INDOOR PROPAGATION MODELING AT 2.4 GHZ FOR IEEE 802.11 NETWORKS

Dinesh Tummala, B.S.

Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

December 2005

APPROVED:

Robert Akl, Major Professor
Albert B. Grubbs, Committee Member and Chair
  of the Department of Engineering
  Technology
Robert G. Hayes, Committee Member
Vijay Vaidyanathan, Committee Member
Oscar N. Garcia, Dean of the College of
  Engineering
Sandra L. Terrell, Dean of the Robert B. Toulouse
  School of Graduate Studies

Tummala, Dinesh. *Indoor Propagation Modeling at 2.4 GHz for IEEE 802.11 Networks*. Master of Science (Engineering Technology), December 2005, 109 pp., 18 tables, 80 figures, 47 titles.

Indoor use of wireless systems poses one of the biggest design challenges. It is difficult to predict the propagation of a radio frequency wave in an indoor environment. To assist in deploying the above systems, characterization of the indoor radio propagation channel is essential. The contributions of this work are two-folds. First, in order to build a model, extensive field strength measurements are carried out inside two 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 purpose of this study is to characterize the indoor channel for 802.11 wireless local area networks at 2.4 GHz frequency. This thesis 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. Finally, the propagation models from the two buildings are compared to validate the generated equations.

ACKNOWLEDGEMENTS

I express my gratitude of thanks to my major advisor and Chair of Department of Engineering Technology Dr. Albert B.Grubbs for his support, confidence, encouragement, and guidance throughout my graduate program and in completing this thesis. From the formative stages of this thesis, to the final draft, I am indebted to my supervisor, Dr. Robert Akl, whose expertise, understanding, and patience, added considerably to my graduate experience. I thank the members of my committee, Dr. Robert G. Hayes, and Dr. Vijay Vaidyanathan for the assistance, careful reading and suggestions they provided at all levels of the research project.

I would also like to thank my supervisors at work Mr. Ken Brinkley and Mr. Larry Guay for being supportive. I really appreciate the flexible work schedule you provided.

I would also like to thank my family for the support they provided me through my entire life and in particular, I must acknowledge my wife and best friend, Swathi, without whose love, encouragement and editing assistance, I would not have finished this thesis. Finally, but not least, I want to thank my parents Mr. Gopala Krishna and Mrs. Vijaya. Thanks for encouraging me to be an independent thinker, and having confidence in my abilities to go after new things that inspired me. Thanks Dad for taking time to work with me on my mathematics (You were the best mathematics teacher I ever had). Thanks for teaching me that it is important to try to leave the world just a little better than when you came into it. And, of course, thank you both for your constant support through the ups and downs of my academic career. It has been bumpy at times, but your confidence in me has enhanced my ability to get through it all and succeed in the end.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS ii

LIST OF TABLES v

LIST OF FIGURES vi

Chapters

1. INTRODUCTION 1
    - 1.1 Communication Systems 2
    - 1.2 Problem Statement and Objectives 3
    - 1.3 Research Questions 3
    - 1.4 Organization 4

2. INDOOR PROPAGATION MODELING 5
    - 2.1 Introduction 5
    - 2.2 Line of Sight Propagation 5
    - 2.3 Channel Modeling 8
    - 2.4 Propagation Models 8
    - 2.5 Empirical Models 9
        - 2.5.1 Log-Distance Path Loss Model 10
        - 2.5.2 Log-Normal Shadowing 10
    - 2.6 Two-Ray Model 11
    - 2.7 Indoor RF Propagation and Wireless Local Area Network Technology 13
    - 2.8 IEEE 802.11 Standard 15
    - 2.9 Frequency Range and Channel Allocation for 802.11b 16

3. STATISTICAL ANALYSIS 19
    - 3.1 Normal Plot 19
    - 3.2 Standard Normal Distribution 20
    - 3.3 Chi-square Goodness-of-Fit Test 20
    - 3.3.1 Deciding What Value of X2 is Critical for Accepting or Rejecting a Hypothesis 22

3.3.2 Finding p-Value for Chi-square Test 23
3.4 Curve Fitting 24

4. EXPERIMENTAL SETUP 27
4.1 Introduction 27
4.2 Propagation Environment 27
4.2.1 Description of Measurement Scenarios for Building One 31
4.2.2 Description of Measurement Scenarios for Building Two 34
4.3 Hardware and Software Description 34
4.4 Data Acquisition 36
4.5 Numerical Analysis 36

5. NUMERICAL ANALYSIS 38
5.1 Introduction 38
5.2 Analysis of Results 40
5.2.1 Scenario 1: Building One Closed Corridor 40
5.2.2 Scenario 2: Building One Open Corridor 50
5.2.3 Scenario 3: Building One Classroom 59
5.2.4 Scenario 4: Building One Computer Lab 71
5.3 Summary of Results 80

6. COMPARISON WITH SIMILAR SCENARIOS 83
6.1 Introduction 83
6.2 Scenario 1: Building Two Closed Corridor 83
6.3 Scenario 2: Building Two Classroom 93
6.4 Summary 103
6.5 Conclusion 105
6.6 Future Work 106

BIBLIOGRAPHY 107

LIST OF TABLES

Page

2.1 Path loss exponents for different environments [1] 11

2.2 Frequency and channel assignments 17

3.1 Area under the normal curve from 0 to X 21

3.2 Critical values of chi-square distribution with degrees of freedom 25

5.1 Closed corridor X2 table for AP1 (D-Link) 46

5.2 Closed corridor X2 table for AP2 (LinkSys) 47

5.3 Open corridor X2 table for AP1 (D-Link) 57

5.4 Open corridor X2 table for AP2 (LinkSys) 58

5.5 Classroom X2 table for AP1 (D-Link) 67

5.6 Classroom X2 table for AP2 (LinkSys) 68

5.7 Computer lab X2 table for AP1 (D-Link) 77

5.8 Computer lab X2 table for AP2 (LinkSys) 78

6.1 Closed corridor X2 table for AP1 (D-Link) 90

6.2 Closed corridor X2 table for AP2 (LinkSys) 91

6.3 Closed corridor results from Building One and Building Two 92

6.4 Classroom X2 table for AP1 (D-Link) 100

6.5 Classroom X2 table for AP2 (LinkSys) 101

6.6 Classroom results from Building One and Building Two 103

LIST OF FIGURES

Page

1.1 Basic communication system 2

2.1 Two-ray model 13

2.2 802.11b channel overlap 18

4.1 College of Engineering, first floor overview 28

4.2 College of Engineering, second floor overview 29

4.3 College of Engineering, second floor detail 30

4.4 Building One closed corridor 31

4.5 Building One open corridor 32

4.6 Building One classroom 33

4.7 Building One computer lab 33

4.8 Building Two closed corridor 35

4.9 Building Two classroom 35

5.1 Numerical analysis 39

5.2 Building One, closed corridor loss for AP1 (D-Link) 40

5.3 Building One, closed corridor loss for AP2 (LinkSys) 41

5.4 Building One, closed corridor mean loss for AP1 and AP2 42

5.5 Building One, closed corridor curve fitting for AP1 (D-Link) 43

5.6 Building One, closed corridor curve fitting for AP2 (LinkSys) 43

5.7 Building One, closed corridor normal probability plot for AP1 (D-Link) 44

5.8 Building One, closed corridor normal probability plot for AP2 (LinkSys) 45

5.9 Building One, closed corridor standard normal distribution for AP1 (D-Link) 45

5.10 Building One, closed corridor standard normal distribution for AP2 (LinkSys) 48

5.11 Comparison of closed corridor mean loss with two-ray model 49

5.12 Comparison of closed corridor AP1 and AP2 loss with mean signal and two-ray model 50

5.13 Building One, open corridor loss for AP1 (D-Link) 51

5.14 Building One, open corridor loss for AP2 (LinkSys) 51

5.15 Building One, open corridor mean loss for AP1 and AP2 52

5.16 Building One, open corridor curve fitting for AP1 (D-Link) 53

5.17 Building One, open corridor curve fitting for AP2 (LinkSys) 54

5.18 Building One, open corridor normal probability plot for AP1 (D-Link) 54

5.19 Building One, open corridor normal probability plot for AP2 (LinkSys) 55

5.20 Building One, open corridor standard normal distribution for AP1 (D-Link) 56

5.21 Building One, open corridor standard normal distribution for AP2 (LinkSys) 56

5.22 Comparison of open corridor mean loss with two-ray model 60

5.23 Comparison of open corridor AP1 and AP2 loss with mean signal and two-ray model 60

5.24 Building One, classroom loss for AP1 (D-Link) 61

5.25 Building One, classroom loss for AP2 (LinkSys) 61

5.26 Building One, classroom mean loss for AP1 and AP2 62

5.27 Building One, classroom curve fitting for AP1 (D-Link) 63

5.28 Building One, classroom curve fitting for AP2 (LinkSys) 64

5.29 Building One, classroom normal probability plot for AP1 (D-Link) 65

5.30 Building One, classroom normal probability plot for AP2 (LinkSys) 65

5.31 Building One, classroom standard normal distribution for AP1 (D-Link) 66

5.32 Building One, classroom standard normal distribution for AP2 (LinkSys) 66

5.33 Comparison of classroom mean loss with two ray-model 70

5.34 Comparison of classroom AP1 and AP2 loss with mean signal and two-ray model 70

5.35 Building One, computer lab loss for AP1 (D-Link) 71

5.36 Building One, computer lab loss for AP2 (LinkSys) 72

5.37 Building One, computer lab mean loss for AP1 and AP2 72

5.38 Building One, computer lab curve fitting for AP1 (D-Link) 74

5.39 Building One, computer lab curve fitting for AP2 (LinkSys) 74

5.40 Building One, computer lab normal probability plot for AP1 (D-Link) 75

5.41 Building One, computer lab normal probability plot for AP2 (LinkSys) 76

5.42 Building One, computer lab standard normal distribution for AP1 (D-Link) 76

5.43 Building One, computer lab standard normal distribution for AP2 (LinkSys) 79

5.44 Comparison of computer lab mean loss with two ray model 80

5.45 Comparison of computer lab AP1 and AP2 loss with mean signal and two ray model 81

5.46 Results at a glance 82

6.1 Building Two, closed corridor loss for AP1 (D-Link) 84

6.2 Building Two, closed corridor loss for AP2 (LinkSys) 84

6.3 Building Two, closed corridor mean loss for AP1 and AP2 85

6.4 Building Two, closed corridor curve fitting for AP1 (D-Link) 86

6.5 Building Two, closed corridor curve fitting for AP2 (LinkSys) 87

6.6 Building Two, closed corridor normal probability plot for AP1 (D-Link) 88

6.7 Building Two, closed corridor normal probability plot for AP2 (LinkSys) 88

6.8 Building Two, closed corridor standard normal distribution for AP1 (D-Link) 89

6.9 Building Two, closed corridor standard normal distribution for AP2 (LinkSys) 89

6.10 Comparison of closed corridor mean loss with two-ray model 93

6.11 Comparison of closed corridor AP1 and AP2 loss with mean signal and two-ray model 94

6.12 Building Two, classroom loss for AP1 (D-Link) 94

6.13 Building Two, classroom loss for AP2 (LinkSys) 95

6.14 Building Two, classroom mean loss for AP1 and AP2 96
6.15 Building Two, classroom curve fitting for AP1 (D-Link) 97
6.16 Building Two, classroom curve fitting for AP2 (LinkSys) 97
6.17 Building Two, classroom normal probability plot for AP1 (D-Link) 98
6.18 Building Two, classroom normal probability plot for AP2 (LinkSys) 99
6.19 Building Two, classroom standard normal distribution for AP1 (D-Link) 99
6.20 Building Two, classroom standard normal distribution for AP2 (LinkSys) 102
6.21 Comparison of classroom mean loss with two-ray model 104
6.22 Comparison of classroom AP1 and AP2 loss with mean signal and two-ray model 104

CHAPTER 1

INTRODUCTION

Wireless communication is one of the most active areas of technology development of our time. This development is being driven primarily by the transformation of what has been largely a medium for supporting voice telephony into a medium for supporting other services, such as the transmission of video, images, text, and data. Thus, similar to the developments in wireline capacity in the 1990s, the demand for new wireless capacity is growing at a very rapid pace.

The impact of wireless technology has been and will continue to be profound. The convergence of different standards that define how wireless devices interact will allow the creation of a global wireless network that will deliver a wide variety of services. Cellular phones are currently the most obvious sign of the advent of wireless technology, but mobile telephones are only the tip of the cellular revolution. The first rush to wireless was for voice. Now, the attention is on data. Presently, there are many types of wireless networks in use around the world. Most new devices have access to the internet. A big part of this market is the wireless internet. The Internet is increasingly becoming a multimedia experience. For wireless networks to compete with their fixed counterparts, wireless networks need to obtain higher data rates [2].

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 [3] and Europe's HyperLAN [4]. The 802.11 protocol set, popularly known as Wi-Fi, includes wireless network standards that allow data transmission up to a theoretical 54 Mbps [5].

WLANs operate mainly in a indoor environment. It is very difficult to predict how a

Figure 1.1: Basic communication system.

RF wave travels in an indoor environment. So there is a need for developing an indoor propagation model to predict RF wave behavior more accurately.

1.1 Communication Systems

Any communication system can be viewed as a link between a source and a destination where information is sent from the source and received at the destination. The intervening stages are shown in Figure 1.1. The transmitter takes the information from the source and codes it in a form suitable for transfer over the channel such that the cost of transmission is minimal. In this context, cost is a function of the bandwidth used, the time taken to perform the communication, the degree to which the transmission interferes with other transmissions occurring simultaneously and the amount of information that is lost in the communication process. The channel is a description of how the communications medium alters the signal that is being transmitted. Finally the receiver takes the signals that have been altered by the channel, and attempts to recover the information that was sent by the source. This recovered signal is passed to the destination as the received information.

For a radio communication system, the channel describes how the electromagnetic propagation of a transmitted signal provides that signal at the receiver. In a mobile communication system, the channel changes according to the movement of the communicating entities and other objects that have an effect on the electromagnetic fields at the receiver. The purpose of this study is to characterize the indoor channel for 802.11b wireless local area networks at 2.4 GHz frequency [6].

1.2 Problem Statement and Objectives

WLANs are rapidly gaining popularity. These networks are primarily targeted for indoor use, and are most often based on either the IEEE 802.11 Ethernet-type protocols or the Bluetooth Special Interest Group (SIG), both using the unlicensed bands at 2.4 to 2.5 GHz, IEEE 802.11b [6] and Bluetooth [7]), or at 5.15 to 5.85 GHz, IEEE 802.11a [8]. The European HiperLAN standard is also designed for operation around 5.2 to 5.8 GHz [4].

Indoor use of wireless systems poses one of the biggest design challenges. It is difficult to predict the propagation of a RF wave in an indoor environment [9][10]. To assist in deploying the above systems, characterization of the indoor radio propagation channel is essential.

The proposed innovation characterizes the indoor channel by developing a propagation model at 2.4 GHz for different scenarios commonly found in buildings. By using this propagation model, network analysis and simulation can be developed. This will facilitate faster and more efficient deployment of wireless networks.

1.3 Research Questions

The research questions addressed in this study are stated below for hypotheses testing.

1. Is multipath fading observed in indoor radio propagation at 2.4 GHz distributed normally?

    - **Null Hypotheses:**

      Multipath fading observed in indoor radio propagation at 2.4 GHz is not a normal distribution.

    - **Alternative Hypotheses:**

      Multipath fading observed in indoor radio propagation at 2.4 GHz is a normal distribution.

Normal probability plot and Chi-square Goodness of fit tests are used to verify the above hypotheses.

2. Does indoor radio propagation at 2.4 GHz depend on the indoor environment? Indoor environment or indoor channel consists of hard and soft partitions (Section 2.7).

    - **Null Hypotheses:**

      Indoor radio propagation at 2.4 GHz is not dependent on the indoor environment.

    - **Alternative Hypotheses:**

      Indoor radio propagation at 2.4 GHz is dependent on the indoor environment.

1.4 Organization

This thesis creates a model of an indoor propagation channel at 2.4 GHz for different scenarios commonly found in buildings. The remainder of this work consists of the following chapters.

Chapter 2 reviews the published work that has been conducted in the field of channel measurement and modeling. Concepts in channel modeling and measurements are examined.

Chapter 3 describes the statistical analysis required to measure the quality of the models developed in this study.

Chapter 4 describes the experimental setup, the software and hardware used for measurements, and the propagation environment in which measurements are done. A detailed description of each measurement scenario is discussed.

Chapter 5 does a numerical analysis of measurements conducted in each scenario. The study determines equations that describe path loss for each scenario.

Chapter 6 compares the measurements from scenarios in different buildings and compares them to measurements from similar scenarios in Chapter 5. Conclusions and possible direction of future work in this field are also presented.

CHAPTER 2

INDOOR PROPAGATION MODELING

2.1 Introduction

A signal radiated from an antenna travels along one of the three routes: ground wave, sky wave, or line of sight (LOS). Based on the operating frequency range, one of the three predominates. LOS propagation is the mode of propagation which is of interest in this paper.

2.2 Line of Sight Propagation

At frequencies higher than 30 MHz, LOS is the dominant propagation mode. The ionosphere reflects less of the signal as the frequency is increased beyond 30 MHz. A signal can thus be transmitted either to a satellite or to a receiving antenna which is in the line of sight of the transmitting antenna.

In a communication system, a received signal will differ from the transmitted signal due to various transmission impairments. The most significant transmission impairments for LOS transmission are [2]:

- Attenuation: The strength of a signal falls off with distance over any transmission medium. This reduction in strength or attenuation is logarithmic for guided media. Whereas attenuation is a more complex function of distance and the makeup of the atmosphere for an unguided media.

- Free space loss: In any wireless communication, the signal disperses with distance. A receiving antenna will receive less signal power the farther it is from the transmitting antenna. Assuming all the sources of impairments are nullified the transmitted signal attenuates over distance because the signal is being spread over a larger and larger area. This form of attenuation is known as free space loss.

- Fading: Fading refers to the time variation of received signal power caused by changes in the transmission medium or path. Fading is the most challenging technical problem in designing a communication system. In a fixed environment, fading is affected by changes in atmospheric conditions. Whereas in a mobile environment where either the receiving or transmitting antenna is in motion relative to the other, the relative location of various obstacles changes with time, causing complex transmission effects.

- Multipath: Multipath is defined as a propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. The direct and reflected signals are often opposite in phase, which can result in a significant signal loss due to mutual cancelation in some circumstances. Depending on the differences in the path lengths of direct and reflected waves, the composite signal can be either larger or smaller than the direct signal. Multipath is most troublesome indoors and in areas where many metallic surfaces are present. Multipath is caused by the following propagation mechanisms:

  - Reflection: Reflection occurs when a propagating electromagnetic wave impinges upon an object which has very large dimensions when compared to the wavelength of the propagating wave. Reflections occur from the surface of the earth and from buildings and walls. The reflected waves may interfere constructively or destructively at the receiver.

  - Diffraction: Diffraction occurs when the radio path between the transmitter and receiver is obstructed by a surface that is large compared to the wavelength of the radio wave. The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacle, giving rise to a bending of waves around the obstacle, even when a line-of-sight path does not exist between transmitter and receiver.

  - Scattering: Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, and where the number of obstacles per unit volume is large. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel.

  These three propagation effects influence system performance in various ways depending on local conditions and as a mobile unit moves through the medium. Diffraction and scattering are generally minor effects if there is a clear LOS between transmitter and receiver although reflection may have a significant impact. In cases where there is no LOS, diffraction and scattering are the primary means of signal reception.

- Refraction: Refraction is defined as a change in direction of an electromagnetic wave resulting from changes in the velocity of propagation of the medium through which it passes. This may result in a situation in which only a fraction or no part of the line of sight wave reaches the receiving antenna.

- Noise: In any transmission event, a received signal will consist of the transmitted signal, modified by various distortions imposed by the transmission medium, plus additional unwanted signals that are inserted by the medium. These unwanted signals are referred to as noise or interference. Noise is the major limiting factor in any communications system performance.

- Atmospheric absorption: Atmospheric absorption is an additional loss due to the presence of different atmospheric elements such as water vapor and oxygen etc. A peak attenuation occurs in the vicinity of 22 GHz due to water vapor. At frequencies below 15 GHz, the attenuation is less.

2.3 Channel Modeling

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 building designs that are particularly suited to supporting radio communication systems.

2.4 Propagation Models

In the literature, there are numerous experimental and theoretical studies of indoor propagation [11][12][13][14][15][16][10]. 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 802.11b 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.

A propagation model is a set of mathematical expressions,diagrams, and algorithms used to represent the radio characteristics of a given environment [17]. The prediction models can be either empirical (also called statistical) or theoretical (also called deterministic), or a combination of these two. While the empirical models are based on measurements, the theoretical models deal with the fundamental principles of radio wave propagation phenomena.

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.

On the basis of the radio environment, the prediction models can be classified into two main categories, outdoor and indoor propagation models. Further, in respect to the size of the coverage area, the outdoor propagation models can be subdivided into two additional classes, macrocell and microcell prediction models. A discussion of one empirical and one theoretical model used in this study is presented in the following sections.

2.5 Empirical Models

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 [17]. The empirical model used in this study is Log-distance Path Loss Model.

2.5.1 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 [1]. The average path loss PL(d) for a transmitter and receiver with separation d is:

$$PL(d) \ \propto \ \left(\frac{d}{d_0}\right)^n, \tag{2.1}$$

or

$$PL(\mathrm{dB}) \ = \ PL(d_0) \ + \ 10 \ n \ \log \left(\frac{d}{d_0}\right), \tag{2.2}$$

where n is the path loss exponent which indicates the rate at which path loss increases with distance d. Close in reference distance (d_0) is determined from measurements close to the transmitter. The plot for distance d versus path loss PL on a log-log scale is a straight line with a slope equal to $10n$. This value of n depends on the specific propagation environment, i.e., type of construction material, architecture, location within building. Lower the value of n lower the signal loss. The values of n range from 1.2 (Waveguide effect) to 6 [17]. For example, in free space, n is equal to 2, and when obstructions are present, n will have a larger value. Table 2.1 lists typical path loss exponents obtained in various radio environments.

2.5.2 Log-Normal Shadowing

Random shadowing effects occuring 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 [1]. This phenomenon is referred to as log-normal

Table 2.1: Path loss exponents for different environments [1].

Environment	Path Loss Exponent, n
Free Space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

shadowing. Variations in environmental clutter at different locations having the same T-R separation is not accounted for in equation (2.2). This leads to measured signals which are vastly different than the average value predicted by (2.2). To account for the variations described above equation (2.2) is modified as:

$$PL(\mathrm{dB}) \;=\; PL(d_0) \;+\; 10\;n\;\log\left(\frac{d}{d_0}\right) + X_\sigma, \tag{2.3}$$

where X_σ is a zero-mean Gaussian distributed random variable with standard deviation σ.

The close-in reference distance d_0, the path loss exponent n, and the standard deviation σ, 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.

2.6 Two-Ray Model

Site specific propagation models are based on electromagnetic-wave propagation theory to characterize indoor radio propagation. Unlike statistical models, site specific propagation models do not rely on extensive measurement, but a greater detail of the indoor environment is required to obtain an accurate prediction of signal propagation inside a building.

In theory, electromagnetic-wave propagation characteristics could be exactly computed by solving Maxwell's equations with the building geometry as boundary conditions. Unfortunately, this approach requires very complex mathematical operations and requires considerable computing power, beyond that of current microcomputers. Hence it is not economical for the characterization of indoor radio wave propagation. Therefore, approximate numerical methods are of interest. Ray tracing is an intuitively appealing method for calculating radio signal strength, time-invariant impulse response, root mean square (RMS) delay spread and related parameters in an indoor environment [18][19][20][21].

The concept of ray-tracing modeling is based on the fact that high-frequency radio waves behave in a ray-like fashion. Therefore, signal propagation can be modeled as ray propagation. By using the concept of ray-tracing, rays may be launched from a transmitter location and the interaction of the rays with partitions within a building modeled using well-known reflection and transmission theory.

Ray tracing can be much less demanding of computation than methods based on Maxwell's equations. With the computing powers currently available on personal computers and workstations, the ray-tracing approach provides a challenging but feasible method of propagation modeling. Reliable site specific ray-tracing propagation prediction models, for each building that is based on its detailed geometry and construction, can be very effective tools in designing indoor communication systems.

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 a 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 2.1. The transmitting antenna of height h_1 and the receiving antenna of

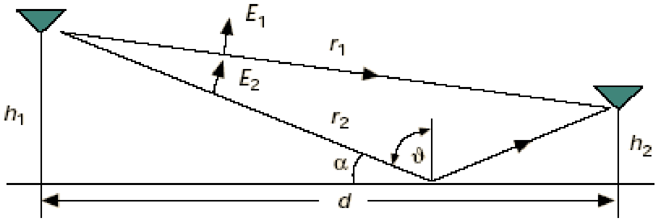


Figure 2.1: Two-Ray Model.

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

$$P_r \;=\; P_t \left(\frac{\lambda}{4\pi}\right) \left[\frac{1}{r_1}\, e^{(-jkr_1)} \;+ \Gamma(\alpha)\frac{1}{r_2}\, e^{(-jkr_2)}\right]^2 \quad , \tag{2.4}$$

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 α and the polarization.

The reflection coefficient is given by

$$\Gamma(\Theta) \;=\; \frac{cos\Theta \;-\; a\sqrt{\epsilon_r \;-\; sin^2\Theta}}{cos\Theta \;+\; a\sqrt{\epsilon_r \;-\; sin^2\Theta}} \ , \tag{2.5}$$

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

2.7 Indoor RF Propagation and Wireless Local Area Network Technology

Indoor use of wireless systems poses one of the biggest design challenges. RF propagation obstacles can be termed hard partitions if they are part of the physical or structural components of a building. On the other hand, obstacles formed by office furniture and fixed or movable structures that do not extend to a buildings ceiling are considered soft partitions. Radio signals effectively penetrate both kinds of obstacles or partitions in ways that are very hard to predict. An indoor propagation model is needed to predict the propagation of a transmitted signal in this environment.

WLANs are implemented as an extension to wired LANs within a building and can provide the final few meters of connectivity between a wired network and the mobile user.

WLAN configurations vary from simple, independent, peer-to-peer connections between a set of PCs, to more complex, intra-building infrastructure networks. There are also point-to-point and point-to-multipoint wireless solutions. A point-to-point solution is used to bridge two local area networks, and to provide an alternative to cable between two geographically distant locations (up to 30 miles). Point-to-multi-point solutions connect several, separate locations to one single location or building. Both point-to-point and point-to-multipoint can be based on the 802.11b standard or on more costly infrared-based solutions that can provide throughput rates up to 622 Mbps. In a typical WLAN infrastructure configuration, there are two basic components:

- Access Points: An access point or a base station connects to a LAN by means of Ethernet cable. Usually installed in the ceiling, access points receive, buffer, and transmit data between the WLAN and the wired network infrastructure. A single access point supports on average twenty users and has a coverage varying from 20 meters in areas with obstacles (walls, stairways, elevators) up to 100 meters in areas with clear line of sight. A building may require several access points to provide complete coverage and allow users to roam seamlessly between access points.
- Wireless Client Adapter: A wireless adapter connects users via an access point to the rest of the LAN. A wireless adapter can be a PC card in a laptop, an ISA or PCI adapter in a desktop computer, or fully integrated within a handheld device.

2.8 IEEE 802.11 Standard

IEEE 802.11 is a family of specifications for WLANs developed by the Institute of Electrical and Electronics Engineers. The 802.11 standard specifies parameters for both the physical and medium access control (MAC) layers of a WLAN [3]. The physical layer handles the transmission of data between nodes. The MAC layer consists of protocols responsible for maintaining the use of the shared medium. Work on 802.11 began in 1987 within the IEEE 802.4 group.

There are three physical layers for WLANs: two radio frequency specifications (RF - direct sequence and frequency hopping spread spectrum) and one infrared. Most WLANs operate in the 2.4 GHz license-free frequency band and have throughput rates up to 2 Mbps.

There are various versions of the 802.11 standard. A brief description of the more popular revisions is given below.

- 802.11a: 802.11a operates at radio frequencies between 5 GHz and 6 GHz [8]. The modulation scheme used is orthogonal frequency-division multiplexing (OFDM). OFDM, also called multicarrier modulation, uses multiple carrier signals at different frequencies, sending some of the bits on each channel. This is similar to Frequency Division Multiplexing (FDM). The only difference between FDM and OFDM is that in OFDM all the sub-channels are dedicated to a single data source.

  The data rates vary based on the noise level, distance from the transmitting antenna, and the propagation environment. Possible data rates for 802.11a are 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. Maximum range for this standard is 200 feet.

- 802.11b: 802.11b often called Wi-Fi, being the most popular of all the standards, operates in the 2.4 GHz frequency [6]. It is an extension of the 802.11 standard. Typical data rates for 802.11b are 5.5 and 11 Mbps. The modulation scheme used is Direct Sequence Spread Spectrum. The chipping rate is 11 MHz, the same as in

802.11, providing the same occupied bandwidth.

Although the data rates are slower than 802.11a, the range is higher, up to 300 feet. The frequency band used (2.4 GHz) can have significant interference problems from such devices as microwave, cordless phones, and Bluetooth devices.

- 802.11g: 802.11g is the newest member of the 802.11 family. This standard combines the best of 802.11a and 802.11b. Like 802.11b, 802.11g operates in the 2.4 GHz frequency and can achieve ranges up to 300 feet, but like 802.11a, it reaches speeds up to 54 Mbps. 802.11g uses a hybrid complementary code keying OFDM modulation [5].

- 802.11i: 802.11b uses Wired Equivalent Privacy (WEP) protocol to address security concerns. WEP itself is more or less an implementation of encryption with built-in message authentication and data integrity systems. The sheer number and variety of vulnerabilities discovered within WEP shows what could arise when security is not designed from the ground up. The future of wireless LAN security is currently being entrusted to 802.11i [22] [23]. IEEE is developing this wireless LAN standard, which focuses strictly on security and improving upon the protocols offered by the previous 802.11 standards. There are three main areas that the IEEE 802.11i wants to improve on over 802.11b: 1) authentication, 2) key management and 3) data transfer. All of these areas were severely lacking in WEP.

2.9 Frequency Range and Channel Allocation for 802.11b

As mentioned above, 802.11b networks operate in the ultra high frequency band, specifically between 2.4 and 2.5 GHz. Transmission does not take place at a single frequency. There are a total of fourteen channels for use, and the modulation technique spreads the transmission over multiple channels for effective use of the frequency spectrum. Table 2.2 gives the frequency of each channel [24]. The United States uses channels 1-11, Europe uses channels

Table 2.2: Frequency and channel assignments.

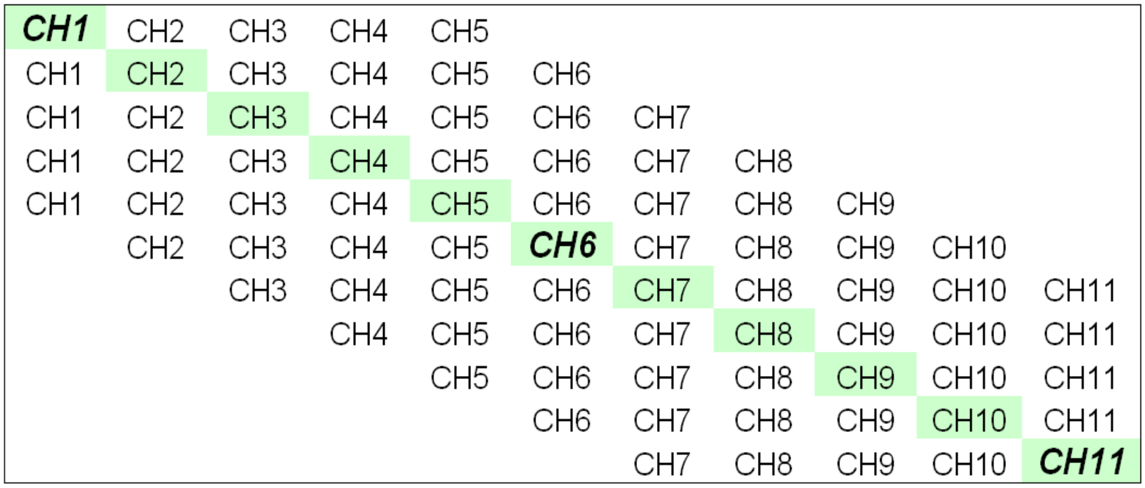
CHANNEL	FREQUENCY	CHANNEL	FREQUENCY
1	2.412 GHz	8	2.447 GHz
2	2.417 GHz	9	2.452 GHz
3	2.422 GHz	10	2.457 GHz
4	2.427 GHz	11	2.462 GHz
5	2.432 GHz	12	2.467 GHz
6	2.437 GHz	13	2.472 GHz
7	2.442 GHz	14	2.484 GHz

1-13, and Japan uses channels 1-14.

Interference is maximum between any two adjacent channels. For instance, data transmission and the effect of interference due to adjacent channels can be compared to conversations happening in 11 rooms. Each room has people having different conversations. People in room one can hear the conversations in rooms one, two, three, four, and five.

People in room six can hear the conversations of rooms two through ten, but cannot hear anything from rooms one and eleven. People in room eleven can hear the conversations of rooms seven, eight, nine, and ten. For people to have noise free conversations they should be in rooms one, six, and eleven.

In 802.11b, there are only three non-overlapping channels, channels one, six, and eleven as shown in Figure 2.2.



CH1	CH2	CH3	CH4	CH5						
CH1	CH2	CH3	CH4	CH5	CH6					
CH1	CH2	CH3	CH4	CH5	CH6	CH7				
CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8			
CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9		
	CH2	CH3	CH4	CH5	**CH6**	CH7	CH8	CH9	CH10	
		CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
			CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
				CH5	CH6	CH7	CH8	CH9	CH10	CH11
					CH6	CH7	CH8	CH9	CH10	CH11
						CH7	CH8	CH9	CH10	**CH11**

Figure 2.2: 802.11b channel overlap.

CHAPTER 3

STATISTICAL ANALYSIS

3.1 Normal Plot

A normal probability plot is a useful graph for assessing whether data comes from a normal distribution. Many statistical procedures make the assumption that the underlying distribution of the data is normal, so this plot can provide some assurance that the assumption of normality is not being violated. Normal plot is a scatterplot of the percentiles of the data versus the percentiles of a population having the normal distribution. If the data comes from a normal population, the resulting points should fall closely along a straight line. If the observations fall along a relatively straight line (using the so-called "fat pencil" test), then the data is probably normal [25][26]. To further confirm if the distribution is normal a goodness of fit test can be used.

These plots are produced by using following steps[26]:

1. The observations are ranked from smallest to largest, x_1, x_2, ...x_n.
2. The ordered observations x_j are plotted against their observed cumulative frequency on a graph with the y-axis appropriately scaled for the hypothesized (Normal) distribution.
3. If the hypothesized distribution adequately describes the data, the plotted points fall approximately along a straight line. If the plotted points deviate significantly from the straight line, then the hypothesized distribution is not appropriate.
4. In assessing the "closeness" of the points to a straight line, the "fat pencil" test is often used. If the points are all covered by the imaginary pencil, then the hypothesized (Normal) distribution is likely to be appropriate.

3.2 Standard Normal Distribution

A useful transformation in statistics is standardization. Sometimes called "converting to Z-scores" it has the effect of transforming the original distribution to one in which the mean becomes zero and the standard deviation becomes 1. A Z-score quantifies the original score in terms of the number of standard deviations that the score is from the mean of the distribution. (3.1) is used to convert from an original or "raw" score to a Z-score.

$$Z = \frac{\text{(Raw Score)} - \text{(Mean)}}{\text{(Standard Deviation)}}. \tag{3.1}$$

The process of converting or transforming scores on a variable to Z-scores is called standardization. Any distribution can be converted to a standardized distribution. However the symmetry of the original distribution remains unchanged. If the original distribution was skewed to start with, it will still be skewed after the Z-score transformation. In the special case where the original distribution can be considered normal, standardizing will result in what is known as the standard normal distribution. The advantage of this is that tables exist in any statistics textbook for the area under the curve for the standard normal distribution. Table 3.1 contains the area under the standard normal curve from 0 to Z. This can be used to compute the cumulative distribution function values for the standard normal distribution.

3.3 Chi-square Goodness-of-Fit Test

When an analyst attempts to fit a statistical model to observed data, he or she 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

Table 3.1: Area under the normal curve from 0 to X.

X	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.00000	0.00399	0.00798	0.01197	0.01595	0.01994	0.02392	0.02790	0.03188	0.03586
0.1	0.03983	0.04380	0.04776	0.05172	0.05567	0.05962	0.06356	0.06749	0.07142	0.07535
0.2	0.07926	0.08317	0.08706	0.09095	0.09483	0.09871	0.10257	0.10642	0.11026	0.11409
0.3	0.11791	0.12172	0.12552	0.12930	0.13307	0.13683	0.14058	0.14431	0.14803	0.15173
0.4	0.15542	0.15910	0.16276	0.16640	0.17003	0.17364	0.17724	0.18082	0.18439	0.18793
0.5	0.19146	0.19497	0.19847	0.20194	0.20540	0.20884	0.21226	0.21566	0.21904	0.22240
0.6	0.22575	0.22907	0.23237	0.23565	0.23891	0.24215	0.24537	0.24857	0.25175	0.25490
0.7	0.25804	0.26115	0.26424	0.26730	0.27035	0.27337	0.27637	0.27935	0.28230	0.28524
0.8	0.28814	0.29103	0.29389	0.29673	0.29955	0.30234	0.30511	0.30785	0.31057	0.31327
0.9	0.31594	0.31859	0.32121	0.32381	0.32639	0.32894	0.33147	0.33398	0.33646	0.33891
1.0	0.34134	0.34375	0.34614	0.34849	0.35083	0.35314	0.35543	0.35769	0.35993	0.36214
1.1	0.36433	0.36650	0.36864	0.37076	0.37286	0.37493	0.37698	0.37900	0.38100	0.38298
1.2	0.38493	0.38686	0.38877	0.39065	0.39251	0.39435	0.39617	0.39796	0.39973	0.40147
1.3	0.40320	0.40490	0.40658	0.40824	0.40988	0.41149	0.41308	0.41466	0.41621	0.41774
1.4	0.41924	0.42073	0.42220	0.42364	0.42507	0.42647	0.42785	0.42922	0.43056	0.43189
1.5	0.43319	0.43448	0.43574	0.43699	0.43822	0.43943	0.44062	0.44179	0.44295	0.44408
1.6	0.44520	0.44630	0.44738	0.44845	0.44950	0.45053	0.45154	0.45254	0.45352	0.45449
1.7	0.45543	0.45637	0.45728	0.45818	0.45907	0.45994	0.46080	0.46164	0.46246	0.46327
1.8	0.46407	0.46485	0.46562	0.46638	0.46712	0.46784	0.46856	0.46926	0.46995	0.47062
1.9	0.47128	0.47193	0.47257	0.47320	0.47381	0.47441	0.47500	0.47558	0.47615	0.47670
2.0	0.47725	0.47778	0.47831	0.47882	0.47932	0.47982	0.48030	0.48077	0.48124	0.48169
2.1	0.48214	0.48257	0.48300	0.48341	0.48382	0.48422	0.48461	0.48500	0.48537	0.48574
2.2	0.48610	0.48645	0.48679	0.48713	0.48745	0.48778	0.48809	0.48840	0.48870	0.48899
2.3	0.48928	0.48956	0.48983	0.49010	0.49036	0.49061	0.49086	0.49111	0.49134	0.49158
2.4	0.49180	0.49202	0.49224	0.49245	0.49266	0.49286	0.49305	0.49324	0.49343	0.49361
2.5	0.49379	0.49396	0.49413	0.49430	0.49446	0.49461	0.49477	0.49492	0.49506	0.49520
2.6	0.49534	0.49547	0.49560	0.49573	0.49585	0.49598	0.49609	0.49621	0.49632	0.49643
2.7	0.49653	0.49664	0.49674	0.49683	0.49693	0.49702	0.49711	0.49720	0.49728	0.49736
2.8	0.49744	0.49752	0.49760	0.49767	0.49774	0.49781	0.49788	0.49795	0.49801	0.49807
2.9	0.49813	0.49819	0.49825	0.49831	0.49836	0.49841	0.49846	0.49851	0.49856	0.49861
3.0	0.49865	0.49869	0.49874	0.49878	0.49882	0.49886	0.49889	0.49893	0.49896	0.49900

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 are divided into k bins and the test statistic is defined as in

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}, \tag{3.2}$$

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.

3.3.1 Deciding what value of X^2 is critical for accepting or rejecting a hypothesis

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*) [27]. 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, σ^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

$$df = \text{No. of data bins } (k) - \text{No. of constraints} \tag{3.3}$$

For chi-square test statistic with k data bins the only constraint is

$$\text{No. of observed data points} = \text{No. of expected data points} \tag{3.4}$$

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 [27]. 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.

3.3.2 Finding p-value for Chi-square Test

By using (3.2) and (3.3) we can get values for chi-square test statistic X^2 and degrees of freedom df. The final step is to refer to a professionally prepared table (Table 3.2) of the probabilities of X^2 values. These tables come in a variety of sizes, depending upon how many subdivisions (columns) are present, and how high the degrees of freedom go. The table lists the degrees of freedom as the headings to the rows. Across the top are probability figures - the probability of the Chi-Square. The interior of the table consists of the sum of the X^2 values themselves.

How to use Table 3.2:

1. Find the degrees of freedom from the data and look in the left-hand column of the table.

2. Scan across the row of X^2 values beside the *df* number for two values which bracket the calculated X^2 number. This means that one of the figures will be larger, and the other will be smaller. If the table were subdivided into enough columns, one might have found the exact calculated value on the table. Generally, one has to be satisfied with finding the bracketing numbers.
3. Look up at the top of the table to see which probabilities correspond to the bracketing X^2 values. If the exact X^2 value is not found on this table, its probability would have fallen somewhere between these two.

3.4 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 [26].

For Log-distance Path Loss Model discussed in section 2.5.1 a linear least squares curve fitting is used. The least-squares line uses a straight line equation as shown below

$$Y \; = \; P_1 X \; + \; P_2, \tag{3.5}$$

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

$$\Pi \; = \sum_{i=1}^{n}[y_i - f(x_i)]^2 \; = \; \sum_{i=1}^{n}[y_i - (P_1 x_i + P_2)]^2. \tag{3.6}$$

Table 3.2: Critical values of chi-square distribution with degrees of freedom.

	Probability of exceeding the critical value									
df	0.995	0.99	0.975	0.95	0.9	0.1	0.05	0.025	0.01	0.005
1	—	—	0.001	0.004	0.016	2.706	3.841	5.024	6.635	7.879
2	0.01	0.02	0.051	0.103	0.211	4.605	5.991	7.378	9.21	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.86
5	0.412	0.554	0.831	1.145	1.61	9.236	11.07	12.833	15.086	16.75
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812	18.548
7	0.989	1.239	1.69	2.167	2.833	12.017	14.067	16.013	18.475	20.278
8	1.344	1.646	2.18	2.733	3.49	13.362	15.507	17.535	20.09	21.955
9	1.735	2.088	2.7	3.325	4.168	14.684	16.919	19.023	21.666	23.589
10	2.156	2.558	3.247	3.94	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.92	24.725	26.757
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.3
13	3.565	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688	29.819
14	4.075	4.66	5.629	6.571	7.79	21.064	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32	34.267
17	5.697	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.39	10.865	25.989	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191	38.582
20	7.434	8.26	9.591	10.851	12.443	28.412	31.41	34.17	37.566	39.997
21	8.034	8.897	10.283	11.591	13.24	29.615	32.671	35.479	38.932	41.401
22	8.643	9.542	10.982	12.338	14.041	30.813	33.924	36.781	40.289	42.796
23	9.26	10.196	11.689	13.091	14.848	32.007	35.172	38.076	41.638	44.181
24	9.886	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.98	45.559
25	10.52	11.524	13.12	14.611	16.473	34.382	37.652	40.646	44.314	46.928
26	11.16	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642	48.29
27	11.808	12.879	14.573	16.151	18.114	36.741	40.113	43.195	46.963	49.645
28	12.461	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278	50.993
29	13.121	14.256	16.047	17.708	19.768	39.087	42.557	45.722	49.588	52.336
30	13.787	14.953	16.791	18.493	20.599	40.256	43.773	46.979	50.892	53.672

The MATLAB curve fitting tool box is used to find the linear fit in the discussions to follow in Chapter 5.

CHAPTER 4

EXPERIMENTAL SETUP

4.1 Introduction

This chapter outlines the experimental procedure involved, the hardware and software used, the propagation environment, different scenarios considered, and the research design used for generating an indoor propagation model. The experimental procedure involves identifying different measurement scenarios, measurement of signal levels in each scenario, followed by numerical analysis of the data collected.

4.2 Propagation Environment

The power received by a mobile receiver is influenced by the characteristics of the propagation environment. If a generalization study for indoor propagation is to be made, it is essential that we identify the features that influence the propagation characteristics in different buildings. In this section, a brief description is given of the buildings where the measurements were made.

Experiments are conducted in two different buildings. In the first building experiments are conducted for four different scenarios. The College of Engineering, University of North Texas, Research Park was chosen for conducting the first set of experiments. The facility is a two floor building. Figure 4.1 gives an overview of the first floor, Figure 4.2 gives an overview of the second floor, and Figure 4.3 gives a detailed view of the part of the second floor where the experiments will be conducted. The second set of experiments are conducted in General Academic Building (GAB) in the University of North Texas main campus. Signal measurements are conducted for only two scenarios in this building.

Figure 4.1: College of Engineering, first floor overview.

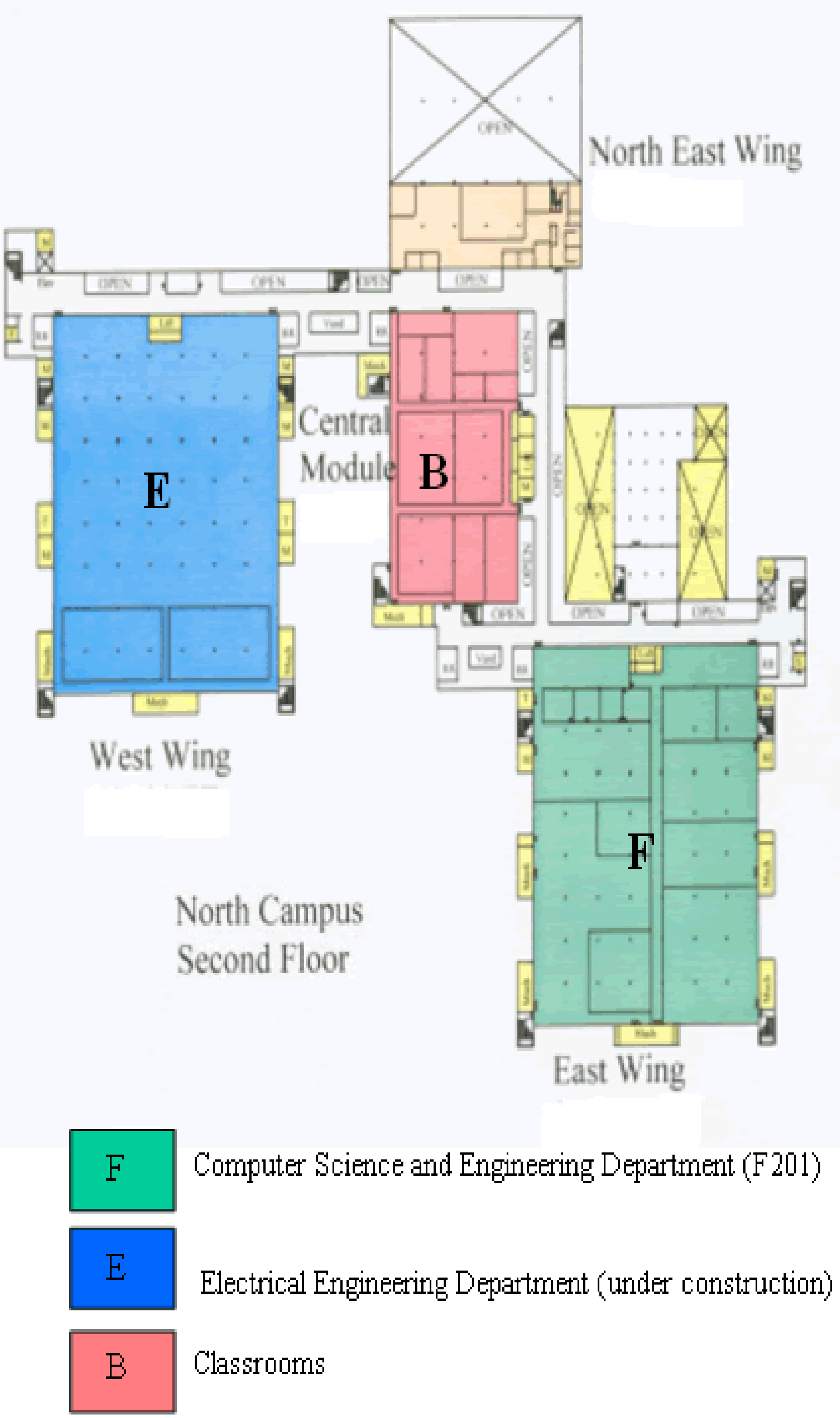


Figure 4.2: College of Engineering, second floor overview.

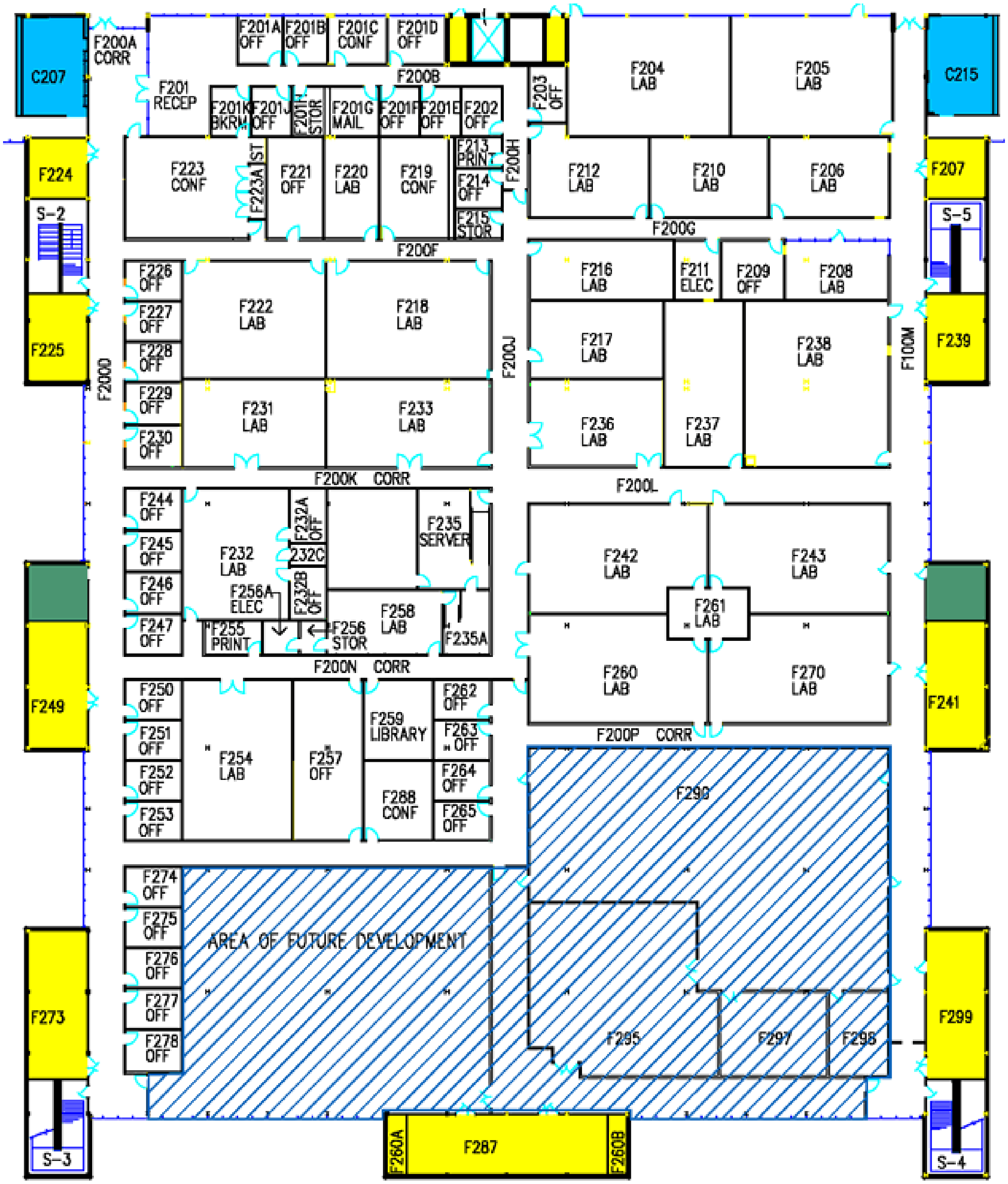


Figure 4.3: College of Engineering, second floor detail.

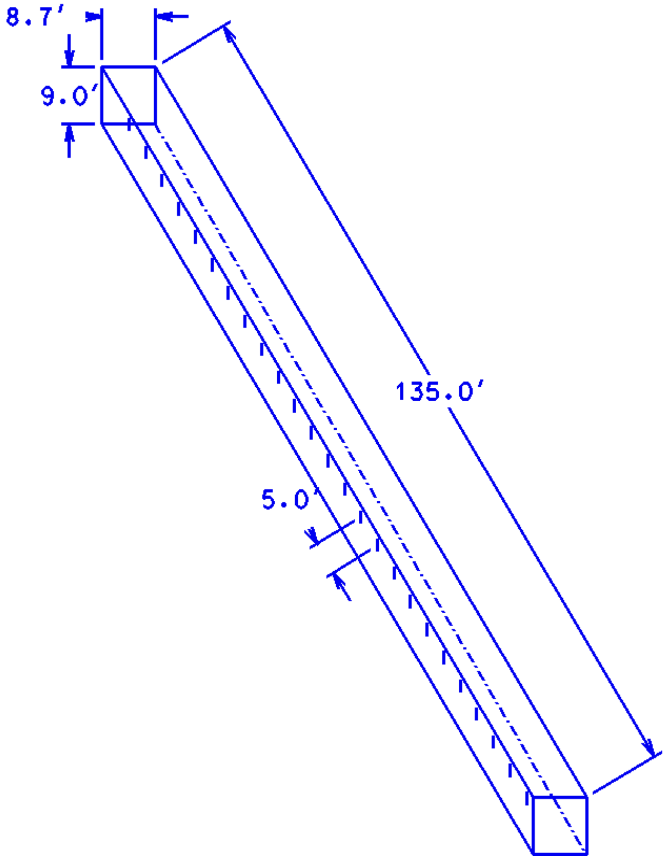


Figure 4.4: Building One Closed Corridor.

4.2.1 Description of Measurement Scenarios for Building One

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 on the second floor of building one 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. Figure 4.4 gives a blue print of the corridor and also shows the different locations at which measurements are taken.
- Open corridor: An open corridor on the second floor of building one is used for signal

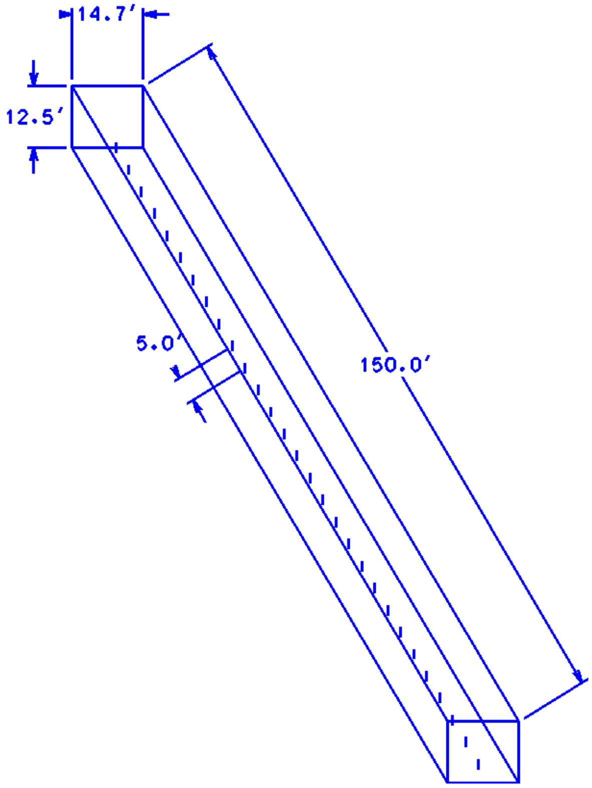


Figure 4.5: Building One Open Corridor.

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. Figure 4.5 gives a blue print of the corridor and also shows the different locations at which measurements are taken.

- Class room: A lecture room with furniture and computers 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. Figure 4.6 gives a blue print of the room and also shows the different locations at which measurements are taken.

- 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. Figure 4.7 gives a blue print of the room

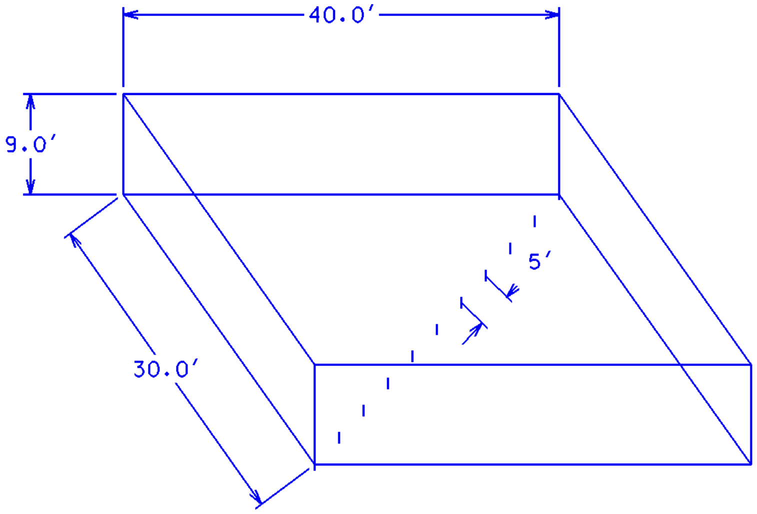


Figure 4.6: Building One Classroom.

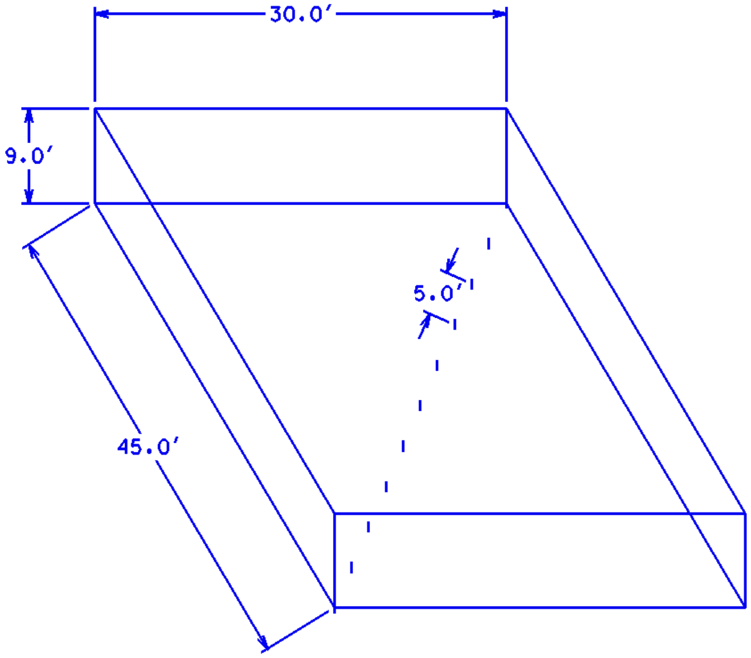


Figure 4.7: Building One Computer Lab.

and also shows the different locations at which measurements are taken.

4.2.2 Description of Measurement Scenarios for Building Two

Two scenarios in building two that are similar to building one scenarios closed corridor and classroom are considered for measurements. The scenarios used will help in comparing the results from building one. The scenarios are described as follows:

- Closed Corridor: A closed corridor on the third floor of building two is used for signal measurements. This corridor is closed on both sides with walls. This corridor is 8'9.25" high and 8'6" wide. Signal measurements are taken at every five feet interval in the middle of the corridor. Figure 4.8 gives a blue print of the corridor and also shows the different locations at which measurements are taken.
- Class room: A lecture room with furniture and computers is considered for signal measurements. This room is 30' X 24'X 8'9.25". Signal measurements are taken at every five feet interval diagonally across the room. Figure 4.9 gives a blue print of the room and also shows the different locations at which measurements are taken.

In all of the above described scenarios the measurements of the two access points are done alternately. A laptop with the wireless client adapter is moved away from the access point at fixed distance intervals and the signal strength at each interval is measured by rotating the laptop along its axis.

4.3 Hardware and Software Description

The measurements are done using two separate access points. The access points are from different manufacturers. One is LinkSys [28], the other is D-Link [29]. Both access points are IEEE 802.11b compliant. The access points operate at 2.4 GHz and provide a bandwidth

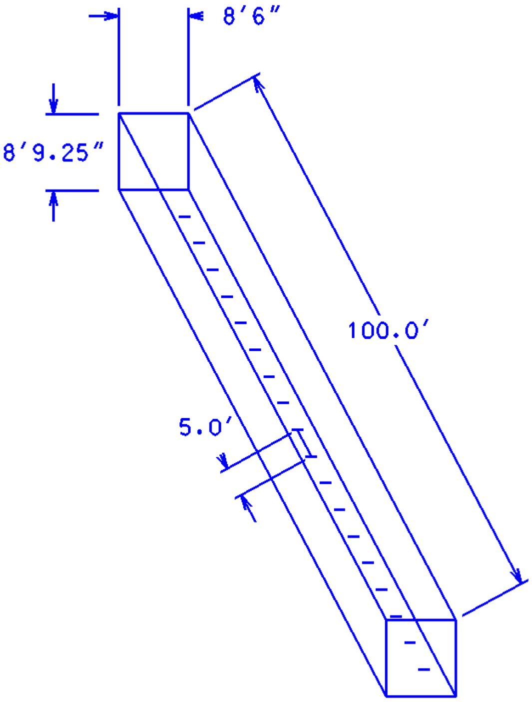


Figure 4.8: Building Two, Closed Corridor.

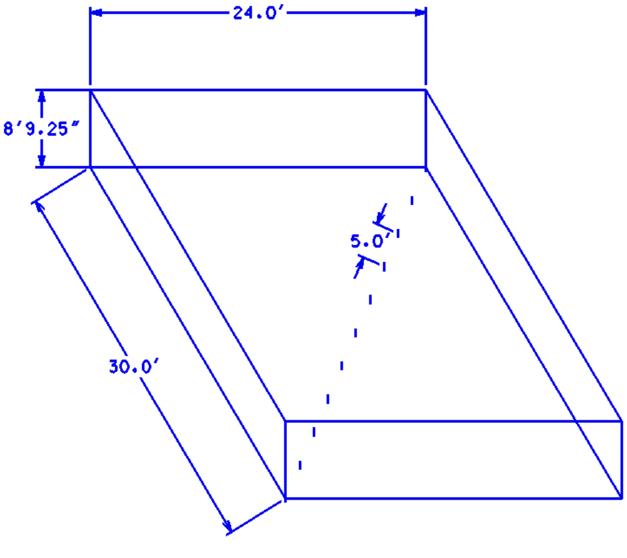


Figure 4.9: Building Two, Classroom.

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 [30] which is a tool for Windows that allows one to measure the signal level of WLANs using 802.11a, 802.11b or 802.11g.

4.4 Data Acquisition

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.

4.5 Numerical Analysis

Numerical analysis is performed to generate a path loss model on the collected data in each scenario. The data is subjected to following steps of numerical analysis.

1. Use Curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model:

   A scatter plot for signal levels at different distance intervals is drawn with distance ratio d/d_0 as X-axis and path loss PL as Y-axis on a loglog scale. As discussed in Section 2.5.3, a linear equation of the form (3.5) is generated using MATLAB curve fitting tool. The slope of the linear equation generated is equal to $10n$ where n is the path loss exponent, which indicates the rate at which path loss increases with distance d. Now that we know n (path loss exponent) for a scenario, we will be able to relate distance d with path loss PL as shown in (2.1).

2. Evaluate Standard deviation σ, for Log-Normal Distribution:

Before we evaluate Standard deviation σ for Log-Normal Distribution we need to prove that the shadowing effect over the range of distance intervals is a normal distribution. This is achieved using Normal Plot, Standard Normal Distribution, and Chi-square goodness-of-fit test.

Loss differential can be defined as difference between mean path loss at each distance interval compared to the measured data at each interval. As discussed in Section 2.10.1 if the scatter plot of Loss differential is a straight line we can say the distribution is normal. Once the normality of the distribution is established, mean and standard deviation are calculated.

3. Standard Normal Distribution & Chi-Square Goodness-of-Fit Test:

   Section 3.2 describes standardization of a distribution by converting raw scores into Z-scores using (3.1). Standardizing Loss differential will result in a standard normal distribution with zero mean and a standard deviation of one. Since the shape of the distribution is not effected by standardization, Chi-square goodness-of-fit test is calculated to further verify numerically, if the distribution is normal.

CHAPTER 5

NUMERICAL ANALYSIS

5.1 Introduction

This chapter describes the numerical analysis for scenarios in Building One as described in Chapter 4. In order to extract useful information from the raw measurement data, data processing is necessary and includes the following steps (Figure 5.1):

1. Calculate the mean signal levels.
2. Using least squares method to calculate curve fitting.
3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.
4. Using Normal Plot, verify normal distribution.
5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.
6. Calculate Chi-square Goodness-of-Fit Test.
7. Compare with two-ray model.

The close-in reference distance d_0, the path loss exponent n, and the standard deviation σ, statistically describe the path loss model for a specific T-R separation. Chi-square Goodness-of-Fit Test and standard normal distribution are used to quantitatively evaluate the quality of Normal Distribution.

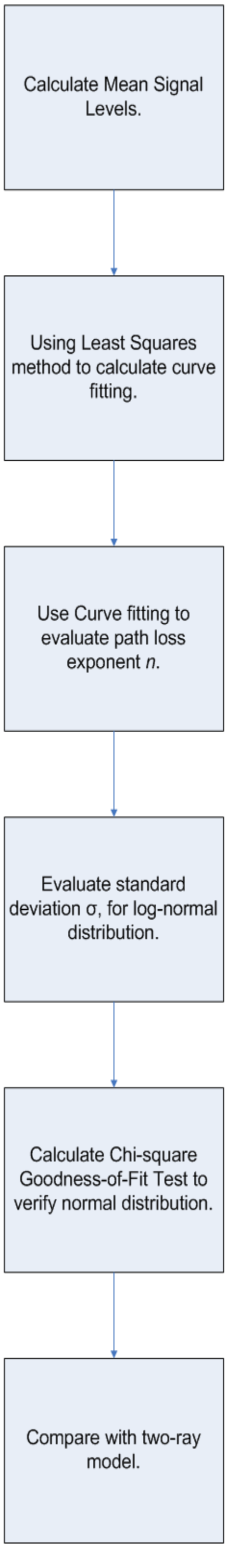


Figure 5.1: Numerical Analysis.

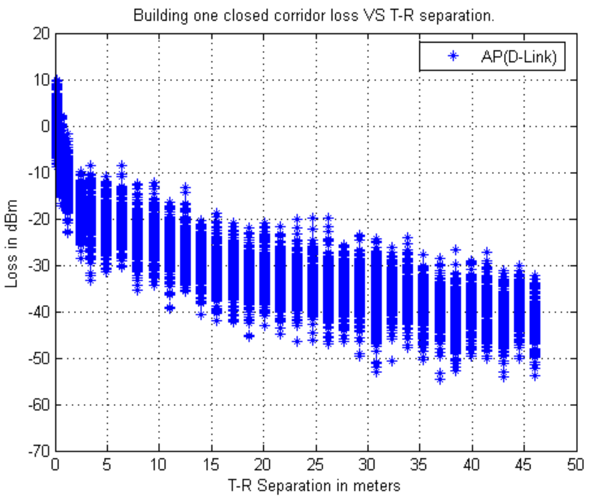


Figure 5.2: Building One, closed corridor loss for AP1 (D-Link).

5.2 Analysis of Results

5.2.1 Scenario 1: Building One Closed Corridor

Figure 5.2 and Figure 5.3 gives the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in a closed corridor at The College of Engineering, University of North Texas, Research Park (Figure 4.4). As seen from Figure 5.2 and Figure 5.3 loss increases as one goes further away from the access point. The laptop used to measure the signal strength is moved at different distance intervals and at each distance interval the laptop is rotated twice along its axis. Due to this rotation during measurements, the observed signal strength and loss variation is more than when the laptop is not rotated.

1. Calculate mean signal levels.

   Mean values of loss at each distance interval is calculated. Figure 5.4 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R

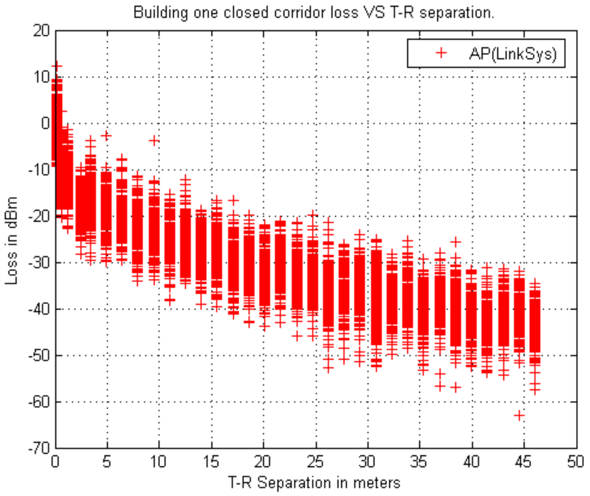


Figure 5.3: Building One, closed corridor loss for AP2 (LinkSys).

separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in a closed corridor.

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. Figures 5.5 and 5.6 show the linear curve fitting for the data collected using D-Link (AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

Closed corridor curve fitting for AP1 (D-Link)

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 15.72 (15.68, 15.77)

p2 = 0 (fixed at bound)

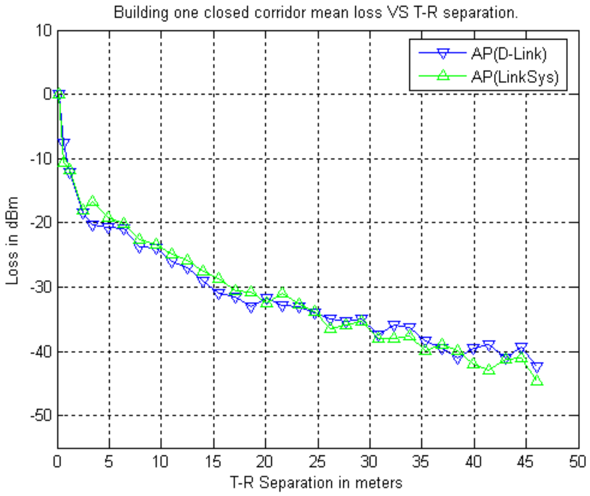


Figure 5.4: Building One, closed corridor mean loss for AP1 and AP2.

Closed corridor curve fitting for AP2 (LinkSys)

Linear model Poly1:

$f(x) = p1 * x + p2$

Coefficients (with 95 percent confidence bounds):

$p1 = 15.8\ (15.76,\ 15.85)$

$p2 = 0$ *(fixed at bound)*

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

Curve fitting gives a linear equation of the form (3.5) which when compared to (2.2) helps in determining the value for path loss exponent n. From Figures 5.5 and 5.6 and output results listed above we get the slope of the curve to be 15.72 for D-Link and 15.8 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e., calculated path loss exponents (n) for D-link and LinkSys access points in closed corridor is 1.572 and 1.58. The next step is to evaluate Log normal shadowing. Before evaluating Log normal shadowing, normal probability plot is used to verify if the distribution is normal.

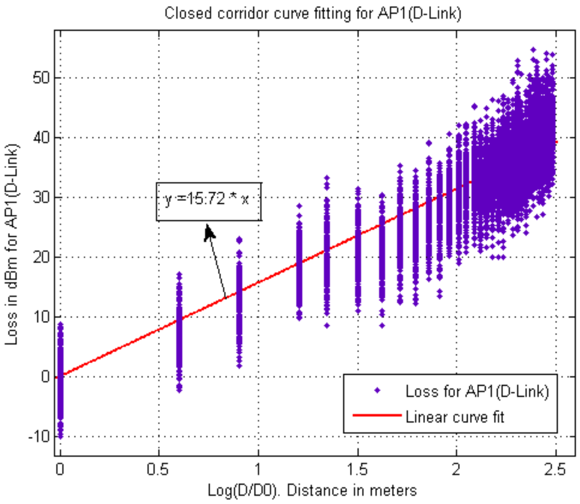


Figure 5.5: Building One, closed corridor curve fitting for AP1 (D-Link).

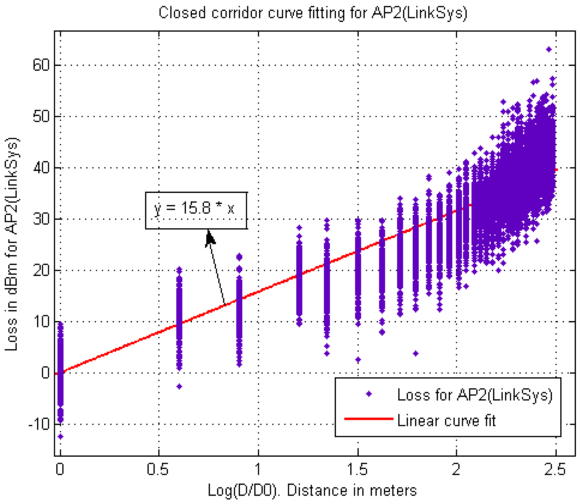


Figure 5.6: Building One, closed corridor curve fitting for AP2 (LinkSys).

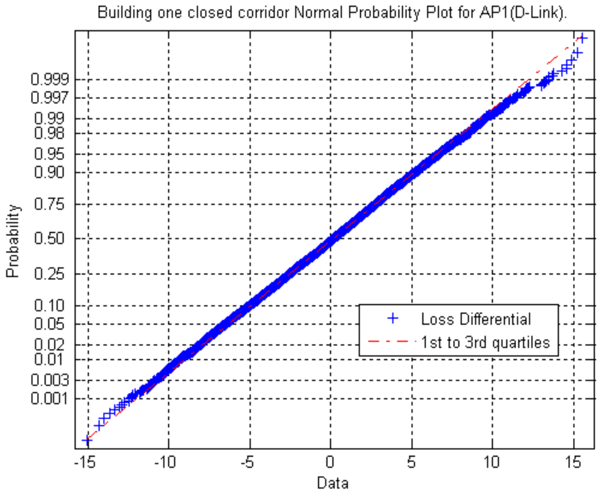


Figure 5.7: Building One, closed corridor normal probability plot for AP1 (D-Link).

4. Using Normal Plot, verify normal distribution.

   In this part of the analysis we calculate the loss differential, which is a measure of variation or scatter of loss compared to the mean value of loss calculated above. Normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots from Figure 5.7 and Figure 5.8 indicate that the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

   Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 3.9849 and for LinkSys standard deviation is 4.022. Using (3.1) loss differential is standardized. Figure 5.9 and Figure 5.10 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test.

   As discussed in section 3.3 to evaluate goodness of fit we need to calculate test statistic

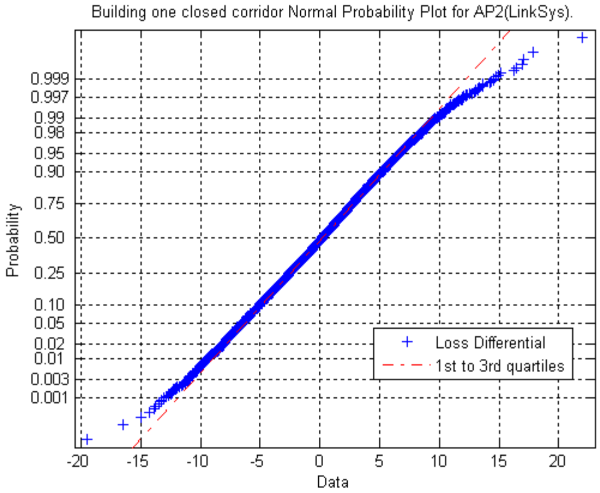


Figure 5.8: Building One, closed corridor normal probability plot for AP2 (LinkSys).

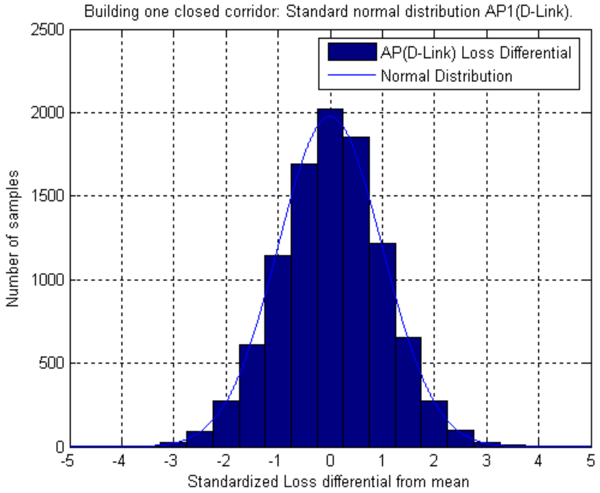


Figure 5.9: Building One, closed corridor standard normal distribution for AP1 (D-Link).

Table 5.1: Closed corridor X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-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	-

Table 5.2: Closed corridor X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.010009	1	97.92
-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	8	1.9706
-3.25 to -2.75	0.002403	24.052	22	0.17501
-2.75 to -2.25	0.009245	92.533	92	0.0030725
-2.25 to -1.75	0.027835	278.6	260	1.2418
-1.75 to -1.25	0.065591	656.5	611	3.1535
-1.25 to -0.75	0.12098	1210.9	1139	4.2656
-0.75 to -0.25	0.17467	1748.2	1710	0.83609
-0.25 to 0.25	0.19741	1975.9	2043	2.2782
0.25 to 0.75	0.17467	1748.2	1859	7.0183
0.75 to 1.25	0.12098	1210.9	1217	0.031045
1.25 to 1.75	0.065591	656.5	637	0.57923
1.75 to 2.25	0.027835	278.6	268	0.40334
2.25 to 2.75	0.009245	92.533	94	0.023251
2.75 to 3.25	0.002403	24.052	27	0.36143
3.25 to 3.75	0.000489	4.8944	13	13.424
3.75 to 4.25	7.80E-05	0.7807	5	22.803
4.25 to 4.75	1.00E-05	0.10009	1	8.0911
4.75 to 5.25	1.00E-06	0.010009	1	97.92
Total Observations	-	10009.0404	10009	-

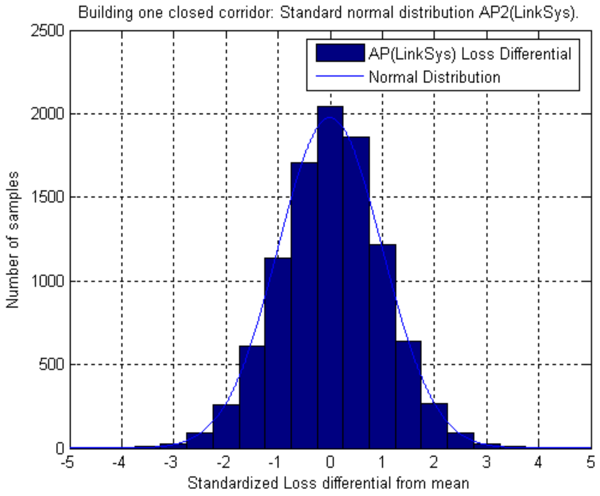


Figure 5.10: Building One, closed corridor standard normal distribution for AP2 (LinkSys).

X^2 and degrees of freedom df. Table 5.1 and 5.2 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. To find the expected value for a particular bin, the area under standard normal curve for the bin is multiplied by total observations. Chi-square statistic is calculated using (3.2). 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. As discussed in section 3.3, the degrees of freedom df = 13 - 1 = 12.

From Table 5.1 X^2 for AP1 (D-Link)= 16.152, and from Table 5.2 X^2 for AP2 (LinkSys)= 20.3699 By using Table 3.2 we can identify to p-value associated with X^2 and df values.

We now have our 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).

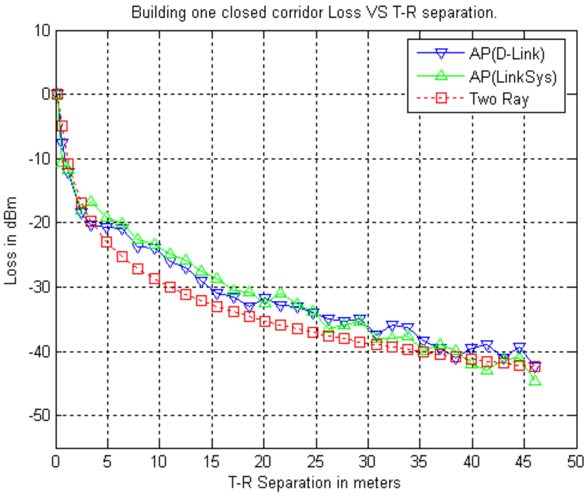


Figure 5.11: Comparison of closed corridor mean loss with two-ray model.

Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP2 $= 20.3699$, lies between 18.549 and 21.026. The corresponding probability is $0.10 < p < 0.05$. 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 AP2 (LinkSys).

7. Compare with two-ray model.

A graphical comparison is made between measured data and the two-ray model. Figure 5.11 and Figure 5.12 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal deteriorates at a faster rate in two-ray model than in actual measurements.

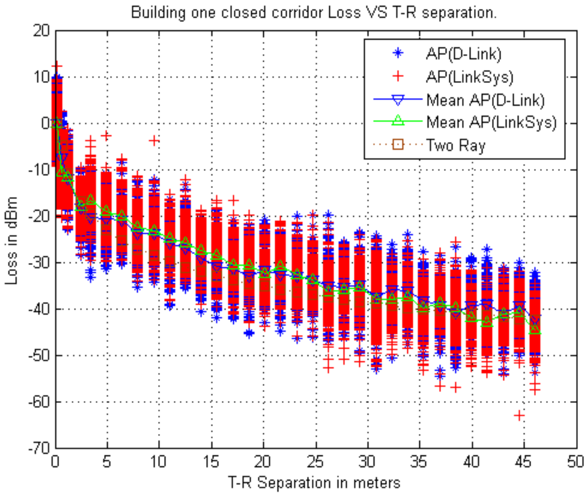


Figure 5.12: Comparison of closed corridor AP1 and AP2 loss with mean signal and two-ray model.

5.2.2 Scenario 2: Building One Open Corridor

Figure 5.13 and Figure 5.14 gives the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in an open corridor at The College of Engineering, University of North Texas, Research Park (Figure 4.5). As seen from Figure 5.13 and Figure 5.14 loss increases with distance relative to the access point.

1. Calculate mean signal levels.

   Mean values of loss at each distance interval is calculated. Figure 5.15 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in an open corridor.

2. Using least squares method to calculate curve fitting.

   Using MATLAB curve fitting tool, a linear fit is calculated using least squares method.

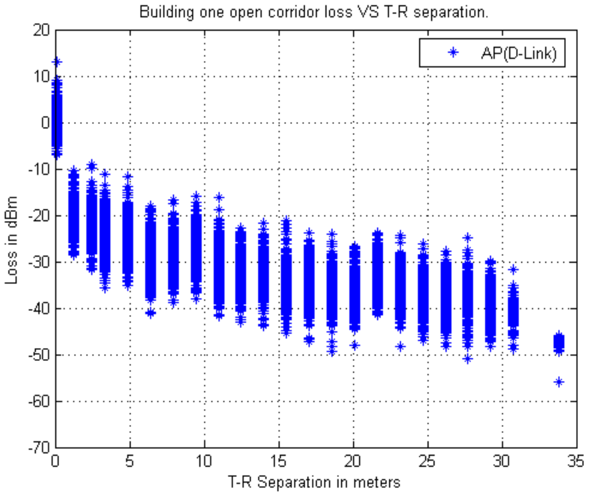


Figure 5.13: Building One, open corridor loss for AP1 (D-Link).

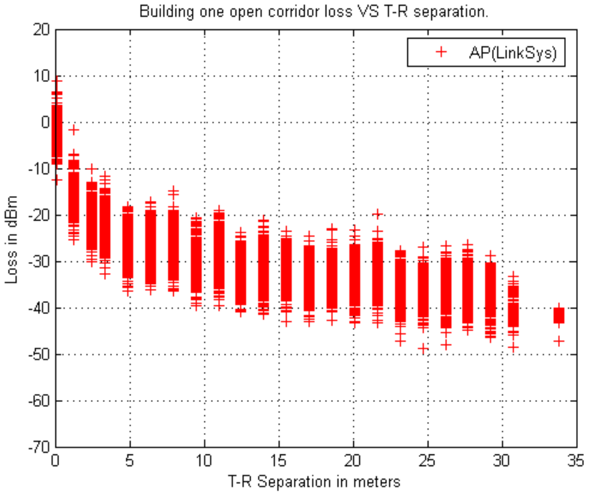


Figure 5.14: Building One, open corridor loss for AP2 (LinkSys).

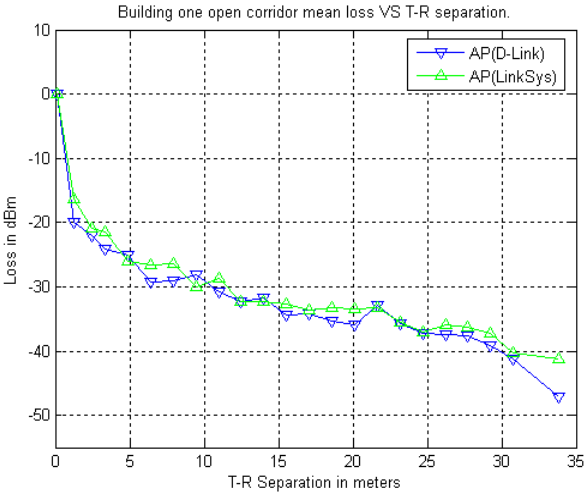


Figure 5.15: Building One, open corridor mean loss for AP1 and AP2.

Figures 5.16 and 5.17 show the linear curve fitting for the data collected using D-Link (AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

Open corridor curve fitting for AP1 (D-Link).

Linear model Poly1:

$f(x) = p1 * x + p2$

Coefficients (with 95 percent confidence bounds):

$p1 = 16.88$ *(16.84, 16.92)*

$p2 = 0$ *(fixed at bound)*

Open corridor curve fitting for AP2 (LinkSys).

Linear model Poly1:

$f(x) = p1 * x + p2$

Coefficients (with 95 percent confidence bounds):

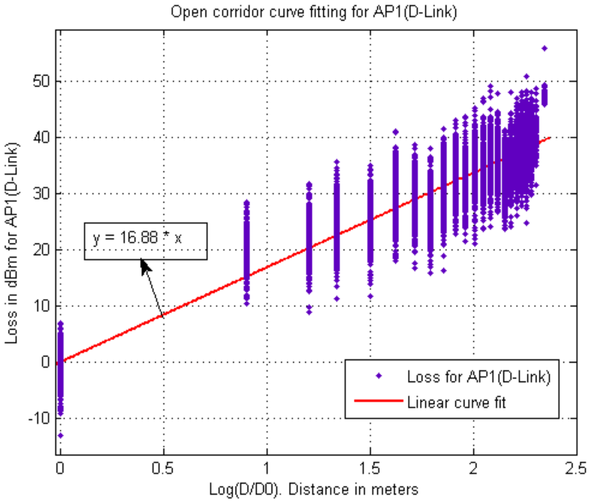


Figure 5.16: Building One, open corridor curve fitting for AP1 (D-Link).

p1 = 16.3 (16.26, 16.34)

p2 = 0 (fixed at bound)

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

   From Figures 5.16 and 5.17 and output results listed above we get the slope of the fitted curve to be 16.88 for D-Link and 16.3 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e., calculated path loss exponents (n) for D-link and LinkSys access points in open corridor is 1.688 and 1.63.

4. Using Normal Plot, verify normal distribution.

   As discussed in Scenario 1 (Closed corridor), normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots from Figure 5.18 and Figure 5.19 indicate that the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

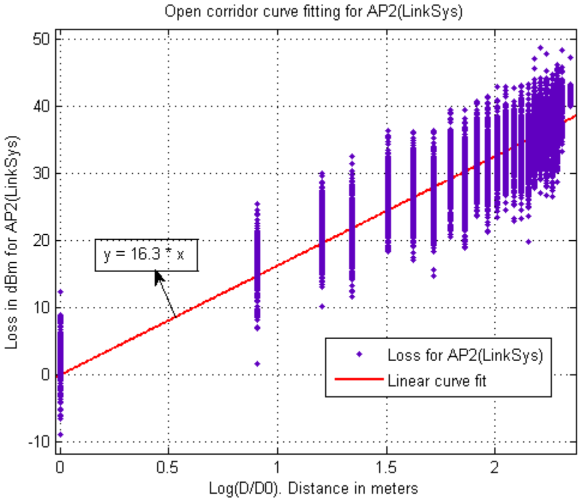


Figure 5.17: Building One, open corridor curve fitting for AP2 (LinkSys).

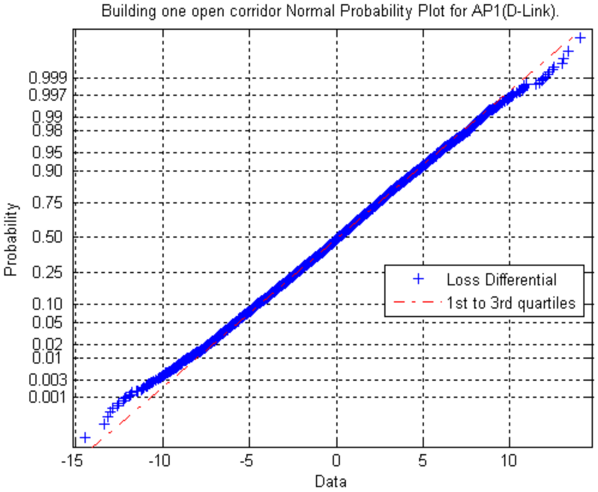


Figure 5.18: Building One, open corridor normal probability plot for AP1 (D-Link).

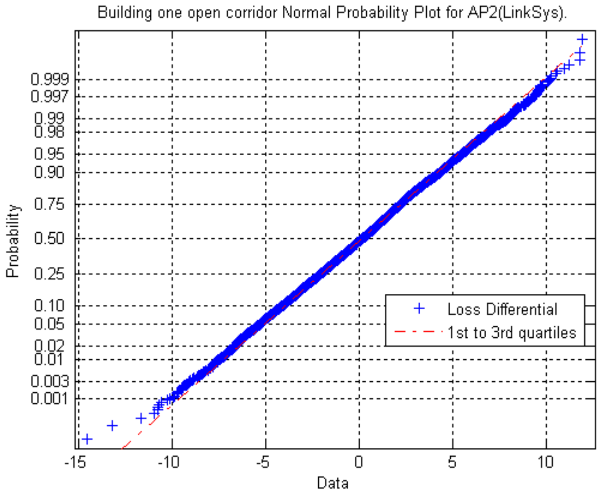


Figure 5.19: Building One, open corridor normal probability plot for AP2 (LinkSys).

Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 3.5773 and for LinkSys standard deviation is 3.2642. Using (3.1) loss differential is standardized. Figure 5.20 and Figure 5.21 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test

As discussed in section 3.3 to evaluate goodness of fit we need to calculate test statistic X^2 and degrees of freedom df. Table 5.3 and 5.4 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. To find the expected value for a particular bin, the area under standard normal curve for the bin is multiplied by total observations. Chi-square test statistic is calculated using (3.2). 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. As discussed in section 3.3, degrees of freedom df = 13 - 1 = 12.

From Table 5.3 X^2 for AP1 (D-Link)= 20.0012, and from Table 5.4 X^2 for AP2 (LinkSys)= 37.6687 By using Table 3.2 we can identify to p-value associated with

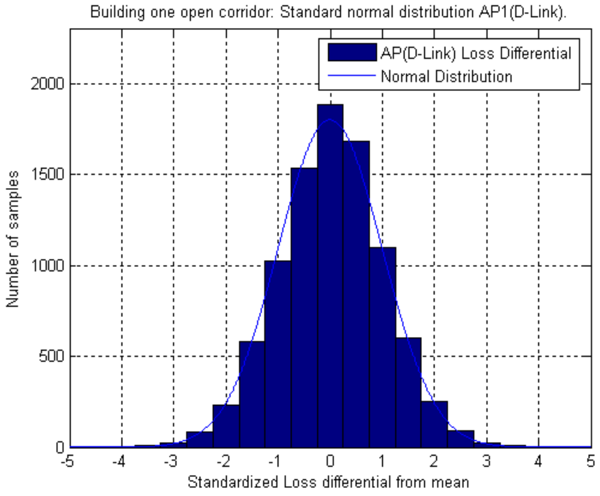


Figure 5.20: Building One, open corridor standard normal distribution for AP1 (D-Link).

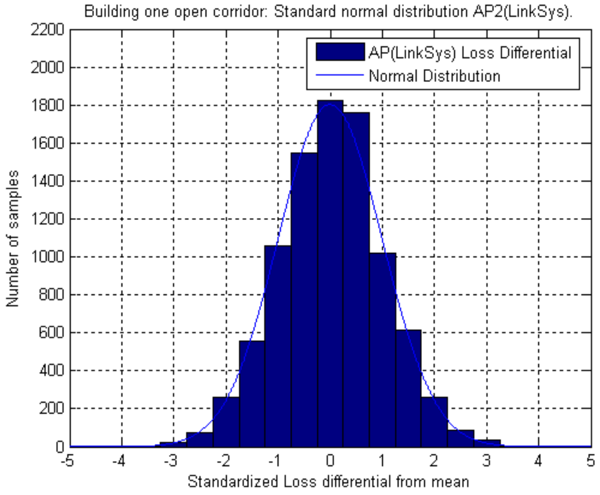


Figure 5.21: Building One, open corridor standard normal distribution for AP2 (LinkSys).

Table 5.3: Open corridor X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.009133	0	0.009133
-4.75 to -4.25	1.00E-05	0.09133	0	0.09133
-4.25 to -3.75	7.80E-05	0.71237	1	0.11613
-3.75 to -3.25	0.000489	4.466	12	12.709
-3.25 to -2.75	0.002403	21.947	26	0.74864
-2.75 to -2.25	0.009245	84.435	81	0.13971
-2.25 to -1.75	0.027835	254.22	233	1.7708
-1.75 to -1.25	0.065591	599.04	582	0.48486
-1.25 to -0.75	0.12098	1104.9	1023	6.0697
-0.75 to -0.25	0.17467	1595.2	1538	2.0528
-0.25 to 0.25	0.19741	1803	1884	3.6414
0.25 to 0.75	0.17467	1595.2	1683	4.8297
0.75 to 1.25	0.12098	1104.9	1098	0.042991
1.25 to 1.75	0.065591	599.04	599	3.03E-06
1.75 to 2.25	0.027835	254.22	250	0.069954
2.25 to 2.75	0.009245	84.435	88	0.15056
2.75 to 3.25	0.002403	21.947	22	0.00012994
3.25 to 3.75	0.000489	4.466	12	12.709
3.75 to 4.25	7.80E-05	0.71237	1	0.11613
4.25 to 4.75	1.00E-05	0.09133	0	0.09133
4.75 to 5.25	1.00E-06	0.009133	0	0.009133
Total Observations	-	9133.041666	9133	-

Table 5.4: Open corridor X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.009133	0	0.009133
-4.75 to -4.25	1.00E-05	0.09133	1	9.0406
-4.25 to -3.75	7.80E-05	0.71237	1	0.11613
-3.75 to -3.25	0.000489	4.466	6	0.52687
-3.25 to -2.75	0.002403	21.947	21	0.040829
-2.75 to -2.25	0.009245	84.435	76	0.84257
-2.25 to -1.75	0.027835	254.22	260	0.13155
-1.75 to -1.25	0.065591	599.04	556	3.0927
-1.25 to -0.75	0.12098	1104.9	1061	1.7436
-0.75 to -0.25	0.17467	1595.2	1544	1.6449
-0.25 to 0.25	0.19741	1803	1821	0.18024
0.25 to 0.75	0.17467	1595.2	1759	16.814
0.75 to 1.25	0.12098	1104.9	1020	6.5225
1.25 to 1.75	0.065591	599.04	617	0.53831
1.75 to 2.25	0.027835	254.22	263	0.30344
2.25 to 2.75	0.009245	84.435	89	0.24685
2.75 to 3.25	0.002403	21.947	33	5.567
3.25 to 3.75	0.000489	4.466	5	0.063841
3.75 to 4.25	7.80E-05	0.71237	0	0.71237
4.25 to 4.75	1.00E-05	0.09133	0	0.09133
4.75 to 5.25	1.00E-06	0.009133	0	0.009133
Total Observations	-	9133.041666	9133	-

X^2 and *df* values.

We now have our chi square statistic X^2 for AP1 and AP2 (20.0012 and 37.6687), our predetermined level of significance (0.05), and our degrees of freedom ($df = 12$). Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP1 = 20.0012, lies between 18.549 and 21.026. The corresponding probability is $0.10 < p < 0.05$. 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).

Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP2 = 37.6687, lies beyond 28.3. So the corresponding probability *p*-value is less that 0.005. This is not an acceptable significance level.

7. Compare with two-ray model.

   A graphical comparison is made between measured data and two-ray model. Figure 5.22 and Figure 5.23 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal strength variation is similar in two-ray model and open corridor measurements.

5.2.3 Scenario 3: Building One Classroom

Figure 5.24 and Figure 5.25 gives the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in an classroom at The College of Engineering, University of North Texas, Research Park (Figure 4.6). As seen from Figure 5.24 and Figure 5.25 loss increases as one goes further away from the access point.

1. Calculate mean signal levels.

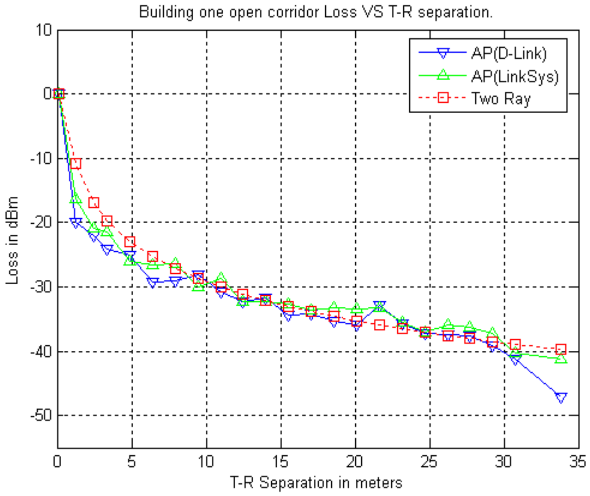


Figure 5.22: Comparison of open corridor mean loss with two-ray model.

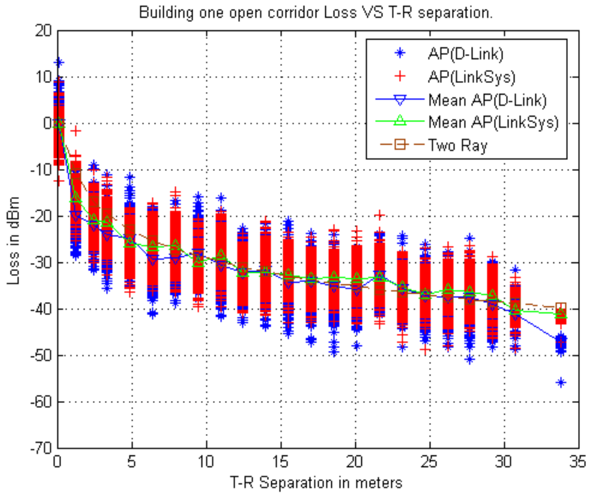


Figure 5.23: Comparison of open corridor AP1 and AP2 loss with mean signal and two-ray model.

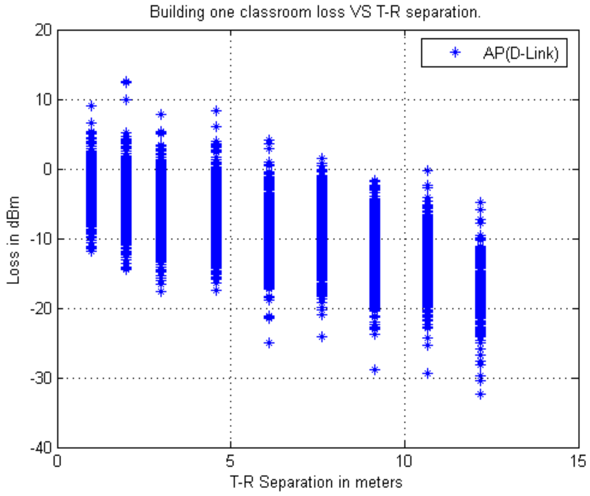


Figure 5.24: Building One, classroom loss for AP1 (D-Link).

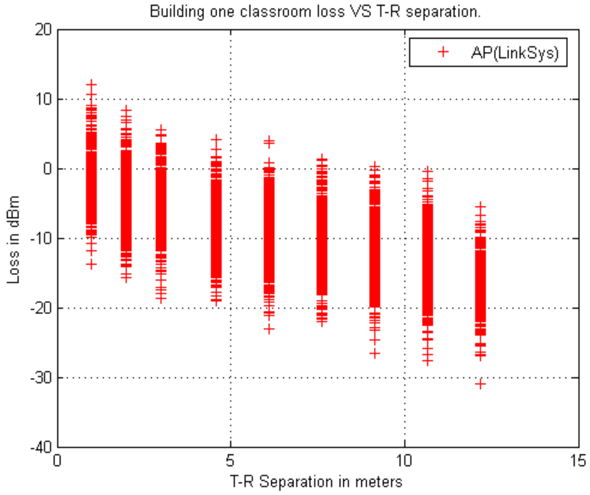


Figure 5.25: Building One, classroom loss for AP2 (LinkSys).

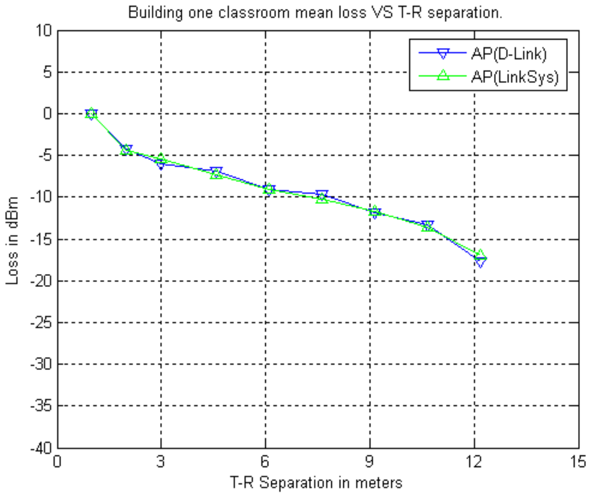


Figure 5.26: Building One, classroom mean loss for AP1 and AP2.

Mean values of loss at each distance interval is calculated. Figure 5.26 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in a classroom.

2. Using least squares method to calculate curve fitting.

Figures 5.27 and 5.28 show the linear curve fitting for the data collected using D-Link (AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

Classroom curve fitting for AP1 (D-Link).

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 12.58 (12.44, 12.72)

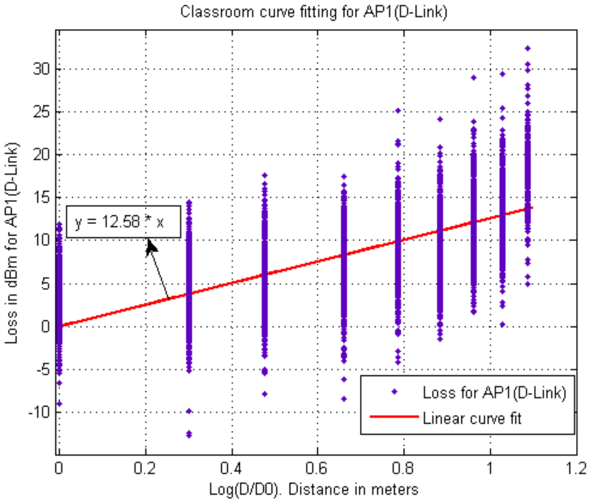


Figure 5.27: Building One, classroom curve fitting for AP1 (D-Link).

p2 = 0 (fixed at bound)

Classroom curve fitting for AP2 (LinkSys).

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 12.63 (12.49, 12.78)

p2 = 0 (fixed at bound)

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

   From Figures 5.27 and 5.28 and output results listed above we get the slope of the fitted curve to be 12.58 for D-Link and 12.63 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e., calculated path loss exponents (n) for D-link and LinkSys access points in a classroom is 1.258 and 1.263.

4. Using Normal Plot, verify normal distribution.

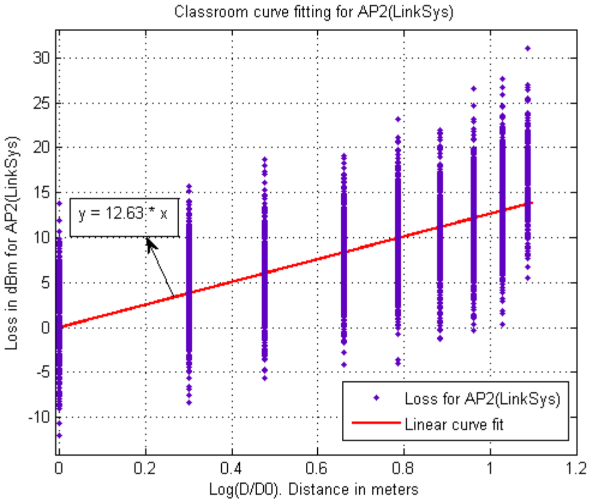


Figure 5.28: Building One, classroom curve fitting for AP2 (LinkSys).

As discussed in Scenario 1 (Closed corridor), normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots from Figure 5.29 and Figure 5.30 indicate that the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

   Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 3.7607 and for LinkSys standard deviation is 4.053. Using (3.1) loss differential is standardized. Figure 5.31 and Figure 5.32 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test.

   Table 5.5 and 5.6 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. To find the expected value for a particular bin, the area under standard normal curve for the bin is multiplied by total observations. Chi-square test statistic is calculated

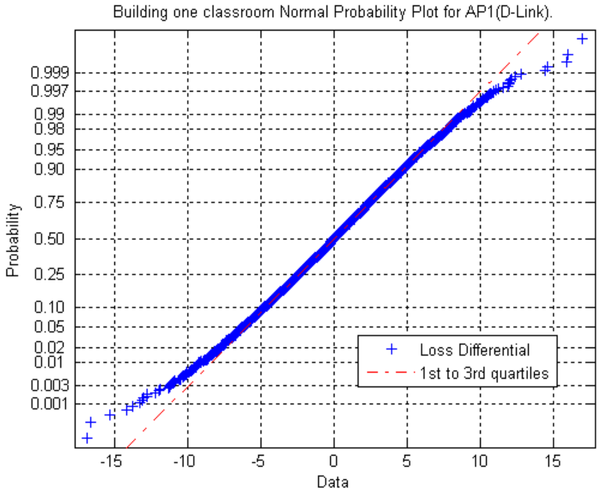


Figure 5.29: Building One, classroom normal probability plot for AP1 (D-Link).

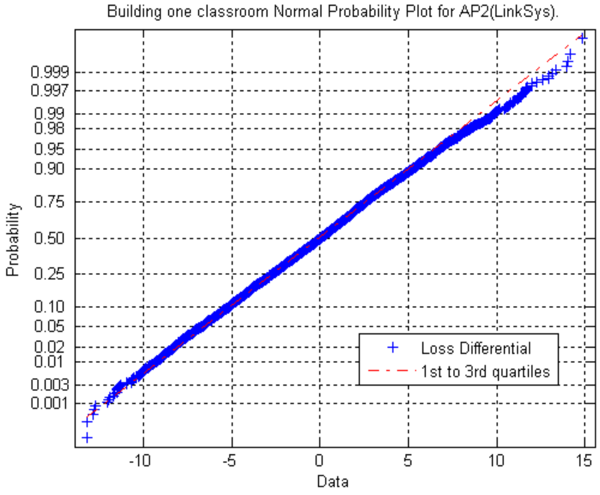


Figure 5.30: Building One, classroom normal probability plot for AP2 (LinkSys).

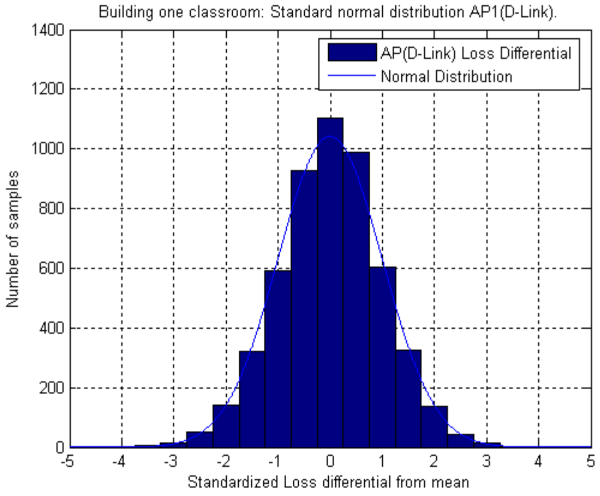


Figure 5.31: Building One, classroom standard normal distribution for AP1 (D-Link).

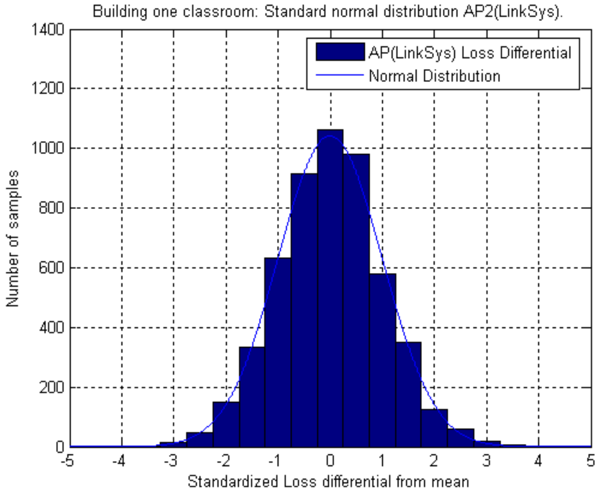


Figure 5.32: Building One, classroom standard normal distribution for AP2 (LinkSys).

Table 5.5: Classroom X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.005276	0	0.005276
-4.75 to -4.25	1.00E-05	0.05276	2	71.868
-4.25 to -3.75	7.80E-05	0.41153	2	6.1314
-3.75 to -3.25	0.000489	2.58	6	4.5336
-3.25 to -2.75	0.002403	12.678	15	0.42519
-2.75 to -2.25	0.009245	48.777	50	0.030684
-2.25 to -1.75	0.027835	146.86	142	0.16067
-1.75 to -1.25	0.065591	346.06	320	1.9622
-1.25 to -0.75	0.12098	638.28	590	3.6519
-0.75 to -0.25	0.17467	921.54	926	0.021606
-0.25 to 0.25	0.19741	1041.6	1103	3.6253
0.25 to 0.75	0.17467	921.54	987	4.6502
0.75 to 1.25	0.12098	638.28	605	1.7352
1.25 to 1.75	0.065591	346.06	324	1.41E+00
1.75 to 2.25	0.027835	146.86	137	0.66166
2.25 to 2.75	0.009245	48.777	44	0.46777
2.75 to 3.25	0.002403	12.678	16	0.87032
3.25 to 3.75	0.000489	2.58	2	0.13037
3.75 to 4.25	7.80E-05	0.41153	3	16.281
4.25 to 4.75	1.00E-05	0.05276	2	71.868
4.75 to 5.25	1.00E-06	0.005276	0	0.005276
Total Observations	-	5276.089132	5276	-

Table 5.6: Classroom X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.005276	0	0.005276
-4.75 to -4.25	1.00E-05	0.05276	0	0.05276
-4.25 to -3.75	7.80E-05	0.41153	0	0.41153
-3.75 to -3.25	0.000489	2.58	1	0.96757
-3.25 to -2.75	0.002403	12.678	15	0.42519
-2.75 to -2.25	0.009245	48.777	46	0.15806
-2.25 to -1.75	0.027835	146.86	149	0.031258
-1.75 to -1.25	0.065591	346.06	333	0.49273
-1.25 to -0.75	0.12098	638.28	631	0.083032
-0.75 to -0.25	0.17467	921.54	916	0.033279
-0.25 to 0.25	0.19741	1041.6	1064	0.48385
0.25 to 0.75	0.17467	921.54	981	3.8368
0.75 to 1.25	0.12098	638.28	580	5.3214
1.25 to 1.75	0.065591	346.06	351	0.070573
1.75 to 2.25	0.027835	146.86	125	3.2531
2.25 to 2.75	0.009245	48.777	58	1.7441
2.75 to 3.25	0.002403	12.678	20	4.2284
3.25 to 3.75	0.000489	2.58	6	4.5336
3.75 to 4.25	7.80E-05	0.41153	0	0.41153
4.25 to 4.75	1.00E-05	0.05276	0	0.05276
4.75 to 5.25	1.00E-06	0.005276	0	0.005276
Total Observations	-	5276.089132	5276	-

using (3.2). 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. As discussed in section 3.3, degrees of freedom *df* = 13 - 1 = 12.

From Table 5.5 X^2 for AP1 (D-Link)= 19.6687, and from Table 5.6 X^2 for AP2 (LinkSys)= 20.1618 By using Table 3.2 we can identify to *p*-value associated with X^2 and *df* values.

We now have our chi-square test statistic X^2 for AP1 and AP2 (19.6687 and 20.1618), our predetermined level of significance (0.05), and our degrees of freedom (*df* =12). Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP1 = 19.6687, lies between 18.549 and 21.026. The corresponding probability is $0.10 < p < 0.05$. 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).

Finding the Chi square distribution table with 12 degree of freedom and reading along the row we find our value of X^2 for AP2 = 20.1618, lies between 18.549 and 21.026. The corresponding probability is $0.10 < p < 0.05$. 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 AP2 (LinkSys).

7. Compare with two-ray model.

   A graphical comparison is made between measured data and two-ray model. Figure 5.33 and Figure 5.34 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal strength deteriorates much higher in two-ray model when compared to classroom measurements.

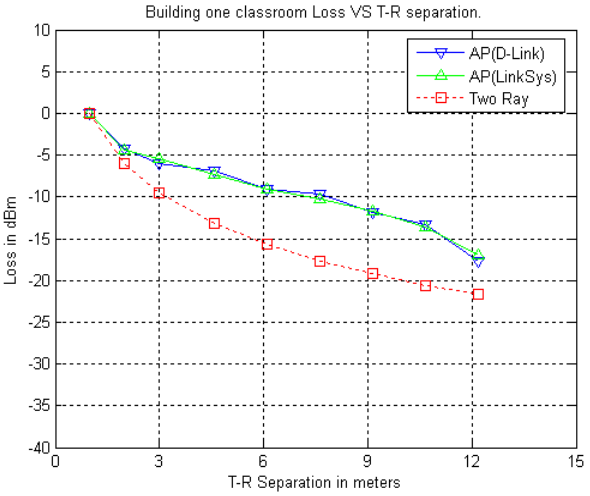


Figure 5.33: Comparison of classroom mean loss with two ray-model.

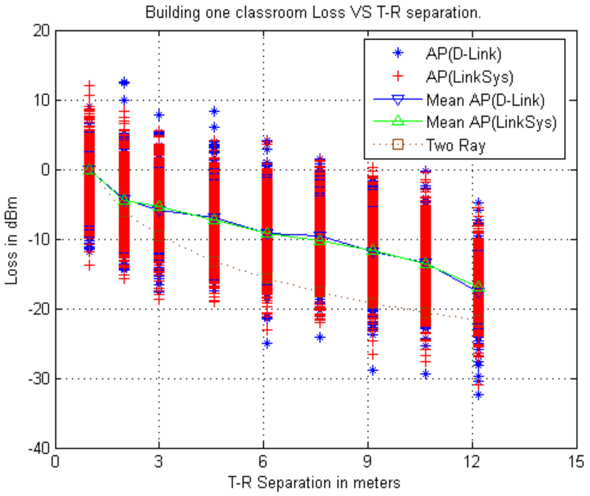


Figure 5.34: Comparison of classroom AP1 and AP2 loss with mean signal and two-ray model.

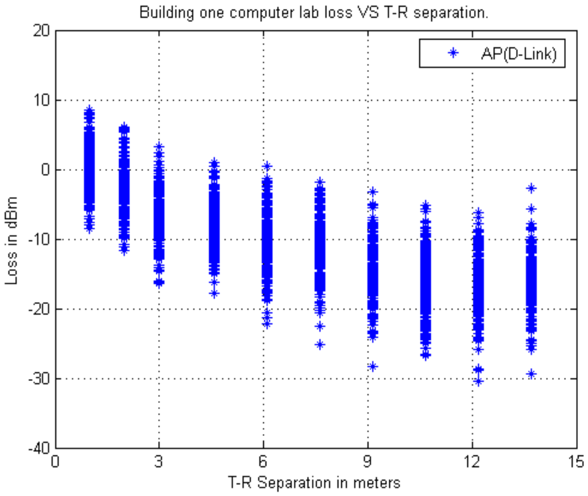


Figure 5.35: Building One, computer lab loss for AP1 (D-Link).

5.2.4 Scenario 4: Building One Computer Lab

Figure 5.35 and Figure 5.36 gives the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in an computer lab at The College of Engineering, University of North Texas, Research Park (Figure 4.7). As seen from Figure 5.35 and Figure 5.36 loss increases as one goes further away from the access point.

1. Calculate mean signal levels.

   Mean values of loss at each distance interval is calculated. Figure 5.37 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in a computer lab.

2. Using least squares method to calculate curve fitting.

   Using MATLAB curve fitting tool, a linear fit is calculated using least squares method. Figures 5.38 and 5.39 show the linear curve fitting for the data collected using D-Link

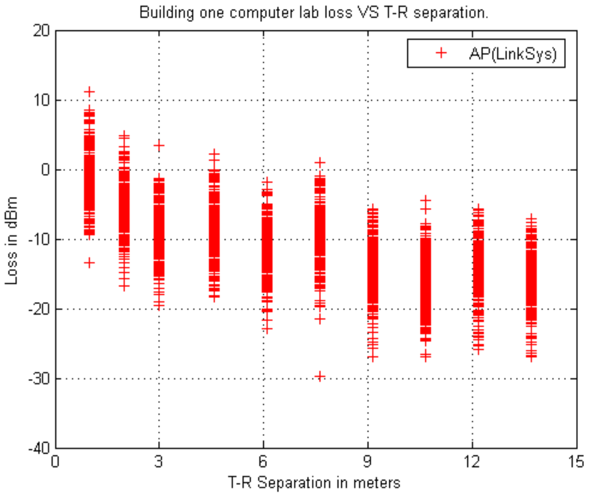


Figure 5.36: Building One, computer lab loss for AP2 (LinkSys).

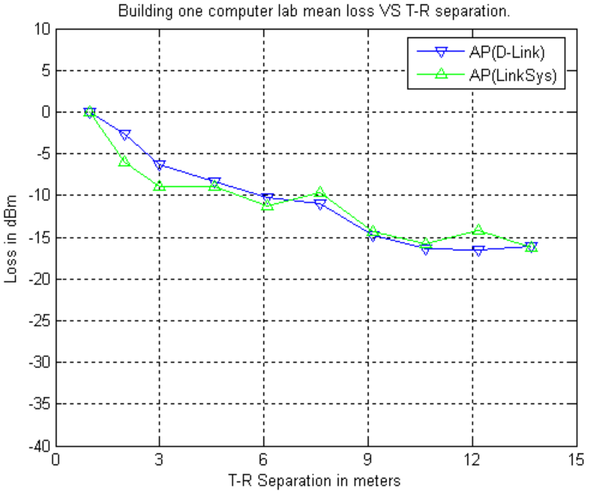


Figure 5.37: Building One, computer lab mean loss for AP1 and AP2.

(AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

Computer lab curve fitting for AP1(D-Link)

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 14.47 (14.29, 14.65)

p2 = 0 (fixed at bound)

Computer lab curve fitting for AP2(LinkSys)

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 14.28 (14.09, 14.47)

p2 = 0 (fixed at bound)

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

   From Figures 5.38 and 5.39 and output results listed above we get the slope of the fitted curve to be 14.47 for D-Link and 14.28 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e. calculated path loss exponents (n) for D-link and LinkSys access points in a computer lab is 1.447 and 1.428.

4. Using Normal Plot, verify normal distribution.

   As discussed in Scenario 1 (Closed corridor), normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots

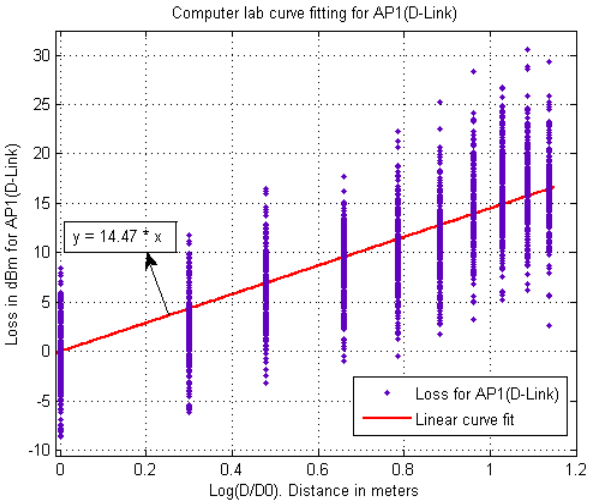


Figure 5.38: Building One, computer lab curve fitting for AP1 (D-Link).

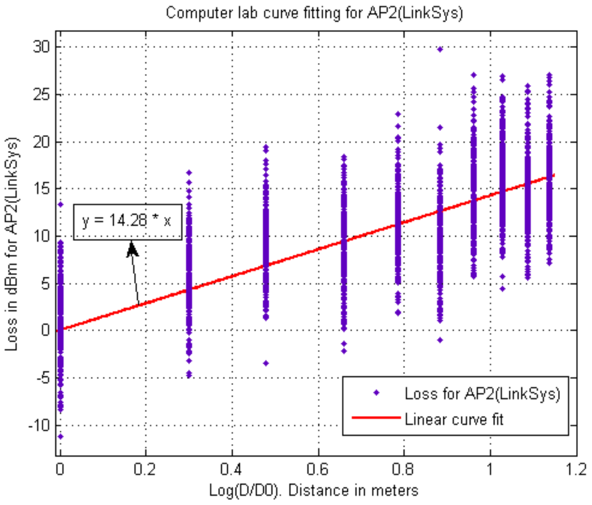


Figure 5.39: Building One, computer lab curve fitting for AP2 (LinkSys).

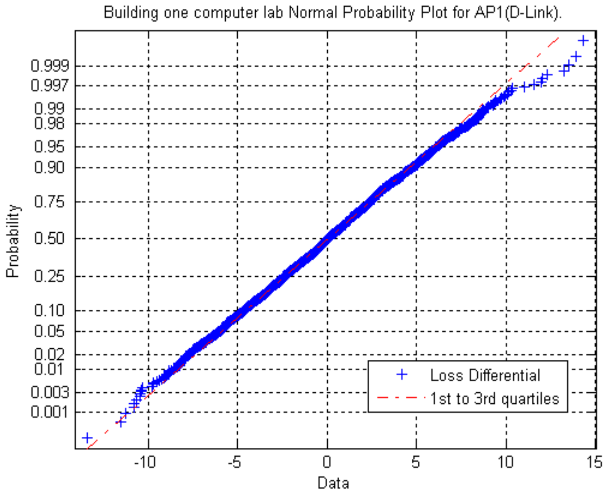


Figure 5.40: Building One, computer lab normal probability plot for AP1 (D-Link).

from Figure 5.40 and Figure 5.41 indicate that the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

   Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 3.7049 and for LinkSys standard deviation is 3.8460. Using (3.1) loss differential is standardized. Figure 5.42 and Figure 5.43 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test.

   As discussed in section 3.3 to evaluate goodness of fit we need to calculate test statistic X^2 and degrees of freedom df. Table 5.7 and 5.8 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. To find the expected value for a particular bin, the area under standard normal curve for the bin is multiplied by total observations. Chi-square test statistic is calculated using (3.2). To evaluate if the distribution is

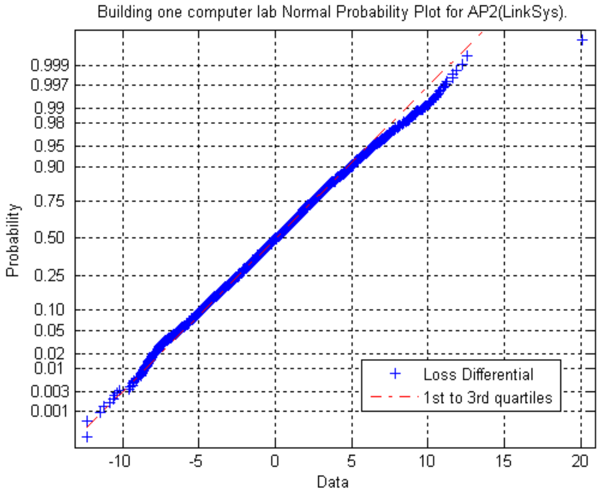


Figure 5.41: Building One, computer lab normal probability plot for AP2 (LinkSys).

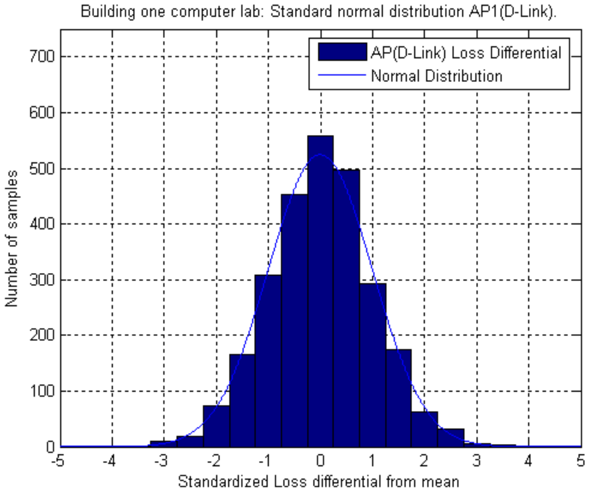


Figure 5.42: Building One, computer lab standard normal distribution for AP1 (D-Link).

Table 5.7: Computer lab X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.002657	0	0.002657
-4.75 to -4.25	1.00E-05	0.02657	0	0.02657
-4.25 to -3.75	7.80E-05	0.20725	0	0.20725
-3.75 to -3.25	0.000489	1.2993	1	0.068934
-3.25 to -2.75	0.002403	6.3848	10	2.047
-2.75 to -2.25	0.009245	24.564	19	1.2603
-2.25 to -1.75	0.027835	73.958	74	2.43E-05
-1.75 to -1.25	0.065591	174.28	165	0.49365
-1.25 to -0.75	0.12098	321.44	308	0.56183
-0.75 to -0.25	0.17467	464.09	452	0.31483
-0.25 to 0.25	0.19741	524.53	558	2.1362
0.25 to 0.75	0.17467	464.09	496	2.1944
0.75 to 1.25	0.12098	321.44	293	2.516
1.25 to 1.75	0.065591	174.28	175	3.01E-03
1.75 to 2.25	0.027835	73.958	63	1.6235
2.25 to 2.75	0.009245	24.564	32	2.251
2.75 to 3.25	0.002403	6.3848	5	0.30034
3.25 to 3.75	0.000489	1.2993	4	5.6139
3.75 to 4.25	7.80E-05	0.20725	2	15.508
4.25 to 4.75	1.00E-05	0.02657	0	0.02657
4.75 to 5.25	1.00E-06	0.002657	0	0.002657
Total Observations	-	2657.035154	2657	-

Table 5.8: Computer lab X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.002657	0	0.002657
-4.75 to -4.25	1.00E-05	0.02657	0	0.02657
-4.25 to -3.75	7.80E-05	0.20725	0	0.20725
-3.75 to -3.25	0.000489	1.2993	0	1.2993
-3.25 to -2.75	0.002403	6.3848	6	0.023188
-2.75 to -2.25	0.009245	24.564	18	1.754
-2.25 to -1.75	0.027835	73.958	83	1.1056
-1.75 to -1.25	0.065591	174.28	167	0.30371
-1.25 to -0.75	0.12098	321.44	309	0.48133
-0.75 to -0.25	0.17467	464.09	468	0.032983
-0.25 to 0.25	0.19741	524.53	537	0.29663
0.25 to 0.75	0.17467	464.09	496	2.1944
0.75 to 1.25	0.12098	321.44	287	3.6897
1.25 to 1.75	0.065591	174.28	170	0.10488
1.75 to 2.25	0.027835	73.958	69	0.33232
2.25 to 2.75	0.009245	24.564	33	2.8972
2.75 to 3.25	0.002403	6.3848	12	4.9384
3.25 to 3.75	0.000489	1.2993	1	0.068934
3.75 to 4.25	7.80E-05	0.20725	0	0.20725
4.25 to 4.75	1.00E-05	0.02657	0	0.02657
4.75 to 5.25	1.00E-06	0.002657	1	374.37
Total Observations	-	2657.035154	2657	-

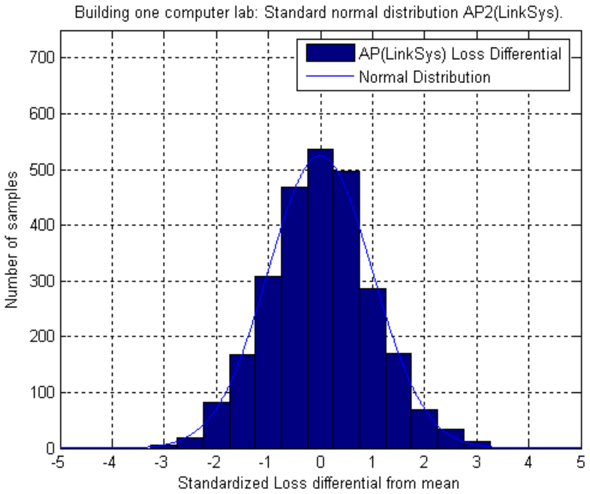


Figure 5.43: Building One, computer lab standard normal distribution for AP2 (LinkSys).

normal, the bins that are used to calculate X^2 are from -3.25 to 3.25, a total of 13 bins. As discussed in section 3.3, degrees of freedom *df* = 13 - 1 = 12.

From Table 5.7 X^2 for AP1 (D-Link)= 15.7022, and from Table 5.8 X^2 for AP2 (LinkSys)= 18.1544 By using Table 3.2 we can identify to *p*-value associated with X^2 and *df* values.

We now have our chi-square test statistic X^2 for AP1 and AP2 (15.7022 and 18.1544), our predetermined level of significance (0.05), and our degrees of freedom (*df* =12). Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP1 = 15.7022, 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).

Finding the Chi-square distribution with 12 degree of freedom and reading along the row we find our value of X^2 for AP2 = 18.1544, lies between 6.304 and 18.549. The corresponding probability is $0.9 < p < 0.1$. This is below the conventionally accepted

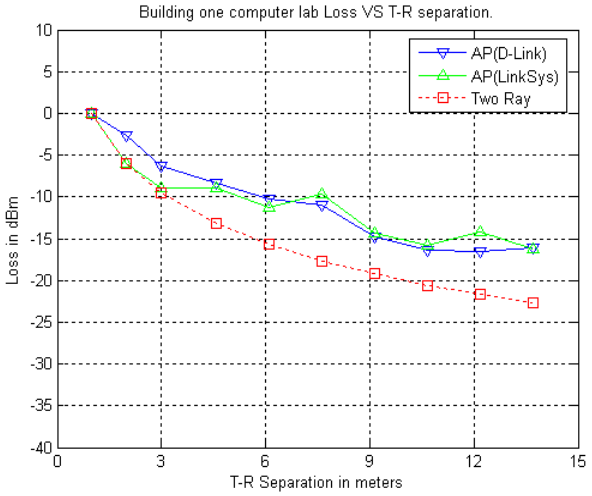


Figure 5.44: Comparison of computer lab mean loss with two ray model.

significance level of 0.05 or 5%, so the null hypothesis that loss differential is normal is verified for AP2 (LinkSys).

7. Compare with two-ray model.

   A graphical comparison is made between measured data and two-ray model. Figure 5.44 and Figure 5.45 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal strength deteriorates much higher in two-ray model when compared to computer lab measurements.

5.3 Summary of Results

In this chapter a numerical analysis is performed on measurements conducted in Building One. Figure 5.46 lists the experimental results for all the scenarios from Building One.

For Building One Closed Corridor, Path loss exponent (n) is 1.572 for AP1 and 1.58 for AP2, Standard deviation (σ) is 3.9849 for AP1 and 4.022 for AP2. Now the Chi-square test statistic (X^2) values for both AP1 and AP2 (16.152 for AP1 and 20.3699 for AP2) are acceptable values to prove that the observed fading is a normal distribution at 5% significance

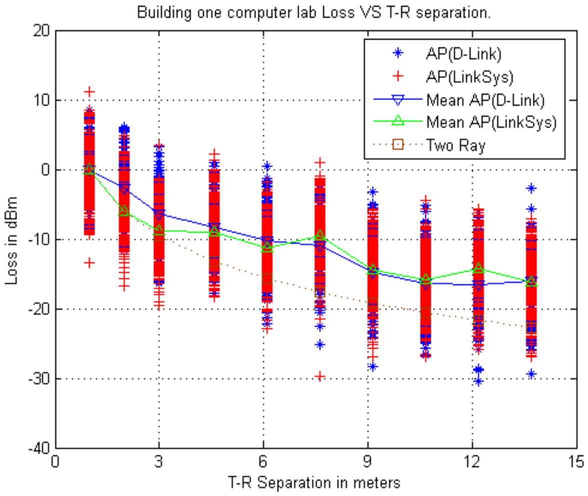
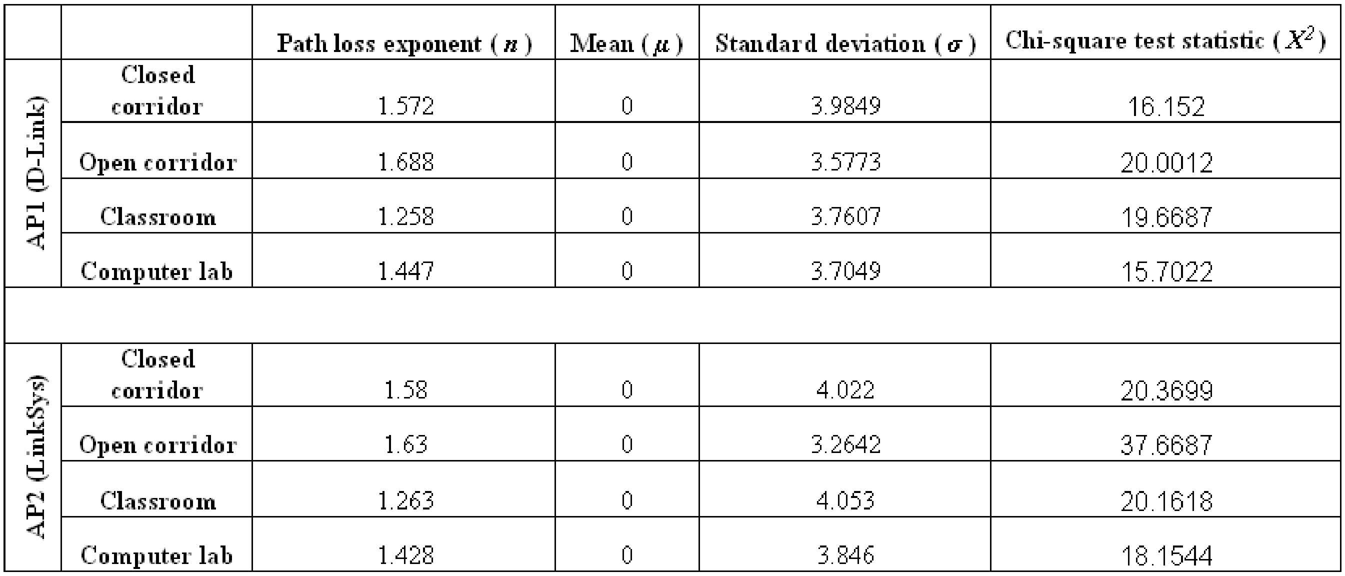


Figure 5.45: Comparison of computer lab AP1 and AP2 loss with mean signal and two ray model.

level. So, for Building One Closed Corridor Alternative Hypotheses is accepted for the first research question.

For Building One Open Corridor, Path loss exponent (n) is 1.688 for AP1 and 1.63 for AP2, Standard deviation (σ) is 3.5773 for AP1 and 3.2642 for AP2. Now the Chi-square test statistic (X^2) value for AP1 (20.0012) is acceptable value to prove that the observed fading is a normal distribution at 5% significance level but for AP2 Chi-square test statistic (X^2) value of 37.6687 is not an acceptable value to prove that the observed fading is a normal distribution at 5% significance level. This is an exception in this study. So, for Building One Open Corridor Alternative Hypotheses is accepted for the first research question.

For Building One Classroom, Path loss exponent (n) is 1.258 for AP1 and 1.263 for AP2, Standard deviation (σ) is 3.7607 for AP1 and 4.053 for AP2. Now the Chi-square test statistic (X^2) values for both AP1 and AP2 (19.6687 for AP1 and 20.1618 for AP2) are acceptable values to prove that the observed fading is a normal distribution at 5% significance level. So, for Building One Classroom Alternative Hypotheses is accepted for the first research question.



		Path loss exponent (n)	Mean (μ)	Standard deviation (σ)	Chi-square test statistic (X^2)
AP1 (D-Link)	Closed corridor	1.572	0	3.9849	16.152
	Open corridor	1.688	0	3.5773	20.0012
	Classroom	1.258	0	3.7607	19.6687
	Computer lab	1.447	0	3.7049	15.7022
AP2 (LinkSys)	Closed corridor	1.58	0	4.022	20.3699
	Open corridor	1.63	0	3.2642	37.6687
	Classroom	1.263	0	4.053	20.1618
	Computer lab	1.428	0	3.846	18.1544

Figure 5.46: Results at a glance.

For Building One Computer lab, Path loss exponent (n) is 1.447 for AP1 and 1.428 for AP2, Standard deviation (σ) 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. So, for Building One Computer lab Alternative Hypotheses is accepted for the first research question.

Varying values for Path loss exponent (n) and Standard deviation (σ) for different scenarios signifies that the path loss and multi path fading vary from scenario to scenario. So, for Building One Alternative Hypotheses is accepted for the second research question.

CHAPTER 6

COMPARISON WITH SIMILAR SCENARIOS

6.1 Introduction

This chapter describes the numerical analysis for scenarios in Building Two as described in Chapter 4 and compares the results with similar scenarios in Building One.

6.2 Scenario 1: Building Two Closed Corridor

Figure 6.1 and Figure 6.2 give the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in a closed corridor at General Academic Building (GAB) in the University of North Texas main campus. As seen from Figure 6.1 and Figure 6.2 loss increases as one goes further away from the access point.

1. Calculate mean signal levels. Mean values of loss at each distance interval is calculated. Figure 6.3 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in a closed corridor for Building Two.

2. Using least squares method to calculate curve fitting.

   Using MATLAB curve fitting tool a linear fit is calculated using least squares method. Figures 6.4 and 6.5 show the linear curve fitting for the data collected using D-Link

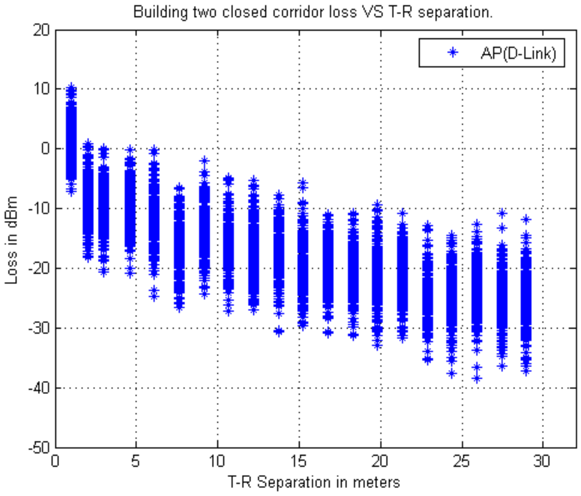


Figure 6.1: Building Two, closed corridor loss for AP1 (D-Link).

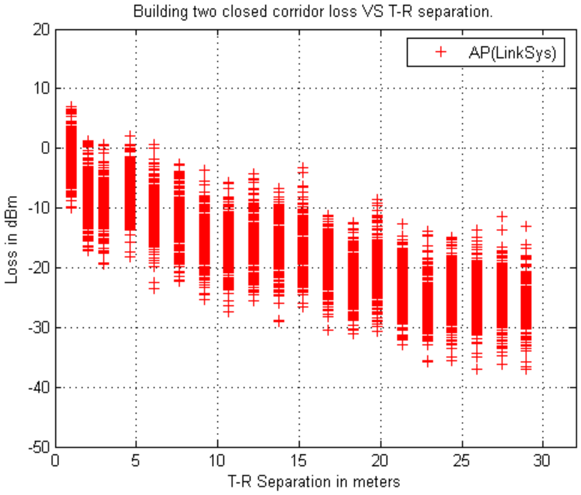


Figure 6.2: Building Two, closed corridor loss for AP2 (LinkSys).

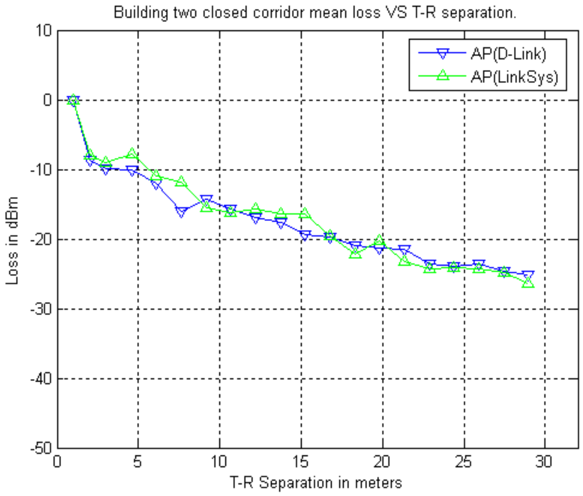


Figure 6.3: Building Two, closed corridor mean loss for AP1 and AP2.

(AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

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

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 16.66 (16.56, 16.76)

p2 = 0 (fixed at bound)

Closed corridor curve fitting for AP2 (LinkSys).

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 16.48 (16.38, 16.58)

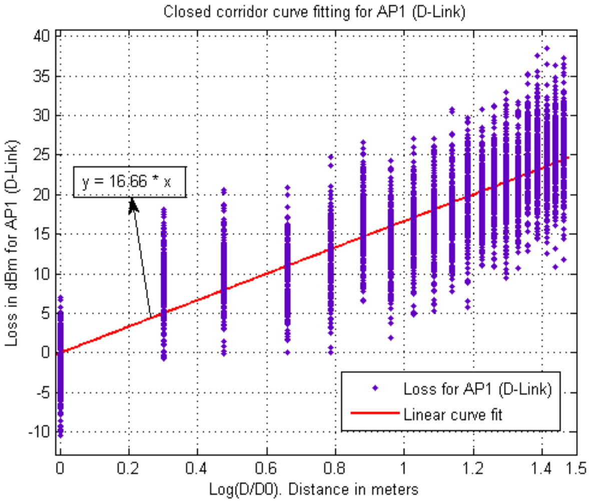


Figure 6.4: Building Two, closed corridor curve fitting for AP1 (D-Link).

p2 = 0 (fixed at bound)

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

From Figures 6.4 and 6.5 and output results listed above we get the slope of the fitted curve to be 16.66 for D-Link and 16.48 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e. calculated path loss exponents (n) for D-link and LinkSys access points in a closed corridor for Building Two is 1.666 and 1.648. From Section 5.2.1 the calculated path loss exponents for D-Link and LinkSys access points in a closed corridor for Building One are 1.572 and 1.58. It can be said that signal strength deteriorates at a faster rate in Building Two. Even though the width of closed corridors in both Building One and Building Two are almost the same, the difference in path loss exponents can be attributed to differences in material used for construction and variation of multi-path caused by height of corridors.

4. Using Normal Plot, verify normal distribution.

Normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots from Figure 6.6 and Figure 6.7 indicate that

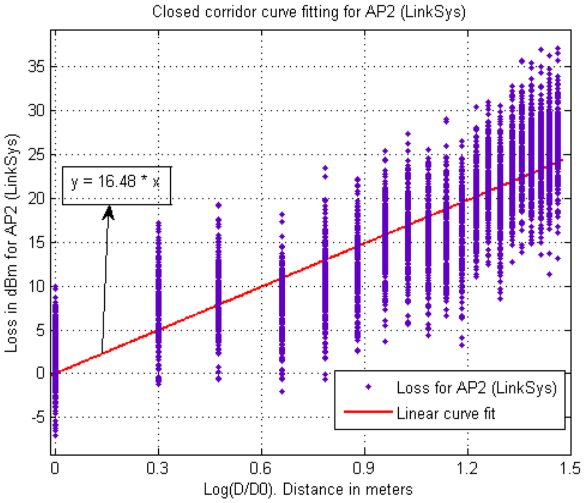


Figure 6.5: Building Two, closed corridor curve fitting for AP2 (LinkSys).

the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

   Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 3.9275 and for LinkSys standard deviation is 3.7699. Using (3.1) loss differential is standardized. Figure 6.8 and Figure 6.9 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test.

   As discussed in section 3.3 to evaluate goodness of fit we need to calculate test statistic X^2 and degrees of freedom *df*. Table 6.1 and 6.2 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. 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. As discussed in section 3.3, degrees of freedom df = 13 - 1 = 12.

   From Table 6.1 X^2 for AP1 (D-Link)= 11.7578, and from Table 6.2 X^2 for AP2

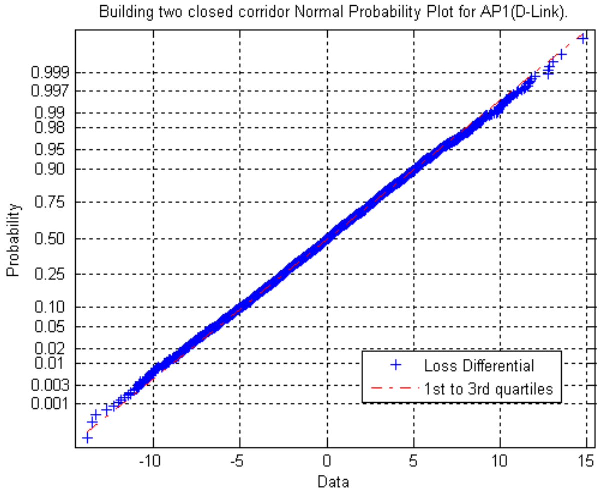


Figure 6.6: Building Two, closed corridor normal probability plot for AP1 (D-Link).

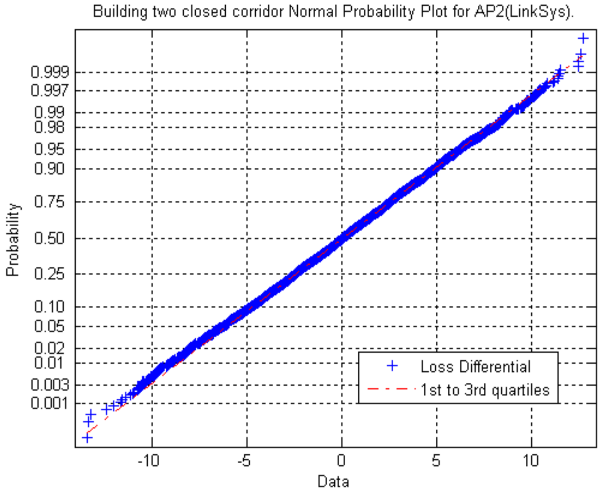


Figure 6.7: Building Two, closed corridor normal probability plot for AP2 (LinkSys).

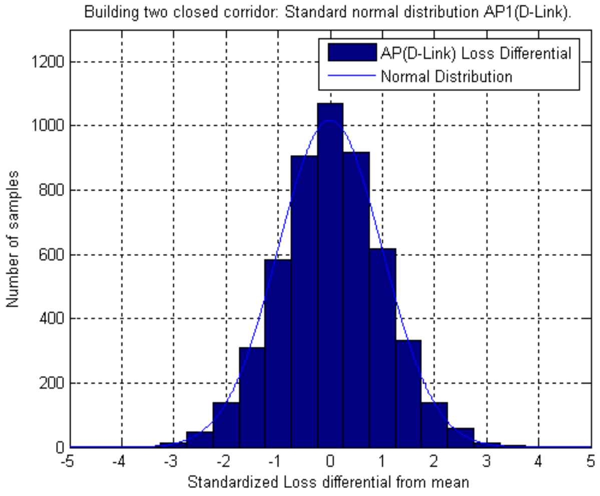


Figure 6.8: Building Two, closed corridor standard normal distribution for AP1 (D-Link).

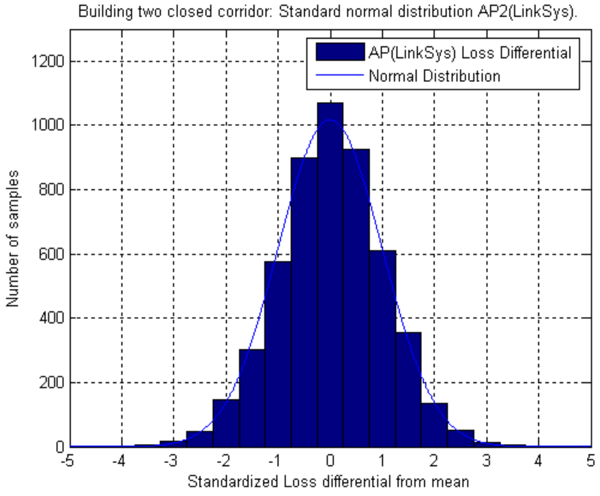


Figure 6.9: Building Two, closed corridor standard normal distribution for AP2 (LinkSys).

Table 6.1: Closed corridor X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.005156	0	0.005156
-4.75 to -4.25	1.00E-05	0.05156	0	0.05156
-4.25 to -3.75	7.80E-05	0.40217	0	0.40217
-3.75 to -3.25	0.000489	2.5213	3	0.090894
-3.25 to -2.75	0.002403	12.39	14	0.20925
-2.75 to -2.25	0.009245	47.667	49	0.037265
-2.25 to -1.75	0.027835	143.52	140	0.0862
-1.75 to -1.25	0.065591	338.19	309	2.519
-1.25 to -0.75	0.12098	623.76	582	2.7961
-0.75 to -0.25	0.17467	900.58	908	0.061169
-0.25 to 0.25	0.19741	1017.9	1069	2.5693
0.25 to 0.75	0.17467	900.58	918	0.33704
0.75 to 1.25	0.12098	623.76	618	0.053237
1.25 to 1.75	0.065591	338.19	331	1.53E-01
1.75 to 2.25	0.027835	143.52	138	0.2121
2.25 to 2.75	0.009245	47.667	59	2.6943
2.75 to 3.25	0.002403	12.39	13	0.030046
3.25 to 3.75	0.000489	2.5213	4	0.86726
3.75 to 4.25	7.80E-05	0.40217	1	0.88869
4.25 to 4.75	1.00E-05	0.05156	0	0.05156
4.75 to 5.25	1.00E-06	0.005156	0	0.005156
Total Observations	-	5156.074372	5156	-

Table 6.2: Closed corridor X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.005156	0	0.005156
-4.75 to -4.25	1.00E-05	0.05156	0	0.05156
-4.25 to -3.75	7.80E-05	0.40217	0	0.40217
-3.75 to -3.25	0.000489	2.5213	4	0.86726
-3.25 to -2.75	0.002403	12.39	16	1.0519
-2.75 to -2.25	0.009245	47.667	48	0.0023232
-2.25 to -1.75	0.027835	143.52	148	0.14002
-1.75 to -1.25	0.065591	338.19	302	3.8722
-1.25 to -0.75	0.12098	623.76	577	3.5057
-0.75 to -0.25	0.17467	900.58	899	0.0027646
-0.25 to 0.25	0.19741	1017.9	1069	2.5693
0.25 to 0.75	0.17467	900.58	927	0.7752
0.75 to 1.25	0.12098	623.76	609	0.34939
1.25 to 1.75	0.065591	338.19	355	0.83584
1.75 to 2.25	0.027835	143.52	136	0.39374
2.25 to 2.75	0.009245	47.667	50	0.11416
2.75 to 3.25	0.002403	12.39	12	0.012268
3.25 to 3.75	0.000489	2.5213	4	0.86726
3.75 to 4.25	7.80E-05	0.40217	0	0.40217
4.25 to 4.75	1.00E-05	0.05156	0	0.05156
4.75 to 5.25	1.00E-06	0.005156	0	0.005156
Total Observations	-	5156.074372	5156	-

Table 6.3: Closed corridor results from Building One and Building Two.

	Building One	Building Two
AP1 (D-Link). Path loss exponent (n)	1.572	1.666
AP2 (LinkSys). Path loss exponent (n)	1.58	1.648
AP1 (D-Link). Mean (μ)	0	0
AP2 (LinkSys). Mean (μ)	0	0
AP1 (D-Link). SD (σ)	3.9849	3.9275
AP2 (LinkSys). SD (σ)	4.022	3.7699

(LinkSys)= 13.6248. By using Table 3.2 we can identify to p-value associated with X^2 and df values.

We now have our chi-square test statistic X^2 for AP1 and AP2 (11.7578 and 13.6248), our predetermined level of significance (0.05), and our degrees of freedom (df =12). From Table 3.2 we can say X^2 for AP1 = 11.7578, 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).

Now for AP2 our value of $X^2 = 13.6248$, 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 AP2 (LinkSys).

Table 6.3 lists the results for AP1 and AP2 from Building One and Building Two. The difference in path loss exponents for a closed corridor in Building One and Building Two is about 5%. So, it can be said that path loss models from Building Two validate the path loss models developed in Building One.

7. Compare with two-ray model.

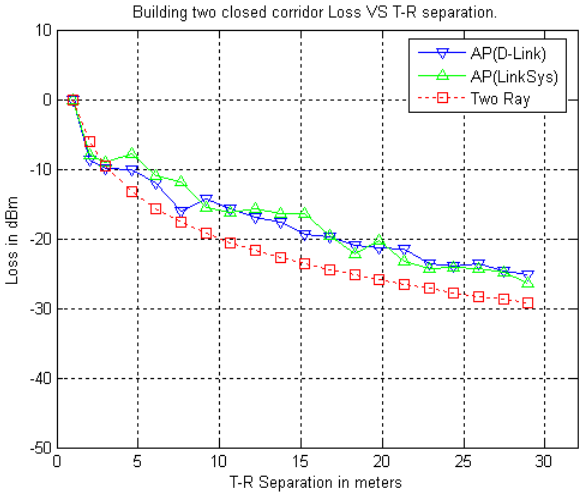


Figure 6.10: Comparison of closed corridor mean loss with two-ray model.

A graphical comparison is made between measured data and two-ray model. Figure 6.10 and Figure 6.11 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal strength deteriorates at a faster rate in two-ray model than in actual measurements.

6.3 Scenario 2: Building Two Classroom

Figure 6.12 and Figure 6.13 gives the loss (in dBm) versus T-R (Transmitter-Receiver) separation (in meters) for AP1 (D-Link) and AP2 (LinkSys) respectively. The experiment was conducted in an classroom at General Academic Building (GAB) in the University of North Texas main campus. As seen from Figure 6.12 and Figure 6.13 loss increases with the distance from the access point.

1. Calculate mean signal levels.

   Mean values of loss at each distance interval is calculated. Figure 6.14 shows a plot between mean loss for both the access points (D-Link and LinkSys) versus T-R separation. As seen from the figure, signal strength deteriorates with increasing T-R

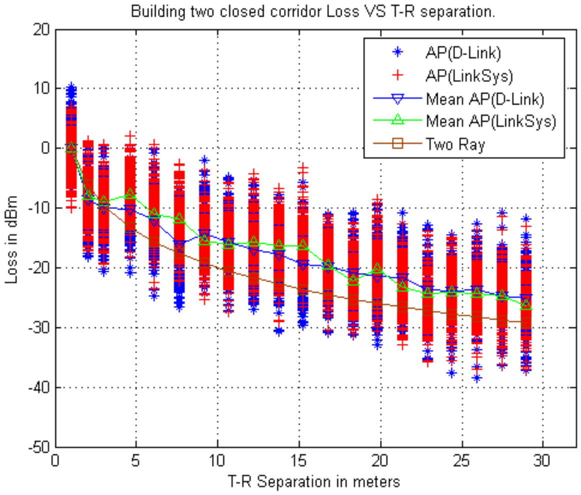


Figure 6.11: Comparison of closed corridor AP1 and AP2 loss with mean signal and two-ray model.

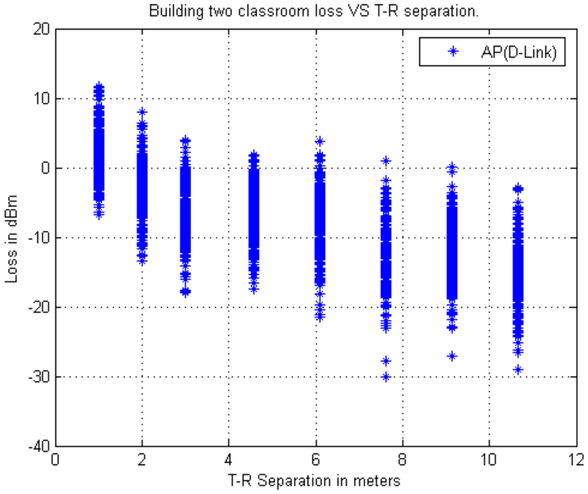


Figure 6.12: Building Two, classroom loss for AP1 (D-Link).

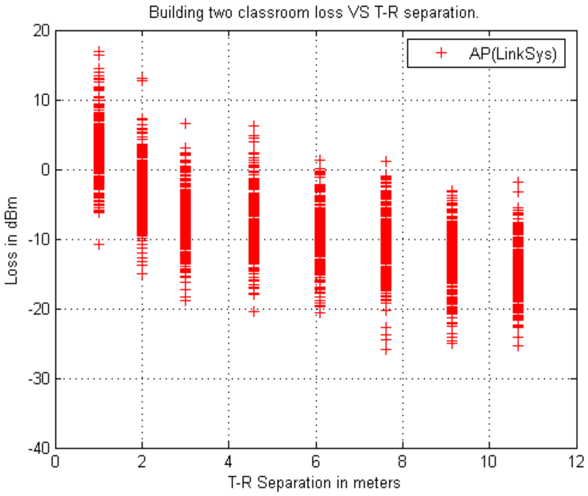


Figure 6.13: Building Two, classroom loss for AP2 (LinkSys).

separation. In the remaining part of the numerical analysis an equation is determined which describes the relationship between loss and T-R separation in a classroom for Building Two.

2. Using least squares method to calculate curve fitting.

   Using MATLAB curve fitting tool a linear fit is calculated using least squares method. Figures 6.15 and 6.16 show the linear curve fitting for the data collected using D-Link (AP1) and LinkSys (AP2) access points. Listed below are the output results from curve fitting.

   Classroom curve fitting for AP1 (D-Link).

   Linear model Poly1:

   $f(x) = p1 * x + p2$

   Coefficients (with 95 percent confidence bounds):

   $p1 = 13$ *(12.74, 13.26)*

   $p2 = 0$ *(fixed at bound)*

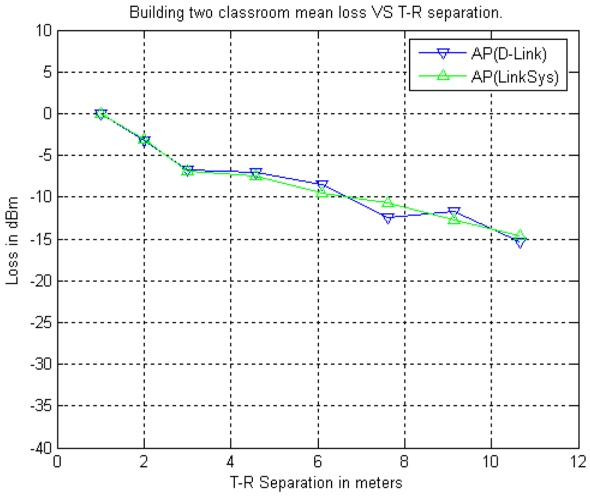


Figure 6.14: Building Two, classroom mean loss for AP1 and AP2.

Classroom curve fitting for AP2 (LinkSys).

Linear model Poly1:

*f(x) = p1 * x + p2*

Coefficients (with 95 percent confidence bounds):

p1 = 12.98 (12.72, 13.25)

p2 = 0 (fixed at bound)

3. Use curve fitting to evaluate path loss exponent n, in Log-distance Path Loss Model.

From Figures 6.15 and 6.16 and output results listed above we get the slope of the fitted curve to be 13.0 for D-Link and 12.98 for LinkSys. From (2.2), the slope of the fitted curve is $10n$, i.e. calculated path loss exponents (n) for D-link and LinkSys access points in a classroom is 1.3 and 1.298. From Section 5.2.1 the calculated path loss exponents for D-Link and LinkSys access points in a classroom for Building One are 1.258 and 1.263. It can be said that signal strength deteriorates at a faster rate in Building Two. Even though the width of dimensions of classrooms in both Building

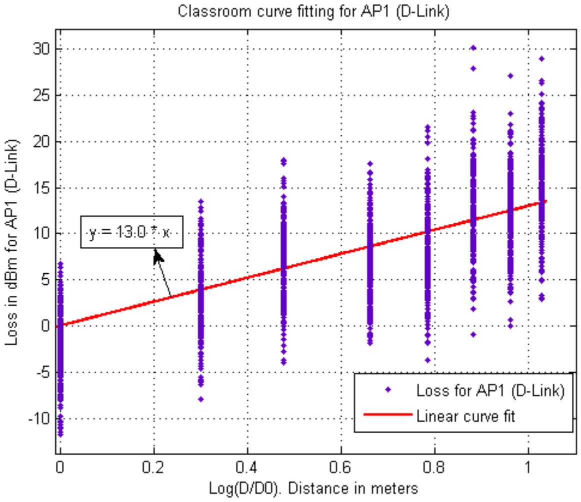


Figure 6.15: Building Two, classroom curve fitting for AP1 (D-Link).

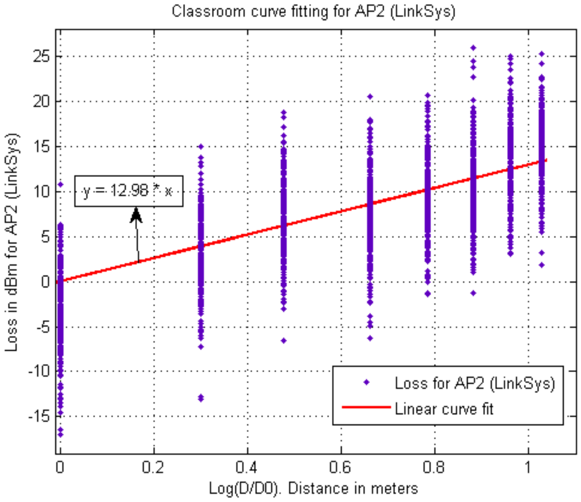


Figure 6.16: Building Two, classroom curve fitting for AP2 (LinkSys).

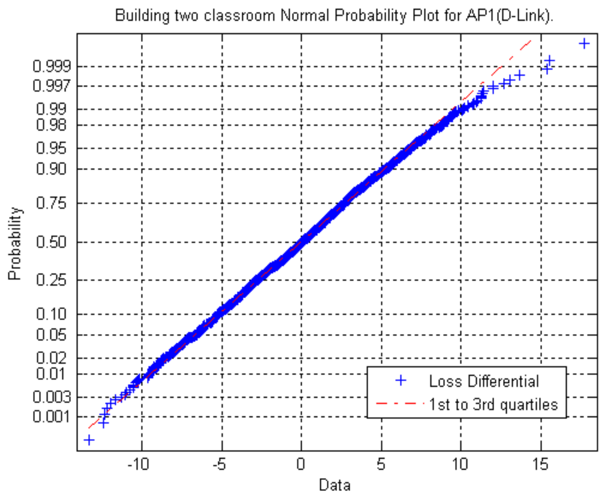


Figure 6.17: Building Two, classroom normal probability plot for AP1 (D-Link).

One and Building Two are almost the same, the difference in path loss exponents can be attributed to differences in material used for construction and types of furniture in the two rooms.

4. Using Normal Plot, verify normal distribution.

   Normal probability plot is used to verify if the variation of loss (loss differential) is distributed normally. The normal plots from Figure 6.17 and Figure 6.18 indicate that the assumption of normality is not unreasonable. Both plots pass the fat pencil test.

5. Evaluate standard deviation σ, for log-normal distribution, and determine standard normal distribution.

   Mean μ, and standard deviation σ of loss differential is calculated for both the access points. Mean is calculated to be 0 and standard deviation for D-Link access point is 4.127 and for LinkSys standard deviation is 4.2860. Using (3.1) loss differential is standardized. Figure 6.19 and Figure 6.20 show the plots for standard normal distributions for AP1 and AP2.

6. Calculate Chi-square Goodness-of-Fit Test.

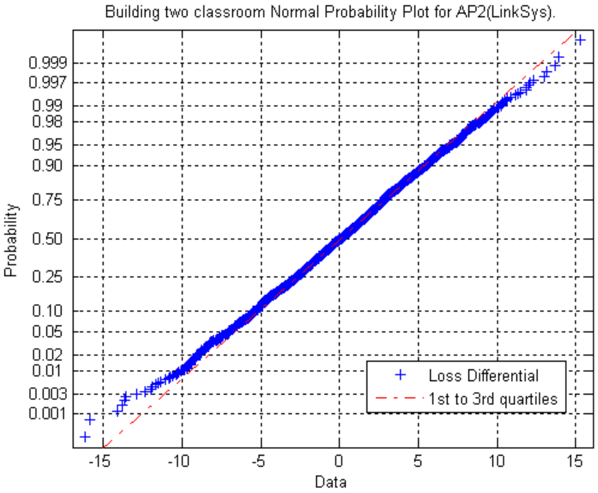


Figure 6.18: Building Two, classroom normal probability plot for AP2 (LinkSys).

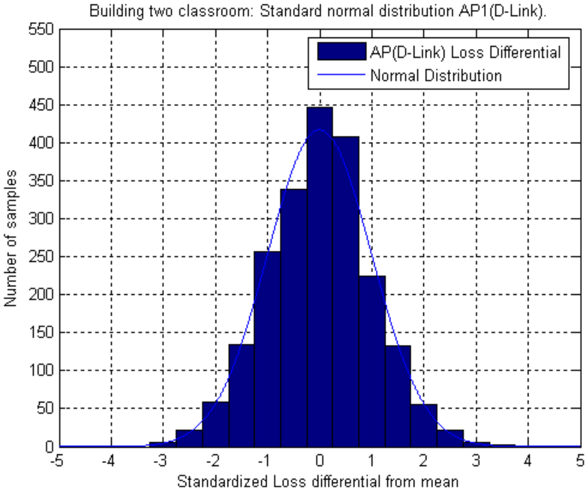


Figure 6.19: Building Two, classroom standard normal distribution for AP1 (D-Link).

Table 6.4: Classroom X^2 table for AP1 (D-Link).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.002112	0	0.002112
-4.75 to -4.25	1.00E-05	0.02112	0	0.02112
-4.25 to -3.75	7.80E-05	0.16474	0	0.16474
-3.75 to -3.25	0.000489	1.0328	0	1.0328
-3.25 to -2.75	0.002403	5.0751	6	0.16854
-2.75 to -2.25	0.009245	19.525	21	0.11136
-2.25 to -1.75	0.027835	58.788	59	0.00076798
-1.75 to -1.25	0.065591	138.53	134	0.14802
-1.25 to -0.75	0.12098	255.51	256	0.00095691
-0.75 to -0.25	0.17467	368.89	339	2.4226
-0.25 to 0.25	0.19741	416.94	446	2.026
0.25 to 0.75	0.17467	368.89	408	4.1454
0.75 to 1.25	0.12098	255.51	225	3.6421
1.25 to 1.75	0.065591	138.53	132	3.08E-01
1.75 to 2.25	0.027835	58.788	56	0.13218
2.25 to 2.75	0.009245	19.525	21	0.11136
2.75 to 3.25	0.002403	5.0751	5	0.0011124
3.25 to 3.75	0.000489	1.0328	2	0.90585
3.75 to 4.25	7.80E-05	0.16474	1	4.2351
4.25 to 4.75	1.00E-05	0.02112	1	45.37
4.75 to 5.25	1.00E-06	0.002112	0	0.002112
Total Observations	-	2112.017744	2112	-

Table 6.5: Classroom X^2 table for AP2 (LinkSys).

Bins	Area under standard normal curve	Expected = Total Obs * Area under STD curve	Observed	Chi Statistic
-5.25 to -4.75	1.00E-06	0.002112	0	0.002112
-4.75 to -4.25	1.00E-05	0.02112	0	0.02112
-4.25 to -3.75	7.80E-05	0.16474	1	4.2351
-3.75 to -3.25	0.000489	1.0328	2	0.90585
-3.25 to -2.75	0.002403	5.0751	7	0.73005
-2.75 to -2.25	0.009245	19.525	17	0.32664
-2.25 to -1.75	0.027835	58.788	62	0.17555
-1.75 to -1.25	0.065591	138.53	123	1.7406
-1.25 to -0.75	0.12098	255.51	238	1.1994
-0.75 to -0.25	0.17467	368.89	374	0.070658
-0.25 to 0.25	0.19741	416.94	419	0.010215
0.25 to 0.75	0.17467	368.89	413	5.2733
0.75 to 1.25	0.12098	255.51	233	1.9823
1.25 to 1.75	0.065591	138.53	133	0.22061
1.75 to 2.25	0.027835	58.788	62	0.17555
2.25 to 2.75	0.009245	19.525	18	0.11918
2.75 to 3.25	0.002403	5.0751	9	3.0353
3.25 to 3.75	0.000489	1.0328	1	0.0010397
3.75 to 4.25	7.80E-05	0.16474	0	0.16474
4.25 to 4.75	1.00E-05	0.02112	0	0.02112
4.75 to 5.25	1.00E-06	0.002112	0	0.002112
Total Observations	-	2112.017744	2112	-

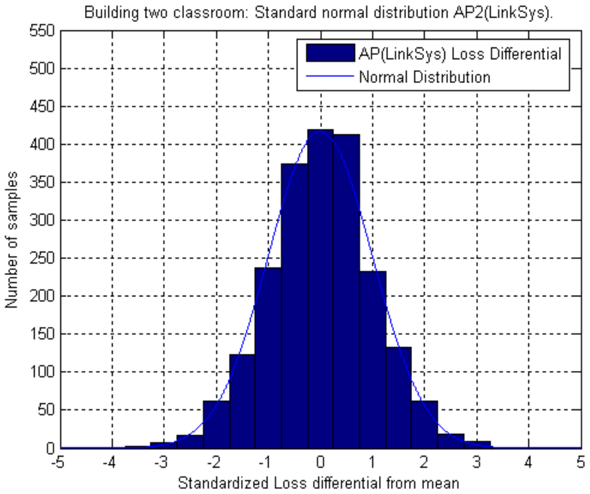


Figure 6.20: Building Two, classroom standard normal distribution for AP2 (LinkSys).

As discussed in section 3.3 to evaluate goodness of fit we need to calculate test statistic X^2 and degrees of freedom *df*. Table 6.4 and 6.5 are used for calculating Chi-square test statistic X^2 for AP1 and AP2. To find the expected value for a particular bin, the area under standard normal curve for the bin is multiplied by total observations. Chi-square test statistic is calculated using (3.2). 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. As discussed in section 3.3, degrees of freedom *df* = 13 - 1 = 12.

From Table 6.4 X^2 for AP1 (D-Link)= 13.2181, and from Table 5.6 X^2 for AP2 (LinkSys)= 15.0594. By using Table 3.2 we can identify to *p*-value associated with X^2 and *df* values.

We now have our chi square statistic X^2 for AP1 and AP2 (13.2181 and 15.0594), our predetermined level of significance (0.05), and our degrees of freedom (*df* =12). From Table 3.2 we can say X^2 for AP1 = 13.2181, 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).

Table 6.6: Classroom results from Building One and Building Two.

	Building One	Building Two
AP1 (D-Link). Path loss exponent (n)	1.258	1.3
AP2 (LinkSys). Path loss exponent (n)	1.263	1.298
AP1 (D-Link). Mean (μ)	0	0
AP2 (LinkSys). Mean (μ)	0	0
AP1 (D-Link). SD (σ)	3.7607	4.127
AP2 (LinkSys). SD (σ)	4.053	4.286

Now for AP2 our value of $X^2 = 15.0594$, 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 AP2 (LinkSys).

Table 6.6 lists the results for AP1 and AP2 from Building One and Building Two. The difference in path loss exponents for a classroom in Building One and Building Two is less than 5%. So, it can be said that path loss models from Building Two validate the path loss models developed in Building One.

7. Compare with two-ray model.

   A graphical comparison is made between measured data and two-ray model. Figure 6.21 and Figure 6.22 show the comparison between the theoretical two-ray model and measured data. It can be seen from these plots that signal strength deteriorates much higher in two-ray model when compared to classroom measurements.

6.4 Summary

Tables 6.3 and 6.6 compare Path loss exponent (n), mean (μ) and Standard deviation (σ) for Closed Corridor and Classroom scenarios in Building One and Building Two. It can be

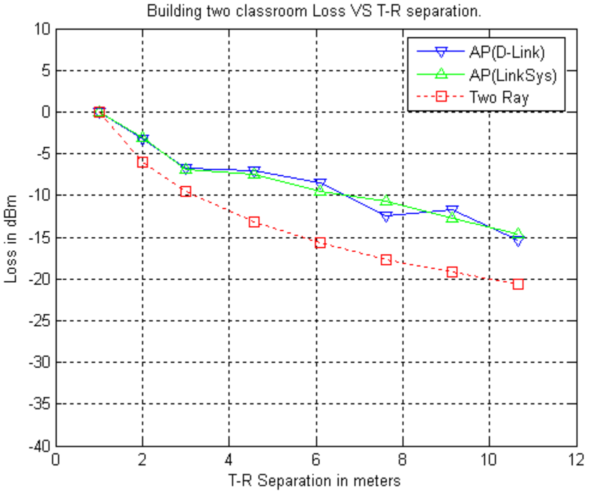


Figure 6.21: Comparison of classroom mean loss with two-ray model.

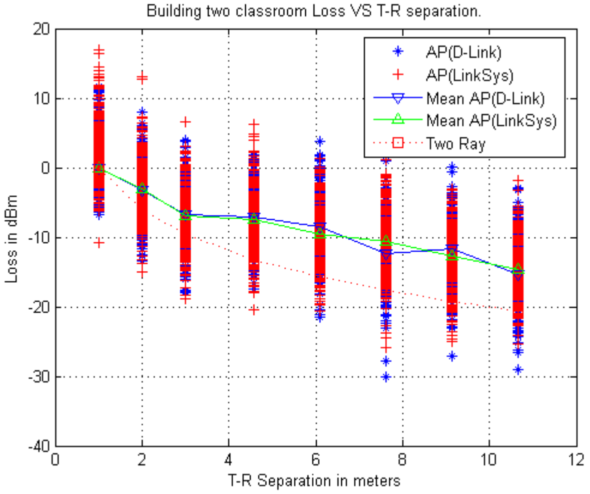


Figure 6.22: Comparison of classroom AP1 and AP2 loss with mean signal and two-ray model.

seen that the Path loss exponent (n), mean (μ) and Standard deviation (σ) of the respective scenarios are approximately equal. So the path loss models developed in chapter 5 can be used in generation of Propagation models for indoor environment.

6.5 Conclusion

In this study indoor propagation models were developed for an Open Corridor, a Closed Corridor, a Classroom and a Computer lab.

In Chapter 2 a brief description of different types of propagation models (Empirical & Deterministic models) was given. Chapter 2 also gives a description of Log-distance Path Loss Model and Log-Normal Shadowing (Empirical model), and Two-Ray Model (Deterministic model). These models are later used in determining path loss equations for different scenarios.

In Chapter 3 statistical tools used to support the findings of the study are described. A detailed description of Normal Plot, Standard Normal Distribution, and Chi-square Goodness-of-Fit Test is given. The chapter also discusses Curve Fitting which was used to calculate the Path Loss exponent (n).

In Chapter 4 a detailed description of the measurement scenarios, the experimental setup, the software, and hardware used for measurements was given.

In Chapter 5 a numerical analysis of measurements in each scenario was conducted and the study determined equations that describe path loss for each scenario. This chapter concludes by accepting Alternative Hypotheses for both the Research Questions.

Chapter 6 does a comparative study of the measurement scenarios in Building One and Building Two. The chapter concludes that there is no difference in path loss models calculated in Building One and Building Two.

6.6 Future Work

We conclude by outlining possible directions for future research:

1. A further extension to this study could be developing an algorithm for Optimal Access Point Selection and Channel Assignment. The path loss equations, and multipath fading calculated in this study can be used to simulate propagation in indoor environments. By combining these two studies a GUI based model can be developed for efficient positioning of Access Points in an indoor environment. A user can specify the maximum number of access points, and the algorithm would find the optimal placement of access points in a given service area.

2. IEEE 802.11b and 802.11g use the unlicensed ISM frequency. Many electric appliances such as microwave ovens, cordless phones, and Bluetooth devices use the same frequency band. The Propagation models can further be extended to consider interferences between these electric devices and wireless LANs.

BIBLIOGRAPHY

[1] T.S. Rappaport. *Wireless Communications Principles and Practice*. Prentice Hall, 1996.

[2] William Stallings. *Wireless Communications and Networks*. Prentice Hall, 2002.

[3] IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. *IEEE Standard 802.11*, 1997.

[4] G.A. Halls. HIPERLAN: the high performance radio local area network standard. *Electronics and Communication Engineering Journal*, 6:289–296, December 1994.

[5] IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications - Amendment 4: Further higher-speed physical layer extension in the 2.4 GHz band. *IEEE Standard 802.11g*, 2003.

[6] IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications - Amendment 2: Higher speed physical layer (PHY) extension in the 2.4 GHz band. *IEEE Standard 802.11b*, 1999.

[7] SIG. Bluetooth specification version 1.1. *http://www.bluetooth.com/dev/specifications.asp*, February 2001.

[8] IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications - Amendment 1: High-speed physical layer in the 5 GHz band. *IEEE Standard 802.11a*, 1999.

[9] D. Dobkin. Indoor propagation issues for wireless LANs. *RF Design; www.rfdesign.com*, September 2002.

[10] H.J. Zepernick and T.A. Wysocki. Multipath channel parameters for the indoor radio at 2.4 GHz ISM band. *IEEE Veh. Technol. Conf.*, 1:190–193, May 1999.

[11] A.F. Agelet, A. Formella, J.M.H. Rabanos, I.F. de Vicente, and P.F. Fontan. Efficient ray-tracing acceleration techniques for radio propagation modeling. *IEEE Veh. Technol. Conf.*, 49:2089–2104, November 2000.

[12] M. Iskander, Z. Yun, and Z. Zhang. Outdoor/indoor propagation modeling for wireless communications systems. *IEEE Antennas and Propagation Society International Symposium*, 2:150–153, July 2001.

[13] S.P.T. Kumar, B. Farhang-Boroujeny, S. Uysal, and C.S. Ng. Microwave indoor radio propagation measurements and modeling at 5 GHz for future wireless LAN systems. *Microwave Conference, 1999 Asia Pacific*, 3:606–609, 30 November-3 December. 1999.

[14] K.A. Remley, H.R. Anderson, and A. Weisshar. Improving the accuracy of ray-tracing techniques for indoor propagation modeling. *IEEE Veh. Technol. Conf.*, 49:2350 – 2358, November 2000.

[15] W.K. Tam and V.N. Tran. Multi-ray propagation model for indoor wireless communications. *Electronics and Communication Engineering Journal*, 32:135–137, January 1996.

[16] J. Tarng and T. Liu. Effective models in evaluating radio coverage on single floors of multifloor building. *IEEE Veh. Technol. Conf.*, 48:782–789, 1999.

[17] A. Neskovic, N. Neskovic, and G. Paunovic. Modern approaches in modeling of mobile radio systems propagation environment. *IEEE Communications Surveys*, http://www.comsoc.org/pubs/surveys, 2000.

[18] T. Holt, I. C. Pahlavan, and J. F. Lee. Ray tracing algorithm for indoor radio propagation modeling. *3rd IEEE Int. Symp. on Personal, Indoor and Mobile Radio Communications*, October 1992.

[19] J. W. McKown and R. L. Hamilton. Ray tracing as a design tool for radio networks. *IEEE Network*, 6:27–30, November 1991.

[20] S. Y. Seidel and T. S. Rappaport. A ray tracing technique to predict path loss and delay spread inside buildings. *IEEE Global Telecommunications Conf.*, 2:649–653, December 1992.

[21] R. Valenzuela. A ray tracing approach to predicting indoor wireless transmission. *IEEE Veh. Technol. Conf.*, 43rd:214–218, May 1993.

[22] IEEE. Wireless LAN medium access control (MAC) and physical layer (PHY) specifications Amendment 6: Medium Access Control (MAC) security enhancements. *IEEE Standard 802.11i*, 2004.

[23] J. C. Chen, M. C. Jiang, and Y. W. Liu;. Wireless LAN security and IEEE 802.11i. *Wireless Communications, IEEE*, 12:27–36, February 2005.

[24] Cyrus Peikari and Seth Fogie. *Maximum Wireless Security*. Sams, 2002.

[25] Statit Software:Process Management Tools and Applications. Statit Bulletin. *http://www.statit.com*, November 1999.

[26] The MathWorks Inc. MATLAB HELP. http://www.mathworks.com.

[27] StatsDirect Statistical Software. Statistical help. http://www.statsdirect.com.

[28] LinkSys A Division of Cisco Systems, Inc. http://www.LinkSys.com/.

[29] D-Link Corporation/D-Link Systems, Inc. http://www.dlink.com/.

[30] M. Milner. Network stumbler version 0.4.0. NetStumbler; www.netstumbler.com, 2001-2004.