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Attenuation Model of Wireless Sensor Network for Large-Scale Farmland Environment

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Abstract

The transmission characteristics of wireless sensor network nodes for large-scale farmland are influenced by factors such as farmland terrain environment, planting density and height. The vegetation canopy can absorb, scatter, and block RF signals, leading to large attenuation of signal strength and significant differences in link quality on the receiving end, which in turn affects the monitoring quality. The dynamic relationships between radio signal transmission, plant height, group range, and crop growth stages are identified through the analysis of summer corn perceptual information path loss at different growth stages. The gradual RSSI attenuation model of wireless sensor network for large-scale farmland environment is established. Research shows that during the corn tassel and seed-filling periods, the RSSI attenuation is most serious and the perception range reaches the minimum value when antenna height falls in the range of 0.5 meter to 1.7 meters. Through the model we can predict the intensity and perception range of the received wireless signals of summer corn on various perception levels at different growth stages. This model serves as the theoretical basis for the deployment of wireless sensor network nodes for large-scale farmland, aiming to achieve maximum monitoring range at minimum equipment cost.

Keywords: *wireless sensor network, RSSI, gradual environmental change, signal attenuation, large-scale farmland*

1. Introduction

In the development of precision agriculture, wireless sensor network [1-2], which has low power consumption and low cost, has been widely applied to real-time monitoring for large-scale farmland production. The monitoring effectiveness depends on the coverage ratio of the wireless sensor network [3], the continuous working time, the data transmission time and some other factors. Therefore, the life-cycle and the transmission characteristics of wireless sensor nodes and other factors are very important to the monitoring quality. The transmission characteristics of wireless sensor node are affected by many factors such as the farmland terrain environment, the crop planting density and height, the foliage density, etc. The vegetation canopy can absorb, scatter, and block RF signals, leading to large attenuation of signal strength [4] and significant differences in link quality on the receiving [5], which in turn affects the monitoring quality, the transmission distance, and the effective network coverage range.

In recent years, research on the transmission characteristics and model of wireless sensor networks for various monitoring environments has attracted more and more attention. Pedro Andrade-Sanchez has conducted tests on radio performance, which includes signal strength, connection quality, and packet loss rate, under various weather conditions in vineyards and orchards. Martin A. Hebel and his group tested the signal performance parameters such as signal attenuation and signal intensity variance on a direct line-of-sight path on smooth grass land. Matthew J. Darr and his group analyzed the influence of various factors in poultry breeding environment on wireless signal transmission loss. Their research shows that the iron cages, cement partitions, and even the poultry themselves have impacts on the signal transmission loss. Most of the current research on wireless signal attenuation are conducted for some specific environments[6], there is few study and research on the influences of wireless signal transmission for gradually changed environments. This paper studied the wireless signal transmission characteristics in gradually changed environment of summer corn field in north

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China. The wireless channel path loss model under the gradual change environment is concluded through the analysis of the test results. Through this model we can predict the coverage range of the wireless sensor network nodes at different growth stages [7], which serves as a foundation for further research on sensor nodes deployment [8], reliable and efficient data transmission, and power consumption control [9].

2. Problem Description

The transmission of wireless signals in farmland is affected by many complex factors. All these factors such as crop type, height, planting density, absorption and scattering of wireless signals by crop stem and leaf can lead to signal attenuation. Even for the same type of crop, its influences on the transmission characteristics of wireless channels are quite different at different growth stages. Therefore, the transmission environment of wireless signals in the farmland varies dynamically according to the changes of farmland environment parameters such as plant height, density, leaf area, soil water, and fertilizer level, etc.

Corn is one of the main grains in north China, the mountain area of southwest China, and other dry valley area. It needs proper watering and has strict planting condition requirements. Soil moisture is one of the main factors affecting corn growth. The dynamic changes of soil moisture at different periods can influence the corn growth, which in turn will affect the corn production. Wireless sensor network is used to promote the corn production. At different growth stages, we set the optimal perception height to reduce signal attenuation, effectively extend the transmission distance, increase the coverage range, control the equipment cost, and achieve maximum monitoring range. Through wireless sensor network, we can timely and effectively collect the soil moisture change information at different growth stages, and irrigate the corn precisely according to related biochemical parameters. All those measures can help to improve the crop water supply, promote the corn growth, and increase the corn production.

In this paper, we took summer corn as the research object, and measured the numerical changes of wireless signals at three typical growth periods respectively. RSSI (Received Signal Strength Indication) [10] is the difference between the real strength of the received signal and the optimal receiving power level. This value directly reflects the efficiency of the radio signal transmission process [11]. Using the measured RSSI data, we analyzed the radio signal loss at different growth stages of summer corn, and studied the effective transmission distance between sensor nodes at different growth periods. Since the crop growing environment changes gradually, we studied the multipath and fading effects of electrical signal transmission [12], and established a communication distance evolution model throughout the whole corn growing season.

Each year, summer corn is usually planted at the end of May, just after the wheat harvest. Its growth cycle can be divided into the following periods: the seedling stage, the heading stage, and the seed-filling stage. Summer corn needs about 70 to 80 days to mature. With the growth of corn, soil water content standards vary at different stages, the height of the corn plants continues to increase, the leaf area expands gradually, and accordingly the wireless signal transmission environment will change and the signal transmission loss will increase [9]. Therefore, radio signal transmission comparison experiments at different growth stages are necessary to help us to understand and analyze the influences of corn growth on short-range radio signal transmission, and provide guidance for designing wireless sensor network based environment monitoring systems for corn fields. We choose three significantly different corn growth stages, namely the seedling stage, the heading stage, and the seed-filling stage, to conduct the wireless signal path loss experiment. On average, the plant spacing and the row spacing are 26cm and 66cm respectively. During the seedling period, the height of summer corn above ground is about 25cm. At this stage, the growing period is quite long, but the height and leaf area change very little. To the analysis of radio signal transmission, this environment is similar to bare field, crops have little influence on signal attenuation. The heading stage comes in early July. During this period, the corn grows very fast, the stalk length and the leaf area and size will double, and the plant height can reach 1.5 to 2 meters. In early August, summer corn goes into the seed-filling stage, the growth of the stalk and leaf reach the highest point, the ear of grain is also gradually full, and the plant height in our experiment is generally around 2 meters at this stage.

3. The RSSI Attenuation Model for Gradually Changed Environments

Wireless signal attenuation is closely related to RSSI. Upon the reception of each data frame, there will be a corresponding RSSI value, which reflects the current signal attenuation situation. The relationship between the transmitting power of wireless signal and the receiving power is usually represented by the channel transmission model shown in equation (1).

$$P_i(d) = P_0 + X_0 - 10\eta \log_{10}\left[\frac{d}{d_0}\right] \tag{1}$$

where $P_i(d)$ represents the receiving power (dBm), P_0 represents the transmitting power when the reference distance is d, X_0 is a Gaussian random variable with the mean of 0, d_0 is the maximum node reference transmission distance, η is the path loss coefficient.

Considering the real growth situation of summer corn at different stages, and also considering that the RSSI attenuation model is easily affected by many factors such as distance, antenna, height, and transmission power, we presents a dynamic RSSI attenuation model in this paper. This dynamic model is based on equation (1). In the new dynamic model, we focus on the gradual change of the environments. According to equation (1), the path loss, Ploss, can be calculated by subtracting the received power from the transmitting power. We get the dynamic attenuation model by conducting regression analysis on the summer corn path loss data in MATLAB, the model can be described by the following equation:

$$P_{loss} = P_0 - P_i(d) = 10\eta \log_{10}\left[\frac{d}{d_0}\right] - X_0 + \Psi(H) + \varepsilon \tag{2}$$

Where $\psi(H)$ is the environment influence function, and its value mainly depends on the crop height. P_{loss} is the path loss to node i, this value is related to environmental factors. ε is a model parameter, we define $\omega = \varepsilon - X_0$.

In the RSSI attenuation model, signal attenuation is related to the signal transmission distance. When the transmission distance becomes more closer, the power attenuation becomes faster, and vice versa.

$$d = d_0 10^{\frac{P_{loss} - \omega - \Psi(H)}{10\eta}} \tag{3}$$

Figure 1 shows the RSSI signal attenuation model. Vertex A represents the top point of the crop, H represents the plant height at different stages. Sensor nodes are placed at E, F, and G respectively. d_i is the communication distance between nodes. Figure 2 shows the measurement structure of the estimation principle of the RSSI attenuation model. Because the measurement is closely related with location, the measured results are strongly related with the location of the antenna. To simplify the equation, we define $\phi(h, H, d)$ as the sub-function which reflects the relationship between the antenna height h, the plant height H, and the transmission distance d.

$$\Psi(h) = 10\Phi(h, H, d) - 10\eta \log_{10}(\frac{d}{d_0}) \tag{4}$$

From equation (2) and equation (4) we can derive the estimation equation of RSSI attenuation model as follows:

$$P_{loss} = 10\Phi(h, H, d) + \omega \tag{5}$$

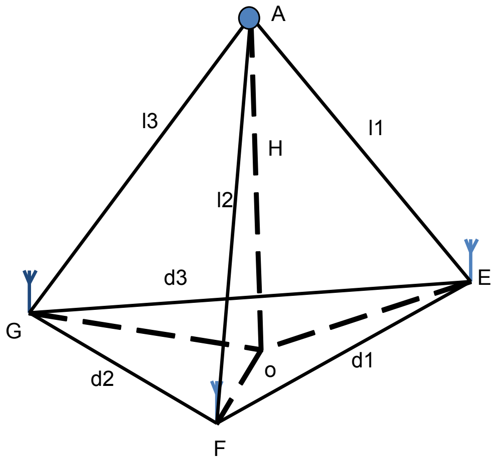

Figure 1. The RSSI Attenuation Model For Gradually Changed Environment.

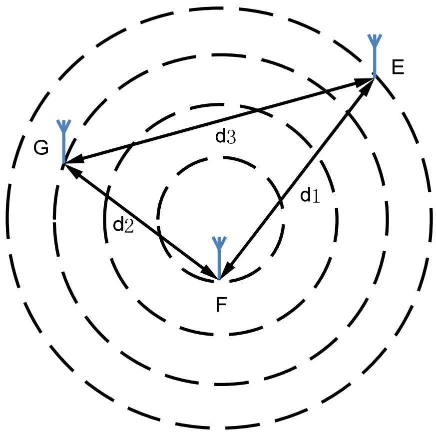

Figure 2. The Measurement Structure of The RSSI Attenuation Model.

4. Analysis of Experiment Results

In a summer corn test-bed, whose dimension is 125×170 square meters, we choose growth stages, the seedling stage, the heading stage, and the seed-filling stage, to conduct the wireless signal path loss experiment. We measured and recorded the change of the RSSI values, and analyzed the radio signal transmission attenuation. We placed two sensor nodes in the test field, the transmission frequency of the sensor node is 2.4 GHz, the reception sensitivity is 110 dBm, the space between the two nodes is 25 meters. The sensor node's antenna height is adjustable. Considering the RSSI attenuation is influenced by many factors such as the antenna height, the transmission distance, and the crop growing status, we studied the characteristics of RSSI attenuation from many aspects.

Antenna height is one aspect which affects the RSSI value. Different antenna heights can lead to different RSSI attenuation level. In our experiment, the distance between the two sensor nodes is 25 meters. The RSSI curve for different antenna heights is shown in Figure 3.

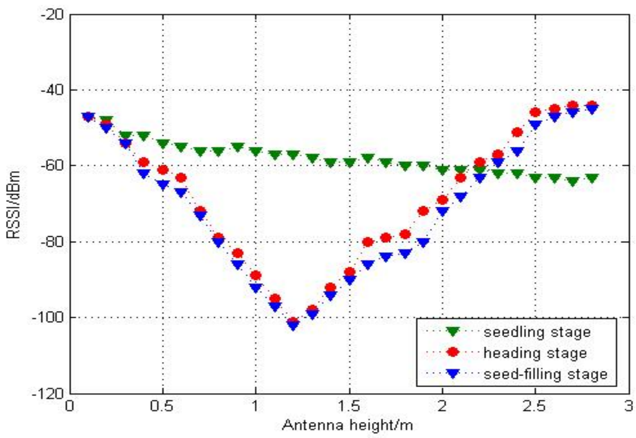

Figure 3. The Signal Attenuation Curve of Summer corn for Different Antenna Heights at Different Growth Stages.

During the seedling stage, the corn roots grow very fast, but the stalk and leaves grow relatively slow. From Figure 3 we can see that the RSSI attenuation is small during the seedling stage. The influence of the crop on the signal transmission is similar to bare land, the attenuation curve is quite flat.

The heading stage is the period in which the corn grows very fast. During the seed-filling stage the corn becomes mature. At those two stages, all the leaves and the stalks reach their mature state. The stalks are tall and thick, the seeds are very dense, and the leaves are dense and big. Therefore, during those two stages, the crop can reflect and scatter the wireless signal, leading to significant RSSI attenuation. From Figure 3 we can see that the RSSI attenuation reaches the maximum value when the antenna height is around 1.2 meters. This result comes out of the growth characteristics of corn. Because there are relatively fewer branches and leaves at the bottom and the top of the corn, the RSSI attenuation when we set the antenna at the bottom or at the top of the corn will be significantly lower than the RSSI attenuation when we set the antenna around the middle of the corn.

From the above experiment results we can draw the conclusion that summer corn branches and leaves will block the wireless signal transmission in different degrees when we set the antenna at different heights. To learn the influence of sensor node blocking on the transmission distance, we conducted the second experiment. First, we set the antenna at different heights. Then we observe the relationship between the transmission range and the RSSI attenuation. The experiment results are shown in Figure 4 and Figure 5. Since the influence of the crop on the signal transmission is similar to bare land at the seedling stage, we did not conduct experiment for this stage.

Figure 4 and Figure 5 show the transmission distance of sensor nodes at the heading stage and the seed-filling stage when we set the antenna heights as 0.3 meter, 1.2 meters, and 1.8 meters respectively. When the RSSI attenuation is close to -110 dBm, the signal is attenuated to sensitivity limit of the receiving node. The transmission distance at this point is the maximum transmission distance for the current antenna height value. We can see that when the antenna height is set to 1.2 meters, because the leaves are most dense at the middle of the corn, wireless signals are seriously scattered and reflected by the corn leaves. Therefore, we see the maximum RSSI attenuation at this antenna height, and the transmission distance of sensor node is the shortest. At the bottom and the top of the corn there are relatively fewer leaves, so the influence of leaves on wireless signal transmission is relatively small, and the transmission distance of sensor node is longer than the transmission distance of sensor node when we set the antenna around the middle of the corn.

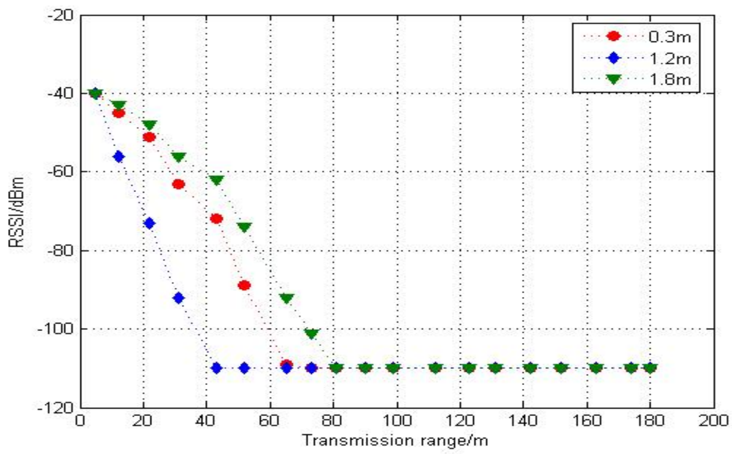

Figure 4. Relationship Between Transmission Range And RSSI For The Heading Stage.

From the below experiment results we can learn that with the growth of the crop, the wireless signal transmission environment will become quite complicated when the height, number of leaves, and leaf coverage area change significantly. Consequently, the signal attenuation degree will also change for different stages. During the seedling stage, the above-ground crop is relatively small, the signal transmission loss mainly comes from the ground reflection. At the heading stage, the height and density of the crop, as well as the density of corn leaves, will increase significantly, leading to more influencing factors. Besides the ground reflection, there are also the signal scattering and diffraction caused by the corn leaves. As a whole, the signal attenuation at the late stages of corn growth is higher than the signal attenuation at the early stage.

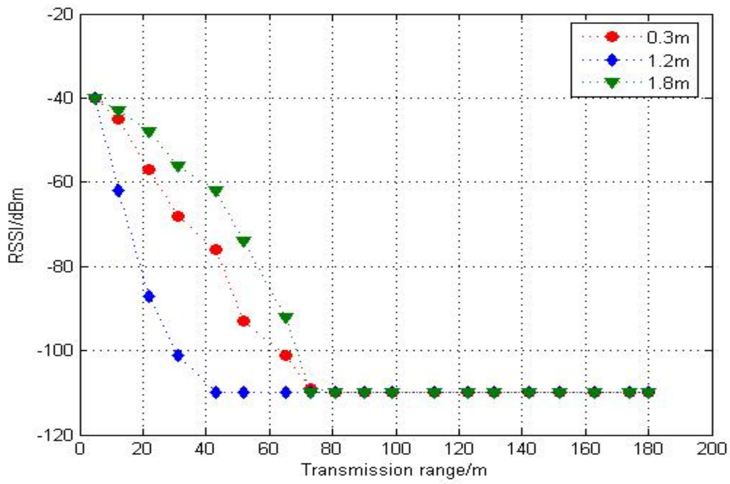

Figure 5. Relationship Between Transmission Range And Rssi For The Seed-Filling Stage.

Through the experiment results listed in Table 1 we can find the changing pattern of the parameters of the path loss change model for the three growth stages of corn. For different growth stages the crop heights are different. With the change of growth stages, the corn stalks and leaves become more and more dense, the signal transmission environment become worse, and the signal attenuation increases significantly. The path loss coefficient decreases with the increase of antenna height. R2 is the correlation coefficient, which compares the theoretical values and the measured values in the experiment.

Table 1. The Experiment Parameters of The Path Loss Model For Three Growth Stages of Corn

stage	crop height H	antenna height h	path loss coefficient η	ω	R2
seedling stage	{0.1,0.2,0.4}	{0.2,0.7,1.6}	{2.15,2.03,1.96}	{62.3,68.5,72.1}	{0.96,0.92,0.93}
heading stage	{1.0,1.2,1.5}	{0.2,0.7,1.6}	{2.21,2.09,1.98}	{66.4,71.6,75.3}	{0.91,0.90,0.94}
seed-filling stage	{1.6,1.8,2.0}	{0.2,0.7,1.6}	{2.74,2.53,2.26}	{64.2,68.9,74.2}	{0.97,0.95,0.92}

From the above experiment results we can find that path loss is related with antenna height, signal transmission distance, and the growing status at different stages. The gradually changed RSSI attenuation model can be described by the following equation:

$$P_{loss} = 10\Phi(h, H, d) + \omega \tag{6}$$

where $\Phi(h,H,d)$ changes according to the influences of different growth stage on the signal transmission environment. Through analysis of the experiment results we conclude the empirical RSSI attenuation model for three different growth stages of summer corn.

During the seedling stage, the above-ground part of the crop has little impact on the signal transmission. The antenna height and the crop height have little influence on RSSI attenuation. For this stage, the attenuation model can be described as follows:

$$\Phi(h,H,d) = -\log_{10}\frac{d}{d_0}[0.37\ln(\tau\frac{h}{H}) - 2.01] \quad (7)$$

During the heading stage, the crop stalks and leaves grow very fast. The influences of antenna height and crop height in the RSSI attenuation model increase gradually. For this stage, the $\Phi(h,H,d)$ function in the RSSI attenuation model is defined as follows:

$$\Phi(h,H,d) = -\log_{10}\frac{d}{d_0}[0.21\ln(\tau\frac{h}{H}) - 2.24] \quad (8)$$

At the seed-filling stage, all the crop leaves are fully expanded and the crop reaches its maximum height. During this period, the influences of antenna height and crop height on RSSI attenuation reach the maximum value. For this stage, the $\Phi(h,H,d)$ function can be expressed as follows:

$$\Phi(h,H,d) = -\log_{10}\frac{d}{d_0}[0.45\ln(\tau\frac{h}{H}) - 2.43] \quad (9)$$

5. Conclusion

This paper researched the RSSI attenuation model of wireless sensor network for summer corn farmland. Through large amount of experiment data, we find that the RSSI attenuation characteristics are related with the antenna height and the corn growth stages. The planting of corn demands relatively wide plant spacing and row spacing. For the seedling stage, the crop height is low and the crop leaf coverage area is quite small, thus the RSSI attenuation speed is basically not related with the antenna height. At this period, the signal attenuation speed is the same as the signal attenuation speed on bare land. However, for the heading stage and the seed-filling stage, the corn crop can usually grow to 2 meters tall, and there are dense leaves at the middle of corn.

Accordingly, the RSSI attenuation speed is high at both ends and low in the middle. That is, the attenuation speed at the bottom and the top of the crop is relatively low, while the attenuation speed in the middle of the crop is relatively high. This is because the corn leaves has maximum coverage area in the middle, and the scattering and reflection caused by corn leaves are more serious. Because of the fixed plant spacing and row spacing, the transmission characteristics of wireless signals are quite stable. That is, different sensing location will have basically consistent signal attenuation pattern. Through the analysis of experiment results, we can draw the following conclusions: the RSSI attenuation can be predicted through the path loss model, the path loss parameter is closely related with the antenna height at different growth stages, and the optimal antenna height for different crop growth stages can be predicted. For the heading stage and the seed-filling stage, the optimal antenna height is about 2 meters, the second best value is the height a little bit greater than 1.7 meters.

Through this model we can predict the strength of received signals and the effective signal transmission range, and reduce the redundancy in the deployment of sensor nodes. The model is also a guideline for quick deployment of wireless sensor network nodes. At the same time, this model takes into account of the gradually changed characteristic of crop planting environment. Using this model, we can predict the optimal antenna height, increase the overall wireless network signal transmission rate, and reduce unnecessary path loss. We can monitor the growth of summer corn at different stages via the wireless sensor network, and obtain accurate soil moisture information. With these information, and considering the relationship between different growth stage and the soil moisture, we can irrigate the summer corn in a timely and precise manner. All those measures can help us to increase the crop yield of summer corn, obtaining maximum crop production at minimum cost.

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