Propagation model for 2.4 GHz wireless sensor network in four-year-old young apple orchard

Guo Xiuming[1], Zhao Chunjiang[2*]

(1. *Agricultural Information Institute，Chinese Academy of Agricultural Sciences,Beijing 100081, China*;
2. *National Engineering Research Center for Information Technology in Agriculture, Beijing 100097, China*)

Abstract: Wireless sensor network (WSN) nodes exchange information via wireless signals, whose power can attenuate at different levels according to the propagation environment. The branches and leaves of young apple trees are much sparser than that of adult apple trees. Propagation rules such as propagation distance and attenuation rate are the parameters necessary to know before applying a WSN to a young apple orchard. Field tests were performed, and propagation distance and packet loss rate (PLR) were computed and compared under the two cases: a young apple orchard in fruit period and an open space to find the effect of the apple trees on radio propagation. A model of antenna height and propagation distance was created to forecast the extra path loss caused by the young trees. Validation experiments were performed in a different young apple orchard, and the validation results showed that 70% of R^2 were higher than 0.7, while the smallest being 0.65; 80% RMSE were smaller than 5. The new model was also compared with some classical models such as Cost 235, FITU, ITU-R, and Weissberger model, and the new model was proved to be the best.

Keywords: wireless sensor network (WSN), propagation model, packet loss rate, 2.4 GHz, young apple orchard
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1 Introduction

The apple production is high in China, however, some common problems exist in China's apple industry such as low level of technology, extensive management, poor disease-resistant ability.

Wireless sensor network (WSN) is a promising technology and it has been increasingly used in agriculture. WSN applied in the apple orchard can collect environmental data and information of the trees themselves, based on which right decisions can be made timely to improve the apple production and quality[1,2]. WSN is composed of sensor nodes that communicate with each other by wireless radio signals. The wireless signal attenuation can be caused by physical phenomena such as scatter, reflection, and absorption during propagation. Transmission rules such as the attenuation rate, the coverage range, and the packet loss rate (PLR) are necessary for applying a WSN in an apple orchard. The density of branches and leaves and the canopy size of a young apple tree are much different from those of an adult apple tree, and young apple trees may have different influences on wireless radio propagation.

Many studies have been performed on characteristics of wireless radios propagation in different kinds of vegetation types including wheat land[3], orange orchard[4], durian garden[5] and plum orchard[6]. They paid attention to different factors including the antenna height, vegetation depth and the propagation frequency etc. and

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Biographies: Guo Xiuming, PhD, assistant researcher, research interests: key information technologies of WSN application in agriculture. Email: guoxiuming@caas.cn.

***Corresponding author: Zhao Chunjiang,** PhD, Professor, research interests: key technologies in information agriculture. Mailing address: National Engineering Research Center for Information Technology in Agriculture, Number 11, Shuguang Garden Middle Street, Haidian District, Beijing 100097, China. Email: zhaocj@nercita.org.cn.

deduced the propagation characteristics through measurements and contrastive analysis with the existing models. Besides a single vegetation type, propagation characteristics of wireless radio in some complex agricultural environments were also researched. Azevedo and Santos[7] performed field tests in forests with dozens of tree species to find an empirical propagation model for forest environments at tree trunk level. Ndzi et al.[8] presented wireless sensor network coverage measurements in a mixed crop farmland, and a log-linear model was proposed and validated for application in mixed crop environment. Adhikari et al.[9] carried out simulations to find out the behavior of an electromagnetic wave propagating through a leafy vegetation layer, and a simple model was assumed to estimate the macroscopic effective dielectric constant.

It can be concluded from the reported literature that wireless radio had different propagation rules in different vegetation types. Some researchers have conducted studies on propagation characteristics of wireless radio propagation in apple orchards. Andrade-Sanchez et al.[10] performed a range of tests to quantify the performance of agricultural WSN in an apple orchard, they paid attention to different metrics of radio performance such as packet delivery and signal strength instead of radio propagation characteristics. Guo et al.[11] studied the propagation characteristics of 2.4 GHz radio in a traditional adult apple orchard, and concluded that the attenuation at each height could be forecasted by a log-normal model[12], and the attenuation rate was the fastest between 1 m and 2.25 m.

A young apple orchard is generally referred to as an apple orchard less than five years old, and a young apple tree is different from an adult one in tree height, canopy structure, leaf area, etc. The transmission rules are necessary to be made clear before applying a WSN to a young apple orchard. The field tests were performed in a young apple orchard in Beijing, China. Coverage range and PLR were computed and analyzed. An empirical model was deduced for the 2.4 GHz radio propagation in a young apple orchard. The model was validated using measurements in a different young apple orchard.

2 Materials and methods

Field tests were performed in a young apple orchard on Nankou farm, Beijing, China. The orchard was built in 2008 and had a line spacing of approximately 5 m and a strain spacing of approximately 3 m. The trees were approximately 2.5 m high with trunk heights of approximately 0.3 m. The canopy was small and sparse canopy shape, with a width of approximately 1.5 m and a height of approximately 2 m. The test was performed in fruiting period on June 4th when the apple diameter was approximately 15 mm;

A measurement system was constructed using some IRIS nodes, and a gateway MIB520CB. Both the IRIS node and the MIB520CB were manufactured by Crossbow Company in America. An IRIS node can automatically compute the receiving signal strength index (RSSI) that can be converted to the receiving power. The RX sensitivity of an IRIS node is -91 dBm. The system contained a transmitter, 18 receivers, and a sink node. Both the transmitter and the receiver were composed of an IRIS node, and the sink node was composed of an IRIS connected to a gateway MIB520CB, which transmitted the data to a laptop via a USB interface. The sender, the receivers and the sink node were all boxed in a PVC container. All the nodes were fixed on a small plane board that was fastened to a three-meter-long pole such that the board could be raised and lowered along the pole. The pole was inserted into a triangular leg brace and could be rotated around the brace (Figure 1).

Figure 1 The young apple orchard for measurements

The typical direction along a line of trees in which the apple trees had the greatest impact on radio propagation was selected for the test. The measurement was performed along the same line of trees. The transmitter was fixed between the same two selected apple trees. The receivers were placed consecutively from tree 1 to tree 18 away from the transmitter and were in line with the trees. The strain spacing was about three meters; therefore, the propagation distance for each of the 18 consecutive measurement points was 3, 6, 9… up to 3×18=54 m. The transmitter sent signals, the receivers received the signals, computed the RSSIs, and sent them to the sink node that transmitted the RSSIs to the laptop via the USB interface.

RSSI was measured at 10 heights from 0.5 m at the bottom to 2.75 m at the top of the canopy at a fixed spacing of 0.25 m. The RSSI was also measured at 1 m away from the transmitter at each height. A large number of randomly distributed leaves can significantly change the signal strength even when there is little variation in the position of the receiving antenna. Two hundred RSSIs were measured at four locations close to the position of each sending antenna, and the average value of the 800 RSSIs was calculated as the RSSI at the center position. A schematic of the measurement method can be seen in Figure 2 in which only five trees and six heights are shown for simplicity.

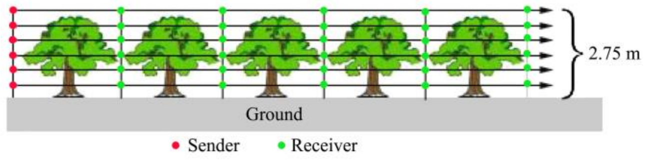


Figure 2 The measurement method schematic

Field tests were also repeated in an open space beside the orchard to find the young apple trees' effect on radio propagation through comparative study.

3 Results and discussion

Some extra tests in farther distances were conducted to measure the coverage range when the RSSI did not decay to the receiver sensitivity of the receiver at some heights. Figure 3 shows the coverage range at different heights under the two cases: in the orchard and in the open space. The coverage range in the open space was always farther than in the orchard. The difference was larger at lower heights, and decreased with the increasing antenna height. That indicated that the young trees made a difference in the radio propagation at all the heights, even at the top canopy where the leaves were sparse.

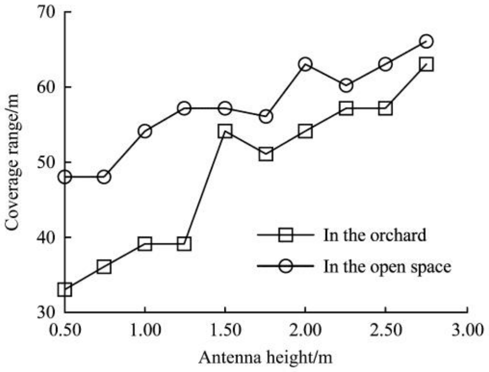
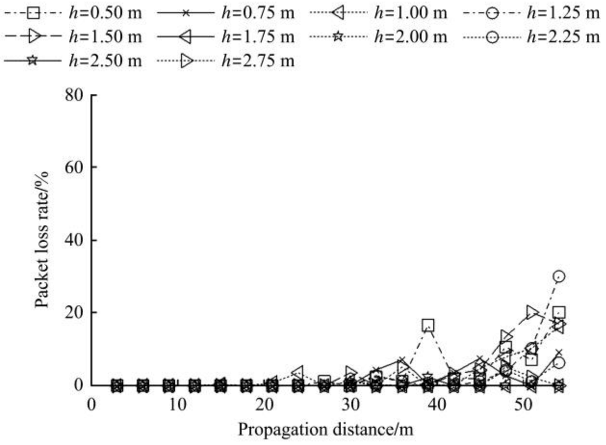
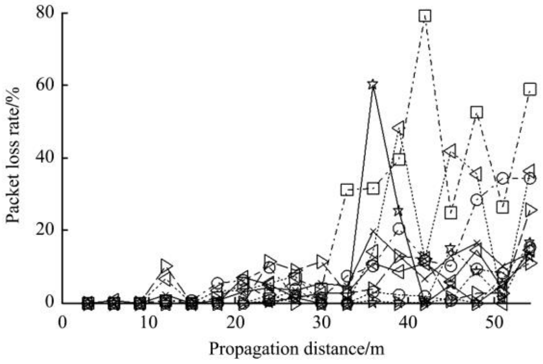


Figure 3 Coverage range at different heights

PLR is an important index for evaluating a WSN's performance, therefore, PLRs were calculated at each height in the orchard and in the open space (Figure 4).



a. In the open space



b. In the orchard

Figure 4 PLRs at different heights

The results show that the young apple trees made an obvious difference in PLR. When the propagation distance was smaller than 40 m, the packet loss rarely occurred in the open space, and the PLR values were about 10% between 20 m and 40 m in the orchard. When the distance was larger than 40 m, slight packet loss happened at some heights in the open space, and the packet loss was huge especially at lower heights in the orchard, with the biggest PLR of 80%.

4 Modeling and validation

4.1 Modeling

Regression analysis results show that the path loss at each height under the two cases can both be fitted by the log-normal model:

$$\mathrm{PL}_{LN}(\mathrm{db}) = \mathrm{PL}(d_0) + 10n\log_{10}(d/d_0) \tag{1}$$

where, n represents the rate at which the signal attenuates with the distance; $\mathrm{PL}(d_0)$ (in dBm) denotes the path loss at a known reference distance d_0 in the far-field. d_0 was set 1 m in the study. The fitted values of statistical determination coefficient R^2 were all bigger than 0.93. d is the distance between the measurement point and the signal source ?

Figure 5 shows the fitted n and PL(1) values at different heights. Some rules of change could be found. Firstly, the parameter n gradually decreased linearly with antenna height both in the open space and in the orchard. The main reason may be the ground effect on radio propagation. Both n and PL(1) were always larger in the orchard than those in the open space at the same height. That indicated that the apple trees increased the attenuation regardless of the heights, which was consistent with the PLR analysis results. Finally, differences between PL(1) values at adjacent heights changed much greater in the apple orchard than that in the open space. This was the result of extensive scatter caused by a large amount of leaves and branches in the apple orchard.

The fitting equation between n and the antenna height h was calculated in the open space (Equation (2)) and in the orchard (Equation (3)) by the least squares regression. The fitted R^2 was 0.85 and 0.67 respectively.

$$n = -0.2943h + 2.941 \tag{2}$$

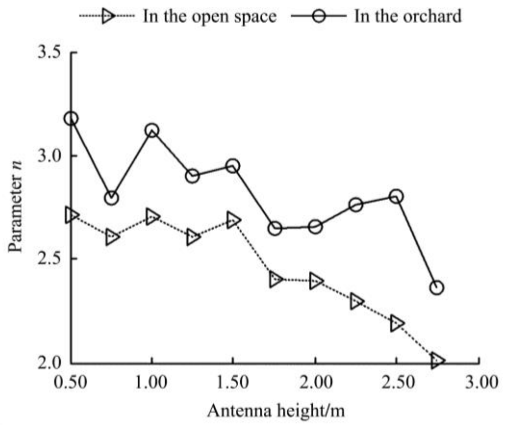
$$n = -0.2436h + 3.214 \tag{3}$$

PL(1) at different heights had little difference in the open space with the largest difference being 2.7, and the average 41.4 was calculated as the PL(1) in all the heights. PL(1) increased with increasing height in the orchard, and could be computed by a linear equation of the antenna height:

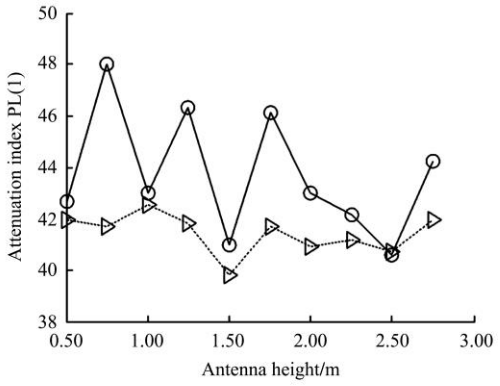
$$\mathrm{PL}(1) = -1.133h + 45.6 \tag{4}$$

Using equations (1)-(4), the excess path loss PL_E caused by young apple trees could be calculated below:

$$\mathrm{PL\_E} = (0.507h + 2.73)\log_{10} d - 1.133h + 4.2 \tag{5}$$



a. The parameter n



b. The parameter PL(1)

Figure 5 Variation in n and PL(1) with antenna height

4.2 Validation

Validation tests were performed in a different young apple orchard in Beijing. The measurement method was the same as that for modeling. Table 1 shows the R^2 values for the fits of the computed results using the new model to the measured data and the corresponding root mean square errors (RMSEs). Most of R^2 were between 0.65 and 0.90 with the smallest value being 0.61, and most of RMSE were between 3 and 5, with the smallest value being 2.12. The wireless radio power might change great even if the position of the receiving antenna changed a little due to the impact of a large number of leaves and branches. It was difficult to forecast the signal power accurately. The computed values of R^2 and RMSE were reasonable, therefore, the new model was suitable for forecasting the path loss in a young apple orchard.

Table 1 R^2 and RMSEs for fitting of results computed using new model to measured data

	Antenna height *h*/m									
	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50	2.75
R^2	0.61	0.75	0.65	0.75	0.71	0.69	0.82	0.94	0.87	0.90
RMSE	4.77	3.30	6.10	5.76	4.36	4.61	3.25	4.96	2.12	3.65

4.3 Comparison analysis

To find the new model's performance, the new model was compared with some existing models: Cost 235 model[13], FITU model[14], ITU-R model[15], and Weissberger model[16]. The COST 235 model considers the situations in which the trees are in-leaf or out-of-leaf. The excess attenuation is given by:

$$L_{COST}(\mathrm{dB})=\begin{cases}15.6f^{-0.009}d^{0.26}\ , & \text{in-leaf}\\ 26.6f^{-0.2}d^{0.5}\ , & \text{out-of-leaf}\end{cases} \tag{6}$$

The lateral ITU-R model takes into account the lateral component where the signal follows the tree-tops, which is defined by:

$$L_{LITU}(\mathrm{dB})=0.48f^{0.43}d^{0} \tag{7}$$

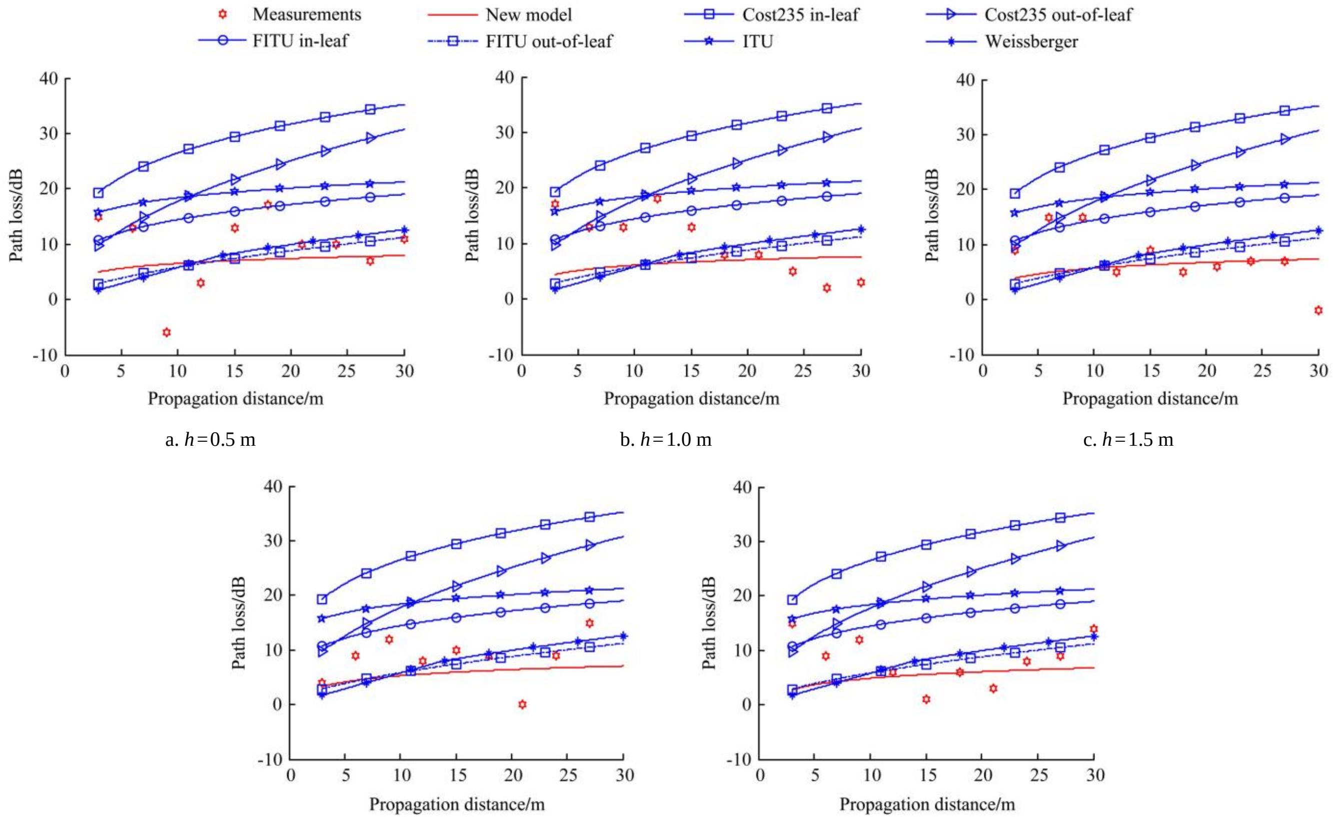
Based on the ITU-R recommendation, Al-Nuaimi and Stephens have developed a model using measurement data at 11.2 and 20 GHz with *f* in MHz and *d* in m.

$$L_{FITU}(\mathrm{dB})=\begin{cases}0.39f^{0.39}d^{0.25}\ , & \text{in-leaf}\\ 0.37f^{0.18}d^{0.59}\ , & \text{out-of-leaf}\end{cases} \tag{8}$$

Weissberger model estimates the excess attenuation produced by vegetation with *f* in GHz and *d* in m.

$$L_W(\mathrm{dB})=\begin{cases}0.45f^{0.284}d & d\le 14m\\ 1.33f^{0.284}d^{0.588} & 14m\le d\le 400m\end{cases} \tag{9}$$

The comparison results between the measurements and the new model and some existing models are shown in Figure 6. Some conclusions could be drawn. First, the existing models were very different from each other because each of the models aimed at a certain application environment. For example, the predictions of COST235 in-leaf model are much larger than that of FITU in-leaf model, although they both pay attention to the situation when there are no leaves on trees. Second, the measurement fluctuated around the new model at each height, this may be caused by the multi-path phenomenon of wireless radio propagation in the young apple orchard. Lastly, the new model had similar trend with the FITU out-of-leaf model and Weissberger model, but very different trend with the other models, with the biggest path loss being the Cost 235 in-leaf model.



a. *h*=0.5 m b. *h*=1.0 m c. *h*=1.5 m

d. *h*=2.0 m e. *h*=2.5 m

Figure 6 Comparison between measurements and the new model and some existing models

The RMSEs between the measurements and the new model and the existing models were computed (Table 2). RMSEs between the new model and the measurements were between 5.0 and 7.5, and they were smaller than most of that between the measurements and the other models, so the new model performed the best. The wireless radio propagated through more than one path because of many influence factors such as the leaves and the ground, and the path loss at a fixed position varied at a certain range, therefore, the 5.0-7.5 RMSE agreed with the real situation. FITU out-of-leaf model followed the new model, and most of its RMSE values were bigger than that of the new model with the biggest value 1.15 at h=1.5 m, however, the RMSE was a little smaller than that of the new model at h=2.5 m. It could be concluded that the FITU out-of-leaf model was best suited for the path loss of 2.4 GHz propagation in young apple orchards among the existing noted models. The third was Weissberger model, whose RMSEs were between 6 and 9 and larger than FITU out-of-leaf by less than 1 at all the heights.

Table 2 RMSEs for fitting of measurements to different models

Antenna height/m	New model	Cost235 In-leaf	Cost235 Out-of-leaf	FITU In-leaf	FITU Out-of-leaf	ITU-R	Weissberger
0.5	6.86	21.36	15.40	9.44	6.98	11.91	7.18
1.0	7.08	21.48	16.49	9.58	8.11	11.46	8.73
1.5	5.63	23.21	17.59	10.58	6.78	13.05	7.58
2.0	7.33	24.48	18.72	12.25	8.18	14.78	8.72
2.5	5.66	22.08	16.06	9.37	5.55	12.05	6.25

5 Conclusions

1) Trees increased the attenuation regardless of the antenna height in a young apple orchard. The coverage range was always smaller in the orchard than in the open space, with the biggest difference being approximately 20 meters. The young apple trees had indeed smaller influence on the radio propagation than the adult trees. Wireless radio can travel further in the young orchard than the adult one at every height, and the antenna height where the trees impacted radio propagation most was different between them. In the young apple orchard, the propagation distance increased with the increasing antenna height, while the propagation distance decreased first and then increased with the increasing antenna height in the adult orchard. This may be because the difference of leaf spatial distribution of young apple trees is smaller than that of adult trees.

2) PLR was generally greater in the young apple orchard than that in the open space, regardless of the antenna height. The PLR values at lower heights increased rapidly when the distance was larger than 30 m in the young orchard, while the PLR increased slightly in the open space. While in the adult apple orchard, PLR increased rapidly at about 12 m, and it was much smaller at 30 m in the adult apple orchard.

3) The path loss can be fitted by the log-normal model at each height both in the open space and in the young orchard. The attenuation index n linearly decreased with the increasing height under the two cases. The log-normal model is an extremely versatile model, and it has been confirmed that the path loss of wireless radio propagation in many kinds of vegetation can be predicted by it.

4) A new model was developed to forecast the excess path loss caused by young apple trees. The validation results showed that most of R^2 were larger than 0.65, and most of RMSE values were between 3 and 5.

5) The new model was compared with some existing models. The results showed that the new model performed better than the other models, and its RMSEs was smaller than the FITU out-of-leaf model by 1-2. FITU out-of-leaf model used the measurement data at 11.2 and 20 GHz, and the higher the frequency is, the greater the effect is, so the prediction accuracy of FITU out-of-leaf model was worse than the new model. Weissberger model was ranked third, and its RMSEs were greater than FITU out-of-leaf model by less than 1 at all the heights.

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