Study on the Signal Transmission Characteristics of 2.4GHz Wireless Network in Dorms

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Abstract—**In accordance with the deployment requirements of WLAN node in college student dorms and its features of application environment, this paper studies the relevance among factors like radio-frequency signal transmission characteristics, communication distance, AP height and transmission path, etc., with a case study of AP radio frequency 2.4GHz. Experiments show that the attenuation of wireless network signal in student dorms conforms to Keenan-Motley model. When AP is fixed, the signal strength received by laptop generally reduces with the increase of communication distance, yet just opposite with packet loss rate. When deploying AP, 1.25-1.75 height is ideal, and one-side coverage of 3 dorm rooms optimal. Based on the above researches, a relational model of AP height, communication distance and received signal strength is established. In it, model parameter K and AP height display a cubic polynomial relationship, and attenuation coefficient n and AP height show a quadratic polynomial relationship. Experiment results demonstrate that this model can satisfactorily predict the received signal strength of different AP heights and communication distances, providing technical support for wireless network deployment in student dorms.**

Index Terms—**2.4GHz; WLAN; Student dorms; Signal attenuation**

I. INTRODUCTION

Wireless Local Area Networks (WLAN), which serves as a network established within a certain area through wireless communication technology as well as the result of combination between computer network and wireless communication technology, can provide the functions of Local Area Network (LAN) and allow users to access internet network at time and any place with using wireless multi-address channel as the transmission medium [1] [2]. The primary purpose of introducing WLAN is to supplement LAN for users; but with the advancement of WLAN in terms of mobility, expandability, safety and transmission speed, WLAN has managed to meet the requirements of manageable wireless network featuring high capacity, multiple users and wide coverage [3]. WLAN is undergoing the evolution from being a supplement for LAN to operable public wireless local area network, hence becoming an inevitable supplement to 3G/4G mobile network. During the summer vacation of 2015, Northwest Agriculture and Forestry University were planning WLAN in student living area. WLAN planning refers to design of reasonable and feasible wireless network layout according to the requirements upon coverage and capacity as well as other special ones in combination with the terrain features of the covered area with the lowest investment to satisfy the current demand and meanwhile ensure future expandability of network. The most important thing in WLAN planning lies in how to deploy Access Point (AP) nodes in the complex environment of student dorms [4], so it is essential to study the transmission features of wireless signal in student dorms and to establish signal transmission signal, for this can provide the important technical support for WLAN network planning. There are 3 frequency ranges in WLAN planning [5], namely ISM range of 2400-2483.5GHz, 5.8GHz ISM range of 5725-5850MHz and global frequency planning of 5GHz-range W(R)LAN (455MHz bandwidth). This paper adopts the most widely used 2.4GHz wireless signal in WLAN planning as the research subject. Factors like the internal walling, tile-laid floor and windows in student dorms can all influence wireless signal transmission. Therefore, in order to solve the key technological problems in student dorms deployment, this paper mainly studies the transmission features of wireless signal sent by AP in student dorms under different transmission directions and heights, conducts on-field measurement of received signal strength from 3 different directions and of different AP heights, and establishes a model for predicting attenuation of 2.4GHz signal in student dorms, so as to provide the technical foundation for highly stable and reliable WLAN node deployment.

II. EXPERIMENTS

A. Experiment Environment and Materials

The experiment took place at the 18# student dorm of the south campus of Northwest Agriculture and Forestry University located in Yangling District of Shaanxi Province. The dorm rooms from 103 to 119 at the first floor were selected as experiment environment, with corridors, washrooms and staircases in them. The dorm room was 7.5m in length and 3.8m in width. At the top, there was metal ceiling with a height of 2.85m. The experiment equipment was H3C-WA4620i wireless AP equipment (Hangzhou H3C Communication Technology Co., Ltd.), with a transmission frequency of 2.4GHz and wireless gain of 7dBi. Laptop IBM T430s was used at the receiving end; and the network card was Intel(R) Centurion(R) Wireless-N 2200. Insider was installed on laptop to obtain the instantaneous value of Received Signal Strength Indicator (RSSI), with the unit being dBM [6]. The test ranged from October 25th, 2015 to October 30th, 2015, with an average temperature of 29℃ and an average humidity of 50%.

B. Experiment Methods

The working mode of AP was changed to FAT, the Dynamic Host Configuration Protocol (DHCP) service initiated, and the intelligent antenna turned off [7]. The laptop then obtained the 192.168.1.2 address from AP (IP address 192.168.0.50). Later on, AP was fixed on a 2.25m long insulated plastic post, and the test heights in corridors were respectively 0.75m, 1.25m, 1.75m, 2.25m and 2.75m (with the tile-laid floor as reference). The AP-sent power was fixed at 20dBm; when all-directional antenna was used, it gained extra 7dBi. 20 groups of RSSI instantaneous value P_i were taken at each test point to find out their $\overline{P}$ as the RSSI value of that point. The calculation method is as follows:

$$\overline{P} = \frac{1}{20}\sum_{i=1}^{20} P_i \quad (1)$$

Where, P_i is the instantaneous signal strength value of i group; $\overline{P}$ is the average received signal strength.

1) Different Transmission Paths Experiment between wireless AP and Laptop

The AP fixed at the plastic post was placed at the center of corridor (90cm from the entrance of 103 dorm room), and sent 2.4G wireless signals to west at respective heights of 0.75m, 1.25m, 1.75m, 2.25m and 2.75m. The laptop placed on a 0.75m high table among 105-111 dorm rooms were kept away from AP and arranged in an interval of 2.1m, hence producing 9 test points with this path marked as L_1. To test the influence of the complex dorm environment upon 2.4GHz wireless signal transmission features in a comprehensive and multi-perspective manner, other two paths L_2 and L_3 were also chosen. Both the angles between paths L_1 and L_2 and path L_3 were 24.8°. The received signal strength and packet loss rate at 9 different distances corresponding to each AP height of the paths L_2 and L_3 were measured. The experiment design scheme was as shown in Fig. 1.

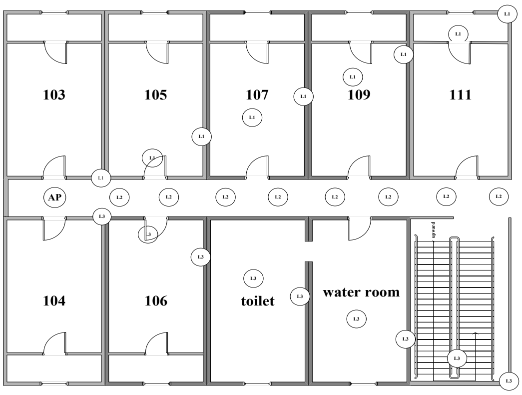

Figure 1. Experiment Scheme Chart

2) Packet Loss Rate Test Method

Packet Loss Rate (PLR) refers to the ratio of lost data packet number in the sent data packet number, which is relevant to the data packet length and frequency and regarded as an important indicator for measuring signal level [8]. The PLR test method is as follows:

DOS order ping 192.168.0.50 -n 50 was run on laptop to send the PLR of 50 data packets. The calculation method is as follows:

$$R = \frac{L}{50} \times 100\% \quad (2)$$

Where, L is the number of lost data packet; and R is PLR.

Path Loss [8] refers to the amount of loss caused by transmission environment between emitter and receiver. There were Line of Sight (LOS) and Non Line of Sight (NLOS) in sending/receiving antenna [9]. In student dorms, the theoretical model, i.e., Keenan-Motley model [10] [11], was uniformly adopted.

$$P_r(d) = P_r(d_0) - 10\lg\frac{d}{d_0} + \sum_{j=1}^{j} N_{uj}L_{uj} + \sum_{i=1}^{i} N_{fi}L_{fi} \quad (3)$$

The attenuation x of other factors was taken into consideration. The formula of modified modelis expressed as:

$$P_r(d) = P_r(d_0) - 10\lg\frac{d}{d_0} + \sum_{j=1}^{j} N_{uj}L_{uj} + \sum_{i=1}^{i} N_{fi}L_{fi} + X \quad (4)$$

Where *d* is the distance between AP and laptop, with the unit being m; d_0 is reference distance, with the unit being m; $P_r(d_0)$ is the power of received signal, with the unit being dBm; N_{uj} and N_{fi} are the numbers of different walls and floors going through by emitted signals; L_{uj} and L_{fi} are the loss factors of different walls and floors; *n* is attenuation coefficient depending on the value of environment and building type;

When d_0=1, The model formula is:

$$P_R = \overline{P_r(d)} = A - 10n\lg d + \sum_{j=1}^{j} N_{uj}L_{uj} + \sum_{i=1}^{i} N_{fi}L_{fi} + X \quad (5)$$

Where, P_R is received signal strength, with the unit being dBm; A is the received signal power at the point of 1m, with the unit being dBm.

$$A + \sum_{j=1}^{j} N_{uj}L_{uj} + \sum_{i=1}^{i} N_{fi}L_{fi} + X = K \quad (6)$$

The formula can be simplified as:

$$P_R = K - 10n\lg d \quad (7)$$

Formula (7) was used for regression analysis model. In Matlab, the least square method was adopted to obtain RSSI values at different AP heights and under different paths for regression analysis.

3) Model Evaluation Indicator

Root mean square error (RMSE) was used to evaluate the performance of model. Smaller RMSE demonstrated higher estimation precision of the model [12].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\overline{P}-P_e\right)}{N}} \quad (8)$$

where, P_e is the calculated value of signal strength, with the unit being dBm; $\overline{P}$ is the average of measured signal strength, with the unit being dBm; and N is the measured times.

III. TEST RESULT AND ANALYSIS

A. Analysis of test results of L_1 path

1) Received signal strength

The average signal strength of 9 points on the corridors and in the student dorms 105, 107, 109 and 111 at the following five AP height levels, 0.75m, 1.25m, 1.75m, 2.25 m and 2.75 m, along L_1 path is as shown in Fig.2.

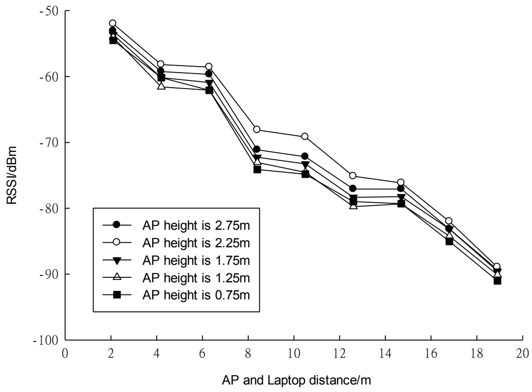

Figure 2. Strength of received signals at different heights and distances

It can be seen from Fig. 2 that at each height RSSI tends to decrease with the increase of the distance till it reaches the RSSI -91.02dBm. When AP is located at the same distance as the laptop and its height apart from above ground is 1.25m, RSSI reaches its maximum value, indicating that AP has the strongest transmitted signal strength when its height apart from above ground is 1.25m and laptop receiving the signal is at the height of 0.8m. When AP is located at the same distance as the laptop receiving the signal, it shows that the higher the AP height (higher than 1.25m) above the ground, the smaller the RSSI.

2) Packet loss rate

Packet loss rate of L_1 path at the following five AP height levels, 0.75m, 1.25m, 1.75m, 2.25 m and 2.75 m, and at different positions of 9 test points is as shown in Figure 3.

It can be seen from Figure 3 that, at each height level, no packet loses in the corridor and dorms 105 and 107, and the packet loss rate is lower at dorm109 but larger at the door of dorm111's balcony. This is because the interior wall of the dorms greatly weakens the strength of signals transmitted by AP. At the corner of dorm 111's balcony, the last test point, since the wireless signal transmitted by AP has a very poor capacity of diffraction against the barriers such as the brick walls with windows and the interior walls of the dorm, and the signal reduces to -91.02dBm at the corner under the sunshine. Due to the special environment of the dorm's balcony, its rear wall being load bearing wall and its east-west walls being brick walls with tiles outside, in addition to the signal being diffracted and scattered by glass door of balcony, the tile floor on the balcony, rear wall, east-west walls and the top of the balcony will also reflect the wireless signal, thus influencing its transmission. After the signal reduces to receiving sensitivity, there is a severe packet loss rate, which fluctuates and changes with the increasing distance between AP and laptop, showing an increasing tendency in general.

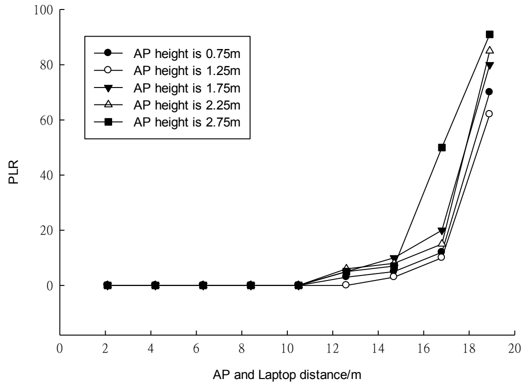

Figure 3. Packet loss rate at different AP heights and distances

3) Matlab-based regression analysis

Regression analysis was conducted to RSSI values measured at five different heights by using Matlab software. Please see Table 1 for fitted values of various parameters, in which R^2 is the determination coefficient [13-14], the indicator of statistical analysis to show the closeness of correlativity between the theoretical calculating value and the measured value. The closer to 1 the value is, the higher the relativity is. Table 1 shows that the smallest value of determination coefficient R^2 is 0.8899 and the biggest value is 0.9308, indicating that the attenuation of AP signal at different heights along L_1 path basically meets that in the log-distance path attenuation model, and it is relatively reasonable to use the log-distance path loss model to describe and predict the features of the transmission of wireless signals at the student dorms.

TABLE I.
REGRESSION ANALYSIS OF THE TEST DATA AT DIFFERENT AP HEIGHTS

AP height/m	K /dBm	n	R^2
0.75	-37.046	3.6469	0.9066
1.25	-35.540	3.6454	0.8899
1.75	-38.133	3.6213	0.9198
2.25	-38.901	3.6483	0.9308
2.75	-38.366	3.7208	0.9202

It can be seen fromTable1 that n reaches the biggest value of 3.7208 when AP height is 2.75, the reason of which is that the metal ceiling sheet leads to the attenuation of wireless signals when AP gets close to the corridor ceiling. When AP height is 0.75, the value of n, 3.6469, is bigger than the one, 3.6454, when AP height is 1.25. This is because the height is too close to the floor tile surface which reflects the wireless signal transmitted by AP. The value of n increases first and then decreases with the rising of height. Fitted results show that the attenuation coefficient and AP height h meet quadratic polynomial relation model, as shown in Fig. 4.

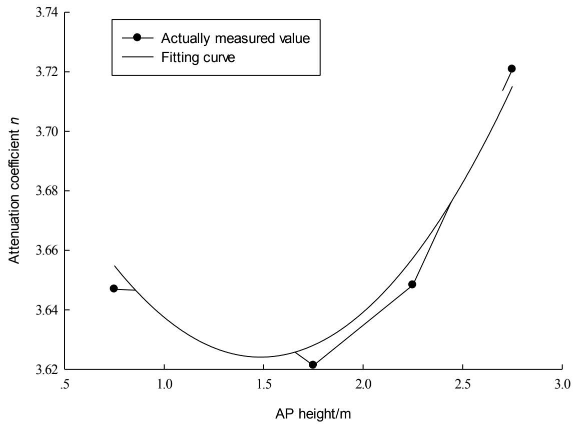

Figure 4. Attenuation coefficient at different AP heights

The fitted determination coefficient R^2 is 0.9048. The relation model of AP height and attenuation coefficient n at the student dorms fitted out is:

$$n = 0.0569h^2 - 0.169h + 3.7496 \tag{9}$$

In the formula, h represents AP height in meters.

Table 1 shows that polynomial fitting can also be used in parameter k and AP height. Respectively being fitted with quadratic polynomial and cubic polynomial, the fitting relations are as follows in Fig.5.

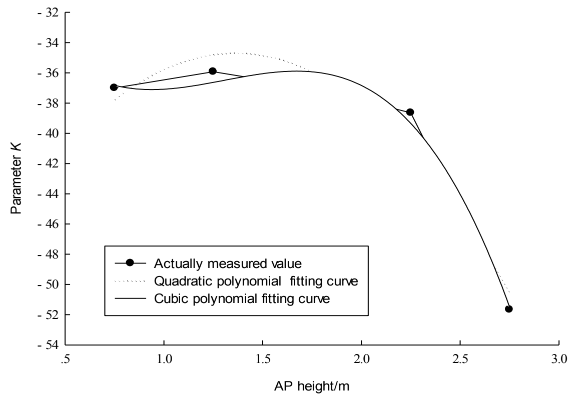

Figure 5. K value at different AP heights

Fitting results of quadratic polynomial:

$$K = -0.0334h^2 - 1.0832h - 35.583 \tag{10}$$
$$R^2 = 0.5064$$

Fitting results of cubic polynomial:

$$K = 0.36013h^3 - 18.94h^2 + 28.943h - 49.526 \tag{11}$$
$$R^2 = 0.9166$$

Compared with R^2, cubic polynomial fitting was used. The fitting results show that the model parameter k and the AP height h have a cubic polynomial relation, while the attenuation coefficient n and the AP height h have a quadratic polynomial relation.

Substituting formulas (9) and (11) into formula (7), the strength model of AP wireless signal received by the student dorms along L_1 path can be obtained:

$$P_R = 0.36013h^3 - 18.94h^2 + 28.943h - 49.526 - \left(0.0569h^2 - 0.169h + 3.7496\right)\lg d \tag{12}$$

4) Model verification

To verify the RSS attenuation prediction model, the dorms115-118 were selected for the experimental verification. Verification results are as shown in Fig.6.

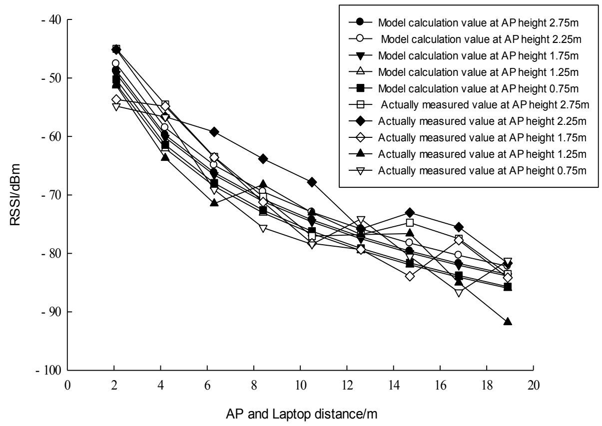

Figure 6. Comparison of model calculation value and the actually measured value

TABLE II.
DETERMINATION COEFFICIENT AND ROOT-MEAN-SQUARE ERROR OF PREDICTED MODEL CALCULATION RESULTS AND MEASURED DATA AT DIFFERENT AP HEIGHTS

AP height/m	R^2	RMSE/dBm
0.75	0.917	3.294
1.25	0.872	4.093
1.75	0.908	3.469
2.25	0.899	3.634
2.75	0.904	3.546

To evaluate the precision of the model, the determination coefficient R^2 and the root-mean-square RMSE, which are reflecting data fluctuation, were calculated [15], as shown in Table 2. In Table2, the determination coefficient between model calculation value and actually measured value at AP height 2.25m is 0.899, the minimum; and it reaches the biggest value at AP height 1.75m. RMSE value is between 3.2943~4.093 dBm. It can be seen from the model verification results that the difference between actually measured RSSI and predicated model calculation RSSI is relatively small; the prediction model established can better predicate the strength of signals received by the student dorms at different heights and distances.

B. Analysis of Test Results of Different Paths

1) Received signal strength of Different Paths

See Table 3 for the received signal strength at various test nodes of L_2 path and L_3 path. It can be known from Table 3 that, in the three paths, the RSSI at each AP height decreases with the increase of the distance between AP and laptop. When the distance between AP and laptop is relatively small, the decrease of RSSI is big; when the distance increases, the decrease gets smaller. When the AP height apart from above ground is 2.75m，the RSSI at each path reaches its maximum value.

TABLE III.
RECEIVED SIGNAL STRENGTH OF DIFFERENT PATHS

Path	AP height/m	AP and Laptop Distance/m								
		2.1	4.2	6.3	8.4	10.5	12.6	14.7	16.8	18.9
	0.75	53.08	-59.25	-59.67	-71.12	-72.18	-77.08	-77.08	-83.15	-89.32
	1.25	-51.99	-58.19	-58.57	-68.11	-69.17	-75.12	-76.14	-82.01	-88.95
L_1	1.75	-53.65	-60.17	-60.92	-72.25	-73.26	-78.34	-78.24	-83.16	-89.56
	2.25	-54.05	-61.58	-62.07	-73.04	-74.54	-79.75	-79.35	-84.25	-90.11
	2.75	-54.51	-60.17	-62.09	-74.11	-74.82	-78.99	-79.31	-85.04	-91.02
	0.75	-50.15	-51.01	-52.27	-54.12	-56.79	-57.53	-58.92	-60.12	-62.04
	1.25	-50.08	-50.48	-51.37	-53.09	-55.89	-57.38	-58.49	-59.89	-61.59
L_2	1.75	-50.17	-51.58	-52.54	-55.23	-56.56	-57.78	-60.28	-60.67	-62.87
	2.25	-50.25	-51.63	-52.98	-55.58	-57.02	-58.08	-60.45	-61.23	-63.07
	2.75	-50.34	-52.98	-53.95	-57.25	-60.23	-63.14	-63.95	-67.01	-69.78
	0.75	-52.07	-59.35	-60.57	-70.65	-71.85	-75.44	-76.32	-89.32	-82.33
	1.25	-51.09	-58.46	-58.39	-70.03	-71.23	-74.63	-75.19	-86.29	-81.38
L_3	1.75	-53.17	-60.13	-63.59	-71.43	-72.53	-77.26	-79.15	-89.83	-83.67
	2.25	-54.12	-61.23	-63.06	-74.58	-77.47	-78.01	-80.23	-90.05	-84.56
	2.75	-55.04	-61.09	-62.35	-73.97	-78.86	-79.05	-81.99	-91.17	-87.34

TABLE IV.
PACKET LOSS RATE OF DIFFERENT PATHS

PATH	AP HEIGHT/M	AP AND LAPTOP DISTANCE/M								
		2.1	4.2	6.3	8.4	10.5	12.6	14.7	16.8	18.9
	0.75	0	0	0	0	0	3	5	12	70
	1.25	0	0	0	0	0	0	3	10	62
	1.75	0	0	0	0	0	5	10	20	80
L_1	2.25	0	0	0	0	0	6	8	15	85
	2.75	0	0	0	0	0	5	7	50	91
	0.75	0	0	0	0	0	0	0	0	0
	1.25	0	0	0	0	0	0	0	0	0
L_2	1.75	0	0	0	0	0	0	0	0	0
	2.25	0	0	0	0	0	0	0	0	0
	2.75	0	0	0	0	0	0	0	0	0
	0.75	0	0	0	0	0	2	5	60	23
	1.25	0	0	0	0	0	3	7	55	22
L_3	1.75	0	0	0	0	0	5	9	65	40
	2.25	0	0	0	0	0	2	8	66	35
	2.75	0	0	0	0	0	3	7	70	41

But there are also exceptions, such as in L_3 path. When the distance between AP and laptop is 16.8m, the RSSI value in L_3 path is bigger than the one when the distance between them is 18.9m, which is because that the node at the distance of 18.9m is directly facing the stair head, so the wireless signal transmitted by AP can be reflected by the tiling walls, while the node at the distance of 16.8m is over against the walls that absorb the signal. In L_2 path, the RSSI at each node at each AP height is far smaller than that at the same distance, which is because that the L_2 path is on the stairs passage without barriers; thus the wireless signals transmitted by AP get little interference, which have high signal strength. In the test scheme, the four test nodes at the dormitories 107 and 108, and 109 and 110 were symmetrically distributed. Table 3 shows that there is small difference in RSSI value at each height of these four symmetrical nodes, which is because that, although it fits its surrounding building environment, the clothes hanging on the walls, the placement of furniture and the disturbance of the wireless router to the signal in dormitories during testing bring tiny difference at symmetrical nodes. The change features are not obvious in the different paths, at the same sending and receiving distance and different AP heights. This is because the student apartment's environment is relatively complex. Rooms, bathrooms and stairs have effects on the wireless signal transmitted by AP, and the metal ceilings at corridors, tiling floor, tiling walls will have an influence on the signal by absorbing, reflecting and diffracting.

2) Packet loss rate of Different Paths

It can be seen from Table 4 that, in L_1 path, the packet loss begins at different heights and at the distance of 12.6m of the sending and receiving nodes, and the packet loss rate at the distance of 18.9m of the sending and receiving nodes is over 10%. In L_2 path, because no barrier affects the wireless signal at corridors, no packet loses in the test nodes. In L_3 path, packet loses appear at the distance of 12.6m of the sending and receiving node, and raise above 10%, while reaching its maximum value at the distance of 16.8m, which is much severer than that at the distance of 18.9m. This is because the strength of signal at the distance of 18.9m of the sending and receiving node is bigger than that at the distance of 16.8m. It can be seen from the Table1 and Table4 that, the better the received signal strength of the laptop, the higher signal transmitted reliability and the better communication quality. The attenuation of signal strength in L_1 path and L_3 path at the distances of 16.8m and 18.9m is too big and the packet loss is over 10%, so that the laptop and AP can't communicate normally; thus it is appropriate to set an AP in three dormitories at one side while wiring.

3) Regression analysis of Different Paths

Keenan-Motley model was adopted to conduct regress analysis of RSSI in different paths and under different heights, and then the regression parameters of path loss model of the three paths under different heights were obtained, as shown in table 5.

TABLE V.
REGRESSION ANALYSIS OF DIFFERENT PATHS

Path	AP Height/m	n	K /dBM	R^2
L_1	0.75	3.6469	-37.046	0.9066
	1.25	3.6454	-35.54	0.8899
	1.75	3.6213	-38.133	0.9198
	2.25	3.6483	-38.901	0.9308
	2.75	3.7208	-38.366	0.9202
L_2	0.75	1.263	-44.067	0.9024
	1.25	1.1792	-44.726	0.903
	1.75	1.3385	-43.828	0.9
	2.25	1.3665	-43.854	0.9135
	2.75	2.0234	-40.917	0.9029
L_3	0.75	3.5724	-37.298	0.893
	1.25	3.5189	-36.556	0.9041
	1.75	3.6011	-38.458	0.9212
	2.25	3.6291	-39.588	0.9233
	2.75	3.8239	-38.597	0.9168

It can be known from table 5 that the biggest coefficient of determination is 0.9308, while the smallest is 0.8899. In the L_2 and L_3 transmission paths, the attenuation coefficient reaches the minimum at the height of 1.25m, while in the L_1 transmission path the attenuation coefficient reaches the minimum at the height of 1.75m.

Beside, all the paths reach the maximum when AP is at the height of 2.75m, the reason of which lies in that the suspended ceiling of aluminous gusset plate will exert a greater influence upon wireless signal when AP is at the height of 2.75m. Regression analysis was conducted of the L2 and L3 paths according to the analysis method of L1 path, so as to obtain the model of received AP wireless signal strength in student dorm be obtained by the formula (13):

$$P_R = \begin{cases} 0.36013h^3 - 18.94h^2 + 28.943h - 49.526 - \left(0.0569h^2 - 0.169h + 3.7496\right) lgd \left(L_1\right) \\ 0.9373h^3 - 3.1301h^2 + 2.9814h - 45.029 - \left(0.3857h^2 - 1.0085h + 1.8248\right) lgd \left(L_2\right) \\ 3.1767h^3 - 16.31h^2 + 24.089h - 47.499 - \left(0.1264h^2 - 0.3198 + 3.7384\right) lgd \left(L_3\right) \end{cases} \quad (13)$$

IV. CONCLUSION

(1) In student dorms, received signal strength indicator (RSSI) presents an overall attenuate trend with the increase of communication distance when AP is fixed; when RSSI attenuates to -75dBm, packet loss starts. Packet loss probability shows an increasing trend as communication distance increases with the node of bigger signal strength attenuation facing a more severe packet loss.

(2) Relation model among AP height, transmission distance and RSSI is constructed via fitting in the student dorms, the parameters K of which present a cubic polynomial relation with AP height h while attenuation coefficient n shows a quadratic polynomial relation with AP height h. The results of validation model demonstrate that the biggest determination coefficient is 0.917, and the smallest is 0.899, with root-mean-square error (RMSE) being in the range of 3.2943~4.093 dBm. The measured data fit well with the calculated values; thus the model can preferably predict RSSI.

(3) In different paths and under different heights, wireless signal transmission characteristics in student dorms conform with Keenan-Motley model with fitting parameters being between 0.8899~0.9308.

(4) The empirical formula (13) between signal strength and height is obtained.

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