

# INDOOR PROPAGATION MODELING AT 2.4 GHZ FOR IEEE 802.11 NETWORKS

Robert Akl and Dinesh Tummala  
Department of Computer Science and Engineering  
University of North Texas, Denton, Texas, 76207  
rakl@cse.unt.edu

Xinrong Li  
Department of Electrical Engineering  
University of North Texas, Denton, Texas, 76207  
xinrong@unt.edu

## ABSTRACT

The purpose of this study is to characterize the indoor channel for 802.11 wireless local area networks at 2.4 GHz frequency. This work presents a channel model based on measurements conducted in commonly found scenarios in buildings. These scenarios include closed corridor, open corridor, classroom, and computer lab. Path loss equations are determined using log-distance path loss model and log-normal shadowing. The Chi-square test statistic values for each access point are calculated to prove that the observed fading is a normal distribution at 5% significance level. A numerical analysis of measurements in each scenario was conducted and the study determined equations that describe path loss for each scenario.

## KEY WORDS

WiFi, Chi-square Statistic, Path Loss, Channel Modeling.

## 1 Introduction

Wireless Local Area Networks (WLANs) provide network services where it is difficult or too expensive to deploy a fixed infrastructure. WLANs can coexist with fixed infrastructure to provide mobility and flexibility to users. The primary WLAN standards are IEEE 802.11 [1] and Europe's HyperLAN [2]. The 802.11 protocol set, popularly known as Wi-Fi, includes wireless network standards that allow data transmission up to 54 Mbps [3]. WLANs operate mainly in an indoor environment.

In order to evaluate the effectiveness of coding and processing techniques for a given channel prior to construction, a model of the channel must be developed that adequately describes the environment. Such analysis reduces the cost of developing a complex system by reducing the amount of hardware required for evaluation of performance.

Indoor channels are highly dependent upon the placement of walls and partitions within the building. As placement of these walls and partitions dictates the signal path inside a building. In such cases, a model of the environment is a useful design tool in constructing a layout that leads to efficient communication strategies. To achieve this aim, a channel model of an indoor environment must be applied to various layout plans of offices which will lead to the characterization of design methodologies.

A channel model is useful in determining the mechanisms by which propagation in the indoor environment occurs, which in turn is useful in the development of a communication system. By examining the details of how a signal is propagated from the transmitter to the receiver for a number of experimental locations, a generic model may be developed that highlights the important characteristics of a given indoor environment. Generic models of indoor communications can then be applied to specific situations to describe the operation of a radio system, and may also be used to generate designs that are particularly suited to supporting radio communication systems.

The contributions of this work are two-folds. First, in order to build a model, extensive field strength measurements are carried out inside different buildings. Then, path loss exponents from Log-distance Path loss Model and standard deviations from Log-Normal Shadowing, which statistically describe the path loss models for a different Transmitter Receiver separations and scenarios, are determined. The Chi-square test statistic values for each access point are calculated to prove that the observed fading is a normal distribution at 5% significance level. Finally, a numerical analysis of the measurements in each scenario was conducted and the study determined equations that describe path loss for each scenario.

The remainder of this paper is organized as follows. In section 2, channel modeling and measurements are examined. Section 3 describes the statistical analysis required to measure the quality of the models developed in this study. Section 4 describes the experimental setup, the software and hardware used for measurements, and the propagation environment in which measurements are done. In section 5, numerical results of measurements conducted in each scenario are presented. Finally, the conclusions drawn from this paper are summarized in section 6.

## 2 Indoor Propagation Modeling

In the literature, there are numerous experimental and theoretical studies of indoor propagation [4–9]. These models tend to focus on a particular characteristic like temporal fading or inter-floor losses. This study aims at developing an indoor propagation model from measurements taken using 802.11 compliant access point and client adapters. The study focuses on generating different loss equations

for different scenarios in indoor environments. Using these equations, an accurate model can be developed to visualize the propagation phenomenon for different buildings with changing indoor environments.

In the empirical models, all environmental influences are implicitly taken into account regardless of whether they can be separately recognized. This is the main advantage of these models. Because deterministic models are based on the principles of physics they may be applied to different environments without affecting the accuracy. In practice, their implementation usually requires a huge database of environmental characteristics, which is sometimes either impractical or impossible to obtain. The algorithms used by deterministic models are usually very complex and lack computational efficiency. For that reason, the implementation of the deterministic models is commonly restricted to smaller areas of microcell or indoor environments.

Both theoretical and measurement based propagation models indicate that average received signal power decreases logarithmically with distance. Empirical models help in reducing computational complexity as well as increasing the accuracy of the predictions [10]. The empirical model used in this study is Log-distance Path Loss Model.

## 2.1 Log-distance Path Loss Model

In both indoor and outdoor environments the average large-scale path loss for an arbitrary Transmitter-Receiver (T-R) separation is expressed as a function of distance by using a path loss exponent,  $n$  [11]. This value of  $n$  depends on the specific propagation environment, i.e., type of construction material, architecture, and location within a building. Lowering the value of  $n$  lowers the signal loss. The values of  $n$  range from 1.2 (Waveguide effect) to 8 [10]. For example, in free space,  $n$  is equal to 2, and when obstructions are present,  $n$  will have a larger value.

## 2.2 Log-Normal Shadowing

Random shadowing effects occurring over a large number of measurement locations which have the same T-R separation, but different levels of clutter on the propagation path is referred to as Log-Normal Distribution [11]. This phenomenon is referred to as log-normal shadowing. Variations in environmental clutter at different locations having the same T-R separation is not accounted for by the log-distance path loss model alone. This leads to measured signals which are vastly different than the average value predicted by using the log-distance path loss model. To account for these variations, the average path loss  $PL(d)$  for a transmitter and receiver with separation  $d$  thus becomes

$$PL(\text{dB}) = PL(d_0) + 10 n \log \left( \frac{d}{d_0} \right) + X_\sigma, \quad (1)$$

where  $X_\sigma$  is a zero-mean Gaussian distributed random variable with standard deviation  $\sigma$ .

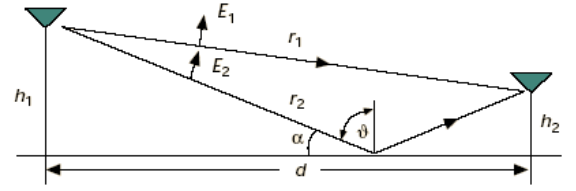


Figure 1. Two-Ray Model.

The close-in reference distance  $d_0$ , the path loss exponent  $n$ , and the standard deviation  $\sigma$ , statistically describe the path loss model for an arbitrary location having a specific T-R separation. This model can be used in computer simulation to provide received power levels for random locations in communication system design and analysis.

## 2.3 Two-Ray Model

The ray-tracing approach approximates the scattering of electromagnetic waves by simple reflection and refraction. The degree of transmission and reflection of a signal through and off an obstacle is related to the complex permittivities of the obstacle. One of the propagation models based on ray-optic theory is the Two-Ray model. Two-Ray model is used in this study because all the scenarios considered in this study have one reflecting surface, i.e., we have a direct path and reflected path. It is used for modeling of Line of Sight radio channel as shown in Figure 1. The transmitting antenna of height  $h_1$  and the receiving antenna of height  $h_2$  are placed at distance  $d$  from each other. The received signal  $P_r$  for isotropic antennas, obtained by summing the contribution from each ray, can be expressed as

$$P_r = P_t \left( \frac{\lambda}{4\pi} \right)^2 \left[ \frac{1}{r_1} e^{(-jkr_1)} + \Gamma(\alpha) \frac{1}{r_2} e^{(-jkr_2)} \right]^2, \quad (2)$$

where  $P_t$  is the transmitted power,  $r_1$  is the direct distance from the transmitter to the receiver,  $r_2$  is the distance through reflection on the ground, and  $\Gamma(\alpha)$  is the reflection coefficient depending on the angle of incidence  $\alpha$  and the polarization. The reflection coefficient is given by

$$\Gamma(\Theta) = \frac{\cos\Theta - a\sqrt{\epsilon_r - \sin^2\Theta}}{\cos\Theta + a\sqrt{\epsilon_r - \sin^2\Theta}}, \quad (3)$$

where  $\Theta = 90 - \alpha$  and  $a = 1/\epsilon$  or 1 for vertical or horizontal polarization, respectively.  $\epsilon_r$  is a relative dielectric constant of the reflected surface. The signal strengths from theoretical and empirical models are compared in this study.

### 3 Statistical Analysis

#### 3.1 Chi-square Goodness-of-Fit Test

When an analyst attempts to fit a statistical model to observed data, they may wonder how well the model actually reflects the data. How “close” are the observed values to those which would be expected under the fitted model? One statistical test that addresses this issue is the chi-square goodness-of-fit test. The chi-square test is used to test if a sample of data came from a population with a specific distribution. The chi-square goodness-of-fit test is applied to binned data. This is actually not a restriction since for non-binned data you can simply calculate a histogram or frequency table before generating the chi-square test. However, the value of the chi-square test statistic are dependent on how the data is binned.

The chi-square test is defined for the hypothesis:

$H_0$ : The data follow a specified distribution.

$H_a$ : The data do not follow the specified distribution.

Test Statistic: For the chi-square goodness-of-fit computation, the data is divided into  $k$  bins and the test statistic is defined as in

$$X^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}, \quad (4)$$

where  $O_i$  is the observed frequency for bin  $i$  and  $E_i$  is the expected frequency for bin  $i$ . Put simply if the computed test statistic  $X^2$  is large, then the observed and expected values are not close and the model is a poor fit to the data.

Before understanding how to reject or accept a hypothesis we need to understand two terms which help in this process.

**Degrees of Freedom:** The number of independent pieces of information that go into the estimate of a parameter is called the degrees of freedom ( $df$ ) [12]. In general, the degrees of freedom of an estimate is equal to the number of independent scores that go into the estimate minus the number of parameters estimated as intermediate steps or constraints in the estimation of the parameter itself. For example, if the variance,  $\sigma^2$ , is to be estimated from a random sample of  $N$  independent scores, then the degrees of freedom is equal to the number of independent scores ( $N$ ) minus the number of parameters estimated as intermediate steps (one, mean) and is therefore equal to  $N - 1$ .

In chi-square test statistic with  $k$  data bins, degrees of freedom can be calculated as the number of data bins  $k$  minus the number of constraints. For chi-square test statistic with  $k$  data bins the only constraint is the number of observed data points equal to the number of expected data points. Therefore,  $df$  for a chi-square test statistic with  $k$  data bins is equal to  $k - 1$ .

**Level of Significance or  $p$ -value:** The  $p$ -value or calculated probability is the estimated probability of rejecting the null hypothesis ( $H_0$ ) of a study question when that hypothesis is true [12]. The term significance level is used

to refer to a pre-chosen probability and the term “ $p$ -value” is used to indicate a probability that one calculates after a given study.

The smaller the  $p$ -value, the more strongly the test confirms the null hypothesis. A  $p$ -value of .05 or less confirms the null hypothesis “at the 5% level” that is, the statistical assumptions used imply that only 5% of the time would the supposed statistical process produce a finding this extreme if the null hypothesis were false. A  $p < 0.05$  is considered statistically significant and  $p < 0.001$  is considered statistically highly significant.

#### 3.2 Curve Fitting

Field data is often accompanied by noise. Even though all control parameters (independent variables) remain constant, the resultant outcomes (dependent variables) vary. A process of quantitatively estimating the trend of the outcomes, also known as regression or curve fitting, therefore becomes necessary.

The curve fitting process fits equations of approximating curves to the raw field data. Nevertheless, for a given set of data, the fitting curves of a given type are generally not unique. Thus, a curve with a minimal deviation from all data points is desired. This best-fitting curve can be obtained by the method of least squares.

For Log-distance Path Loss Model a linear least squares curve fitting is used. The least-squares line uses a straight line equation as shown below

$$Y = P_1X + P_2, \quad (5)$$

to approximate the given set of data,  $(x_1, y_1), (x_2, y_2), \dots, (x_n, y_n)$ , where  $n \geq 2$ . The best fitting curve  $f(x)$  has the least square error, i.e.,

$$\Pi = \sum_{i=1}^n [y_i - f(x_i)]^2 = \sum_{i=1}^n [y_i - (P_1x_i + P_2)]^2. \quad (6)$$

### 4 Experimental Setup

Four different scenarios are considered for measurements. The scenarios used will help in developing signal loss equations, by which a generalization for propagation in an indoor environment at 2.4 GHz can be obtained. The scenarios are described as follows:

- **Closed Corridor:** A closed corridor is used for signal measurements. This corridor is closed on both sides with walls. This corridor is 9' high and 8'7" wide. Signal measurements are taken at every five feet interval in the middle of the corridor.
- **Open corridor:** An open corridor is used for signal measurements. The corridor is open on one side and closed with a wall on the other side. This corridor is 12'5" high and 14'7" wide. Signal measurements are taken at every five feet interval in the middle of the corridor.

- Class room: A lecture room with furniture is considered for signal measurements. This room is 40' X 30' X 9'. Signal measurements are taken at every five feet interval diagonally across the room.
- Computer lab: A computer lab with furniture and computers is considered for signal measurements. This room is 45' X 30' X 9'. Signal measurements are taken at every five feet interval diagonally across the room.

The measurements are done using two separate access points. The access points are from different manufacturers. One is LinkSys [13], the other is D-Link [14]. Both access points are IEEE 802.11b compliant. The access points operate at 2.4 GHz and provide a bandwidth of 11 Mbps. A laptop attached with a wireless client adapter is used to measure the signal strength. The client adapter used is manufactured by LinkSys.

The signal measurements were done using the software NetStumbler [15] which is a tool for Windows that allows one to measure the signal level of WLANs using 802.11a, 802.11b or 802.11g. Using NetStumbler measurements were taken for the above described scenarios. In each scenario the signal strength was measured for both (LinkSys and D-Link) access points at regular increments of distance. At each interval signal measurements were taken by rotating the laptop twice along its axis.

## 5 Numerical Results

We present a detailed analysis of the steps required to extract and process the information from the raw measurement data for the closed corridor scenario:

1. Calculate the mean signal levels. Mean values of loss at each distance interval are calculated for both the access points (D-Link and LinkSys) versus T-R separation.
2. Using least squares method to calculate curve fitting. MATLAB curve fitting tool which is a graphical user interface tool is used to visually explore data and fits as scatter plots. A linear fit is calculated using least squares method. Figure 2 shows the linear curve fitting for the data collected using D-Link (AP1) access point.
3. Use curve fitting to evaluate path loss exponent  $n$ , in Log-distance Path Loss Model. From Figure 2 we get the slope of the curve to be 15.72 for D-Link and 15.8 for LinkSys (the figure is not shown for space constraints), the slope of the fitted curve is  $10n$ , i.e., calculated path loss exponents ( $n$ ) for D-link access point in closed corridor is 1.572.
4. Using Normal Plot, verify normal distribution. The loss differential, which is a measure of variation or

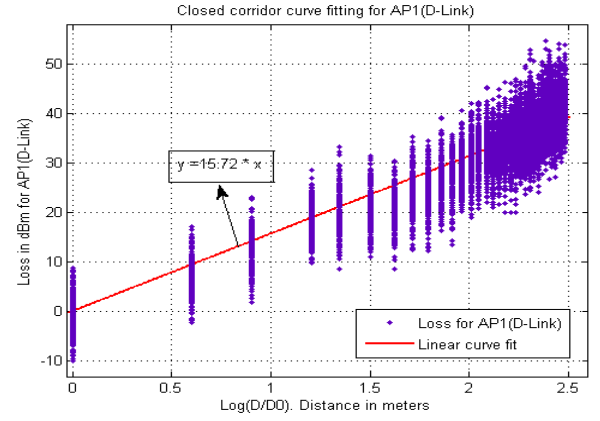


Figure 2. Closed corridor curve fitting for AP1 (D-Link).

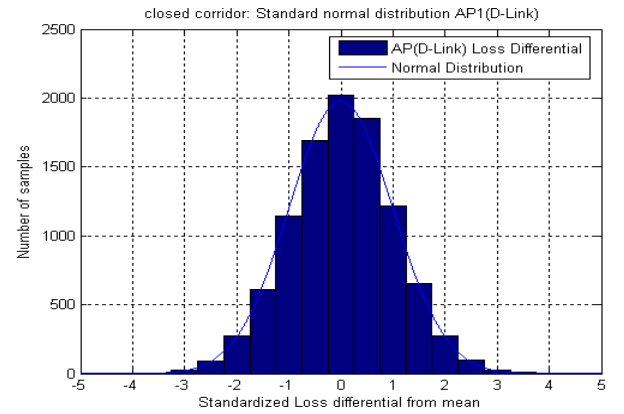


Figure 3. Closed corridor standard normal distribution for AP1 (D-Link).

scatter of loss compared to the mean value of loss calculated above, is determined. Normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally.

5. Evaluate standard deviation  $\sigma$ , for log-normal distribution, and determine standard normal distribution. Mean  $\mu$ , and standard deviation  $\sigma$  of loss differential is calculated for both access points. The mean is zero and the standard deviation for D-Link access point is 3.9849 and for LinkSys is 4.022. Figure 3 shows the plot for standard normal distributions for AP1.
6. Calculate Chi-square Goodness-of-Fit Test. Table 1 is used for calculating Chi-square test statistic  $X^2$  for AP1. To find the expected value for a particular bin, the area under standard normal curve (AUC) for the bin is multiplied by total observations. Chi-square statistic is calculated using (4). To evaluate if the distribution is normal the bins that are used to calculate  $X^2$  are from -3.25 to 3.25, a total of 13 bins. The degrees of freedom  $df = 13 - 1 = 12$ .

Table 1. Closed corridor  $X^2$  table for AP1 (D-Link).

| Bins               | AUC      | Obs * AUC  | Observed | Chi Stat  |
|--------------------|----------|------------|----------|-----------|
| -5.25 to -4.75     | 1.00E-06 | 0.010009   | 0        | 0.010009  |
| -4.75 to -4.25     | 1.00E-05 | 0.10009    | 0        | 0.10009   |
| -4.25 to -3.75     | 7.80E-05 | 0.7807     | 1        | 0.0616    |
| -3.75 to -3.25     | 0.000489 | 4.8944     | 6        | 0.24974   |
| -3.25 to -2.75     | 0.002403 | 24.052     | 23       | 0.045981  |
| -2.75 to -2.25     | 0.009245 | 92.533     | 91       | 0.025404  |
| -2.25 to -1.75     | 0.027835 | 278.6      | 277      | 0.0091947 |
| -1.75 to -1.25     | 0.065591 | 656.5      | 613      | 2.8824    |
| -1.25 to -0.75     | 0.12098  | 1210.9     | 1147     | 3.3688    |
| -0.75 to -0.25     | 0.17467  | 1748.2     | 1692     | 1.8087    |
| -0.25 to 0.25      | 0.19741  | 1975.9     | 2019     | 0.93984   |
| 0.25 to 0.75       | 0.17467  | 1748.2     | 1854     | 6.399     |
| 0.75 to 1.25       | 0.12098  | 1210.9     | 1215     | 0.014095  |
| 1.25 to 1.75       | 0.065591 | 656.5      | 654      | 9.52E-03  |
| 1.75 to 2.25       | 0.027835 | 278.6      | 277      | 0.0091947 |
| 2.25 to 2.75       | 0.009245 | 92.533     | 100      | 0.60252   |
| 2.75 to 3.25       | 0.002403 | 24.052     | 25       | 0.037395  |
| 3.25 to 3.75       | 0.000489 | 4.8944     | 13       | 13.424    |
| 3.75 to 4.25       | 7.80E-05 | 0.7807     | 2        | 1.9043    |
| 4.25 to 4.75       | 1.00E-05 | 0.10009    | 0        | 0.10009   |
| 4.75 to 5.25       | 1.00E-06 | 0.010009   | 0        | 0.010009  |
| Total Observations | -        | 10009.0404 | 10009    | -         |

The Chi-square statistic  $X^2$  for AP1 and AP2 (16.152 and 20.3699), our predetermined level of significance (0.05), and our degrees of freedom ( $df=12$ ). Finding the Chi-square distribution table with 12 degree of freedom and reading along the row we find our value of  $X^2$  for AP1 = 16.152, lies between 6.304 and 18.549. The corresponding probability is  $0.9 < p < 0.1$ . This is below the conventionally accepted significance level of 0.05 or 5%, so the null hypothesis that loss differential is normal is verified for AP1 (D-Link).

- Compare with two-ray model. A comparison is made between measured data and the two-ray model. Figure 4 shows the comparison between the theoretical two-ray model and measured data. It can be seen from the plot that signal deteriorates at a slightly faster rate in two-ray model than in actual measurements.

The above steps are repeated for each of the scenarios. The results are summarized below:

- For Open Corridor, Path loss exponent ( $n$ ) is 1.688 for AP1 and 1.63 for AP2. Standard deviation ( $\sigma$ ) is 3.5773 for AP1 and 3.2642 for AP2. The Chi-square test statistic ( $X^2$ ) values for both AP1 and AP2 (20.0012 for AP1 and 27.6687 for AP2) are acceptable values to prove that the observed fading is a normal distribution at 5% significance level. Figure 5 shows the comparison between the theoretical two-ray model and measured data.
- For Classroom, Path loss exponent ( $n$ ) is 1.258 for AP1 and 1.263 for AP2. Standard deviation ( $\sigma$ ) is 3.7607 for AP1 and 4.053 for AP2. The Chi-square test statistic ( $X^2$ ) values for both AP1 and AP2 (19.6687 for AP1 and 20.1618 for AP2) are acceptable

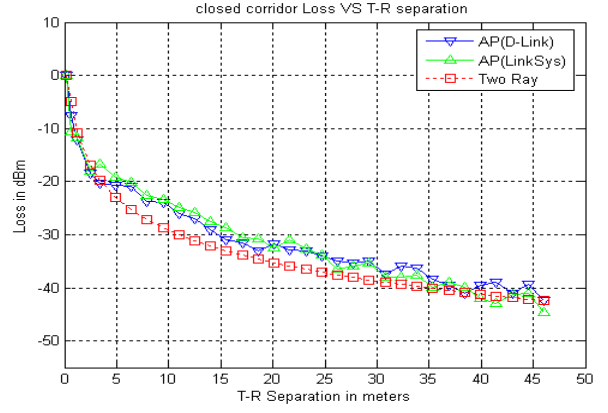


Figure 4. Comparison of closed corridor signal strength mean loss with two-ray model.

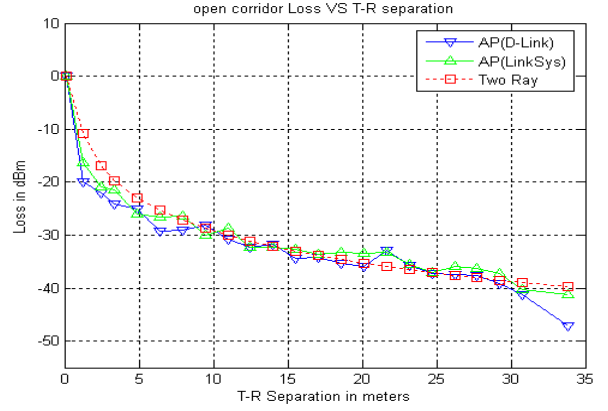


Figure 5. Comparison of open corridor signal strength mean loss with two-ray model.

values to prove that the observed fading is a normal distribution at 5% significance level. Figure 6 shows the comparison between the theoretical two-ray model and measured data.

- For Computer lab, Path loss exponent ( $n$ ) is 1.447 for AP1 and 1.428 for AP2. Standard deviation ( $\sigma$ ) is 3.7049 for AP1 and 3.846 for AP2. Now the Chi-square test statistic ( $X^2$ ) values for both AP1 and AP2 (15.7022 for AP1 and 18.1544 for AP2) are acceptable values to prove that the observed fading is a normal distribution at 5% significance level. Figure 7 shows the comparison between the theoretical two-ray model and measured data.

## 6 Conclusions

In this study indoor propagation models were developed for an a closed corridor, open corridor, a classroom, and a computer lab. Log-distance Path Loss Model and Log-Normal

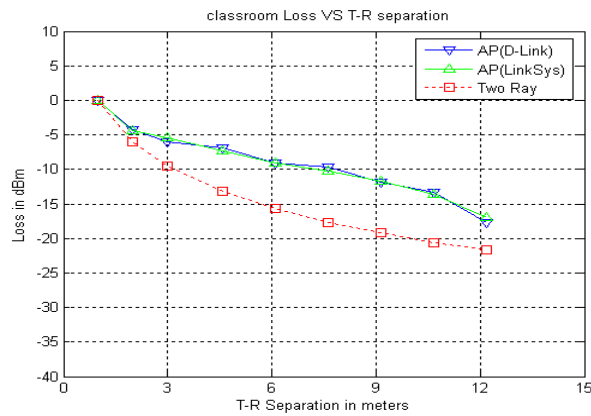


Figure 6. Comparison of classroom signal strength mean loss with two-ray model.

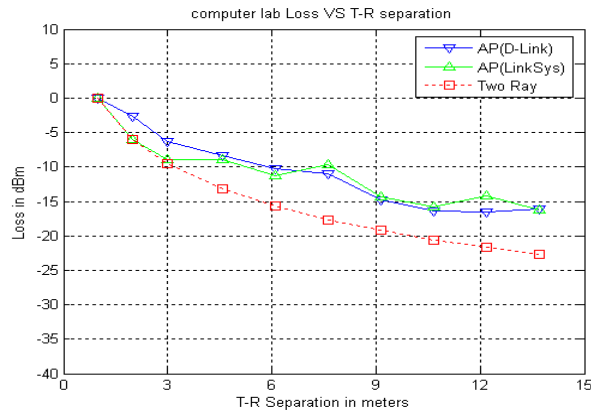


Figure 7. Comparison of computer lab signal strength mean loss with two-ray model.

Shadowing (Empirical model), and Two-Ray Model (Deterministic model) were used in determining path loss equations for different scenarios. A detailed description of the measurement scenarios, the experimental setup, the software, and the hardware used for measurements was presented. The Chi-square test statistic values for each access point were calculated to prove that the observed fading is a normal distribution at 5% significance level. A numerical analysis of measurements in each scenario was conducted and the study determined equations that describe path loss for each scenario.

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