Comparison of Ray Tracing and Measurement Results for 5GHz Band Wireless Channels

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Master of Science

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This thesis titled
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Abstract

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Comparison of Ray Tracing and Measurement Results for 5GHz Band Wireless Channels

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This thesis describes a comparison of ray tracing results obtained using a commercial ray tracing software tool (Wireless Insite) to measured channel impulse response results for 5 GHz wireless band channels. Four sets of measurements were taken at an open parking lot by varying the transmitter and receiver positions with respect to the building. The channel impulse response, mean excess delay and root mean square delay spread were obtained from the measurements. We approximated the same environment in the software and obtained the channel impulse response and root-mean-square (RMS) delay spread (DS). The ray tracing and measured power delay profiles (PDPs) were first compared qualitatively, then the measured and ray tracing RMS-DS values were compared quantitatively.

An accuracy analysis was done by varying the objects used in the ray tracing program and assessing the effects of this on results. A perturbation analysis was also conducted by varying by small amounts the transmitter distance, receiver distance, the number of reflections, and combinations of these to assess potential errors in our measured distance and hypothesized numbers of significant reflections. The results showed that the PDPs obtained using ray tracing are comparable to the measured results.
qualitatively and the perturbation analysis helped in modeling the inaccuracies involved during the measurements.

Director of Thesis: David W. Matolak

Approved: _____________________________________________________________

David W. Matolak

Associate Professor Electrical Engineering and Computer Science
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<tr>
<td>1G</td>
<td>First Generation</td>
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<tr>
<td>2G</td>
<td>Second Generation</td>
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<tr>
<td>3G</td>
<td>Third Generation</td>
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<tr>
<td>4G</td>
<td>Fourth Generation</td>
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<tr>
<td>PDP</td>
<td>Power Delay Profile</td>
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<tr>
<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>DS</td>
<td>Delay Spread</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication Service</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Networks</td>
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<tr>
<td>W-CDMA</td>
<td>Wireless Code Division Multiple Access</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile communications</td>
</tr>
<tr>
<td>DTED</td>
<td>Digital Terrain Elevation Data</td>
</tr>
<tr>
<td>DXF</td>
<td>Drawing Exchange Format</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>NSMA</td>
<td>National Spectrum Management Association</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite Difference Time Domain</td>
</tr>
<tr>
<td>TIFF</td>
<td>Tagged Image File Format</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>BVS</td>
<td>Berkeley Varitronics Systems</td>
</tr>
<tr>
<td>LOS</td>
<td>Line Of Sight</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitter</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
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<tr>
<td>Rx</td>
<td>Receiver</td>
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<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>NTT</td>
<td>Nippon Telegraph and Telephone</td>
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<tr>
<td>NMT</td>
<td>Nordic Mobile Telephone</td>
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<tr>
<td>TACS</td>
<td>Total Access Communication Systems</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone System</td>
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<tr>
<td>DAMPS</td>
<td>Digital Advanced Mobile Phone System</td>
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<tr>
<td>WiSE</td>
<td>Wireless Systems Engineering Software</td>
</tr>
<tr>
<td>CIR</td>
<td>Channel Impulse Response</td>
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<tr>
<td>FSPL</td>
<td>Free Space Path Loss</td>
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<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>dBm</td>
<td>Decibels above 1 milliwatt</td>
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<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>m</td>
<td>Meter</td>
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<tr>
<td>ns</td>
<td>Nano Second</td>
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Chapter 1

Introduction

1.1 Introduction

This chapter describes the recent growth of wireless communications and related work in the field of wireless communication, specifically work on channel modeling and ray tracing models. Section 3 in this chapter discusses the importance of wireless channel modeling and section 4 provides a literature review that summarizes related work in channel modeling and ray tracing techniques. Section 5 explains the scope of this thesis.

1.2 Growth of Wireless Communication

Wireless communication is an integral segment in the field of communications. The beginning of wireless communications was in the early industrial age where information was transmitted by means of torch lights, smoke signals, flashing mirrors, etc., over short distances [1]. In that period information was transmitted only over line of sight (LOS) paths. The telegraph and telephone systems came into existence in 1838 and 1895, respectively, which laid some of the foundation upon which radio communication was developed. There were significant advancements in the field of radio communications from that period.

The first radio mobile telephone, invented in 1924, was the major development in mobile radio that happened soon after 1915, when the first wireless voice transmission was established [1]. Much research and development on radio also took place during the two world wars. In the 1950’s and 60’s, there were many more developments in the wireless field, out of which the main concept developed was the cellular concept. By
using this cellular concept, a larger number of users could operate on the same frequencies without significantly disturbing one another. This was possible via the frequency re-use concept, which enabled a given portion of frequency spectrum to be re-used after a sufficient separation distance (this concept is also used in broadcast radio). The cellular concept created new opportunities to use wireless technologies. The first cellular concept design was tested and deployed in Chicago in 1983.

After the early attempts at using mobile radio telephone, the cellular 1st generation (1G) started in the early 1980’s [1]. The 1G systems used analog frequency modulation and frequency division multiple access (FDMA) / frequency division duplexing (FDD). This first cellular system was primarily designed to carry narrow band circuit-switched voice services. Major examples of 1G systems are Nippon Telegraph and Telephone (NTT), Nordic Mobile Telephone (NMT), Total Access Communication Systems (TACS), and Advanced Mobile Phone System (AMPS) that were used in the United States and Australia. The data rates and data carrying capacity of the 1G cellular systems were moderate and the cost was very high. Narrowband digital AMPS (DAMPS) was developed later as a newer version of the AMPS systems. It was designed to support 3 times the number of users of the AMPS systems.

The second generation (2G) cellular systems deployed in the early 1990’s (including DAMPS) had more features than the 1G cellular systems [2]. They had larger data rates and lower costs. The 2G systems used digital modulation schemes and time division multiple access (TDMA) and code division multiple access (CDMA) techniques. All the 2G systems also used FDD. Major 2G standards included the Global System for Mobile Communication (GSM), Personal Digital Cellular (PDC, Japan) and the CDMA
standard, Interim Standard-95 (IS 95, which evolved to cdmaOne). These systems were also more power efficient, as they used advanced error correction coding, sleep modes, and transmit power control. These systems were also used for supporting voice services as in 1G systems. Moreover, 2G systems provided data services like short messaging services (SMS) and email. The Integrated Digital Enhanced Network (iDEN) was introduced in 1994 by Motorola; this was a TDMA based system which provided an exclusive push to talk feature in cell phones.

The 2.5G set of systems are advanced versions of the 2G cellular systems that provide a larger capacity by increasing the number of “bearer slots” [2] allocated to a user. For 2G systems only one bearer slots was allocated, which limits the data rate. For the 2.5G systems the maximum data rate available was 115 kbps compared to 9.6 kbps for 2G systems. General packet radio service (GPRS) and high speed circuit switched data (HSCSD) are examples of 2.5G standards. The 2.5G systems are mainly aimed at increasing the data rates of the 2G systems.

The need for even larger data rates and spectral efficiency lead to newer sets of cellular systems defined as 3G systems [2]. The 3G systems were compatible with all the older systems. These systems aimed to solve the incompatibility issues between the GSM and CdmaOne standards. The 3G systems enabled the single mobile user to use voice and data transfer simultaneously. CdmaOne, also known as Cdma 2000, was developed on the basis of IS 95 and IS 95B. The wideband CDMA (W-CDMA) system was developed based on the GSM principles and is also called Universal Mobile Telecommunication Service (UMTS). CdmaOne provides high data rates and high quality of service compared to the older 2G and 2.5G standards.
Due to the continuing increase in the number of users and the increased need for higher data rates, wireless local area networks (WLANs) became a solution for portable communications [2]. The primary standard for WLANs is the IEEE 802.11 standard. There are 3 major types of standards within the IEEE 802.11 standard. One is the 802.11a standard used in the 5 GHz band, and the second one is the 802.11b standard used in the 2.4 GHz band. The third most popular version is the 802.11g which works in both 5 and 2.4 GHz bands. The 802.11g standard supports facilities such as roaming and dual band public WLAN’s. The primary difference between the WLANs and cellular (any generation) is that the WLANs are designed to operate in very low mobility environments, or portable environments, where a user may move a laptop for example from one location to another, but does not communicate with the LAN while in motion. In contrast, cellular radio systems were designed from the beginning to operate in vehicular environments.

1.3 Importance of Channel Modeling

In wireless communication, the most stressful element to the transmitted signal can be the channel. In a terrestrial setting, the channel can consist of a number of components which will cause the transmitted signal to undergo multiple reflections, refractions, and diffractions. Reliable transmission of a signal through a communication channel faces challenges such as path loss, delay and phase shift, shadowing, and noise and interference [1]. Modeling of wireless channels helps in determining how the channel affects the transmitted signal quantitatively. For narrow band signals, it helps in estimating accurately the received signal power variations.
Channel modeling also helps in designing channel countermeasures such as equalization and diversity. Knowledge of channel characteristics also helps in reducing system design costs, since accurate knowledge of the power of various multipath components and the delay associated with each multipath component can be directly used in receiver design. The effectiveness of channel coding can be improved by having an accurate channel model that provides knowledge of the environment to be analyzed. Wireless channel models can also be used in communication system analysis, e.g., they may enable simulation of delay and packet loss ratio, which is helpful in ensuring good quality of service (QoS) for both 3G and 4G standard users [3].

1.4 Literature Review

This section discusses related work in the field of wireless channel modeling, particularly for ray tracing and the hybrid (a combination of deterministic and statistical approach) models. We also review comparisons of ray tracing with measured results in various frequency bands.

Ray Tracing is an analytical technique by which the propagation of electromagnetic waves through a communication channel can be predicted and modeled. This can be done when objects in the environment are large compared to the wavelength. Ray tracing employs various “ray-optics” techniques (uniform theory of diffraction) to model propagating waves by rays.

The author of [4] discusses a comparison of ray tracing results with measured results for an outdoor environment for a frequency range of 2.2 to 2.6 GHz. The measurements were done in two different areas: one was an area in which line of sight (LOS) was maintained between transmitter and receiver, and the other covered non line
of sight (NLOS) regions. A network analyzer was used for all measurements. Statistics for delay profiles-- RMS delay spread-- were used to characterize the channel dispersion. The author also conducted analysis for finding the effects of varying object dielectric constant on the simulated results. The analysis showed that the results are not significantly affected by the variation of dielectric constant of the walls in the environment, for measurements conducted in LOS region, whereas the results can be significantly affected by the variation in NLOS regions. Comparison of simulated and measured results, in terms of both propagation path loss and RMS delay spread, was also done by varying the layout of the geometry of the environment under consideration. The results show that varying the simulation layout (ray tracing model) geometry and neglecting distant environment components significantly affects the path loss and RMS delay spread.

Reference [5] describes an analysis of the accuracy of ray tracing techniques in comparison with measurements. The analysis was done at two frequencies, 1.8 and 2.5 GHz. The measurements were conducted in an indoor environment on different floors of an engineering building at the University of Cantabria, Spain. The transmitter and receiver antenna were placed at 2.1 m and 1.5 m above the floor, respectively. The receiver antenna was moved along a 2 m long linear path. The authors conducted both narrow band and wide band channel measurements and analyzed results using a simulation tool based on geometric optics (GO) and the uniform theory of diffraction (UTD) (both high-frequency methods, like ray tracing). For narrow band analysis the vector signal analyzer recorded data at every 0.032 mm. The transmitter position was fixed and the motion of the receiver was controlled by a computer motor controller.
Measured and analytical ray tracing power delay profiles showed good agreement in the wideband analysis, specifically in terms of statistics of RMS-DS values. In the narrow band analysis, the mean power and small scale fading statistics were compared and results shows that site specific model results give good agreement with measured results.

Wireless channel modeling is of great importance in determining how the channel affects a transmitted signal and this information can be used in design of channel counter measures. In [6], the authors describe a channel characterization effort on a university campus, specifically Ohio University. The wideband measurements were done in the 5 GHz band. Parameters that were computed from the data include mean excess delay, root mean square delay spread, maximum excess delay, and delay window; these were obtained from the measured power delay profiles. Frequency correlation estimates were also obtained. Campus channel models were also developed.

Reference [7] described modeling the wireless channel from measured data in an outdoor (airport) environment in the 5 GHz band. The MATLAB® routines written for processing measured data and determining channel models were also used in this thesis. This dissertation also provides a detailed explanation of various statistical parameters and thresholding techniques used in data processing and channel model development.

In [8], the author discusses channel modeling via ray tracing programs for an indoor environment. Two sets of measurements were done at identical positions, one with an omni directional antenna at both transmitter and receiver and the other with directional antennas at both ends. Channel statistics discussed in this paper are signal power attenuation and RMS delay spread. The ray tracing program was used for generating “maps” of signal power attenuation and RMS delay spread. The maps were generated by
moving the receiver, and for each location of interest, the received signal power was computed for a cone of rays from the transmitter. The author also described methods by which the processing can be reduced, and the importance of these maps for designing antenna beam widths and quantifying coverage. There is a good agreement between measured and analytical results; the authors used their results to generate maps for analyzing the quality of coverage.

The author in [9] describes various methods by which ray tracing results can be improved. The precision of the ray tracing method was assessed by comparing simulation results with measured results for indoor environments, where the size of scatterers is comparable to the operating wavelength. The paper provides background discussion on various parameters such as diffraction coefficients by which the accuracy of ray tracing can be improved. The reference is cited here because this thesis also addresses the accuracy of ray tracing techniques in comparison to measured results. The author of [9] states that when the size of the obstacle is comparable to the wavelength, diffracted rays are more prominent than reflected rays.

The authors in [10] discuss major characteristics of wireless channel propagation in an outdoor environment. This paper also explains the importance of conducting channel measurements in the appropriate (in this case 5 GHz) band. The actual measurements were conducted at 5.3 GHz in urban, rural and suburban regions. This paper provides ranges of values for different parameters like mean excess delay and RMS delay spread. The RMS delay spread for the wideband outdoor propagation channel ranged from 22-88 ns and is dependent on the height of the transmitter as well as link distance.
In [11], three different models were developed in which the geometry of propagation paths can be predicted accurately. Measurements were conducted at 5.3 GHz on an open road with trees, an open road with buildings, and a parking lot where many vehicles are parked. The transmitter was placed at 3 different heights from 2 m to 3.5 m. The receiver was placed at a constant 1.8 m height. The measurements were also conducted at regular intervals of 15 min with the antennas fixed. The first measurements were conducted to analyze the signal gain when the receiver is in motion and the second measurements provide the variations in signal strength due to the environmental effects such as wind, trees and buildings. The author modeled the environment using ray tracing for all these scenarios and compared the signal gain with that of the measured signal gain. The measured signal path gain agreed very well with the modeled results for the first two scenarios and in the case of parking lot, the difference between the statistical and deterministic (ray tracing?) approach was only approximately 1dB.

There are many hybrid models that have been developed via a combination of deterministic and statistical channel modeling techniques. An example of a hybrid model developed for an indoor environment is discussed in [12]. Measurements were done at 2.44 GHz, and deterministic analyses were conducted which predicted the propagation effects quite well. The site specific (deterministic) model uses ray tracing technique for analyzing the signal strength at various positions. The hybrid model, which is a deterministic approach, was shown to predict the signal statistics along with the cluttering effects of the environment by considering the value of diffused scattering: this scattering was classified as either light scattering or heavy scattering, and is included in the model along with other propagation phenomena.
Various textbooks were also used as references in this thesis. Reference [13] is a useful text that discusses the channel impulse response and its characterization. In [14], the author explains basic propagation of radio waves and effects upon wireless signals. Chapters 1 and 2 discuss the various frequency band allocations, the basics of very high frequency (VHF) and ultra high frequency (UHF) wave propagation, and the growth of wireless communications. Chapter 5 discusses various fading models and various methods of characterizing environments with many multipath components. The concept of RMS delay spread is explained in chapter 6. A basic description of ray tracing is provided in chapter 7.

As noted, in addition to purely deterministic ray tracing models, there are also hybrid models that are developed using site specific models in combination with models developed using statistical data in indoor environments [12]. This paper explains a hybrid model that was developed by combining the ray tracing techniques, to calculate the mean signal strength, along with the simulation model, which provides the cluttering effect that is caused by the scatterers and the roughness of the surface, to characterize an indoor environment.

Another useful reference is the software manual [15] for the ray tracing program we use, Wireless Insite. The manual describes software features and the material and antenna databases built into the software. In this thesis, this software is used to model the same environment where measurements were taken. The software generates power delay profiles, which are compared with measurements.
1.5 Thesis Scope

The objective of this thesis is to compare ray tracing results to measured results for 5 GHz wireless band channels. The measurements were carried out at a center frequency of 5120 MHz in an outdoor environment (the Innovation Center parking lot, Ohio University, Athens, OH). The measurements were taken at four different positions in the same environment by moving the transmitter and receiver locations with respect to the building. The data obtained from the measurements was used to generate power delay profiles and RMS delay spread was calculated.

The Wireless Insite software is an electromagnetic simulation tool that was used to predict the propagation of waves through a wireless channel. The same outdoor environment in which measurements were taken was modeled (approximated) in the Wireless Insite software, and analytical power delay profiles and delay spreads were obtained. Based on the results obtained from ray tracing and measurements, a quantitative comparison of delay domain statistics (primarily RMS-DS) was done.

In this thesis, the accuracy of ray tracing results with respect to measured results is analyzed by conducting a “perturbation analysis,” in which we vary multiple parameters in the analytical model (e.g., transmitter position, receiver position, antenna gain) by small amounts and see how they affect delay domain statistics. The aim of the perturbation analysis was to determine how difficult it would be to make analytical results agree with measurements, and in addition judge the sensitivity of the ray tracing program to small changes in environment parameters. The accuracy of the ray tracing results were also judged by restricting the maximum number of reflections and diffractions the program uses in its computations.
1.6 Thesis Outline

Chapter 1 reviews the growth of wireless communications, the importance of channel modeling, and previous related work done in the field of wireless communication, channel modeling and ray tracing. This chapter also describes the scope of this thesis. The second chapter explains the channel impulse response (CIR) and important CIR statistics like mean excess delay (MED) and RMS delay spread. Chapter 2 also gives a detailed description of the ray tracing model, Wireless Insite, and its features. Chapter 3 describes the environment, measurement technique, transmitter set up, receiver set up, sample power delay profile (PDP) and RMS delay spread results. Chapter 4 discusses the comparison of power delay profiles obtained from ray tracing and measurements, comparison of RMS delay spreads, and the results of the perturbation analysis conducted to analyze the accuracy of ray tracing results in comparison to the measured results. Last, chapter 5 provides a summary, conclusions and future work for this thesis.
Chapter 2

Overview of Channel Modeling

2.1 Introduction

This chapter provides an overview of wireless channel modeling. Section 2 discusses the channel impulse response. Section 3 explains important channel impulse response statistics including mean excess delay and RMS delay spread. Section 4 discusses ray tracing models and various types of channel models. Section 5 explains the Wireless Insite software and its features.

2.2 Channel Impulse Response

The impulse response of a channel is defined as the response of a channel when the input is a unit impulse [13]. As noted, the channel often represents the most stressful impairment to wireless communications. Typically there is a large number of objects in the environment, and some of these object positions vary with time. The transmitted signal can be reflected, diffracted and scattered from these objects, and this leads to multiple replicas of signal arriving at the receiver; these replicas are termed multipath components. The impulse response of a wireless channel is generally time varying and spatially varying, so comprehensive analysis often addresses both these dimensions. The impulse response provides a linear system perspective but it also encompasses information regarding the nature of propagation delays due to the reflections and diffractions from various sources and the delays and the path loss associated with all multipath components.
A linear channel can be completely characterized by its impulse response [13]. The distortionless channel is defined as a channel which has same delay for all the frequency components associated with it. The impulse response of a distortionless channel is the output at time \( t \) in response to an impulse input at time \( t-\tau \), and this is given by,

\[
g(\tau,t)=A(t)\delta(t-\tau(t))
\]  

(2.1)

where \( A(t) \) represents the time dependent attenuation factor, \( \pi(t) \) is time-varying delay. Equation (2.1) corresponds to a distortionless channel only if the rate of the time variation is much slower than the signaling rate. Distortionless means that the signal “shape” is not changed by the channel. This corresponds to a frequency domain response that is flat in amplitude, and linear in phase. For time invariant distortionless channels, the impulse response becomes,

\[
g(t)=A \delta(t-\tau)
\]  

(2.2)

The impulse response of a wireless channel that consists of large number of multipath components will be time and spatially varying, which yields a channel that is (if characterized statistically) statistically non stationary in time and space. Complicated wireless channels are often modeled statistically to characterize the variations of the multipath components and the signal strength at various points in the channel.

2.3 Channel Impulse Response Statistics

In this section we discuss commonly used channel impulse response (CIR) statistics. These parameters are calculated from the channel impulse response or power delay profiles. The power delay profile (or multipath intensity profile) is a plot of the
power of each multipath component versus delay. The channel impulse response statistics we discuss are the mean excess delay and RMS delay spread. The general for of CIR is expressed as [20],

\[ h(\tau; t) \]  \hspace{1cm} (2.3)

### 2.3.1 Mean Excess Delay (MED)

The mean excess delay is the first moment of the power delay profile [13]. It can be written as,

\[ \mu_T = \frac{\int_{0}^{\infty} \phi_g(\tau) d\tau}{\int_{0}^{\infty} \phi_g(\tau) d\tau} \approx \frac{\sum_{k} (\tau_k \alpha_k^2)}{\sum_{k} (\alpha_k^2)} \]  \hspace{1cm} (2.4)

where \( \tau \) represents the delay associated with each multipath component, \( \phi_g(\tau) \) represents the power delay profile and \( \alpha_k \) represents the amplitude associated with the kth multipath component. In our case, the mean excess delay is calculated from power delay profiles (PDPs) obtained from measurements and this is compared with the MED calculated from the channel impulse responses obtained from Wireless Insite.

### 2.3.2 Root Mean Square Delay Spread (RMS-DS)

RMS delay spread quantifies the spread in delays from the average delay [13]. It is given by the equation,

\[ \sigma_T = \sqrt{\frac{\int_{0}^{\infty} (\tau - \mu_T)^2 \phi_g(\tau) d\tau}{\int_{0}^{\infty} \phi_g(\tau) d\tau}} \approx \sqrt{\frac{\sum_{k} (\tau_k^2 \alpha_k^2)}{\sum_{k} (\alpha_k^2)}} - \mu_T^2 \]  \hspace{1cm} (2.5)

where all the parameters have been previously defined.
The RMS delay spread is not the only the way of quantifying a channel’s time dispersion. Strictly, delay spread is the time delay difference between the first and last arriving signal components associated with a single transmitted pulse. Other measures of delay dispersion include delay window and CIR duration with some dynamic range. RMS-DS is though a useful and common measure.

Via the convolution relationship, linear channels with small delay spread cause very little time spreading of a transmitted signal; conversely, channels with large delay spreads cause substantial time spreading, which can yield signal distortion.

2.4 Ray Tracing

Ray Tracing is a common prediction technique by which the propagation of electromagnetic rays through a communication channel can be modeled. The electromagnetic rays passing through a communication channel will undergo various reflections, refractions and diffractions due to the presence of obstacles like buildings, humans, moving and parked vehicles, and various other components in the environment [2]. The prediction of multipath propagation of the waves through the channel is calculated based on Maxwell’s equations. Since Maxwell’s equations are quite complex, the ray tracing algorithm uses high frequency approximations and considers the wavefronts to be plane waves.

As noted, the wireless channel is the often the most substantial impairment to wireless communications. The transmitted signal is affected by the obstacles present in the environment and this can produce various multipath components [16]. There are many ways of approximating and simplifying the model for multipath propagation phenomena. This leads to a number of ways by which channels can be modeled. Two
types of channel models are deterministic models and statistical channel models. Ray tracing is a deterministic channel model.

Deterministic channel models are those in which the channel is precisely determined analytically [16]. In this type of channel model, the number, location and size of all reflectors, scatterers and diffractors are known over time. Such deterministic channel models are quite complex to develop if the environment has many obstacles. Accurate knowledge of electrical parameters (e.g., conductivity and permittivity) of the materials and the location and size of each object is required for developing these models. Deterministic models typically use some electromagnetic modeling tools for their analysis of multipath phenomena. One example of such a tool is the Wireless Insite program, which uses ray tracing to analyze propagation. The accuracy of the deterministic channel model depends on its complexity, and this in turn generally depends on the geometry of the environment and on the accuracy of the simulation material database.

Statistical models are models in which the number, size and location of the reflectors or obstacles are unknown [16]. These models are often empirical, and depend on analysis of statistical data collected from the environment through measurements. Analytical statistical models are also widely used, with the Rayleigh and Ricean fading being the most common for modeling fading amplitude distributions. The complexity of statistical models is typically far less than that of deterministic models, since the statistical models do not depend upon any electromagnetic analysis.

Ray tracing models are deterministic models where the propagation of rays are estimated using simulation tools [1]. There are several available ray tracing programs,
such as Wireless Insite and Wireless Systems Engineering Software (WiSE). The Wireless Insite software we use allows development of both indoor and outdoor ray tracing models. These models depend on the propagation environment. The computations used for developing the ray tracing models make use of the antenna database, materials database and the built in objects in the software to model a given environment.

In the ray tracing models, the size, location and the number of reflectors, transmitters and absorbers must be specified over time, and the accuracy of model output results--often in the form of CIRs-- depends on the availability of exact geometry in the database. The Wireless Insite software allows us to create an environment using the built in database and it also allows the creation of objects imported from other formats.

A complex environment will have many obstacles or reflectors and this can result in large number of multipath components. If the number of multipath components is large, then the complexity of the ray tracing program also increases [1]. In this thesis, ray tracing is used to model an outdoor environment. In the case of outdoor environments with a large number of multipath components, the model developed using the Insite software will not perfectly match the real environment due to inaccuracies in the creation of objects – their sizes, shapes, relative locations, etc., can only be approximated. The same is true indoor environments.

When a ray is passed through a communication channel, there will be a reduction in the signal strength. This depends on various factors such as number, size and location of reflectors, free space path loss and the antenna gain. The free space path loss depends on the distance through which the ray is propagated [17]. Free space path loss is the loss in the strength of the signal for a path through free space. The multipath components have
a larger free space path loss than the line of sight component, since the line of sight component will have the least distance between the transmitter and receiver. The Free Space Path Loss (FSPL) is given by [17]

$$FSPL = \left( \frac{4\pi df}{c} \right)^2$$

(2.6)

where $d$ is the distance between transmitter and receiver, $f$ is the frequency of operation, and $c$ is the speed of light. The power received depends on the gain of the receiving antenna, transmitting antenna, distance between transmitter and receiver, and the frequency of operation. The power received at the receiver in free space can be written as [17]

$$P_r = \frac{P_t G_t G_r (\frac{c}{4\pi df})^2}{2}$$

(2.7)

where $P_r$ is the power received, $P_t$ is the power transmitted, $G_t$ is the transmitter antenna gain and $G_r$ is the receiver antenna gain.

Examples of ray tracing models are the two ray model and multiray model [1]. A two ray model is defined as a model with one line of sight ray and one dominant reflected ray. The line of sight component is the signal from transmitter to receiver through free space directly. The reflected ray can be a reflection from the ground or from a building. Figure 2.1 shows a two ray model.
In the case of a two ray model, the model requires the height of both the antennas, the distance between them and the location of the main reflector. The received power in the case of a two ray model can be written as [1]

\[ P_r = P_t \left( \frac{G_t G_r h_t h_r}{d^2} \right)^2 \]  

(2.8)

\[ P_r \ (dBm) = P_t \ (dBm) + 10 \log_{10}(G_t) + 20 \log_{10}(h_t h_r) - 30 \log_{10}(d) \]  

(2.9)

where \( P_r \) is the received power, \( P_t \) is the transmitted power, \( h_t \) is the height of the transmitter, \( h_r \) is the height of the receiver, \( d \) is the distance between the transmitter and receiver. These equations assume that the reflection is near perfect, and that \( d >> h_t, h_r \). A multi ray tracing model consists of a larger number of reflected rays, refracted rays, and diffracted rays. In this thesis, I have employed a multiray model for an outdoor environment. Figure 2.2 illustrates the multiray model which contains multipath components from various buildings, vehicles and other objects.

**Figure 2.1: Two ray model (adapted from [7])**
There can be single reflections or multiple reflections, and diffractions from each object in the multiray model [1]. The complexity of the ray tracing model depends on the number of multipath components used. A simple environment with a small number of multipath components can be modeled more accurately than one with a large number of components because the locations, size and the properties of all the materials can potentially be determined more accurately for a small number of objects, but this is not so for a big location with large number of objects, lots of human interactions and other interactions from moving obstacles such as vehicles.

2.5 Wireless InSite

Wireless Insite software is a channel modeling tool which can predict the propagation of electromagnetic rays through a communication channel [15]. It can be used to model both indoor and outdoor environments. It can produce various outputs which include channel impulse responses. The propagation paths and the coverage areas can be viewed using the project view in a 3-dimensional format. The tool provides various options to import various types of terrain and buildings from formats like Digital
Terrain Elevation data (DTED), Drawing Exchange Format (DXF) and United States Geological Survey (USGS). The terrain, vehicles and buildings can be generated using the editor tool within the Wireless Insite software. The floor plan editor helps in generating multiple types of floor plans, and also allows the creation of windows, doorways and ceilings of any size at any point. There are various materials that are available in the materials database that can be assigned directly to each facet (surface).

The properties of each material such as thickness, permittivity, conductivity, reflection coefficient and transmission coefficient are built into the Insite software and can be changed according to the application [15]. The thickness of the material should be specified according to the application. When the facets are assigned a material, the properties of the material can be changed accordingly so that the properties will apply only to the particular facet and the properties of the original material in the database are not affected. The materials that are included in the materials database are listed in Table 2.1.
Table 2.1: Various materials included in the materials database (based on [15]).

<table>
<thead>
<tr>
<th>EXTERIOR BUILDING MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete Wall</td>
</tr>
<tr>
<td>Brick Wall</td>
</tr>
<tr>
<td>Wood</td>
</tr>
<tr>
<td>Plate Glass</td>
</tr>
<tr>
<td>Reflective Glass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INTERIOR BUILDING MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layered Dry Wall</td>
</tr>
<tr>
<td>Layer 1: Dry wall, Layer 2: Air, Layer 3: Dry wall</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TERRAIN MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet ground</td>
</tr>
<tr>
<td>Dry Ground</td>
</tr>
<tr>
<td>Fresh Water</td>
</tr>
<tr>
<td>Sea Water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FOLIAGE MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense Deciduous in Leaf</td>
</tr>
<tr>
<td>Sparse Deciduous in Leaf</td>
</tr>
<tr>
<td>Dense Deciduous in Leaf</td>
</tr>
<tr>
<td>Sparse Deciduous in Leaf</td>
</tr>
<tr>
<td>Dense Pine Forest</td>
</tr>
<tr>
<td>Sparse Pine Forest</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MISCELLANEOUS MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Space</td>
</tr>
<tr>
<td>Perfect Absorber</td>
</tr>
</tbody>
</table>

There are different types of transmitter and receiver sets used in the Wireless Insite software [15]. The major types are point-point, route, xy grid, horizontal arc and vertical arc. In the point-point type, the location of the transmitter and the receiver can be independently specified to any particular point. Using the route type, evenly spaced points are placed along a line as series of line segments. The xy grid allows the area to be
occupied with evenly spaced transmitter or receiver points on a Cartesian grid. This will cover larger areas than other types of transmitter-receiver sets. In the horizontal arc type, transmitter or receiver points can be placed along a fixed arc whose diameter can be specified. The vertical arc type allows placing the receiver and transmitter points above and below the xy plane. The other types of sets available are cylinder, polygon, vertical surface and point of face. For applications where we use only one transmitter and receiver, the point type is typically used. The positions and the height of the transmitter and the receiver can be specified as required using the Wireless Insite’s Site Specifying tools.

The software allows the user to choose the transmitter and receiver antenna from the list of antennas in the database [15]. The antenna database includes omni directional, short dipole, short monopole, linear dipole, half wave dipole, linear monopole, quarter wave monopole, circular loop, square loop, axial mode helix, horn, rectangular aperture, circular aperture, parabolic reflector, circular micro-strip patch, rectangular micro-strip patch, generic antenna patterns, wireless insite antenna format, National Spectrum Management Association (NSMA), odyssey, Finite Difference Time Domain (XFDTD) format, user defined and imported antenna patterns. The transmitter and receiver can be placed in the project using the software editing tool.

The software also allows the user to change the properties of the antenna. This includes the antenna height, radiated power, and antenna pattern. The selected antenna’s dimensions can also be adjusted within the program without affecting the original database [15]. The software uses the term “antenna waveform” to represent the waveform of the RF pulse. The RF pulse is transmitted at 5.12 GHz. There are eight different types
of antenna waveforms that can be used according to user application. The different antenna waveform types for the transmitted signal that can be changed in the Wireless Insite are Blackman envelope, Gaussian pulse, Hamming envelope, Hanning envelope, sinusoid, raised cosine, Tukey envelope and user defined waveform. In this thesis, the RF pulse is windowed with a blackman window. The frequency of operation and the operational bandwidth can be altered according to the application.

New features like objects and images can also be added to the floor plan by importing from other formats into the Insite software [15]. The major formats that can be imported to the Wireless Insite software are DXF, DTED, Tagged Image File Format (TIFF) and geo TIFF images. The software allows the user to create the study area that defines the area in which we wish to analyze propagation. The study area can be created either by specifying its location and size or by allowing the software to fit all features in the program within the study area. The properties of the study area allow the user to select the propagation model, ray spacing, number of reflections, number of transmissions, number of diffractions, and the ray tracing method.

There are nine propagation models built into the Wireless Insite software [15]. Each of the propagation models has its own properties, which limit the maximum number of reflections, transmissions, diffractions, antenna types, range, ray tracing methods, maximum frequency and minimum frequency. The capabilities of different propagation models can be found in [15]. The urban canyon, fast 3D urban, full 3D and vertical plane models are the models used in Wireless Insite software which follow the ray tracing approach combined with the Uniform Theory of Diffraction. The advanced properties of the study area such as number of reflections before and after diffraction, transmissions
before and after diffraction and the path loss threshold can be varied according to the application.

The project hierarchy feature in Wireless Insite allows the user to view the features, structures, substructures and the faces organized in a hierarchical order [15]. The project view section of the software allows the user to view the complete structure 3-dimensionally. The propagation paths can be made visible once the simulation is done. Figure 2.3 shows an example of a project view of an environment with one building and a transmitter and receiver. The yellow line shows the boundaries of the study area, which defines the area for analyzing propagation.

Figure 2.3: Example of Project view showing the 3-D view of a simple outdoor environment

The software does not allow the user to include diffuse scattering while simulating the environment. The software outputs can be selected from a number of built
in outputs given in a list [15]. The various outputs that are available are received power,
path loss, path gain, time of arrival, delay spread, electric field magnitude, electric field
phase, animated fields, complex electric field, direction of arrival, mean direction of
departure, power delay profile, Doppler shift, terrain profiles, electric field vs. frequency,
electric field vs. time, complex impulse response, total received power, mean direction of
departure, and diagnostic data. The output is saved as text files in the output section. The
software allows viewing the output data such as power in dBm, the total received power,
channel impulse response, complex electric field, delay and power delay profiles using a
text editor. These output files are stored in a folder with the name of the study area in
.p2m formats which can be accessed through the text editor.
Chapter 3

Analysis and Experiments

3.1 Introduction

In this chapter, the measurement technique, analysis, experiments and results are discussed. Section 2 explains the experiments, the channel sounder equipment used for measurements, the transmitter set up, receiver set up, measurement procedures, and a description of the environment where the measurements were conducted. The environment description also discusses the various positions in which the measurements were taken. Section 3 discusses example PDP results obtained from the measured data and section 4 explains the RMS delay spread results obtained from the measured data for all positions. In section 5, we explain the method of approximating the measurement environment in Wireless Insite, and the PDP and RMS delay spread results obtained from Wireless Insite.

3.2 Experiments

The first step in the experimental part of the work was to plan the environment suitable for conducting measurements using the channel sounder. The environment under consideration was a simple outdoor environment with very few reflectors around. The equipment used for channel measurements consists of the channel sounder, antennas (horn and omni directional antennas), transmitter and receiver power supplies, miscellaneous radio frequency (RF) components such as RF cables, attenuators and adapters, laptop computer, uninterruptible power supply (UPS), and battery pack. The
second step of the experimental work was calibrating the channel sounder equipment to ensure rubidium oscillator lock for enough time to ensure accurate measurements.

The third step in the work was planning the exact measurement points at which to place the transmitter and receiver. The final step of the experimental work was to remove the channel sounder from calibrating mode and switches it to the experimental mode, then collect the power delay profiles. Four sets of measurements were conducted at the Innovation Center parking lot with different transmitter and receiver locations.

3.2.1 Channel Sounder

The channel sounder is the equipment that is used for taking wireless channel measurements. It was made by Berkeley Varitronics Systems (BVS) [18], and is a customized version of their “Raptor” model channel sounder. It consists of two major units: one is the transmitter and the other is the receiver. Figure 4 shows a picture of the channel sounder. The image was taken outside the Multiuser Mobile Communication laboratory at Ohio University.

The transmitter shown on left in Figure 3.1 has an adjustable output power and transmitting frequency [18]. The frequency range is 5090-5250 MHz. Both the transmitter and receiver have separate power supplies; the receiver is powered by a battery when used for mobile measurements. The equipment should be trained before taking measurements in order to ensure the frequency locking of rubidium oscillators. The training of the equipment and the measurement technique is explained in the fourth section of this chapter.
3.2.2 Environment Description

The measurements were carried out in an open parking lot (Innovation Center parking lot, Ohio University, Athens). The open parking lot was chosen in order to create a simple, nearly two ray model with one LOS path and one reflected ray (from the building). Figure 3.2 shows the Innovation Center building and the parking lot. The figure also shows the transmitter and receiver locations where the measurements were taken.
There are many obstacles in the environment, such as lamp posts, a basketball board, parking signs, a metal fence around the building, the car in which we conveyed the equipment to the site, distant buildings, vehicles passing by on the road, and people moving around. These obstacles made the environment more complex than a simple 2-ray setting, and the analysis showed that the model is indeed not a two ray model, but is a multi ray model. The car was parked ~25 m from the building. There were no additional cars parked in that parking lot. The Innovation Center building is made of brick. Four sets
of measurements were taken in the same environment by varying the transmitter and receiver positions. The four positions are shown in Figure 3.3.

![Figure 3.3: Measurement Positions](image)

The first set of measurements was taken with transmitter (Tx) placed at position Tx1, which is 10 m from the Innovation Center building. The receiver was placed at position Rx1, 10 m from the building and 5 m to the right of the transmitter. The second sets of measurement was taken with transmitter at position Tx2 and receiver at position Rx2. The second set of measurements was taken by moving the transmitter and receiver 5 m further from the building compared to the position where the first set of measurements was taken. The third set of measurements was taken with transmitter at position Tx3 and
receiver at position Rx3. The last set of measurements was taken with transmitter at position Tx4 and receiver at position Rx4.

3.2.3 Transmitter Setup

The equipment needed for the transmitter set up is the sounder transmitter, transmitter power supply, battery, directional horn antenna and cables [18]. For setting up the transmitter for taking measurements, the transmitter is connected to the transmitter power supply and power supply is connected to the battery backup. The RF cable which connected the receiver to the transmitter for training is removed and the horn antenna is connected to the transmitter. Figure 3.4 shows the transmitter set up.

![Transmitter Set up Image](image)

Figure 3.4: Transmitter set up

The carrier frequency of the transmitter was set to 5120 MHz and the chip rate was set to 50 Mcps (yielding a roughly 50 MHz bandwidth signal). The power level of
the transmitter was set to 33 dBm. In order to set up a two ray model with one LOS path and one reflected path mainly from the building, the horn antenna was used as the transmitter antenna in which the main lobe was focused on the building. The gain of the directional horn antenna is ~17 dBi.

3.2.4 Receiver Setup

The equipment needed for receiver set up is the sounder receiver, receiver power supply, battery pack, omni directional antenna, laptop and cables [18]. For setting up the receiver for taking measurements, the receiver is connected to its battery, and the antenna connected to the receiver RF connector. Figure 3.5 shows the receiver set up. The carrier frequency of the receiver was also set to 5120 MHz and the chip rate selected to match that used at the transmitter.
3.3 Measurement Description

The training and initialization of the equipment were conducted at Multiuser Mobile Communication Laboratory, Stocker Center, Ohio University. For the training and initialization, the transmitter and receiver are directly connected using an RF cable with a 40 dB attenuator. This is to ensure that the power received at the receiver is $\leq-10$ dBm. The transmitter and receiver are connected to the power supplies. The receiver was connected to the laptop, in which the Raptor software is installed. The transmitter frequency is 5120 MHz, and the chip rate is set to 50 Mcps. The power of the transmitter
is set to 5 dBm before turning the RF transmit ON. The RF power is turned ON for training. The training was done for one day.

The RF cable is removed from the transmitter and receiver for the actual measurement setup. Transmit and receive antennas are connected to transmitter and receiver, respectively. The power of the transmitter is increased to 33 dBm. The battery is not disconnected while taking it out of the training mode, i.e., the battery pack is always connected to the receiver. The transmitter is connected to the UPS for both training and measurement so that the power is not disconnected. The sounder equipment was then taken to the Innovation Center parking lot to conduct the measurements. The measurements were conducted at four different positions as described.

3.4 Power Delay Profile Results

The power delay profile (PDP) is a plot showing the relative power of each multipath component versus the delay. An example PDP is shown in Figure 3.6. The PDP shown in Figure 3.6 was obtained from the measurements conducted at position 1 as explained in section 3.2.2. The plot shows 54 multipath components captured at the receiver after multiple reflections and refractions from the obstacles. The abscissa indicates the delay associated with each multipath component. The PDPs were plotted using MATLAB.
3.5 Approximating the Environment in Wireless Insite

The environment where the measurements were actually taken is approximated using the Wireless Insite’s floor plan editor. Figure 3.7 shows the approximated environment using the Wireless Insite software. The Innovation Center building is approximated using brick as the outside material and the windows of the buildings were created using glass as the material. The size and the location of the windows and the building were approximated. The paved parking lot is approximated as dry earth which is shown in Figure 3.7 in green. The study area is shown by the yellow line which defines the area for analyzing propagation.
The metal box shown in the figure 3.7 approximates the car that was parked in the parking lot. The basketball board and the parking sign posts were approximated as metal poles whose height was approximated. The results from the Wireless Insite analysis were extracted, and the power delay profile was plotted using MATLAB.
Chapter 4

Results and Discussion

4.1 Introduction

This chapter discusses the results obtained from the comparison and perturbation analysis of ray tracing and measurement results for 5 GHz wireless band channels. The second section discusses the pre processing of the measured data obtained from the Raptor software. The third section shows the comparison of PDPs obtained for measured and ray tracing (analytical). The fourth section discusses the RMS-DS statistics for the different sets of measurements. The fifth section discusses the use of an amplitude threshold for eliminating weaker multipath components. The threshold was applied to four sets of measurement results. The next section explains the perturbation analyses conducted to assess the accuracy of the ray tracing results compared to the measured results; the measure of “goodness of fit” we used is the RMS-DS.

4.2 Data Processing

This section discusses the processing of the data obtained from measurements. The raw data obtained from the channel sounder cannot be directly used in MATLAB to obtain the channel models. The raw data obtained from the channel sounder is stored in a log file which is in a proprietary .rap format. This data is converted to an ASCII format to make it readable by MATLAB. The BVS sounder Chameleon software converts the data in the .rap format to the .out format. This file contains the information in ASCII format. This data can be easily imported into MATLAB and therein used to develop the channel models. Figure 4.1 shows the Chameleon software’s data conversion screen.
The raw data is converted to the .out log file, and this file contains the power (in dBm), phase (in radians) and RSSI (in dBm). The software allows the user to convert various other measured data into the .out log file such as RTC date, RTC time, current frequency and others using the field selection window as seen from Figure 4.1. The delimiter allows the separation of the field values in the output file. The software allows the user to use four types of delimiter. They are comma, space, tab and semicolon. In this thesis the data collected at the four positions was converted from the .rap format to .out
format using the delimiter comma. The data in the output log file is a matrix with the values of power, phase and RSSI for different samples (values of delay). This data is read into MATLAB for processing.

4.3 Comparison of Power Delay Profiles

The data obtained after the pre processing is collected and separated into phase, power and RSSI vectors. The PDPs gives the power associated with each multipath component. The PDPs collected will have thermal noises associated with it which will include unwanted multipath components into the PDPs. Noise thresholding was then applied in order to remove unwanted likely noise components along with the channel data. The value of the noise threshold is calculated and the components with power less than the threshold value were set to -130dB. This process is conducted for all the PDPs to eliminate the noise components. For our case, the data for power is of length 1020 samples per PDP. This is then parsed into two PDPs of length 510 and since the second PDP is a replication of the first, it was eliminated. The PDPs are then averaged to produce a single (mean) PDP. The average PDP is then normalized.

The data collected from Wireless Insite for each position was also normalized. The data from both the measurements and analysis were shifted in amplitude as needed to make the peak values the same. The comparison of PDPs was done for four different positions. Figure 4.2 shows a comparison of PDPs obtained for the measured and ray tracing results at position 1.
Figure 4.2: Comparison of Power Delay profiles for measured and analytical data with all multipath components for position 1

At position 1, the distance between transmitter and receiver is 5 m and the distance between the Innovation Center building and transmitter is 10 m. The analytical results are the results obtained from Wireless Insite. Figure 4.3 shows the image from Wireless Insite with transmitter and receiver at position 1, and with 4 metal poles and 3 metal parking signs and a metal box representing the car. The image was taken after running the ray tracing program.
The rays in the figure 4.3 show the reflected and the refracted rays from the obstacles around. The color coding of the rays indicate the power levels associated with each multipath components. The red color indicates the stronger paths and then the green and blue color indicates the weakest signal. The measured data was collected for approximately 60 seconds for each Tx/Rx location pair. The PDPs obtained from the measurements and the ray tracing in Figure 4.2 are comparable qualitatively. There are 54 impulses in the measured PDP. There are many more multipath components in the measured data than in the analytical data. Many of these measured components are very weak components, at power level nearly 70 dB lower than that of the multipath component with maximum power. These weak (possibly diffuse) components will
contribute little to the RMS-DS. Hence these multipath components can be eliminated by applying a threshold, discussed in the next section.

For position 2, the distance between the transmitter and receiver was kept the same: 5 m. The distance between transmitter and the building, and the receiver and building, was increased from 10 m to 15 m. The PDPs were again collected for approximately 60 seconds. Similar data processing was done and the PDPs for measured and ray tracing data are shown in Figure 4.4.

![Comparison of Power Delay Profiles with all multipath components](image)

**Figure 4.4: Comparison of Power Delay profiles for measured and analytical data with all multipath components for position 2**

The ordinate shows the relative power in dB and the abscissa shows the delay in micro seconds. The comparison of PDPs at position 2 in Figure 4.4 shows that the results are again qualitatively comparable. There are again many multipath components in the measured PDP with larger delays and very low power, as in position 1. These weaker
components are not present in the analytical PDP obtained from Wireless Insite. The measured PDP is the average PDP.

The comparison of PDPs for the measurements and analysis for position 3 is shown in Figure 4.5.

Figure 4.5: Comparison of Power Delay profiles for measured and analytical data with all multipath components for position 3

For position 3, the distance between transmitter and building, and receiver and building is 10 m. The distance between the transmitter and receiver was increased from 5 m to 10 m. For position 4, the measured data was obtained by moving the transmitter and receiver 5 m towards the building, while keeping the distance between the transmitter and
receiver constant at 10 m. The plot showing the comparison of power delay profiles for position 4 is shown in Figure 4.6.

Figure 4.6: Comparison of Power Delay profiles for measured and analytical data with all multipath components for position 4

The PDPs for the measurements and analysis are comparable qualitatively for the fourth position as well. For all these measured results, the weaker multipath components may be due to reflections obtained from buildings farther away, from vehicles passing by, from people moving around, from the iron fencing around the building, and possibly from other objects in the environment. The differences in the amplitude values between
measurements and analysis for all positions is likely due to the inaccuracies in the conductivities, permittivity’s and dimensions of the objects used in the software analysis. For example, the parking lot, in front of building was paved, but was simulated as dry earth. Another example is the basketball board, which was 15 m away from the location where the measurements were taken, was created as metal poles which might give produce a larger value power for the reflected multipath components.

The differences in the delays between the multipath components obtained from measurements and analysis may be due to the inaccuracies in the construction of building using the floor plan editor in Wireless Insite. Some of the windows and doors were open while we took measurements, and these were modeled as closed windows and door in the software. The open windows and doors could produce additional multipath components with larger delays since the rays get reflected inside the buildings and received at the receiver. The modeling of transmissions through the walls was also disabled in the simulation, which could also account for the larger delay multipath components.

### 4.4 RMS-DS Results

A histogram of RMS-DS for PDPs from all four positions was obtained. Recall that the RMS-DS measures the spread in delay from the average delay. The histogram shows the number of samples associated with each value of RMS-DS from the total number of profiles (1063 profiles). Figure 4.7 shows a histogram of RMS-DS for position 1. The mean value of the RMS-DS is 9.771 ns, and he standard deviation is 4.6438 ns. The maximum value of RMS-DS is 74.714 ns. During measurements, there were cars passing on the nearby road, and as noted, there were additional buildings (not modeled in the ray tracing). The reflections from these farther buildings will produce components
with larger delays, and this can account for the larger values of RMS-DS seen in Figure 4.7.

![Histogram of RMS Delay Spread](image1)

**Figure 4.7: Histogram of RMS-DS for position 1**

![Power delay profile](image2)

**Figure 4.8: PDP plot for position 1 with RMS-DS = 8.6920ns**
Figure 4.9: PDP plot for position 1 with RMS-DS = 16.8144 ns

Figure 4.10: PDP plot for position 1 with RMS-DS = 56.4012 ns
Single power delay profiles with RMS-DS values of 8.692 ns, 16.814 ns and 56.401 ns are shown in Figures 4.8-4.10, respectively. The plot with RMS-DS of 56.401 ns has many multipath components with higher power relative to the maximum value. This could be due to strong reflections from cars passing by. The plot with RMS-DS value of 8.692 ns has very few strong multipath components with higher values of delay. These examples show that the reflections with larger delays and higher power were not seen all the time.

For position 2, the transmitter and receiver was moved 5 m away from the building. The distance between the transmitter and receiver was 5 m. Figure 4.11 shows the histogram of RMS-DS for position 2. The mean value of RMS-DS for the position 2 is 17.674 ns, and the standard deviation is 5.9245 ns. For this position also, most of the samples were concentrated around the mean value. The small standard deviation shows that there is not much difference between the power delay profiles. The maximum value of RMS-DS is 54.01 ns.
The mean value of RMS-DS increased when we moved from the position 1 to position 2, which is due to the increased delay of the multipath components when the transmitter and receiver position is moved away from the building. For position 3, the receiver position was moved 5 m away from the transmitter, keeping the distance from building to the transmitter and receiver constant at 15 m. The delays for the multipath components will increase from the first position since the distance between the transmitter and the receiver is increased. The histogram of RMS-DS for position 3 is shown in Figure 4.12.
The mean value of the RMS-DS for position 3 is 13.23 ns, larger than that of position 1 where the mean value of RMS-DS was 8.6920 ns. The standard deviation of the RMS-DS for position 3 is 4.5626 ns—again a very small value. Figure 4.12 also shows some PDP samples with larger value of RMS-DS: the maximum value of RMS-DS for position 3 is 44.022 ns.

In the case of position 4, the transmitter and receiver were moved closer to the building by 5 m and the distance between the transmitter and receiver was 15m. The histogram of RMS-DS for position 4 is shown in Figure 4.13.
The mean value of RMS-DS for position 4 is 55.4118 ns. For this position, the value of the RMS-DS changed substantially over the set of measured PDPs. The standard deviation of RMS-DS for position 4 is 80.1705 ns. This larger value of standard deviation indicates more scattering from nearby cars. Figure 4.14 shows one PDP obtained for position 4 with RMS-DS of 9.9483 ns. This power delay profile has RMS-DS value less than that of the mean RMS-DS value at that position.
Figure 4.14: PDP plot for position 4 with RMS-DS = 9.9483 ns

Figure 4.15: PDP plot for position 4 with RMS-DS = 52.3344 ns
Figure 4.16: PDP plot for position 4 with RMS-DS = 203.0889 ns

Figure 4.17: PDP plot for position 4 with RMS-DS = 369.7075 ns
Figure 4.15 shows a PDP for position 4 with RMS-DS of 52.3344 ns. This PDP has RMS-DS close to the mean value of RMS-DS for position 4. This plot shows that there are few strong reflections at higher delays. Figure 4.16 shows a PDP with RMS-DS of 203.0889 ns. This plot has many strong multipath components with very larger delays. Figure 4.17 shows a PDP for position 4 with RMS-DS value of 369.7075 ns. This PDP has most of its multipath components at very low power. One hypothesis is that this was caused by movement of people, which could have acted as absorbers to reduce the power of most of the low-delay multipath components. There are very few PDPs with this large a value of RMS-DS.

4.5 Employing a Threshold

The RMS-DS is the channel impulse response statistic that is used as a criterion to determine a threshold for eliminating the weaker multipath components from the PDP. An average PDP is obtained for each position. The average PDP is then normalized. This normalized PDP is then plotted along with the normalized ray tracing PDP obtained from Wireless Insite for each position.

Thresholding is done by selecting a value for the relative power, with respect to the maximum value, below which all multipath components are discarded. Thresholding is applied to both the analytical and measured profiles. Threshold values we used range from 20 dB to 60 dB in steps of 10 dB. The threshold value which does not affect the RMS-DS can be used as an appropriate threshold to eliminate the weaker components.

Thresholding is conducted in order to analyze the difference in the analytical and measured RMD-DS. By employing the threshold, many of the potentially negligible components will be removed and the difference in the RMS-DS may be accounted for.
Some of these weaker components in the measured profile are likely “diffuse” components that do not emanate from reflections, but are scattered components that the ray tracing program cannot emulate.

Table 4.1: RMS-DS and MED values after thresholding for position 1.

<table>
<thead>
<tr>
<th>THRESHOLD</th>
<th>MEASURED (ns)</th>
<th>Δ (%)</th>
<th>ANALYTICAL (ns)</th>
<th>Δ (%)</th>
<th>MEASURED (ns)</th>
<th>ANALYTICAL (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All objects</td>
<td>6.5921</td>
<td>0</td>
<td>11.152</td>
<td>0</td>
<td>60.296</td>
<td>67.339</td>
</tr>
<tr>
<td>60dB</td>
<td>6.555</td>
<td>0.56</td>
<td>11.152</td>
<td>0</td>
<td>60.295</td>
<td>67.339</td>
</tr>
<tr>
<td>50dB</td>
<td>6.5481</td>
<td>0.67</td>
<td>11.152</td>
<td>0</td>
<td>60.295</td>
<td>67.339</td>
</tr>
<tr>
<td>40dB</td>
<td>6.4688</td>
<td>1.87</td>
<td>11.086</td>
<td>0.59</td>
<td>60.286</td>
<td>67.329</td>
</tr>
<tr>
<td>30dB</td>
<td>5.4816</td>
<td>16.8</td>
<td>10.122</td>
<td>9.23</td>
<td>60.138</td>
<td>67.164</td>
</tr>
<tr>
<td>20dB</td>
<td>4.4705</td>
<td>32.1</td>
<td>9.6004</td>
<td>13.9</td>
<td>60.313</td>
<td>67.054</td>
</tr>
</tbody>
</table>

Table 4.1 shows the position 1 RMS-DS and MED values when various threshold values are applied. The table also indicates the percentage change in the value of RMS-DS when the thresholding is applied against the one without thresholding. The PDP with “all objects” in Table 2 is the PDP with no thresholding. Here for a 60 dB threshold, the percentage change in the RMS-DS is 0.56% for the measured and 0% for analytical. For a 40 dB threshold, the percentage change in the RMS-DS for the measured and analytical increases to 1.87% and 0.59% respectively. This also indicates that insignificant change in the RMS-DS value. When a the threshold is 30 dB, the percentage change in the RMS-
DS for the measured and analytical is substantial: 16.84% and 9.236% respectively. A threshold of 20 dB threshold yields even larger changes, as expected.

Thus for position 1 a 40 dB threshold can be used without substantially changing the RMS-DS. Note that the analytical RMS-DS value remains almost the same after thresholding of 40 dB. Figure 4.18 shows the PDPs after applying the threshold for position 1. When the potentially weaker multipath components are eliminated, the PDPs of measured and the analytical data are qualitatively more comparable.
Comparision of Power Delay Profiles with threshold = 60 dB normalized to unit energy

![Graph (a)](image-a)

Comparision of Power Delay Profiles with threshold = 50 dB normalized to unit energy

![Graph (b)](image-b)
Comparision of Power Delay Profiles with threshold = 40 dB normalized to unit energy

Comparision of Power Delay Profiles with threshold = 30 dB normalized to unit energy
Figure 4.18: Comparison of power delay profiles for position 1 after applying different threshold values. Plots shown above have thresholding value of (a) 60 dB, (b) 50 dB, (c) 40 dB, (d) 30 dB and (e) 20 dB

Table 4.2: RMS-DS and MED values after thresholding for position 2

<table>
<thead>
<tr>
<th>Position 2</th>
<th>RMS-DS</th>
<th>Mean energy delay (med)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured(ns)</td>
<td>Analytical(ns)</td>
</tr>
<tr>
<td>All objects</td>
<td>7.3426</td>
<td>0</td>
</tr>
<tr>
<td>60 dB</td>
<td>7.3092</td>
<td>0.45</td>
</tr>
<tr>
<td>50 dB</td>
<td>7.3092</td>
<td>0.45</td>
</tr>
<tr>
<td>40 dB</td>
<td>7.3092</td>
<td>0.45</td>
</tr>
<tr>
<td>30 dB</td>
<td>6.1535</td>
<td>16.19</td>
</tr>
<tr>
<td>20 dB</td>
<td>4.2548</td>
<td>42.05</td>
</tr>
</tbody>
</table>
Table 4.2 shows the results of RMS-DS and the MED values after thresholding for position 2. In this position also, a threshold of 40 dB or larger yields a negligible percentage change in the RMS-DS.

Table 4.3: RMS-DS and MED values after thresholding for position 3

<table>
<thead>
<tr>
<th>Position 3</th>
<th>RMSDS</th>
<th>Measured (ns)</th>
<th>Δ (%)</th>
<th>Analytical(ns)</th>
<th>Δ (%)</th>
<th>Measured (ns)</th>
<th>Analytical(ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All objects</td>
<td>8.5477</td>
<td>0</td>
<td>11.310</td>
<td>0</td>
<td>37.579</td>
<td>104.04</td>
<td></td>
</tr>
<tr>
<td>60 dB</td>
<td>8.452</td>
<td>1.11</td>
<td>11.310</td>
<td>0</td>
<td>37.577</td>
<td>104.04</td>
<td></td>
</tr>
<tr>
<td>50 dB</td>
<td>8.4431</td>
<td>1.22</td>
<td>11.310</td>
<td>0</td>
<td>37.575</td>
<td>104.04</td>
<td></td>
</tr>
<tr>
<td>40 dB</td>
<td>8.3965</td>
<td>1.77</td>
<td>11.200</td>
<td>0.97</td>
<td>37.570</td>
<td>104.03</td>
<td></td>
</tr>
<tr>
<td>30 dB</td>
<td>8.1297</td>
<td>4.89</td>
<td>10.986</td>
<td>2.86</td>
<td>37.527</td>
<td>103.97</td>
<td></td>
</tr>
<tr>
<td>20 dB</td>
<td>6.9914</td>
<td>18.2</td>
<td>10.539</td>
<td>6.82</td>
<td>37.164</td>
<td>104.07</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 indicates the same conclusion for position 3 as found for the first two positions. Finally, Table 4.4 shows the RMS-DS and MED values after thresholding for position 4. Here when a threshold of 60 dB is used, the RMS-DS for the measured data changes by 15% and the analytical RMS-DS does not change. Hence for this position we may not wish to use any threshold, although since the RMS-DS value for this position is so small, the 40 dB threshold is used.
Table 4.4: RMS-DS and MED values after thresholding for position 4

<table>
<thead>
<tr>
<th>Position 4</th>
<th>RMS-DS</th>
<th>Mean Energy Delay (MED)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured (ns)</td>
<td>∆ (%)</td>
</tr>
<tr>
<td>Threshold</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All objects</td>
<td>3.9997</td>
<td>0</td>
</tr>
<tr>
<td>60 dB</td>
<td>3.3849</td>
<td>15.37</td>
</tr>
<tr>
<td>50 dB</td>
<td>3.3506</td>
<td>16.28</td>
</tr>
<tr>
<td>40 dB</td>
<td>3.2688</td>
<td>18.27</td>
</tr>
<tr>
<td>30 dB</td>
<td>2.6883</td>
<td>32.78</td>
</tr>
<tr>
<td>20 dB</td>
<td>2.3211</td>
<td>41.97</td>
</tr>
</tbody>
</table>

For all four positions, the value of the analytical RMS-DS is larger than the measured RMS-DS. Figure 4.19 shows a plot of measured and analytical RMS-DS for for an outdoor environment. This plot is adapted from one in [4]. This plot also shows that the simulated RMS-DS can be larger than the measured RMS-DS, corroborating our finding.
4.6 Perturbation Analysis by increasing Environment Complexity

A perturbation analysis was conducted to “fine tune” the comparison of power delay profiles obtained from measurements and analysis, and determines how the simulation complexity affects agreement. The analysis was conducted for all four positions. This analysis was conducted by adding more and more objects into the simulation and comparing the resulting PDPs with measurements.

For all positions, 4 steps of comparisons were carried out. Step 1 is conducted by creating the simulation environment with only a ground plane and building. The transmitter and receiver were placed in front of the building at position 1. The desired
distance between transmitter and receiver was 5 m, and the desired distances between
transmitter and building, and receiver and building were 10 m. Step 2 added the car in the
simulation. The car was modeled as a metal box, and was placed 25 m from the building.
In the actual environment, there were many metal parking signs and a basketball board in
the environment. Step 3 included those elements into the simulation. In step 3, 4 metal
poles were added. One of the poles represents the basketball board pole and the others
represent the parking signs. The final simulation is conducted with all the objects found
which includes all the parking signs and metal poles.

Figure 4.20: Screen shot of the environment after the simulation for step 1 for
position 1
Figure 4.21: Screen shot of the environment after the simulation for step 2 for position 1

Figure 4.22: Screen shot of the environment after the simulation for step 3 for position 1
Figures 4.20-4.23 shows the screen shots of the environment for position 1 at various steps. The screen shots were taken after the simulation was conducted. Analysis was also conducted for all the other positions. Figure 2.22 shows the PDPs obtained for position 1 for all the different steps. Figure 4.24(a) shows the measured and analytical PDPs for step 1. In this analysis, there is no thresholding applied in order to analyze the analytical and measured RMS-DS. The analytical PDP has very few multipath components. Figure 4.24 parts (b), (c), and (d) show the PDP comparison for steps 2 through 4, respectively. The PDP results show that when we add more elements into the environment, the analytical results became qualitatively more comparable to the measured results. The measured PDPs have many multipath components with higher delays that are removed when we apply the 40 dB threshold.
Figure 4.24: Step wise comparison of PDPs for measurements and simulation for position 1 (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4

Table 4.5 shows the RMS-DS and MED values for different steps of the perturbation analysis. By increasing the number of elements in the environment, the analytical RMS-DS increases when the complexity of the environment increases. The
value of the RMS-DS of 9.6041 ns for step 1 is closest to the measured results, indicating that using a more complex environment does not necessarily increase accuracy.

Table 4.5: RMS-DS and MED values for perturbation analysis by increasing complexity for position 1

<table>
<thead>
<tr>
<th>POSITION 1</th>
<th>RMS-DS</th>
<th>MEAN ENERGY DELAY (MED)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEASURED (ns)</td>
<td>ANALYTICAL (ns)</td>
</tr>
<tr>
<td>STEP 1</td>
<td>6.5921</td>
<td>9.6041</td>
</tr>
<tr>
<td>STEP 2</td>
<td>6.5921</td>
<td>10.131</td>
</tr>
<tr>
<td>STEP 3</td>
<td>6.5921</td>
<td>11.139</td>
</tr>
<tr>
<td>STEP 4 (ALL OBJECTS)</td>
<td>6.5921</td>
<td>11.152</td>
</tr>
</tbody>
</table>

Figure 4.25 shows a similar comparison of PDPs for the step wise analysis for position 2. Figure 4.25 (a), (b), (c), (d) shows the step wise comparison of PDP starting with step 1 to step 4 for position 2. This result also shows that by increasing the complexity of the environment, the analytical results appear to get closer to the measured results. Table 4.6 though shows that the RMS-DS and MED for position 2 does not change the analytical RMS-DS much. The RMS-DS value for the analytical result is still larger than the measured RMS-DS.
Figure 4.25: Step wise comparison of PDP for measurements and simulation for position 2 (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4
Table 4.6: RMS-DS and MED values for perturbation analysis by increasing complexity for position 2

<table>
<thead>
<tr>
<th>POSITION 2</th>
<th>RMS-DS</th>
<th>MEAN ENERGY DELAY (MED)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEASURED (ns)</td>
<td>ANALYTICAL (ns)</td>
</tr>
<tr>
<td>STEP 1</td>
<td>7.3426</td>
<td>19.400</td>
</tr>
<tr>
<td>STEP 2</td>
<td>7.3426</td>
<td>19.632</td>
</tr>
<tr>
<td>STEP 3</td>
<td>7.3426</td>
<td>19.797</td>
</tr>
<tr>
<td>STEP 4 (ALL OBJECTS)</td>
<td>7.3426</td>
<td>19.612</td>
</tr>
</tbody>
</table>

Figure 4.26 shows the PDP comparison results for position 3, and Table 4.7 shows the RMS-DS and MED for the various steps. In this position also, the value of the analytical RMS-DS is larger than the measured results, and when the simulation is conducted at step 1, the difference between the measured and the analytical RMS-DS is the smallest. Figure 4.27 shows the comparison for position 4. The RMS-DS and MED values for position 4 are shown in Table 4.8, and these results yield the same general conclusions.
Figure 4.26: Step wise comparison of PDP for measurements and simulation for position 3 (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4
Table 4.7: RMS-DS and MED values for perturbation analysis by increasing complexity for position 3

<table>
<thead>
<tr>
<th>POSITION 3</th>
<th>RMS-DS</th>
<th>MEAN ENERGY DELAY (MED)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEASURED (ns)</td>
<td>ANALYTICAL (ns)</td>
</tr>
<tr>
<td>STEP 1</td>
<td>8.5477</td>
<td>10.995</td>
</tr>
<tr>
<td>STEP 2</td>
<td>8.5477</td>
<td>11.154</td>
</tr>
<tr>
<td>STEP 3</td>
<td>8.5477</td>
<td>11.330</td>
</tr>
<tr>
<td>STEP 4 (ALL OBJECTS)</td>
<td>8.5477</td>
<td>11.310</td>
</tr>
</tbody>
</table>
Figure 4.27: Step wise comparison of PDP for measurements and simulation for position 4 (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4
### Table 4.8: RMS-DS and MED values for perturbation analysis by increasing complexity for position 4

<table>
<thead>
<tr>
<th>POSITION 4</th>
<th>RMS-DS</th>
<th>MEAN ENERGY DELAY (MED)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MEASURED (ns)</td>
<td>ANALYTICAL (ns)</td>
</tr>
<tr>
<td>STEP 1</td>
<td>3.9997</td>
<td>7.6835</td>
</tr>
<tr>
<td>STEP 2</td>
<td>3.9997</td>
<td>8.2368</td>
</tr>
<tr>
<td>STEP 3</td>
<td>3.9997</td>
<td>9.1613</td>
</tr>
<tr>
<td>STEP 4 (ALL OBJECTS)</td>
<td>3.9997</td>
<td>9.4189</td>
</tr>
</tbody>
</table>

#### 4.7 Perturbation Analysis Varying Additional Parameters

This perturbation analysis was conducted in order to determine whether or not inaccuracies in actual measurement distances and the number of rays used in ray tracing could cause substantial disagreement with analytical results. This analysis was conducted by varying the transmitter and receiver positions, restricting the number of reflections, removing the samples with higher delays, varying the transmitter – receiver inter-distance and combining some of these. As before, we compare the measured and the analytical data via RMS-DS.

#### 4.7.1 Transmitter Position Perturbation

Transmitter perturbation is conducted by varying the transmitter position with respect to the building in front of which the measurements were conducted. The transmitter position is varied only in the simulation. The transmitter position was moved nearer to the building by 0.5 m in steps of 0.1 m, and also farther from the building by 0.5 m in steps of 0.1 m. The receiver position was kept fixed for this set of analyses. CIR
data was collected at each step and was used for calculating the RMS-DS. Table 4.6 shows the RMS-DS values for different positions. The RMS-DS obtained from the measured result for position 1 is 6.5921 ns.

Table 4.9: RMS-DS and MED values for transmitter perturbation analysis

<table>
<thead>
<tr>
<th>DISTANCE FROM BUILDING TO TRANSMITTER (m)</th>
<th>RMS-DS (ns)</th>
<th>MED (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>12.315</td>
<td>68.328</td>
</tr>
<tr>
<td>10.4</td>
<td>11.931</td>
<td>68.160</td>
</tr>
<tr>
<td>10.3</td>
<td>11.796</td>
<td>68.011</td>
</tr>
<tr>
<td>10.2</td>
<td>11.535</td>
<td>67.812</td>
</tr>
<tr>
<td>10.1</td>
<td>11.309</td>
<td>67.588</td>
</tr>
<tr>
<td>10</td>
<td>11.152</td>
<td>67.339</td>
</tr>
<tr>
<td>9.9</td>
<td>10.916</td>
<td>67.109</td>
</tr>
<tr>
<td>9.8</td>
<td>10.67</td>
<td>66.864</td>
</tr>
<tr>
<td>9.7</td>
<td>10.347</td>
<td>66.568</td>
</tr>
<tr>
<td>9.6</td>
<td>10.459</td>
<td>66.329</td>
</tr>
<tr>
<td>9.5</td>
<td>10.282</td>
<td>66.069</td>
</tr>
</tbody>
</table>

The value of RMS-DS obtained via Wireless Insite for the original transmitter position of 10 m away from the receiver was 11.152 ns. The transmitter perturbation analysis was conducted to determine if a small inaccuracy in true position (used in measurements) could be accounted for in simulation, judged by the RMS-DS statistic. As Table 4.9 shows, when the transmitter is moved away from the building, the RMS-DS value increases compared to the value obtained for the original position. When the
transmitter is moved toward the building, the RMS-DS value decreased from the value at
the original position and became closer to the actual RMS-DS value obtained from the
measurements. Note that we limited the maximum distance change to 0.5 m—this is our
estimate of the maximum uncertainty based upon an actual distance measurement. The
conclusion is that this 0.5 m transmitter position shift could indeed be part of the
discrepancy between measurements and analysis, as the 10.23% change in RMS-DS
moves the analytical value closer to the measured.

4.7.2 Receiver Position Perturbation

The receiver perturbation was done by changing the receiver position with respect
to the building, analogous to the transmitter perturbation. (Again note that this is only for
the analytical results.) We used the same distance limits and step sizes, and the
transmitter position was kept fixed for all the measurements at 10 m from the building.
The PDPs collected at each step were used for calculating the RMS-DS. Table 4.10
shows the RMS-DS values for different positions.

Table 4.10: RMS-DS and MED values for receiver perturbation analysis

<table>
<thead>
<tr>
<th>DISTANCE FROM BUILDING TO TRANSMITTER (m)</th>
<th>RMS-DS (ns)</th>
<th>MED (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>10.901</td>
<td>69.104</td>
</tr>
<tr>
<td>9.4</td>
<td>10.921</td>
<td>68.761</td>
</tr>
<tr>
<td>9.3</td>
<td>10.942</td>
<td>68.423</td>
</tr>
<tr>
<td>9.2</td>
<td>10.994</td>
<td>68.068</td>
</tr>
<tr>
<td>9.1</td>
<td>11.086</td>
<td>67.699</td>
</tr>
<tr>
<td>10</td>
<td>11.152</td>
<td>67.339</td>
</tr>
<tr>
<td>10.1</td>
<td>11.214</td>
<td>66.968</td>
</tr>
<tr>
<td>10.2</td>
<td>11.295</td>
<td>66.593</td>
</tr>
<tr>
<td>10.3</td>
<td>11.455</td>
<td>66.191</td>
</tr>
<tr>
<td>10.4</td>
<td>11.558</td>
<td>65.800</td>
</tr>
<tr>
<td>10.5</td>
<td>11.674</td>
<td>65.403</td>
</tr>
</tbody>
</table>
The value of RMS-DS obtained via Wireless Insite when the receiver position is 10 m from the building is 11.152 ns, and the RMS-DS obtained from the measured result for position 1 is 6.5921 ns. The statistics show the same trend as with transmitter position change: when the receiver is moved away from the building, the RMS-DS increases, and when the receiver is moved toward the building, the RMS-DS value decreases, and comes closer to the RMS-DS obtained from measurements. The RMS-DS value changes by 2.25% when the receiver is moved from 10 m to 9.5 m. This implies that changing the receiver position has less effect on improving the agreement between measurements and analysis than does transmitter position shift.

4.7.3 Transmitter and Receiver Combined Perturbation

The transmitter and receiver combined perturbation was conducted by varying the transmitter and receiver positions with respect to the building simultaneously. The first PDPs were obtained with transmitter at 9.5 m and receiver at 10.5 m from the building. For the second step, the receiver is moved 1 m towards the building so that the distance between the building and the receiver becomes 9.5 m and the transmitter is not moved. The transmitter and receiver were then moved 1 m away from the building for the third step. RMS-DS and MED values were obtained for all these different positions and recorded as shown in Table 4.8.
Table 4.11: RMS-DS and MED values for transmitter receiver combined perturbation analysis

<table>
<thead>
<tr>
<th>Transmitter distance from building (m)</th>
<th>Receiver distance from building (m)</th>
<th>RMS-DS (ns)</th>
<th>MED (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5</td>
<td>10.5</td>
<td>10.177</td>
<td>67.742</td>
</tr>
<tr>
<td>9.5</td>
<td>9.5</td>
<td>10.555</td>
<td>64.282</td>
</tr>
<tr>
<td>10.5</td>
<td>10.5</td>
<td>18.815</td>
<td>70.311</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>11.152</td>
<td>70.311</td>
</tr>
</tbody>
</table>

Again, our measured RMS-DS value (assuming transmitter and receiver are 10 m from the building) is 6.5921 ns. Table 4.11 shows that when the transmitter is moved towards the building and the receiver is moved away from the building, the analytical RMS-DS decreases slightly toward the measured value (an 8.74% change from the original position).

Another set of perturbations that was done in order to try to improve agreement between analytical and measured RMS-DS was to change the distance between the transmitter and receiver. The distance from the transmitter and receiver to the building remains at 10 m for this set of simulations. The transmitter is moved away from the receiver and then it is moved closer to the receiver. The results are listed in Table 4.12.

Table 4.12: RMS-DS and MED values when transmitter receiver distance is altered

<table>
<thead>
<tr>
<th>Distance from transmitter to receiver (m)</th>
<th>RMS-DS</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>9.9121</td>
<td>67.866</td>
</tr>
<tr>
<td>5.2</td>
<td>10.121</td>
<td>67.456</td>
</tr>
<tr>
<td>5.1</td>
<td>9.8971</td>
<td>69.201</td>
</tr>
<tr>
<td>5</td>
<td>11.152</td>
<td>67.339</td>
</tr>
<tr>
<td>4.9</td>
<td>10.408</td>
<td>67.031</td>
</tr>
<tr>
<td>4.8</td>
<td>11.489</td>
<td>67.070</td>
</tr>
</tbody>
</table>
Table 4.12 shows that there is a significant change in the value of RMS-DS when the transmitter to receiver distance is increased to 5.5 m--11.12% from the original transmitter-receiver distance of 5 m. Thus this distance between transmitter and receiver can be a non-negligible factor that can account for the discrepancies between measured and analytical RMS-DS.

4.7.4 Reflection Perturbation

Another perturbation analysis that was conducted to improve agreement between analytical and measured RMS-DS is a reflection perturbation. The Wireless Insite software allows the user to restrict the number of reflections, diffractions and transmissions in its ray tracing. Here the analysis was done by restricting the number of reflections. The screen shot of Wireless Insite that shows the various properties that can be changed in order to restrict the simulations is shown in Figure 4.28.

![Figure 4.28: Screen shot of Wireless Insite properties window](image-url)
The number of reflections was allowed to range from 1 to 3 and the value of RMS-DS was calculated for each criterion. These restrictions were done only for position 1. The RMS-DS value when the number of reflections was restricted to 1 is 12.214 ns. There was a 21.45% reduction in the value of RMS-DS for the simulation with 2 and 3 allowed reflections. Table 4.13 shows the RMS-DS and MED values for the reflection perturbation analysis. This shows that the number of reflections plays an important role in the discrepancy between the measured and the analytical results.

Table 4.13: RMS-DS and MED values for reflection perturbation analysis

<table>
<thead>
<tr>
<th>Number of reflection</th>
<th>RMS-DS</th>
<th>(\Delta) (%)</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.214</td>
<td>0</td>
<td>65.716</td>
</tr>
<tr>
<td>2</td>
<td>9.5939</td>
<td>21.45</td>
<td>67.065</td>
</tr>
<tr>
<td>3</td>
<td>9.5939</td>
<td>21.45</td>
<td>67.065</td>
</tr>
</tbody>
</table>

The number of diffractions was also restricted and additional simulations conducted. Table 4.14 shows the RMS-DS value resulting from the analysis. The RMS-DS value increases slightly when the number of diffractions increases. The previous analysis indicated that the number of reflections should not be restricted, so that in addition to this, the simulations in Wireless Insite should be done with maximum number of diffractions possible. The combination of Tx-Rx distance and reflections is also conducted and explained in the following section.
Table 4.14: RMS-DS and MED values for diffraction perturbation

<table>
<thead>
<tr>
<th>Criteria</th>
<th>RMS-DS</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 reflection 1 diffraction</td>
<td>14.290</td>
<td>66.183</td>
</tr>
<tr>
<td>1 reflection 2 diffraction</td>
<td>14.304</td>
<td>66.187</td>
</tr>
</tbody>
</table>

4.7.5 Removing Impulses

Removing impulses is another type of perturbation analysis that was conducted to improve agreement. The objects created for the simulation environment are the building, car, 4 large poles and 4 small poles (parking signs). These objects were removed to see the effect on RMS-DS. Table 4.15 shows the value of RMS-DS when the various elements were removed from the simulated environment.

Table 4.15: RMS-DS and MED values by removing elements from the simulated environment

<table>
<thead>
<tr>
<th>Objects Removed</th>
<th>RMS-DS</th>
<th>MED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>10.032</td>
<td>67.138</td>
</tr>
<tr>
<td>Car and two poles in front of car</td>
<td>9.6360</td>
<td>67.077</td>
</tr>
<tr>
<td>All far elements</td>
<td>9.5944</td>
<td>67.070</td>
</tr>
</tbody>
</table>

The results show that by removing the car, the RMS-DS value changed from 11.152 ns to 10.032 ns and if the two poles were also removed along with the car, the RMS-DS decreased further to 9.6360 ns. When all the “far” elements are removed, the RMS-DS decreased 9.5944 ns.

Another analysis was conducted by placing the transmitter at 9.5m from the building and transmitter-receiver inter-distance to 5.1 m. This combined analysis showed
that the value of RMS-DS 10.151ns. Another combined analysis is conducted by changing the transmitter and receiver inter-distance to 5.1 m and restricting to 2 reflections. The RMS-DS value obtained for the analysis was 9.4369 ns. This result shows that the analytical RMS-DS became much closer to the measured RMS-DS. The result obtained is changed by 18.17%.

Another combined analysis is conducted by placing the transmitter at 9.5m from the building and restricting to 2 reflections. The analytical RMSDS obtained with this setup is 8.5434ns. This result is closer to the measured data of 6.5921ns. The analytical RMSDS obtained is changed by 30.53% from the analytical results obtained when the transmitter and receiver is placed at position1 exactly.

Another analysis was conducted by combining all the results from the combined analysis. This was done by placing the transmitter at 9.5 m from the building, by making the transmitter-receiver inter-distance 5.1 m, and by restricting the number of reflections to 2. The RMS-DS obtained from the combined analysis is 8.4229 ns. This is a 32.40% change from the original analytical RMS-DS calculated for position 1. This combined analysis value is closest to the measured value of RMS-DS. Future users of Wireless Insite should consider such a perturbation analysis. They should also consider employing a threshold to eliminate weak diffuse components as this should generally improve agreement between analytical and measured PDPs. The future users with no measured results can use the ray tracing analysis in order to predict the RMS-DS in that particular environment. They could also obtain the PDP which could predict the PDP at that environment. The PDPs will be accurate if the simulation is carried out with most of the obstacles in the actual environment included and a comparable PDP can be obtained by
employing the threshold condition also. The RMS-DS value can be accurately obtained by restricting the number of reflections if Wireless insite is used in creating the simulations. The variation of the transmitter and receiver distance by a smaller distance could tell you the exact variations that can occur in that particular environment. The perturbation analysis showed that if the measurements were carried out at exactly same positions as simulated, the results will be very close.
Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this thesis, we have compared measured and ray tracing results for a 5 GHz band wireless channel. The comparison of PDPs was conducted for four different transmitter and receiver positions at the same outdoor location. The measured and analytical PDPs were found to be comparable qualitatively for all four positions. We also made quantitative comparisons, in terms of the power delay profile dispersion, quantified by the root-mean square delay spread (RMS-DS). These results showed that the ray tracing results deviate from the measured results—in terms of the RMS-DS—as more objects were added into the simulation environment. The RMS-DS value obtained using the simulations is larger compared to the measured RMS-DS.

The differences between the measured and analytical values of the multipath component amplitudes are due in part to the unavailability of exact parameter values for characteristics such as permittivity and conductivity of building blocks. (We were able only to vary these by varying our choice of software built-in building materials.) There were also delay differences between measured and analytical impulses, which are due to the inaccuracies in the approximation of the simplified building created using the Wireless Insite software, plus inaccuracies in our measurements of distances.

The use of a threshold to eliminate weak (and inconsequential) multipath components was applied to simplify comparison. We also conducted a perturbation analysis, in which we varied distances and the complexity of the ray tracing analysis. The
perturbation analysis showed that the discrepancies in RMS-DS calculated using ray tracing can help model inaccuracies involved in analysis. For our particular setting, we found that the value of RMS-DS from ray tracing was always larger than the RMS-DS value measured. By varying the different parameters, we found that the RMS-DS value comes closer to the measured results. This implies that the ray tracing could provide comparable values of RMS-DS and could predict the comparable multipath components in an outdoor environment.

5.2 Future Work

The first item of future work might be to find an even simpler outdoor environment in which to conduct a comparison. A simpler building structure, with fewer reflecting/diffracting objects would simplify the PDP, and allow more precise “tuning” of the ray tracing set up, and easier evaluation of which parts of the ray tracing program are most important in terms of obtaining agreement with measurements.

Additional future work includes continuing comparison of ray tracing and measured results by the addition of “human being objects.” Ultimately, the analysis should be more accurate by making the ray tracing object properties more accurate. If precise properties of the objects such as conductivity and permittivity could be used in the Insite software, the outputs should be more accurate. The comparison of the ray tracing and measured PDPs could also be done by employing metrics other than RMS-DS. After refining the ray tracing configuration for simpler environments, additional comparison of ray tracing and measured results could be carried out for indoor and more complex outdoor environments.
References


Appendix A

MATLAB CODE

// Averaged PDP value obtained from the Indranil’s Code
// DelX obtained from Indranil’s Code
// xaxis and yaxis is the data obtained from the Wireless Insite
%% normalizing

linearscale1=10.^(3+averagedpdp1(1,:)/10); % converting pdp to linear scale
normalised1(1,:)=10*(log10(linearscale1./sum(linearscale1'))); % Normalizing and Log Scaling

linearscale2=10.^(3+yaxis(1,:)/10); % converting pdp to linear scale
normalised2(1,:)=10*(log10(linearscale2./sum(linearscale2'))); % Normalizing and Log Scaling

x11=normalised1+80;
y11=normalised2+80;

%% plotting with all multipath normalized
figure(1)
stem(DelX,x11)
hold on
stem(xaxis,y11,'r'),grid on
xlim([0 1.2])
title('Comparision of Power Delay Profiles with all multipath components')
xlabel('Delay (\mu sec)')
ylabel('Relative Power (dB)')
legend('Measured','Analytical')

%% Thresholding the analytical values
analythresh=0;
variable(1,:)=max(y11(1,:))-y11(1,:);
for lk = 1:25
    if ( abs(variable(1,lk))<= 20 )
        analythresh(1,lk)= y11(1,lk);
    else
        analythresh(1,lk)= 0 ;
    end
end

%% Thresholding the measured values
measuredthresh=0;
variable1(1,:)=max(x11(1,:))-x11(1,:);
for lk = 1:54
    if ( abs(variable1(1,lk))<= 20 )
        measuredthresh(1,lk)= x11(1,lk);
    else
        measuredthresh(1,lk)= 0 ;
    end
%% Plotting thresholded values

figure(2)
stem(DelX,measuredthresh)
hold on
stem(xaxis,analythresh,'r'),grid on
xlim([0 1.2])
title('Comparision of Power Delay Profiles with threshold = 20 dB normalized to unit energy')
xlabel('Delay (\text{\mu sec})')
ylabel('Relative Power (\text{dB})')
legend('Measured','Analytical')

%% RMSDS for measured
% disp('after normalasing measured')
volt=10.^(measuredthresh/20);
med=0;
msq=0;
DEN=0;
for i=1:54
    med=med+((DelX(i).*((volt(i).^2))));
    msq=msq+((DelX(i).^2)*((volt(i).^2)));
    DEN=DEN+((volt(i).^2));
end
MED=(med)*(10^{-6})/DEN;
RMSDS=sqrt((msq*(10^{-12})/DEN)-MED^2);

%% RMSDS for analytical
% disp('before normalazing analytical')
volt1=10.^(analythresh/20);
med1=0;
msq1=0;
DEN1=0;
for i=1:25
    med1=med1+((xaxis(i).*((volt1(i).^2))));
    msq1=msq1+((xaxis(i).^2)*((volt1(i).^2)));
    DEN1=DEN1+((volt1(i).^2));
end
MED1=(med1)*(10^{-6})/DEN1;
RMSDS1=sqrt((msq1*(10^{-12})/DEN1)-MED1^2);

%% displaying
disp('RMSDS')
RMSDS
RMSDS1
disp('MED')
MED
MED1
%% histogram of RMSDS
figure(3)
hist(RMSDelSpr,150),grid
title('Histogram of RMS Delay Spread')
ylabel('Number of samples')
xlabel('RMSDS(ns)')

%% mean, max and std of RMSDS
mean1=mean(RMSDelSpr)
max1=max(RMSDelSpr)
std1=std(RMSDelSpr)

%% Program to calculate the RMSDS for data from Wirless Insite
clc;
clear all;
%% xaxis and yaxis obtained fromt eh Wireless Insite is used here
xaxis=xaxis.*10^6;

%% normalising
linescale2=10.^(-3+yaxis(1,:)./10);  %% converting pdp to linear scale
normalised2(1,:)=10*(log10(linescale2./sum(linescale2'))));  %% Normalizing and Log Scaling
y11=normalised2+80;

%% Thresholding the analytical values
analythresh=0;
variable(1,:) = max(y11(1,:))-y11(1,:);
for lk = 1:25
  if ( abs(variable(1,lk))<= 100)
    analythresh(lk)= y11(1,lk);
  else
    analythresh(lk)= 0 ;
  end
end

%% RMSDS for analytical
% disp('before normalazing analytical')
volt1=10.^((analythresh/20);
med1=0;
msq1=0;
DEN1=0;
for i=1:25
  med1=med1+((xaxis(i).* (volt1(i).^2)));
  msq1=msq1+((xaxis(i).^2)* (volt1(i).^2));
  DEN1=DEN1+ (volt1(i).^2);
end
MED1=(med1)*(10^-6)/DEN1
RMSDS1=sqrt((msq1*(10^-12)/DEN1)-MED1^2)