.643	0.975	0.985
0	UG-AG	0.910	0.677	0.984	0.994
20	AG-UG	0.944	0.759	0.961	0.989
20	UG-AG	0.986	0.845	0.993	0.994

Through comparing goodness of fit of packet error rate change curve under the sink node horizontal distance and communication mode, cubic polynomial R^2 value is the maximum between 0.985 and 0.994 in 4 kinds of model processing, which indicates that the relate extent of the attenuation of the packet error rate with node burial depth and cubic polynomial model is the best. Cubic polynomial expressions are in 4 kinds of fitting:

$$\begin{cases} y = -0.0004x^3 + 0.0103x^2 - 0.043x + 0.0412 \\ y = -0.0011x^3 + 0.0249x^2 - 0.0974x + 0.0884 \\ y = -0.0015x^3 + 0.0268x^2 - 0.0888x + 0.069 \\ y = -0.0003x^3 + 0.0072x^2 + 0.0222x - 0.0345 \end{cases} \quad (10)$$

TABLE V
R^2 IN THE EFFECT OF SOIL WATER CONTENT ON PACKET ERROR RATE

Sink node horizontal distance/m	Communication mode	Linear	Logarithmic	Quadratic	Compound
0	AG-UG	0.991	0.962	0.998	0.998
0	UG-AG	0.952	0.942	0.976	0.998
20	AG-UG	0.982	0.946	0.989	0.999
20	UG-AG	0.998	0.934	0.998	0.998

Cubic polynomial R^2 value is still the maximum in 4 kinds of model processing of the effect of soil water content on packet error rate and R^2 is also the same as 1. Cubic polynomial expressions are in 4 kinds of fitting:

$$\begin{cases} y = -0.0008x^3 + 0.0046x^2 + 0.074x - 0.064 \\ y = -0.0068x^3 + 0.0615x^2 - 0.0617x + 0.0833 \\ y = -0.0039x^3 + 0.0362x^2 - 0.0142x + 0.12 \\ y = -0.0004x^3 + 0.0039x^2 + 0.0843x + 0.1133 \end{cases} \quad (11)$$

Underground communication model

In the wireless underground sensor network UG-UG communication experiment, the fitting model and the goodness of fit of received signal strength and packet error rate under node burial depth, soil water content and horizontal inter-nodes distance effection are obtained through the Matlab binary quadratic fitting. The fitting model and the goodness of fit are:

$$R_{ss} = -53.8017 + 0.2083N_d - 1.8269S_v - 0.0065N_d^2 + 0.0048N_dS_v + 0.0231S_v^2$$
$$R^2 = 0.814 \quad (12)$$

$$E_r = 0.1313 - 0.0098N_d - 0.0101S_v + 0.0002N_d^2 + 0.0005S_v^2 \quad (13)$$
$$R^2 = 0.885$$

where R_{ss} is the received signal strength, dBm; E_r is packet error rate; N_d is receiving node burial depth, cm; Sv is soil water content，%。

The fitting model and the goodness of fit of received signal strength and packet error rate under node brial depth, soil water content and horizontal inter-nodes distance effection are:

$$R_{ss} = -37.8433 - 0.0502H_s - 0.5746S_v - 0.0103S_v^2 \quad (14)$$
$$R^2 = 0.945$$

$$E_r = 0.0346 - 0.0003H_s - 0.0113S_v + 0.0003S_v^2 \quad (15)$$
$$R^2 = 0.963$$

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

It can be seen from equations that the change of underground receiving node burial depth N_d and soil water content S_v, as well as the horizontal inter-nodes distance H_s and soil water content S_v is the basic binary quadratic relationship on received signal strength R_{ss} and packet error rate E_r in UG-UG communication, goodness-of-fit R^2 is higher.

E. Verification Analysis

To verify received signal strength RSSI attenuation prediction model of AG-UG, UG-AG and UG-UG communications, test is conducted under the 433 MHz frequency and soil water content 10%. The RSSI attenuation model is shown in Fig.12, Fig.13 and Fig.14.

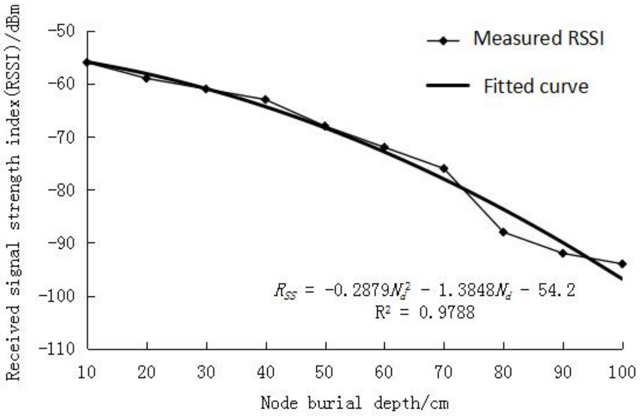


Fig.12 Comparison between computed and measured RSSI in AG-UG

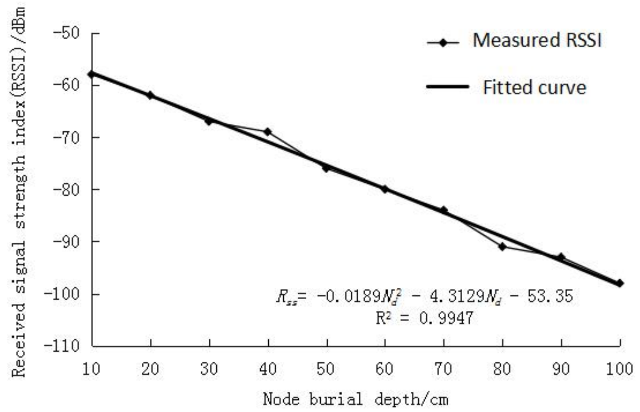


Fig.13 Comparison between computed and measured RSSI in UG-AG

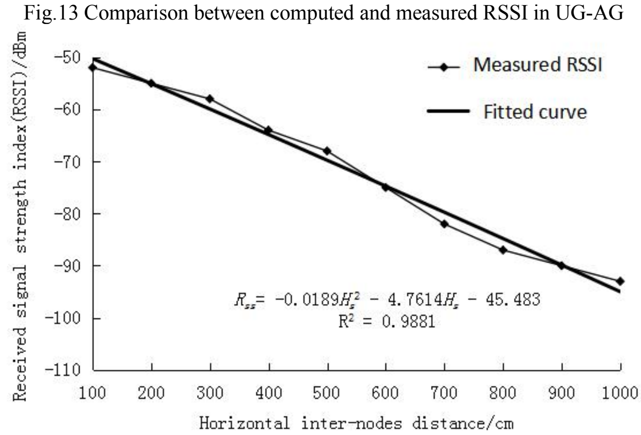


Fig.14 Comparison between computed and measured RSSI in UG-UG

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, node burial depth and horizontal inter-nodes distance is different in AG-UG, UG-AG and UG-UG communication.

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.

To be able to evaluateAG-UG, UG-AG and UG-UG communication prediction model, the SPASS software was used to analyze the goodness-of-fit R^2 and the RMSE, which can reflect data fluctuation better, as shown in Table 6, Table 7 and Table 8.

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

Soil water content/%	R^2	RMSE/dBm
5	0.968	2.571
10	0.949	3.198
15	0.981	1.872
20	0.983	1.987
25	0.991	1.415
30	0.976	3.139

It can be seen from Table 6 that the goodness-of-fit R^2 is 0.949 of soil water content 10% between the model calculation results and the actual measured values. When the soil water content is 25%, it is the maximum 0.991. RMSE at 1.415~3.198dBm.

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

Soil water content/%	R^2	RMSE/dBm
5	0.959	2.906
10	0.994	1.072
15	0.982	1.966
20	0.997	0.729
25	0.993	1.223
30	0.976	1.987

It can be seen from Table 7 that the goodness-of-fit R^2 is 0.959 of soil water content 5% between the model calculation results and the actual measured values. When the soil water content is 20%, it is the maximum 0.997. RMSE at 0.729~2.906dBm.

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

VI. DISGUSSTION

Compare with that in air, the underground communication exhibits significant challenges for the development of wireless underground sensor networks. 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 433 MHz frequency. Measurement results of the received signal strength and packet error rate are conducted regression analysis and curve fitting, attenuation model of received signal strength and the packet error rate are obtained in through-the-earth and underground communication under different sink node arrangement.

Wireless underground sensor network through-the-earth communication, received signal strength decreases with the increase of node burial depth and soil water content and the packet error rate is relatively increases. Received signal strength is weaker and the packet error rate is higher in UG-AG communication than AG-UG communication. Compared with the sink node deployed on the ground surface, received signal strength decreases by 3 dBm to 11 dBm and packet error rate increases by 10% to 30% in AG-UG and UG-AG communication when sink node deployed the horizontal distance.

In through-the-earth and underground communication experiment results, the effect of node burial depth, soil water content and horizontal inter-nodes distance from received signal strength and packet error rate is 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.

VII. CONCLUSION

In this work, we propose the characteristics of aboveground-underground, underground-aboveground and underground-underground communication in the WUSN. The experimental design and results 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 underground communication.

Wireless sensor network signal propagation was studied under the 433 MHz frequency in the wireless sensor network through-the-earth communication and underground communication. From above experiments, we could conclude that:

(1) In the effect of node burial depth on the through-the-earth communication, the minimum received signal strength is -102 dBm and the maximum error rate is about 60%. In the effect of soil water content on the through-the-earth communication, the minimum received signal strength is -103 dBm and the maximum error rate is about 68%. Therefore, soil water content is under a greater impact on the signal attenuation of wireless sensor network communication.

(2) In the UG-UG communication, the received signal strength decrease amplitude reduces and averagely

decreases by 1 dBm when the receiving node burial depth is more than 80 cm, and the packet error rate is not more than 50%. The received signal strength decreases with the increase of the horizontal inter-nodes distance and decrease amplitude is 2 dBm to 3 dBm when soil water content is the maximum 30% and the horizontal inter-nodes distance is larger than 600 cm.

(3) Cubic polynomial model can predict path loss of the signal through-the-earth transmission. Goodness-of-fit of received signal strength R^2 are 0.994~1 and 0.998~1, goodness of fit of packet error rate R^2 is 0.985~0.994 and 0.998~0.985 respectively. Binary quadratic model can predict underground signal transmission attenuation, The received signal strength of goodness of fit R^2 is 0.814 and 0.945, goodness of fit of packet error rate R^2 is 0.885 and 0.963 respectively.

As future work, we have planned to develop a new generation of nodes with more powerful transceivers and more efficient antennas are required for the actual deployment of WUSN applications. On the other hand, we will conduct the effect of more factors on WUSN communication. Moreover, we foresee that wireless underground sensor network information monitoring could be applicable to agricultural irrigation system and we will also further explore this topic.

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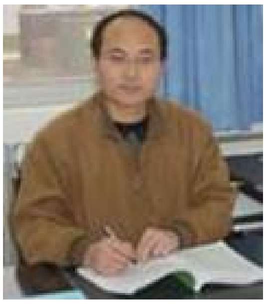
Xiao Q. Yu received the B.S. degree from Department of Information Engineering, Lanzhou University of Finance and Economics, Lanzhou, China in 2006. She received her M.S. degree from Department of Mechanical and Electric Engineering in 2009, Ph.D. degree and postdoctor degree from Department of Water Resources and Architectural Engineering, Northwest A & F University, Shaanxi, China in 2013 and 2016, respectively.

Currently, she is a teacher in School of Computer Science and Technology, North University of China, Shanxi. Her current research interests are Wireless Sensor Networks application.

Zeng L. Zhang received his B.S. degree from Department of Mechanical and Electric Engineering, Harbin institute of Technology, Harbin, and M.S. degree from Department of Mechanical and Electric Engineering, Northwest A & F University, Shaanxi, China in 2000 and 2007, respectively. He received his Ph.D. degree from Department of Water Resources and Architectural Engineering, Northwest A & F University, Shaanxi, China in 2015.
Currently, he is a teacher in Department of Mechanical and Electric Engineering, Northwest A & F University, Shaanxi. His current research interests are in Agricultural Water-Soil Engineering and Wireless Sensor Networks.



Wen T. Han received his B.S. degree from Department of Mechanical and Electric Engineering, Northwest Agriculture University, Shaanxi, China in 1996. M.S. and Ph.D. degree from Department of Mechanical and Electric Engineering, Northwest A & F University, Shaanxi, China in 1999 and 2004, respectively.
Research Interests:
Information monitoring of crop and environment; Intelligent control for precise irrigation; water distribution Simulation of sprinkler irrigation; Development of nozzle. Currently, he published academic papers more than 30, including SCI and EI articles 16; the national invention patent 6.