Wireless Channel Characterization for Large Indoor Environments at 5 GHz

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ABSTRACT

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Wireless Channel Characterization for Large Indoor Environments at 5 GHz

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This thesis provides a wireless channel characterization for large indoor environments in the frequency band around 5120 MHz. Measurements were carried out in two different large indoor locations on the Ohio University campus. Different transmitter positions were chosen at each location and the transmitter was kept stationary during the course of the measurements. For each transmitter position, the receiver was moved around inside to collect data. From the measurement data, we were able to obtain power delay profiles and compute root mean square delay spread values – the most common measure of temporal dispersion. Average delay spreads range from approximately 50-100 ns, with the largest values occurring in non-line of sight conditions at the largest link distances. Our large indoor environments yielded larger delay spreads than those found by other researchers in indoor settings. Tapped delay line channel models were also developed for a channel bandwidth of 10 MHz. by specifying the number of channel taps, the tap amplitude fading distributions and the energy associated with each tap.

Approved: _____________________________________________________________

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>4</td>
</tr>
<tr>
<td>List of Tables</td>
<td>8</td>
</tr>
<tr>
<td>List of Figures</td>
<td>9</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>12</td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>12</td>
</tr>
<tr>
<td>1.2 History of Wireless Communications</td>
<td>12</td>
</tr>
<tr>
<td>1.4 Importance of Channel Characterization</td>
<td>15</td>
</tr>
<tr>
<td>1.4 Thesis Scope</td>
<td>16</td>
</tr>
<tr>
<td>1.5 Thesis Outline</td>
<td>17</td>
</tr>
<tr>
<td>2. Fundamentals of Channel Characterization</td>
<td>18</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>18</td>
</tr>
<tr>
<td>2.2 Typical Channel Models</td>
<td>18</td>
</tr>
<tr>
<td>2.2.1 Deterministic Modeling</td>
<td>18</td>
</tr>
<tr>
<td>2.2.2 Statistical Modeling</td>
<td>19</td>
</tr>
<tr>
<td>2.3 Multipath Fading</td>
<td>19</td>
</tr>
<tr>
<td>2.3.1 Common Statistical Fading Distributions</td>
<td>20</td>
</tr>
</tbody>
</table>
2.4 Channel Impulse Response Approach to Model the Channel ................. 23

2.5 CIR Parameters ............................................................................................. 25

2.5.1 Power Delay Profile ................................................................................ 25

2.6 Literature Review ........................................................................................... 28

3. Measurement Equipment and Procedure ...................................................... 33

3.1 Introduction .................................................................................................... 33

3.2 Measurement Equipment .............................................................................. 33

3.2.1 Channel Sounder ..................................................................................... 33

3.3 Description of Environments ........................................................................ 35

3.3.1 Templeton-Blackburn Memorial Auditorium ..................................... 35

3.3.2 Convocation Center ............................................................................... 39

3.4 Measurement Procedure ............................................................................. 43

3.4.1 Equipment Setup for Calibration ......................................................... 44

3.4.2 Equipment Setup for Measurement ...................................................... 44

4. Results and Analysis of Measurement Data .................................................... 46

4.1 Introduction .................................................................................................. 46

4.2 Measurement Data Processing ..................................................................... 46

4.3 Example Power Delay Profiles .................................................................... 50

4.4 Channel Parameter Results .......................................................................... 53
4.5 Channel Modeling .......................................................... 64
  4.5.1 Tapped Delay Line Model .................................. 64
  4.5.2 Channel Modeling for Large Indoor Environments ... 66

5. Conclusion ................................................................. 78
  5.1 Summary ............................................................ 78
  5.2 Conclusions ......................................................... 78
  5.3 Suggestions for Future Work ................................. 79

References ........................................................................ 80

Appendix 1: Matlab Code .............................................. 84
LIST OF TABLES

Table 4.1 Total Number of PDPs Recorded..........................................................51

Table 4.2 Templeton Blackburn auditorium RMS-DS Statistics (ns).......................56

Table 4.3 Templeton Blackburn auditorium RMS-DS Statistics (ns) with Rx
on stairs data excluded.......................................................................................57

Table 4.4 Convocation center RMS-DS Statistics (ns)..........................................62

Table 4.5 Statistical Channel Model for Auditorium, Tx position on stage.............69

Table 4.6 Statistical Channel Model for Auditorium, Tx position in balcony.........69

Table 4.7 Statistical Channel Model for Convocation Center, Tx position 1..........73

Table 4.8 Statistical Channel Model for Convocation Center, Tx position 2..........73
LIST OF FIGURES

Page

Figure 2.1 Example Power Delay Profile [Adapted from 23]……………………………………26
Figure 3.1 BVS Channel Sounder, transmitter and receiver……………………………………34
Figure 3.2 Pictures of Templeton-Blackburn Auditorium building…………………………35
Figure 3.3 Picture of Templeton-Blackburn Memorial Auditorium, taken from
stage area, showing the three Tx positions………………………………………………………………36
Figure 3.4 View of the auditorium first floor showing Rx path for Tx position 1
(LOS condition)…………………………………………………………………………………………38
Figure 3.5 Pictures of auditorium balcony showing Rx path [33]……………………………39
Figure 3.6 Picture of the Convocation center building [33]…………………………………..40
Figure 3.7 Picture of Convocation Center showing the two Tx positions [34]……………..41
Figure 3.8 Pictures of the Convocation Center [33]…………………………………………..41
Figure 3.9 View of Convocation Center showing measurement area for two
Tx positions [34]……………………………………………………………………………………………42
Figure 3.10 Tx and Rx Equipment Setup…………………………………………………………43
Figure 4.1 PDP plot before applying threshold (Tx position 3 in auditorium)
with RMS-DS=77.41 ns……………………………………………………………………………………49
Figure 4.2 PDP plot after applying the threshold (Tx position 3 in auditorium)
with RMS-DS = 75.12 ns……………………………………………………………………………………50
Figure 4.3 Example PDP plot at Convocation Center for Tx position 1 with
RMS-DS = 58.47 ns……………………………………………………………………52

**Figure 4.4** Example PDP plot at Templeton Blackburn auditorium for Tx position 2 on stage with RMS-DS = 384.09 ns……………………………………………………………………53

**Figure 4.5** RMS-DS histogram for auditorium Tx position 2 on stage, Mean RMS-DS = 57.29 ns…………………………………………………………………………………54

**Table 4.6** RMS-DS histogram for auditorium Tx position 3 in the balcony, Mean RMS-DS = 69.06 ns……………………………………………………………………55

**Figure 4.7** RMS-DS vs. PDP index for Tx position 3 in balcony in the auditorium……58

**Figure 4.8** RMS-DS vs. PDP index for Tx position 2 on stage in the auditorium……59

**Figure 4.9** PDP plot for max RMS-DS for the auditorium Tx position 3 in balcony…..60

**Figure 4.10** RMS-DS histogram for Convocation Center Tx position 1, Mean RMS-DS= 71.01 ns…………………………………………………………………………………61

**Figure 4.11** RMS-DS histogram for Convocation Center Tx position 2, Mean RMS-DS = 69.7 ns…………………………………………………………………………………61

**Figure 4.12** RMS-DS vs. PDP index for Tx position 1 in the Convocation Center……63

**Figure 4.13** RMS-DS vs. PDP index for Tx position 2 in the Convocation Center……63

**Figure 4.14** Tapped Delay Line Model [Adapted from 36]……………………………..65

**Figure 4.15** Tap 1 amplitude histogram & fits for auditorium, Tx position – stage……70

**Figure 4.16** Tap 1 amplitude histogram & curve fits for auditorium, Tx position – balcony………………………………………………………………………………………71

**Figure 4.17** Tap 2 amplitude histogram and curve fits for auditorium, Tx position – stage………………………………………………………………………………………71
Figure 4.18 Tap 2 amplitude histogram and curve fits for auditorium,
Tx position – balcony .................................................................72

Figure 4.19 Tap 1 amplitude histogram and curve fits for Convocation Center,
Tx position 1 .............................................................................74

Figure 4.20 Tap 1 amplitude histogram and curve fits for Convocation Center,
Tx position 2 .............................................................................74

Figure 4.21 Tap 2 amplitude histogram and curve fits for Convocation Center,
Tx position 1 .............................................................................75

Figure 4.22 Tap 2 amplitude histogram and curve fits for Convocation Center,
Tx position 2 .............................................................................75
1. INTRODUCTION

1.1 Introduction

In this chapter, the first section provides a brief history of wireless communications with regard to cellular and Wireless Local Area Network (WLAN) technologies. The next section describes the importance of channel characterization. Last, we provide the scope and outline of this thesis.

1.2 History of Wireless Communications

Wireless communication technology has been growing significantly over the last 15 years. However, its remarkable beginning dates back to the late 1800s when Marconi demonstrated radio transmission for the very first time in 1895. The first wireless voice transmission took place in 1915 and radio technology continued to develop thereafter [1].

The first cellular technology came into existence in the 1940s with the introduction of the first cellular public service in 1946. This system introduced the concept of dividing the service areas into “cells” and reusing the available frequency spectrum to increase capacity without causing interference to the other users [2], [3].

The cellular systems in the 1980s used analog technology and these systems formed the first generation of cellular communication systems. They made use of Frequency Division Multiple Access (FDMA)/ Frequency Division Duplex (FDD) techniques. Some of the first generation cellular systems that were deployed were the Advanced Mobile
Phone System (AMPS), Enhanced Total Access Communication System (ETACS) and Nordic Mobile Telephone (NMT) [4].

These systems were soon followed by the second generation (2G) digital cellular technologies. Better modulation and coding techniques that developed with the digital technology were used in these systems, which improved both system capacity and the quality of radio transmission [4]. The major 2G standards included Interim Standard (IS-54/136), Global System for Mobile Communication (GSM), Personal Digital Cellular (PDC) and IS-95. The first three standards used the Time Division Multiple Access (TDMA) technique whereas the last standard used the Code Division Multiple Access (CDMA) technique. Similar to the 1G technologies, 2G digital technologies also made use of the FDD scheme [4]. These 2G technologies provided data transfer services for text messaging and e-mail applications by using circuit switching [5].

The transition from second to third generation standards happened via General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE) technologies, which were termed as 2.5G standards. These technologies increased the data transfer rates and made use of the existing GSM networks to implement packet data switching [3], [6]. The third generation (3G) cellular standards were collected by the International Telecommunications Union (ITU) and were called IMT-2000 (International Mobile Telecommunications-2000). Compared to 2G systems, these systems were designed to provide enhanced data rates and enable video transfer and roaming services.
around the world. Some of the 3G standards include Universal Mobile Telecommunication System (UMTS), which is WCDMA (Wideband CDMA), CDMA2000 and Digital Enhanced Cordless Telecommunications (DECT) [7].

The fourth generation of cellular standards was recently defined. The Third-Generation Partnership Project (3GPP), a group of industries and other organizations with interest in mobile communication, defined the Long Term Evolution (LTE) set of standards. These standards were developed to meet the growing demands for high speed data rates and to improve the quality of service [8]. The IEEE 802.16e standard, implemented as Worldwide Interoperability for Microwave Access (WiMAX), can be viewed as another 4G standard [9]. Both LTE and WiMAX provide high spectral efficiency and increased user capacity with the use of Multiple Input/Multiple Output (MIMO) antenna technology [8], [9].

WLAN is another area of wireless communication that has been developed by the IEEE 802.11 committee (Institute of Electrical and Electronics Engineers). The committee was started in 1997 and its aim was to provide wireless connection services to fixed and mobile users in a local area. WLANs provides the advantage of mobility to users and reduced installation and maintenance costs as it requires less physical wirings as compared to wired LANs [6]. The medium access method used by WLANs is called Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA). With this mechanism, the device wanting to transmit first listens for transmissions on the wireless channel. If
the channel is busy, the device waits for a random period of time and listens again. If no communication is taking place on the channel, the device starts transmitting and if it does not receive an acknowledgement within a certain period of time, it retransmits [10].

The frequency bands in which the WLAN standards operate are 2.4 GHz and 5 GHz. The WLAN standards include 802.11a, 802.11b, 802.11g and 802.11n [6]. 802.11a operates in the 5 GHz band and it can provide data transfer rates up to 54 Mbps. However it is not compatible with 802.11b and 802.11g standards as they both operate in the 2.4 GHz band. 802.11b can support a maximum data transfer speed of 11 Mbps while 802.11g can support up to 54 Mbps. 802.11n operates in both 2.4 GHz and 5 GHz bands and can support data rates of up to 150 Mbps by making use of MIMO antenna technology in which multiple antennas are used for transmitting and receiving data. Channel bonding is another technology used in 802.11n standard in which the bandwidth is increased by joining 2 frequency bands together. With the channel bonding technique, this standard can support data rates of up to 300 Mbps [11].

1.4 Importance of Channel Characterization

The wireless channel has a degrading effect on the propagation of electromagnetic waves, making these signals weak as they travel from the transmitter to the receiver [12]. The signal path from the transmitter to the receiver is often well modeled as unpredictable, and for an indoor environment, multipath components are created because of reflections from the objects present inside the building, the walls, floor and the ceiling. Each
environment - indoor or outdoor - exhibits different wireless channel characteristics, and by having an accurate and precise channel model, communication system designers can estimate signal coverage, attainable data rates and the best possible location for installing antennas [13]. Having information about the wireless propagation channel is extremely important in the design of radio systems. By modeling the channel, we can obtain quantitative descriptions of the propagation mechanisms that will help us design transmitter and receiver characteristics such as channel (or subcarrier) bandwidth, equalization algorithms, etc., to attain better performance [12]. Whenever any new wireless system standard is developed, standards committees always begin with channel models.

1.4 Thesis Scope

This thesis is aimed at providing a wireless channel characterization for several large indoor environments at a frequency of 5120MHz. Measurements were carried out in Templeton-Blackburn Memorial Auditorium and the Convocation Center on the Ohio University Campus.

For the Templeton-Blackburn Memorial Auditorium, the transmitter was set up in three different locations inside the auditorium and for the Convocation Center, two transmitter locations were chosen. The transmitter was kept stationary during the course of the measurements and for each transmitter location, the receiver was moved around inside.
Power delay profiles were obtained from the measurement data and these profiles were then processed to obtain important channel parameters such as root mean square delay spread and mean excess delay. Tapped delay line models for the indoor wireless channels were also developed for a channel bandwidth of 10 MHz. These channel models describe the randomly time-variant channel by specifying the number of taps (multipath components) for the channel, the tap amplitude fading distributions, and the energy associated with each tap.

1.5 Thesis Outline

The first chapter provides a brief history of the wireless communications, the importance of channel characterization and the scope of my thesis. The second chapter explains about the types of channel models, some common fading distributions, channel impulse response and important channel characteristics like mean excess delay and RMS Delay Spread. It also provides a literature review of some of the relevant work done in the field of channel modeling. The third chapter discusses the measurement procedure and the environments in which the measurements were conducted. The fourth chapter provides the channel parameter results and the channel model. Finally the fifth chapter provides the summary, conclusion and some recommendations for future work for this thesis.
2. FUNDAMENTALS OF CHANNEL CHARACTERIZATION

2.1 Introduction
This chapter deals with the basic concepts involved in the characterization of a wireless channel. The chapter begins with an explanation of the types of channel models available. Statistical fading models such as the Rayleigh, Ricean, Nakagami and Weibull which have been widely used to model wireless channel amplitude variations are discussed here. The fundamental characteristics of channel impulse responses and power delay profiles are also discussed in this chapter. Important channel parameters such as mean excess delay, root mean square delay spread and maximum excess delay - which can be derived from power delay profiles - are also explained. Finally, a literature review of some of the relevant work done in this field for various frequency bands is presented.

2.2 Typical Channel Models
Channel modeling is an important step in the design of wireless communication systems. There are generally two different approaches available for modeling a wireless communication channel: Deterministic Modeling and Statistical Modeling [12].

2.2.1 Deterministic Modeling
In deterministic channel modeling, the environment in which the channel is to be modeled is described in terms of deterministic equations; in practice, it is often recreated on a simulation tool. To simulate the environment, accurate information about the
environment and the properties of objects in the environment has to be obtained. For instance, ray tracing models are deterministic models that can be used to extract various channel parameters. These models give accurate results for the channel characteristics, but when the environment is large and complex, it becomes difficult to model the channel deterministically [12].

2.2.2 Statistical Modeling

In statistical channel modeling, measurements are typically conducted to obtain information about the channel in the environment in which we are interested. The data collected from the measurements is then processed to obtain the channel parameters. The statistical information about the channel obtained from these models is often accurate and since the complexity of the environment is not a matter of concern while taking measurements; it is obviously easier to statistically model channels [12].

2.3 Multipath Fading

A signal travelling from the transmitter to the receiver through a channel usually experiences the three basic propagation mechanisms i.e. reflection, diffraction and scattering due to various objects present in the environment [14]. Multiple components of the signal are formed and these components which arrive at the receiver from many directions are combined to obtain the resultant signal. If the transmitter or the receiver is in motion, the components arrive with varying path lengths, time delays and phases. Depending upon the phase of the components, they are added constructively or
destructively to form the resultant signal. This phenomena leads to distortion and fading of the received signal [15].

2.3.1 Common Statistical Fading Distributions

Multipath fading of a signal can be described by a number of distributions [14]. Some of the most common distributions are presented in this section:

2.3.1.1 Rayleigh Distribution

This distribution is commonly used to describe amplitude fading in extreme cases where the environment is complex with many objects and therefore has no line of sight (LOS) or dominant component between the transmitter and the receiver [12]. The probability density function (PDF) for the Rayleigh distribution is given by [16]

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp \left( \frac{r^2}{2\sigma^2} \right) & 0 \leq r < \infty \\ 0 & r < 0 \end{cases}$$

(2.1)

where $r$ is the amplitude of the received signal and $2\sigma^2$ represents the power of the random multipath components. The complex (or baseband) received signal $x(t)$ consists of in-phase $I$ and quadrature $Q$ components that are Gaussian random variables as per the central limit theorem. These components have zero mean, are independent of each other and are identically distributed [16]. According to the central limit theorem, the summation of independent random variables will be Gaussian distributed even if the individual components have different distribution functions [17].
The amplitude of the received signal $x(t)$ is calculated by $\sqrt{I^2 + Q^2}$ and for the Rayleigh case, its phase is uniformly distributed over the interval $(0, 2\pi)$ [16]. As mentioned in [16], the Rayleigh distribution has commonly been used to describe the fading statistics for data collected in indoor and outdoor environments. A number of cases are mentioned in [16] where experiments conducted in different types of indoor environments have shown that the small scale changes in the amplitude are described by the Rayleigh distribution in the absence of an LOS component.

### 2.3.1.2 Rician Distribution

This distribution is mainly used in cases when the received signal consists of an LOS component along with a number of multipath NLOS components. The PDF for the Rician distribution is given by [16]

$$p(r) = \begin{cases} \frac{r}{\sigma^2} \exp\left(-\frac{r^2 + A^2}{2\sigma^2}\right) I_0 \left(\frac{A r}{\sigma^2}\right) & \text{for} \quad \{A \geq 0, r \geq 0\} \\ 0 & \text{for} \quad r < 0 \end{cases}$$

(2.2)

Here $A$ represents the amplitude of the LOS signal component and $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind. The Rician distribution can also be expressed in terms of $K$ which is called the Rician factor and it is given by [16]

$$K = 10 \log \left(\frac{A^2}{2\sigma^2}\right) \text{ dB}$$

(2.3)
which is the ratio of the power in the LOS component to the power in the multipath components. As $K \to -\infty$, the received signal has no LOS component and the PDF is reduced to a Rayleigh distribution. As $K \to \infty$, the power in the LOS component becomes much larger than the combined power of the multipath components, leading to a non-fading small-variance Gaussian distribution [16].

2.3.1.3 Nakagami Distribution

The Nakagami distribution is capable of approximating other fading distributions under certain conditions and its PDF is given by [18]

$$p(r) = \frac{2}{\Gamma(m)} \left( \frac{m}{2\sigma^2} \right)^m r^{2m-1} \exp \left( -\frac{m}{2\sigma^2} r^2 \right) \quad r \geq 0$$

(2.4)

where $\Gamma(\cdot)$ is the gamma function and $m$ is called the fading figure with the condition $m \geq 1/2$. Depending upon the value of the parameter $m$, the Nakagami distribution can transform to other fading distributions. When $m=1$, the PDF of this distribution reduces to that of the Rayleigh distribution and when $m>1$, the fading distribution is approximately equal to that of the Rician [18]. When $m=1/2$, the PDF becomes a one-sided Gaussian distribution [15]. This distribution can also be used to model channels which undergo fading worse than Rayleigh by selecting the value of $m$ to be between 1/2 and 1 [18].
2.3.1.4 Weibull Distribution

This distribution has been successfully used to describe amplitude fading by certain authors as mentioned in [19]. The PDF of the Weibull distribution, which is a generalization of the Rayleigh distribution, is given by [19]

\[ p(r) = \frac{b}{a^b} r^{b-1} \exp \left( \frac{-r}{a} \right)^b \quad r \geq 0 \quad (2.5) \]

where \( b \) is the shape parameter, representing the fading severity and \( a \) is the scale parameter and is given by [19]

\[ a = \sqrt{\frac{\Omega}{\Gamma\left(\frac{2}{b}\right) + 1}} \quad (2.6) \]

where \( \Gamma(\cdot) \) is the gamma function and \( \Omega \) is the mean square value corresponding to the energy. As mentioned, the received signal envelope for any distribution is given by \( R = \sqrt{I^2 + Q^2} \). For Weibull random variables, one can obtain them by raising a Rayleigh variable \( R \) to a power \((2/b)\) [20].

When \( b = 2 \), this distribution becomes the Rayleigh, and as \( b \) increases, the fading severity reduces [21], thus \( b \) is analogous to the Ricean \( K \) factor.

2.4 Channel Impulse Response Approach to Model the Channel

The channel impulse response (CIR) is the response obtained at the output of the channel when the input is a unit impulse signal [17]. The CIR can be measured by transmitting a pulse electromagnetic wave over the channel. A radio propagation channel can be
considered to be a linearly time varying as well as a spatially varying filter which can lead to distortion of the transmitted signal. The signal that reaches the receiver is typically a number of multipath components which have reduced signal strength, varying time delays and phase shifts. Thus the impulse response of a multipath radio channel is given by [22], [23]

\[
   h(t, \tau) = \sum_{i=0}^{L-1} z_i(t) a_i(t) \exp [j(2\pi f_c \tau_i(t) + \nu_i(t, \tau))] \delta(\tau - \tau_i(t)) \quad (2.7)
\]

where \(z_i(t)\) is the persistence process that denotes the presence or absence of a multipath component [22], \(a_i(t)\) represents the amplitude of the \(i\)th multipath component (MPC) at time \(t\), \(\delta(\cdot)\) is the Dirac delta function, \(L\) is the total number of multipath components and \(\tau_i(t)\) is the corresponding excess delay of the \(i\)th MPC. The excess delay is the difference between the arrival times of the last multipath component and the first component. These components are also subjected to phase shifts as they propagate through free space and other phase shifts as they traverse through the channel, and the phase shift is expressed by \(\exp [j(2\pi f_c \tau_i(t) + \nu_i(t, \tau))]\). In this model, a profile of the impulse response is obtained for each time \(t\) and the delay axis \(\tau\) is divided equally into bins with width \(\Delta\tau = \tau_{i+1} - \tau_i\). Many multipath components can be received within a particular bin and since these components cannot be resolved or separated, they are added and are all represented by only one multipath component. The addition of a large number of multipath components results in the fading of the signal [23]. If the system is considered to be time invariant, the channel impulse response would be [22], [23]
\[ h(\tau) = \sum_{i=0}^{L-1} z_i a_i \exp[j(2\pi f_c \tau_i + v_i(\tau))] \delta(\tau - \tau_i) \] (2.8)

2.5 CIR Parameters

This section discusses the concept of power delay profile and some of the parameters that can be extracted from it. These parameters are often used for representing a channel’s delay domain characteristics [23].

2.5.1 Power Delay Profile

A power delay profile (PDP) is a “power version” of the channel impulse response. A PDP is a plot of the received power versus time delay corresponding to each multipath component. An average PDP is obtained by determining the average of instantaneous power delay profiles measured in a particular area [23]. Figure 2.2 is an example power delay profile which is a plot of relative power vs. time delay.
Important channel parameters can be obtained from a power delay profile. The channel parameters that are often used to represent a multipath channel are: mean excess delay, root mean square delay spread and maximum excess delay [23].

- **Mean Excess Delay**

The mean excess delay is the weighted average of the power delay profile. It is the first moment of a PDP and is given by [23]

\[
\tau = \frac{\sum_i a_i^2 \tau_i}{\sum_i a_i^2}
\]  

(2.9)

where \(a_i^2\) is the square of the amplitudes of the MPC and \(\tau_i\) is the delay.
• **Root Mean Square Delay Spread (RMSDS)**

RMSDS is the square root of the second central moment of a PDP and is given by [23]

\[
\text{RMSDS} = \sqrt{\tau^2 - \bar{\tau}^2}
\]  
(2.10)

where

\[
\bar{\tau} = \frac{\sum_i a_i^2 \tau_i^2}{\sum_i a_i^2}
\]  
(2.11)

RMSDS is a measure of the multipath spread and it can be used to judge the performance of a communication system. It directly relates to inter-symbol interference [16]. The larger the value of RMS-DS, the greater the effect of inter-symbol interference.

• **Maximum Excess Delay**

The maximum excess delay of a PDP is the time taken for multipath signal energy to fall to a value of X dB below the maximum of that particular PDP. It is given by [23]

\[
\text{Max.Excess delay} = \tau_X - \tau_0
\]  
(2.12)

where \(\tau_0\) is the delay of the first multipath signal component and \(\tau_X\) is the maximum value of delay at which the multipath signal component is within X dB from the maximum value [23].
2.6 Literature Review

In this section, a literature review of texts, papers and tutorials used in this thesis is presented. Reference [16] was a useful tutorial that explained statistical channel modeling and various common fading distributions. Chapter 5 in reference [23] discussed the multipath channel impulse response model and various channel parameters. Reference [24] described the procedure for training the channel measurement equipment and conducting the CIR measurements.

A brief overview of some of the work for channel modeling conducted in different frequency bands for indoor environments is presented here. In [25], the authors analyzed the channel characteristics and provided path loss models for indoor environments at 5.3 GHz. A 53.75 MHz bandwidth signal was used and vertically polarized discone omnidirectional antennas were used at the transmitter and at the receiver. Measurements were taken in two office environments, each with different types of building structure with distances varying from 5 -50 m, and measurements were also taken in a large hall of an airport with distance extending up to 200 m. All the measurements were taken in the presence of few people inside the buildings. Line of sight (LOS) and Non-LOS (NLOS) path loss models were developed separately to describe the large scale channel behavior. The cumulative distributive functions (CDF) of Root Mean Square (RMS) Delay Spread were computed. In the office environments, the 90th percentile value of RMSDS was reported to be approximately 30 ns for LOS conditions and 30-50ns for NLOS conditions. In the large airport hall, the values were much larger and were reported to be
120 ns for the LOS condition and 180 ns for the NLOS condition. The tapped delay line model was used to describe the small scale channel behavior. For NLOS situations, the tap amplitudes were Rayleigh distributed and for LOS situations, the first tap was modeled as Ricean and the other taps were Rayleigh distributed.

Reference [26] reported results for channel characteristics at 2.4 GHz for indoor environments. The measurements were conducted in a small cluttered laboratory with dimensions being 7.8 m by 9.95 m and quarter wave monopole antennas were used for the transmitter and receiver. Three people moved around the receiver antenna within a radius of 2 m while taking measurements. The position of the receiver antenna was kept fixed and that of the transmitter antenna was varied for fading measurements. The fading distribution used to model the measured data was Ricean due to the presence of a LOS component. To determine the channel parameters, the transmitter antenna position was kept fixed and the receiver antenna was moved to 4 different positions within the laboratory. For the NLOS situation, the RMSDS value was calculated to be 26.82 ns and for 3 LOS situations, the RMSDS values were 30.55 ns, 24.12 ns and 22.19 ns. A relatively large value of 30.55 ns for the LOS situation was obtained because the receiver antenna in this case was placed near the hallway which caused more scattering of the signal and thus increased the delay spread. The mean excess delay and maximum excess delay were also calculated from the recorded power delay profiles.
In [27], the authors discussed the characterization of an ultra-wideband propagation channel for an indoor environment in the 3-10 GHz band. Measurements were carried out in different types of apartments with all the doors and windows closed while taking the measurements. Vertically polarized dipole antennas were used for the transmitter and the receiver. The transmitter was kept fixed in the living room and the receiver was shifted to different locations inside the apartment, which yielded both LOS and NLOS conditions. The distance between the transmitter and receiver was in the range of 1 to 20 m. Path loss for LOS and NLOS scenarios was determined to describe the large scale behavior of the channel. Channel parameters such as mean excess delay and RMS delay spread were also computed. For a three bedroom apartment, the mean value of RMSDS was reported to be 14 ns for the LOS scenario and 38.61 ns for the NLOS scenario.

In [28], the authors have presented indoor channel characteristics at 1.8 GHz. The measurements were carried out in 2 rooms and a hallway with different types of objects (benches, desks, bookcases, PC terminals, etc.) in the rooms, with and without people moving and for LOS and NLOS scenarios. Omnidirectional antennas were used for the transmitter and the receiver. For three receiver locations, the antenna position was moved short distances from one point to another along a 1.5 m track length. A network analyzer was used for transmitting a signal with power 30 dBm. A reflector was also kept in one of the measurements to observe its effect on the channel. The root mean square delay spread for various receiver positions was calculated from the recorded data. Simulated results using SIRCIM software were obtained. These were compared with the measured data and
they were found to be approximately the same. The authors reported that the number of reflected signals and the signal strength increased when the reflector was placed in the room while taking the measurements, as expected. With the receiver antenna kept stationary, the RMSDS value was reported to be 8.7 ns and 12.5 ns (with reflector in the room) for LOS scenario (Tx-Rx distance = 5.5 m) and 24.5 ns for NLOS scenario (Tx-Rx distance = 4.3 m). With receiver antenna displaced along 1.5 m from its initial position, the mean RMSDS with 20 dB threshold was reported to be 12.5 ns for LOS scenario (Tx-Rx distance = 3.7 m) and 26 ns for NLOS scenario (Tx-Rx distance = 16.4 m). The amplitude fading distribution was reported to be Rayleigh for NLOS scenario and Ricean for LOS scenario.

In [29], the authors have analyzed and compared the indoor channel characteristics at 2.25 GHz and 58 GHz frequencies. Measurements were conducted in a room with dimensions 6 m by 11.2 m. The propagation characteristics of electromagnetic waves differ for different frequency bands. So, two kinds of equipments were used for conducting measurements at the two frequency bands. For the 2 GHz frequency band, a sliding correlator channel sounder was used with a bandwidth of 100 MHz. For the 60 GHz frequency band, an HP 8510C vector network analyzer was used with a bandwidth of 2 GHz. Vertically polarized omnidirectional antennas were used at the transmitter and the receiver for measurements conducted in both frequency bands. The transmitter was kept fixed in one location and the receiver was moved to LOS and NLOS locations within the room. The authors reported that the RMSDS values calculated at 2.25 GHz
frequency were about two times the values calculated at 58 GHz. This is because the penetration loss at higher frequencies is much larger than the loss at lower frequencies. So the multipath components obtained at 58 GHz were reflections only from that room whereas at 2.25 GHz, significant multipath components that were reflected from objects/walls outside that room, having long delays, were also obtained. At 2.25 GHz, the mean RMSDS values were reported to be 20.9 ns for LOS scenario and 27.4 ns for NLOS scenario. At 58 GHz, the mean RMSDS values were reported to be 8.8 ns for LOS scenario and 13.2 ns for NLOS scenario.

As observed from the literature review, there are few references available for channel modeling in the 5 GHz band. In addition, there are even fewer results for channel characterization in large indoor environments. Hence, my thesis presents the channel characterization in this band for large indoor environments.
3. MEASUREMENT EQUIPMENT AND PROCEDURE

3.1 Introduction

The main goal of conducting measurements was to obtain power delay profiles which were then processed to develop models for the indoor, large-building channel. This chapter describes the entire process involved in carrying out these measurements. It discusses the equipment that was used to conduct measurements. A brief description of the indoor environments in which the measurements were made is provided, and the various transmitter locations and receiver paths selected for conducting measurements in those environments are also presented. Finally, a brief explanation of the equipment setup and the measurement procedure is also given.

3.2 Measurement Equipment

The equipment that was used for conducting measurements included two units that constitute the wireless channel sounder, the transmitter (Tx) and receiver (Rx), power supplies for the sounder units, two omnidirectional antennas, a laptop computer, an uninterruptible power supply (UPS), battery pack, RF cables, power cables and extension cords [24]. The following section gives a brief description of the channel sounder.

3.2.1 Channel Sounder

The wireless channel sounder, manufactured by Berkeley Varitronics Systems [30], consists of a transmitter and receiver. This sounder is a modified version of their Raptor
spread spectrum correlator [24]. Figure 3.1 shows a photograph of the transmitter and the receiver.

![Transmitter and Receiver](image)

**Figure 3.1** BVS Channel Sounder, transmitter and receiver

The transmitter has a frequency range from 5.09 GHz to 5.25 GHz and output power can be varied from 5 dBm to 33 dBm. The sounder generates a pseudorandom noise (PN) sequence with a length of 255 chips and BPSK modulates this to the carrier frequency. The chip rate used for the transmitter and the receiver is 50 Mcps, yielding a signal bandwidth of approximately 50 MHz [24]. The channel sounder units (Tx - Rx) each have their own individual power supplies, and a battery pack was also used for the
receiver while taking measurements, since the Tx was fixed in position, but the Rx was
moved.

3.3 Description of Environments

The environment of interest for this thesis is large indoor halls. The two locations chosen
as our large indoor environments on the Ohio University campus were the Templeton-
Blackburn Memorial Auditorium and the Convocation Center.

3.3.1 Templeton-Blackburn Memorial Auditorium

The first set of measurements was conducted in Templeton-Blackburn Memorial
Auditorium. Figure 3.2 has two photographs of the auditorium building showing the front
view and the right side view.

![Front View](image1)  ![Right Side View](image2)

**Figure 3.2** Pictures of Templeton-Blackburn Auditorium building
Figure 3.3 shows a picture taken inside the auditorium and also the 3 locations of the transmitter for our measurements. The auditorium has a first floor and a balcony with a total seating capacity of 2500. The length of the hall measured from the stage to the back of the auditorium is approximately 40.84 meters and the maximum width is around 31.7 meters.

![Image of Templeton-Blackburn Memorial Auditorium](image)

**Figure 3.3** Picture of Templeton-Blackburn Memorial Auditorium, taken from stage area, showing the three Tx positions

The first location of the transmitter was at the back of the first floor and this was near the auditorium’s sound control system. The second location of the transmitter was at the
center of the stage, and the third location was in the balcony, in the middle of the seating area. While conducting measurements, there were four people inside the auditorium and all the doors were kept closed. For all sets of measurements, the transmitter was kept fixed in its position and the receiver was moved around the auditorium (first floor and balcony); this provided both LOS and NLOS conditions.

Figure 3.4 depicts a diagram of the auditorium first floor. The green circle represents the first Tx position and the yellow arrows with red circles represent the approximate walking path in the seating area through which the Rx was carried for the LOS scenario.
Points through which Rx was carried

Stairs to the balcony

Tx position 1

Figure 3.4 View of the auditorium first floor showing Rx path for Tx position 1

(LOS condition)

Figure 3.5 is a picture of the auditorium balcony showing the approximate walking path for the receiver. For the first transmitter position, measurements for LOS and NLOS scenarios were conducted separately: the receiver was moved around the first floor seating area and the stage, yielding LOS conditions; and for this same transmitter position, the receiver was carried to balcony, to produce NLOS conditions. The Rx was
carried in a similar fashion for the other Tx positions as well. For the first Tx position, we
started recording the PDPs after carrying the receiver to the balcony but for the second
and third transmitter position, PDPs were recorded even during the receiver transit on the
stairs.

Figure 3.5 Pictures of auditorium balcony showing Rx path [33]

3.3.2 Convocation Center

The second set of measurements was conducted in the Convocation Center. Figure 3.6
shows a photograph of the Convocation Center building. The building is circular in shape
and the roof is dome shaped [34].
The Convocation Center has a seating capacity of about 13,000 with a playing floor made of maple wood. Its diameter is approximately 100 meters and the roof is made of aluminum over wood fiber which is at a height of about 37.5 meters from the playing floor [34]. There were approximately fifteen people on the floor while conducting measurements. Figure 3.7 is a photograph of the Convocation Center and it shows the two Tx positions used for measurements. Figure 3.8 shows two more photographs: one looking up at the roof and the other showing the seating area.
Figure 3.7 Picture of Convocation Center showing the two Tx positions [34]

Figure 3.8 Pictures of the Convocation Center [33]
Figure 3.9 depicts the measurement area for the two Tx locations. The transmitter was kept fixed in its position for both sets of measurements. For Tx position 1 (point A), the receiver was carried through the seating area from point A to point B and the approximate walking path through which the receiver was carried is depicted with green arrows and circles. Similarly, for Tx position 2 (point C), the receiver was carried from point C to point D through the seating area in a similar way.

**Figure 3.9** View of Convocation Center showing measurement area for two Tx positions [34]
3.4 Measurement Procedure

In this section, the procedure for equipment setup during the training and measurement phases is provided; details are given in [24]. Figure 3.10 shows a picture of the sounder units connected to their respective antennas and the laptop connected to the Rx unit with a serial RS-232 cable. The first part of this section explains the procedure for training/calibrating the equipment. The second part gives a brief explanation of the steps involved in conducting the CIR measurements.

![Transmitter and Receiver Setup]

**Figure 3.10** Tx and Rx Equipment Setup

**Omni directional Antennas**
3.4.1 Equipment Setup for Calibration

The Tx and Rx channel sounders have Rubidium oscillators and to ensure their stability during the entire measurement time, the sounder must be calibrated [24]. To frequency lock the Tx and Rx sounder units, they were connected back to back using an RF cable and a 40 dB attenuator to ensure that power received was below the Rx upper limit of -10 dBm. The sounders were trained for a day before conducting measurements for both the environments. The Tx and Rx units were connected to their respective power supplies which in turn were connected to the UPS. The laptop was connected to the receiver through a serial cable. The transmit frequency was set to 5120 MHz, the chip rate to 50 Mcps and the output power was set to 5 dBm for training. The RF power on the transmitter was turned ON. To begin training, the Raptor software on the laptop was started and then the same frequency and the chip rate as set in the transmitter were selected [24]. The Tx and Rx were left undisturbed to train for almost 24 hours which provided a measurement time of about 2.5 hrs.

3.4.2 Equipment Setup for Measurement

After training the equipment, it was first carried to the desired location to conduct measurements and during transit, the equipment was powered continuously by the UPS. The Tx RF power was turned OFF, and the RF cable connected between the Tx and Rx was removed. Once at the desired Tx location, omnidirectional antennas were connected to the transmitter and the receiver. These antennas have a gain of approximately 1.5 dBi [24]. The Tx sounder remained connected to its power supply while conducting
measurements and the power supply via UPS was connected to local AC power. The transmit frequency and the chip rate were set to 5120 MHz and 50 Mcps respectively, as done during the training. The output power was set to 33 dBm, and to begin measurements, the RF power was turned ON [24].

Before moving, the Rx sounder was connected first to the battery pack and then disconnected from the AC power supply to ensure that it did not lose power. Once at the measurement location, the Raptor software in the laptop was configured for the same frequency and chip rate as set in the transmitter. The receiver sounder with the antenna, laptop and the battery pack was then carried in the indoor environment to collect the measurement data. The data collected for each Tx position was saved in separate log files, which were later processed for modeling the channel.
4. RESULTS AND ANALYSIS OF MEASUREMENT DATA

4.1 Introduction

This chapter discusses in detail the results for wireless channel modeling that were obtained from conducting measurements in the two large indoor environments. It begins with a description of the method used for processing the raw measurement data. It is then followed by some examples of the power delay profiles that were recorded for both environments. Important channel parameter results that were extracted from the measurement data are also discussed in this chapter. Finally, a tapped delay line channel model has also been provided for a 10 MHz channel bandwidth.

4.2 Measurement Data Processing

In this section, the method used to process the data is described; this is paraphrased from [35]. The data obtained from measurements is in a vendor-proprietary .rap format and is stored in log files. These files cannot be read by Matlab directly and thus had to be converted to ASCII format for further processing. The Chameleon software from BVS was used to convert the files from the .rap format to a .out format. This file format can be opened using Excel, Matlab or Notepad [35].

In the Chameleon software, the file to be converted, which is in the .rap format, is selected as the input file. The fields that were selected for conversion included RTC Date, Magnitude in dBm, Phase in radians and Received Signal Strength Indicator (RSSI) in
dBm. The output file was obtained in .out format and the `csvread` command in Matlab was used to read the file [35]. The output of Chameleon provides us with magnitude and phase samples at each delay for half a chip time spacing, as the sampling rate is 100 MHz and we use a bandwidth of 50 MHz. Each sample has magnitude and phase values and about 100 samples are present in each record and one record forms a PDP [22].

The measurement data obtained from the software was then separated into power and phase records using Matlab. The Matlab routines of the author in reference [35] were used in the processing the data. The power records were then subjected to noise thresholding to remove the unwanted noise samples. The algorithm used for this purpose is a constant false alarm probability algorithm. With our measurement data, a threshold of 25 dB was specified such that all the multipath components that were below 25 dB from the maximum value in each power record were considered to be noise and their values were set to zero (-130 dBm as the minimum value in the record) [35].

After eliminating the noise samples, power records were converted to power delay profiles. The power records were converted to linear form i.e. the power in each sample was converted to voltage. In-phase ($I$) and Quadrature ($Q$) values were calculated and were vectorially added to determine the power in each chip. The channel bandwidth used was 50 MHz and this provides a distance resolution of approximately 6 meters, which means that the multipath components can be resolved only if they have a difference of more than 6 meters in their propagation distances [35]. In developing our channel
models, we used a 10 MHz value of bandwidth, since that is a value common in current standards. The 10 MHz channel bandwidth corresponds to a chip time of 100 ns and the model delays are integer multiples of this chip time. The sampling rate of the channel sounder was 100 MHz, so, for our channel model bandwidth of 10 MHz, 10 samples were combined to obtain one chip sample in a PDP [35]. Each power record had about 100 samples which gave us 10 chip samples in each PDP.

The multipath components in a PDP may have different signal strengths depending on the transmission path they take from the transmitter to the receiver. To reduce the complexity of our channel model, we only consider those multipath components that have a significant amount of signal strength and remove the weak multipath components [35]. The energies of the weaker multipath components all together have little effect on our resulting statistics and model. A multipath threshold of 25 dB was chosen based on the research in [35] and the components with power less than 25 dB from the maximum value in each PDP were set to a minimum value (-130 dBm) [35]. Figures 4.1 depicts one of the PDPs obtained from measurements conducted in Templeton Blackburn auditorium for Tx position 3 (balcony) before applying the multipath threshold; this PDP has an RMS-DS value of 77.41 ns.
Figure 4.1 PDP plot before applying threshold (Tx position 3 in auditorium) with RMS-DS=77.41 ns

Figure 4.2 depicts the same PDP after applying the 25 dB threshold to eliminate the weaker multipath components. The maximum value for this PDP was 52.9 dB, thus all the components that were below 27.9 dB were removed. Removing the weak multipath components did not have a significant impact on the RMS-DS value. The RMS-DS value for this PDP plot is 75.12 ns which is only 2 ns less than that before applying the multipath threshold.
Figure 4.2 PDP plot after applying the threshold (Tx position 3 in auditorium) with

\[ \text{RMS-DS} = 75.12 \text{ ns} \]

4.3 Example Power Delay Profiles

This section provides details about the number of PDPs recorded in both the measurement locations for each Tx position in Table 4.1. It also shows some example PDPs recorded at the two measurement locations.
Table 4.1 Total Number of PDPs Recorded

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Tx position</th>
<th>LOS</th>
<th>NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Templeton Blackburn Memorial Auditorium</td>
<td>1 (back of the first floor)</td>
<td>2354</td>
<td>3620</td>
</tr>
<tr>
<td></td>
<td>2 (On the stage)</td>
<td>9599</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 (Balcony)</td>
<td>10894</td>
<td></td>
</tr>
<tr>
<td>Convocation Center</td>
<td>1</td>
<td>6673</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6795</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.3 is a PDP plot obtained from measurements conducted in the Convocation Center for Tx position 1. This PDP has an RMS-DS value of 58.47 ns.
Figure 4.3 Example PDP plot at Convocation Center for Tx position 1 with RMS-DS = 58.47 ns

Figure 4.4 is another example PDP plot obtained from measurements conducted in Templeton Blackburn auditorium with the transmitter on the stage (Tx position 2). This PDP has a much larger RMS-DS value of 384.09 ns.
Figure 4.4 Example PDP plot at Templeton Blackburn auditorium for Tx position 2 on stage with RMS-DS = 384.09 ns

The PDP in Figure 4.4 has a larger RMS-DS than the one in Figure 4.3 because it has a larger number of multipath components with significant power. This is probably due to strong reflections from the walls and the ceiling of the building.

4.4 Channel Parameter Results

In this section, the channel parameter results obtained after processing the measurement data are provided. The RMS-DS values were obtained using the Matlab routine of the author in [35] for all of the data obtained at all measurement locations.
Figures 4.5 and 4.6 are histograms showing the RMS-DS distribution for data obtained from Templeton Blackburn memorial auditorium for Tx position 2 on stage and Tx position 3 in the balcony, respectively. The histogram provides the total number of occurrences for each RMS-DS value. The large values of RMS-DS were likely obtained when the receiver was carried on the stairs from the first floor to the balcony and vice versa as the transmitter had no direct LOS path to the receiver during its transit on the staircase.

Figure 4.5 RMS-DS histogram for auditorium Tx position 2 on stage, Mean RMS-DS = 57.29 ns
Table 4.6 RMS-DS histogram for auditorium Tx position 3 in the balcony, Mean RMS-DS = 69.06 ns

Table 4.2 shows the RMS-DS statistics with minimum, maximum, mean and standard deviation values for the three Tx positions for Templeton Blackburn auditorium. As mentioned in chapter 3, for Tx position 1, measurements for LOS (Rx in the first floor) and NLOS (Rx in the balcony) scenarios were conducted separately.
Table 4.2 Templeton Blackburn auditorium RMS-DS Statistics (ns)

<table>
<thead>
<tr>
<th>Tx Position</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (back of 1st floor)</td>
<td>LOS</td>
<td>49.77</td>
<td>19.32</td>
<td>0.37</td>
</tr>
<tr>
<td>NLOS</td>
<td>95.27</td>
<td>36.34</td>
<td>10.13</td>
<td>388.53</td>
</tr>
<tr>
<td>2 (stage)</td>
<td>57.29</td>
<td>44.3</td>
<td>0.45</td>
<td>384.09</td>
</tr>
<tr>
<td>3 (balcony)</td>
<td>69.06</td>
<td>48.9</td>
<td>0.024</td>
<td>394.71</td>
</tr>
</tbody>
</table>

For Tx position 1, we observe that the mean RMS-DS for the NLOS region is larger than for LOS region, as expected. This is because the multipath components had smaller delays when the receiver was in the LOS region (1st floor) of the transmitter and the relative power of the LOS component is large. In the NLOS region (e.g., Rx in balcony), the mean RMS-DS was large. Also for Tx position 3, large RMS-DS values were probably obtained during Rx transit on stairs or when the Rx was directly beneath the balcony or when the Rx was near the stage in the corners, i.e., NLOS region of the transmitter. The mean RMS-DS for Tx position 2 on stage was slightly smaller than with the Tx in the balcony.

The data for Rx transit on stairs for Tx position 2 (stage) and 3 (balcony) was excluded from the collected data. The RMS-DS statistics were again obtained and the values are shown in Table 4.3. The mean RMS-DS values were slightly smaller after removing the Rx transit on stairs data for both Tx positions. For Tx position in balcony, we still see
large RMS-DS values which were probably obtained when the Rx was in the corners near the stage.

Table 4.3 Templeton Blackburn auditorium RMS-DS Statistics (ns) with Rx on stairs

<table>
<thead>
<tr>
<th>Tx Position</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (stage)</td>
<td>47.34</td>
<td>19.23</td>
<td>0.45</td>
<td>286.71</td>
</tr>
<tr>
<td>3 (balcony)</td>
<td>62.26</td>
<td>43.37</td>
<td>0.024</td>
<td>364.23</td>
</tr>
</tbody>
</table>

Figure 4.7 is a plot of RMS-DS vs. the PDP index for measurements conducted in Templeton Blackburn Auditorium for Tx position 3 in the balcony. PDP index is the profile number that corresponds to a record captured at the receiver at a particular instant of time. As mentioned earlier, each record consists of magnitude and phase samples from which a PDP is formed. The full delay span of the sounder is 5.1 μs, which is obtained by multiplying the length of the PN sequence (255 chips) and the chip time (20 ns). For this delay span, the sounder provides two PDPs per second. We used a delay span of 1 μs, so the sounder provided around twelve PDPs per second [22]. A total of 10,897 power delay profiles were recorded for this run. We have divided the run into several sections. Section A in Figure 4.7 has small RMS-DS values because the receiver was in the balcony creating an LOS scenario. In section B, much larger RMS-DS values are seen during receiver transit on the stairs to the first floor and when the receiver was directly beneath
the balcony: here the Rx is in an NLOS region with respect to the transmitter. In section C, the receiver was carried around the first floor which was again in a LOS region of the transmitter and hence, the small RMS-DS values. In section D, the receiver was carried to the corners near the stage forming a NLOS condition, thus again yielding large RMS-DS values.

**Figure 4.7** RMS-DS vs. PDP index for Tx position 3 in balcony in the auditorium

Figure 4.8 is another plot of RMS-DS and PDP index for measurements conducted in the auditorium for Tx position 2 on the stage. Similar to Figure 4.7, we indicate three
sections A, B and C with small and large values of RMS-DS, broadly defining the LOS and NLOS regions.

Figure 4.8 RMS-DS vs. PDP index for Tx position 2 on stage in the auditorium

Figure 4.9 is another example PDP, which also indicates the mean energy (MED) and RMS-DS delay for a PDP obtained in Templeton Blackburn auditorium for Tx position 3. The large value of 394.71 ns for RMS-DS here is because of the long delays of the multipath components obtained in the auditorium for this NLOS PDP.
**Figure 4.9** PDP plot for max RMS-DS for the auditorium Tx position 3 in balcony

Figure 4.10 and 4.11 are histograms which show the distribution of RMS-DS values for measurements conducted in the Convocation Center. Mean RMS-DS values for two Tx positions, 1 and 2, respectively, are provided.
Figure 4.10 RMS-DS histogram for Convocation Center Tx position 1, Mean RMS-DS=71.01 ns

Figure 4.11 RMS-DS histogram for Convocation Center Tx position 2, Mean RMS-DS = 69.7 ns
The RMS-DS statistics of minimum, maximum, mean and standard deviation values for the two Tx positions in the Convocation Center are shown in Table 4.4. Since the Convocation Center is a large open arena (diameter \( \sim 100 \) m), some multipath components have long delays, thus yielding large RMS-DS values. The large values were most likely obtained when the receiver was in the upper levels of the arena.

Table 4.4 Convocation center RMS-DS Statistics (ns)

<table>
<thead>
<tr>
<th>Tx Position</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.01</td>
<td>27.98</td>
<td>.007</td>
<td>394.75</td>
</tr>
<tr>
<td>2</td>
<td>69.7</td>
<td>28.47</td>
<td>.007</td>
<td>375.62</td>
</tr>
</tbody>
</table>

Figure 4.12 and 4.13 are plots of RMS-DS vs. PDP index for measurements conducted in the Convocation Center for Tx positions 1 and 2 respectively. Sections A, B and C indicate the RMS-DS values for various Rx positions during transit. There are very few PDPs with RMS-DS values greater than 200 ns and they were most likely obtained during receiver transit on the staircases (which had very few steps), from one level to another inside the arena, where the receiver was not in line of sight with respect to the transmitter. This was also evident in Figures 4.10 and 4.11.
Figure 4.12 RMS-DS vs. PDP index for Tx position 1 in the Convocation Center

Figure 4.13 RMS-DS vs. PDP index for Tx position 2 in the Convocation Center
4.5 Channel Modeling

In the section, channel models are provided for large indoor environments in the 5 GHz band for a channel bandwidth of 10 MHz. For our large dense indoor environment, many multipath components are expected and we choose this value of bandwidth to fit current wireless standards (e.g., WLANs). With a 10 MHz bandwidth, we get a delay bin size of 100 ns which means that all components that arrive within the 100 ns bin are vectorially added [22]. A common structure used for wireless channel modeling is the tapped delay line model [36]. The tapped delay line model is explained in the following section.

4.5.1 Tapped Delay Line Model

In this model, we have an input signal, a delay line with “branches” or “taps” and an output signal. The output signal is the weighted sum of all the delayed input signals, where each weight is a time varying function [36]. This model is a sampled version of the channel’s actual continuous time impulse response and these time varying “tap weights” can produce signal distortions; ultimately these effects are caused by the scatterers or objects present in the environment. These objects are responsible for producing many versions of the transmitted signal which are delayed in time and phase shifted when they reach the receiver [36]. This kind of a channel can be represented using a tapped delay line model shown in Figure 4.14.
In Figure 4.14, $x_i(t)$ is the input signal and $y(t)$ is the output signal of the channel. $\Delta \tau$ is the delay increment and it is generally set at a value equal to the time duration of the symbols that are transmitted in a given channel or the reciprocal of the channel bandwidth [36]. In our case, this delay value is 100 ns as the channel bandwidth is 10 MHz. Each delay tap forms a “time bin” and all the components that arrive within a particular time bin are vectorially added to form the time varying function $h(t)$ [36]. The model for an $i^{th}$ tap can be written as [22]

$$h_i(t, \tau) = z_i(t) a_i(t) \exp\left(j v_i(t)\right)$$

(4.1)
Here $z_i(t)$ is “persistence process” that denotes the presence or absence of a multipath component (i.e., $z$ takes the value 0 and 1 only), $a_i(t)$ represents the amplitude of the $i^{th}$ multipath component (MPC) at time $t$ and $\psi_i(t)$ is the phase of the $i^{th}$ MPC [22]. The formula to calculate the total number of taps is given by [35]

$$L = \lceil T_m W \rceil + 1$$

(4.2)

where $T_m$ is the multipath delay spread and $W$ is the channel bandwidth. The $\lceil \ \rceil$ is the ceiling function which rounds the argument to the nearest integer greater than or equal to the argument.

### 4.5.2 Channel Modeling for Large Indoor Environments

In this section, we describe the tapped delay line models developed for the two indoor environments in which we conducted measurements. To develop these models, we calculate the total number of taps, the (average) energy associated with each tap and the probability of tap existence; these are explained in the following sections.

#### 4.5.2. Number of Channel Taps

As explained in the previous section, the number of taps $L$ can be calculated using the formula in (4.2) (i.e., $L = \lceil T_m W \rceil + 1$). For the delay spread $T_m$, we use the mean RMS-DS values of section 4.4. From the histogram plots and the RMS-DS vs. PDP index plots in section 4.4, we saw that there were very few PDPs which had very large RMS-DS values ($> 200$ ns), so the maximum RMS-DS values should not be used to calculate
the number of taps. The minimum and maximum RMS-DS values are of course representative of only a very few PDPs for our set of data. The mean RMS-DS is a better representative of the channel behavior and thus is used to calculate the total number of taps. For our channel bandwidth $W$ of 10 MHz, using the mean RMS-DS from Table 4.2, the number of taps for the auditorium Tx position 3 was calculated to be $L = 2$, for example. We provide results for other cases subsequently.

### 4.5.2.2 Determination of Tap Persistence Probabilities

The tap persistence basically denotes the presence or absence of a tap in this type of channel modeling [22]. As mentioned in chapter 2, a signal travelling from the transmitter to the receiver through a channel may experience reflection, diffraction and scattering due to various objects present in the environment. These objects create MPCs at some instances of time and no MPCs at some other instances of time. This behavior of the channel can be modeled using the persistence process $z_i(t)$ which was defined earlier; can either take the value of 1 to denote the presence of MPCs or 0 to denote the absence of MPCs [22].

The tap persistence process is modeled using a discrete Markov chain model - a random process in which the $n+1^{th}$ state is dependent only on the $n^{th}$ state and not on any of the previous states [22]. Here we define two states 0 and 1 for the tap persistence process $z_i(t)$ where 0 represents the absence of a tap (MPC) and 1 represents the presence of a tap. A multipath threshold of 25 dB is used to determine the persistence process for each MPC.
in a PDP. The MPCs that are within 25 dB of the maximum value in a PDP are
considered significant and are assigned a $z_i(t)$ value of one, else they are assigned a value
of zero. The “long term” probability of a tap to remain in the 1 or the 0 state is called the
steady state probability and the probability of a tap to go from one state to itself or to
another state is called a transition state probability [22].

4.5.2.3 Determination of Tap Energies

The tap energy accounts for all the MPCs that arrive at the receiver within a particular
delay bin [22]. In our case, the delay bin is 100 ns as the channel bandwidth is 10 MHz.
To determine the tap energies we only consider those taps which are valid MPCs, i.e.,
those for which the persistence process $z_i(t) = 1$. The energy of each PDP is first
normalized. The energies from all the PDPs for each particular tap are summed together.
The average energy for each tap is then calculated by dividing this sum by the total
number of PDPs [22].

4.5.2.4 Determination of Tap Amplitude Distributions

To determine the amplitude fading characteristics, the Weibull distribution [35], which
has been explained in chapter two, is used here. As already mentioned, the Weibull shape
parameter $b$ indicates the fading severity: for $b = 2$, this distribution becomes the
Rayleigh, for $b < 2$, it is worse than Rayleigh and for $b > 2$, the fading severity decreases
[21].
Tables 4.5 and 4.6 provide the results for the tap amplitude and probability statistics for our measurement data in Templeton Blackburn memorial auditorium; i.e., these tables are the statistical channel models for this environment. The tap index is the tap number, the shape factor $b$ indicates the fading severity and the tap energy is the average energy for each tap. $P_1$ is the steady state probability for the tap being present, $P_0$ is the steady state probability for the tap being absent, $P_{10}$ and $P_{01}$ are transition state probabilities for a tap to go from state 1 to 0 and from state 0 to 1 respectively, $P_{11}$ and $P_{00}$ are transition state probabilities for a tap to go from state 1 to 1 and from state 0 to 0, respectively [22].

**Table 4.5** Statistical Channel Model for Auditorium, Tx position on stage

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Weibull Shape Factor $b$</th>
<th>Tap Energy</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7513</td>
<td>0.8728</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.5988</td>
<td>0.1272</td>
<td>0.946</td>
<td>0.006</td>
<td>0.8981</td>
</tr>
</tbody>
</table>

**Table 4.6** Statistical Channel Model for Auditorium, Tx position in balcony

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Weibull Shape Factor $b$</th>
<th>Tap Energy</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4162</td>
<td>0.854</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.5412</td>
<td>0.146</td>
<td>0.9573</td>
<td>0.0045</td>
<td>0.9192</td>
</tr>
</tbody>
</table>
Example curve fits for the measured tap amplitude data are also provided: these plots were obtained from distribution fitting tool (*dfittool*) in Matlab [35]. The tool has a graphical user interface with which we can select the desired data and fading distribution, and the tool then provides a plot of probability density function along with our measured data. Figures 4.15 to 4.18 show several tap amplitude histograms and the curve fits for data measured in the auditorium for Tx positions 2 and 3.

![Figure 4.15 Tap 1 amplitude histogram & fits for auditorium, Tx position - stage](image-url)
Figure 4.16 Tap 1 amplitude histogram & curve fits for auditorium, Tx position - balcony

Figure 4.17 Tap 2 amplitude histogram and curve fits for auditorium, Tx position - stage
From Tables 4.5 ad 4.6, we see that for both Tx positions, tap 1 displays moderate fading (better than Rayleigh) with Weibull shape factor \( b > 2 \) and tap 2 exhibits worse than Rayleigh fading severity with \( b < 2 \). The Weibull and Rician densities are both good fits for tap 1 data as seen in Figures 4.15 and 4.16 and the Weibull and Nakagami densities are both good fits for tap 2 data as seen in Figures 4.17 and 4.18. The fitting tool finds the maximum likelihood parameter fits for each distribution. The best fit for our data can be determined from the log likelihood value, which is calculated by the dfittool for each distribution. The distribution with highest value of log likelihood is the best fit for that particular data. For instance, the Weibull log likelihood for Tx position on stage for tap 1
is -8365.88 and the Ricean log likelihood is -8253.3, which indicates that the Ricean
distribution is a slightly better fit for this tap 1 data. But for tap 2 of Tx position on
balcony, the Weibull log likelihood is -1743.58 and the Nakagami log likelihood is -
1782.13. So for this tap 2 data, the Weibull distribution is a better fit.

Tables 4.7 and 4.8 provide analogous results for the tap amplitude and probability
statistics for our measurement data in the Convocation center. Example maximum
likelihood curve fits are provided for the tap amplitude distributions for the tap 1 and tap
2 data measured from Convocation Center in Figures 4.19 through 4.22.

**Table 4.7** Statistical Channel Model for Convocation Center, Tx position 1

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Weibull Shape Factor $b$</th>
<th>Tap Energy</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.5121</td>
<td>0.837</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.9416</td>
<td>0.163</td>
<td>0.9164</td>
<td>0.0213</td>
<td>0.854</td>
</tr>
</tbody>
</table>

**Table 4.8** Statistical Channel Model for Convocation Center, Tx position 2

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Weibull Shape Factor $b$</th>
<th>Tap Energy</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.6812</td>
<td>0.849</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.8685</td>
<td>0.151</td>
<td>0.9102</td>
<td>0.0328</td>
<td>0.8534</td>
</tr>
</tbody>
</table>
**Figure 4.19** Tap 1 amplitude histogram and curve fits for Convocation Center, Tx position 1

**Figure 4.20** Tap 1 amplitude histogram and curve fits for Convocation Center, Tx position 2
**Figure 4.21** Tap 2 amplitude histogram and curve fits for Convocation Center, Tx position 1

**Figure 4.22** Tap 2 amplitude histogram and curve fits for Convocation Center, Tx position 2
From Tables 4.7 and 4.8, tap 1 again shows moderate fading (better than Rayleigh) with the Weibull shape parameter $b > 2$, similar to the tap 1 for the auditorium, whereas tap 2 has an essentially Rayleigh fading. The Weibull, Rician and Nakagami distributions are all good fits the tap 1 data as seen in Figures 4.19 and 4.20. The best fit for tap 1 of Convocation center, Tx position 1 is the Nakagami distribution with a log likelihood value of -4157.28, whereas the Ricean log likelihood is -4274.63 and Weibull log likelihood is -4371.6. The Weibull and Nakagami distributions are both good fits for tap 2 data as seen in Figures 4.21 and 4.22. The best fit for tap 2 of Convocation center, Tx position 1 is the Weibull distribution with a log likelihood value of -1746.45, whereas the Nakagami has a log likelihood of -1749.37.

References [25], [26], [27] and [29] provide RMS-DS values for measurements conducted in indoor environments, the details of which are provided in the literature review section of chapter two. In [25], the authors have calculated the RMS-DS values for office environments and a large airport hall. The CDF 90% RMS-DS values for office environments were reported as 30 ns for LOS conditions and 30 to 50 ns for NLOS conditions. For the large airport waiting hall with distances extending up to 200 m, the CDF 90% RMS-DS values were reported to be 120 ns for LOS conditions and 180 ns for NLOS conditions. We also calculated the 90th percentile RMS-DS values for our data for comparison with the results in [25]. Our Tx-Rx distances are smaller than the distances in [25], but our environment can be considered to be “more open” than the airport waiting hall. For the auditorium, the CDF 90% RMS-DS value for Tx on stage was found to be
86.48 ns and for Tx on balcony, it was 121.6 ns. For the Convocation Center, the CDF 90\% RMS-DS value for Tx positions 1 and 2 was approximately 106 ns. Our 90\th\ percentile values are comparable to those reported in [25], but the maximum RMS-DS values at both our measurement locations were in the range of 375 to 395 ns.

Reference [26] reports mean RMS-DS values for measurements conducted in a small cluttered laboratory. The RMS-DS value was reported to be 26.82 ns for the NLOS scenario and for 3 LOS situations, the RMS-DS values were 30.55 ns, 24.12 ns and 22.19 ns. As mentioned in chapter two, a large value of 30.55 ns for the LOS situation was obtained because the receiver antenna in this case was placed near the hallway which caused more scattering of the signal and thus increased the delay spread. Small RMS-DS values are observed for this small indoor environment.

In [27], the measurements were conducted in a three bedroom apartment and the mean RMS-DS values were reported as 14 ns for the LOS scenario and 38.61 ns for the NLOS scenario. In [29], measurements were conducted in a room and the mean RMS-DS values were reported be 20.9 ns for LOS scenario and 27.4 ns for NLOS scenario. These two measurement locations were also small indoor environments and hence we see small RMS-DS values.
5. CONCLUSION

5.1 Summary
This thesis provided a wireless channel characterization for several large indoor environments in the 5 GHz band. We provided a literature review of similar work done in channel modeling, a description of the two measurement locations used for this thesis and the measurement procedure itself. RMS-DS statistics including mean, standard deviation, minimum and maximum, were provided for both the measurement locations. Channel models were also developed for a channel bandwidth of 10 MHz. These tapped delay line models specified the number of taps for the channel, the tap amplitude fading distributions and the energy associated with each tap.

5.2 Conclusions
From the RMS-DS statistics, we found that the mean RMS-DS (~ 95 ns) for NLOS regions is larger than the mean RMS-DS (~ 50 ns) for LOS regions, as expected. For the Templeton Blackburn auditorium, the mean RMS-DS for the Tx positioned on stage was approximately 57 ns, which was slightly smaller than with the Tx in the balcony, with the mean value approximately 69 ns. For the Convocation Center, both Tx positions exhibited similar RMS-DS statistics with mean value around 70 ns. RMS-DS results from other research performed for indoor environments were also provided for comparison with our work. The 90th percentile RMS-DS values from our data are comparable to the
results reported in [25], but we have some RMS-DS values that are substantially larger, more than three times the 90th percentile values.

The statistical channel models we developed specified the amplitude fading parameters, which included the Weibull shape parameter and the energy in each tap. We also modeled the multipath component persistence, and for this, we specified the tap persistence probabilities using a discrete Markov chain model. Our channel models were for a channel bandwidth of 10 MHz, and contain 2 taps in a tapped-delay line form. Both locations indicated moderate fading i.e., better than Rayleigh fading for the first tap, with the second tap essentially Rayleigh or slightly worse than Rayleigh fading.

5.3 Suggestions for Future Work

Future work may involve collecting data for other possible Tx positions in our measurement locations. Measurements could also be conducted in other large indoor environments for collection of additional RMS-DS statistics and additional channel models. Having more data would improve the statistical reliability of our channel models. Last, channel models could also be developed for other values of channel bandwidth.
REFERENCES


[33] Ohio University, Convocation Center, website, [http://www.ohio.edu/tour/](http://www.ohio.edu/tour/)


clear all;
close all;
clc;

%%%PDPs, RMS-DS and DelX values were obtained from Indranil Sen’s code

%%%Plotting PDPs, histograms

%Plot of Power vs Delay
stem(DelX,PowerdBMN(5819,:)+130)
title('Plot of Power(dB) vs Delay');
xlabel('Delay \mu sec');
ylabel('Relative Power dB');
text(0.7,85,'RMS DS - 118.54 ns');
grid on;

%Plot showing RMS-DS and MED
stem(DelX,PowerdBMN(5137,:)+130)
title('Plot of Power(dB) for max RMSDS vs Delay');
xlabel('Delay \mu sec');
ylabel('Relative Power dB');
text(0.7,47,'RMS DS -394.7193 ');
grid on;
hold on;
line([.394 .394],[0 50],color,'k','linewidth',2)
hold on;
line([.546 .546],[0 50],color,'r','linewidth',2)

%RMS-DS Histogram plot
hist(RMSDelSpr,100)
title('RMS-DS Histogram');
xlabel('RMS-Delay Spread');
ylabel('No of occurences');
85

%Plot of RMS-DS vs PDP Index
PDPindex=1:length(PowerdBMN);
plot(PDPindex,RMSDelSpr)
title('Plot of RMS Delay Spread vs PDP index');
xlabel('PDP index');ylabel('RMS Delay Spread');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 
%%% Determination of Tap Energies

for jj=1:nTapL2;
    for ii=1:length(Tap_temp);
        E(jj,ii)=(Tap_temp(jj,ii)).^2;
        ii=ii+1;
    end
    jj=jj+1;
end
for ii=1:length(Tap_temp);
    NormE(ii)=E(1,ii)+E(2,ii);
    E1(1,ii) = E(1,ii)/NormE(ii);
    E2(2,ii) = E(2,ii)/NormE(ii);
    ii=ii+1;
end
MeasEnergy_Tap1=sum(E1(1,:))/length(Tap_temp)
MeasEnergy_Tap2=sum(E2(2,:))/length(Tap_temp)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% 
%%% To find steady state probabilities and transition state probabilities

%To find steady State probability P(z=1)
for j=1:nTapL2
    mar1=c_marL2(j,:);
    cnt1=0;
    for i=1:length(c_marL2)
        if (mar1(i)==1)
            cnt1=cnt1+1;
        end
    end
    count1(j)=cnt1;
P1(j)=count1(j)/length(c_marL2);
end
count1
P1

% To find transition state probability P10
for j=1:nTapL2
    mar3=c_marL2(j,:);
cnt3=0;
for i=1:length(c_marL2)-1
    if (mar3(i+1)==0) && (mar3(i)==1)
        cnt3=cnt3+1;
    end
end
count3(j)=cnt3;
P10(j)=count3(j)/(length(c_marL2)-1);
end
count3
P10

%To find P11
for k=1:nTapL2
    mar5=c_marL2(k,:);
cnt5=0;
for i=1:length(c_marL2)-1
    if (mar5(i+1)==1) && (mar5(i)==1)
        cnt5=cnt5+1;
    end
end
count5(k)=cnt5;
P11(k)=count5(k)/(length(c_marL2)-1);
end
count5
P11

%To find steady State probability P(z=0)
for k=1:nTapL2
    mar2=c_marL2(k,:);
cnt2=0;
for i=1:length(c_marL2)
    if (mar2(i)==0)
        cnt2=cnt2+1;
    end
end
count2
P0
else
cnt2;
end
count2(k)=cnt2;
P0(k)=count2(k)/length(c_marL2);
end
count2
P0

%To find P01
for k=1:nTapL2
  mar4=c_marL2(k,:);
cnt4=0;
  for i=1:length(c_marL2)-1
    if (mar4(i+1)==1) && (mar4(i)==0)
      cnt4=cnt4+1;
    end
  end
count4(k)=cnt4;
P01(k)=count4(k)/(length(c_marL2)-1);
end
count4
P01

%To find P00
for k=1:nTapL2
  mar6=c_marL2(k,:);
cnt6=0;
  for i=1:length(c_marL2)-1
    if (mar6(i+1)==0) && (mar6(i)==0)
      cnt6=cnt6+1;
    end
  end
count6(k)=cnt6;
P00(k)=count6(k)/(length(c_marL2)-1);
end
count6
P00