Forest Channel Characterization in the 5 GHz Band

A thesis presented to
the faculty of
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of the requirements for the degree
Master of Science

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This thesis titled
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ABSTRACT

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This thesis presents a wireless channel characterization for a forest environment. For
our forest measurements, we used a center frequency of 5.12 GHz to take 50-MHz bandwidth
impulse response estimate measurements. The measurement locations were chosen at
Stroud’s Run State Park, with the transmitter at trail entrances, and the receiver carried along
a path in the forest, of distance up to approximately 150m from the transmitter. Our
measurement results were in the form of power delay profiles, which along with multipath
component phase information, can be used to obtain channel impulse response statistics. The
most important of these is the root-mean-square value of delay spread. Frequency coherence
bandwidths were also obtained from our data. All these results, and the channel models for
this environment, were done for a popular current value of bandwidth: 10 MHz. The
wideband channel models specify the number of channel taps in the tapped delay line model,
the tap energies, Markov tap persistence process parameters for modeling tap appearance and
disappearance, and tap fading amplitude distributions. We found that our measured results
are within expectations based upon the environment, and on some other related work in the
literature. Our models can be useful for wireless system design and optimization in the 5 GHz
band forest environment.

Approved: _____________________________________________________________

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Chapter 1

Introduction

In this chapter, we describe the growth of wireless communication and several important points regarding applications of wireless communication. We then discuss the purpose of this thesis, whose application is forest channel characterization in the 5 GHz frequency band.

1.1 Growth of Wireless Communications

As is well-known, communication channels can be classified as either wired or wireless. In recent years, wireless communication has developed vigorously, and in addition to voice signals, various types of data signals have been used more and more, and this has essentially caused a replacement of analog signaling by digital signaling. Many new wireless communication systems have been developed and have made much progress in recent years. Examples include the Bluetooth system for short range indoor communication, wireless local area networks (WLANs) for communication between portable devices and local access points, the cellular Global System for Mobile Communication (GSM) and Wideband Code Division Multiple Access (WCDMA)
systems (so-called “third generation”). The continued use and new appearance of these wireless technologies shows that we live in a “wireless generation” at the present time.

Wireless communications can be traced to 1901 when Guglielmo Marconi successfully received a wireless signal in Canada, from England. Wireless communications were made mandatory for ships at sea after the Titanic disaster in 1912. The development of air travel and the two world wars also incited growth in the use of wireless technologies. This continued throughout the second half of the 20th century, with digital wired systems becoming popular in the 1960’s and 1970’s. In the early 1980s, cellular telephone systems known the First Generation (1G) systems [1] were developed. The 1G systems used analog frequency modulation (FM) and the frequency division multiple access (FDMA) technique, and in the US this system was termed the advanced mobile phone system (AMPS). The 1G cellular systems used different radio frequency bands to carry different voice signals and this 1G system had no data service. There were also several 1G systems developed in other areas, such as European Total Access Cellular System (ETACS), Radio Telephone Mobile System (RTMS), and the Japanese Total Access Cellular System/Narrowband Total Access Cellular System (JTACS/NTACS) [2].

The Second Generation (2G) cellular systems were developed in the early 1990s. The 2G cellular systems allowed mobile data communication, and these systems are still extensively used. They use digital modulation schemes and time division multiple access (TDMA) as well as FDMA multiplexing schemes [2]. In the USA, 2G cellular systems are sometimes called Personal Communications Service (PCS). There are currently two
dominant 2G techniques: the Global System for Mobile Communications (GSM) which employs TDMA, and cdmaOne, which is uses a different kind of multiplexing called code division multiple access (CDMA) [1]. The main 2G mobile communication systems are/were as follows: (a) Global System for Mobile Communications (GSM), (b) Interim Standard 95 (IS-95) (evolved into cdmaOne), (c) Interim Standard 136 (IS-136), (d) Integrated Digital Enhanced Network (IDEN), (e) Personal Digital Cellular (PDC). These 2G cellular systems operate in the 900 MHz and 1800 MHz frequency bands in Europe and Asia, and in the 850 MHz and 1900 MHz frequency bands in the USA and Canada.

One motivating source to development of Third Generation (3G) systems came from the World Administrative Radio Conference (WARC) in the International Telecommunication Union (ITU). From 1986, the ITU began to analyze how to attain Global Personal Telecommunication including both land communication and satellite communication. The WARC in 1992 (WARC-92) decided to allocate 2 GHz of spectral bandwidth to 3G systems. In the ITU, these 3G cellular systems were called International Mobile Telephony 2000 (IMT-2000) [2]. At present, there appear to be three main 3G systems: (a) CDMA 2000, (b) Wideband CDMA (W-CDMA), and (c) Time Division - Synchronous Code Division Multiple Access (TD-SCDMA).

Nowadays, most companies in the world are using high speed wireless local area networks (WLANs). The IEEE 802.11a or 802.11b standards are well known as the most popular WLAN standards and technologies [3]. Typically, these WLAN modems use omni-directional antennas. This enables the mobile or portable terminals to connect to the
network via an “access point,” which is analogous to a cellular base station. The 802.11a and 802.11b use different frequency bands: the 802.11a system was designed to use the 5 GHz band, and 802.11b was designed to use the 2.4 GHz band.

The Fourth Generation (4G) cellular systems are the next planned extension of 3G cellular systems. According to the ITU, users should be able to get 1000 Mbps during high speed travel. The 4G systems are also designed to have seamless interconnection between 2G and 3G cellular systems as well as WLANs [4].

1.2 Applications of Wireless Communications

In the early days of telephony, if people needed to communicate with others, they used a wired communication system to contact each other. Due to the wireless communication systems which have been developed it is now possible for people to use wireless communication to take the place of traditional wired communication. The wireless communication system has at least one advantage over the wired system, and that is mobility—no wiring is needed to “tether” the user to a fixed location.

Due to advances in wireless communications we can use these devices without wired limits and communicate almost everywhere. For example, we can use wireless communication above water (in a ship, along the harbor), under water (in a submarine, or while scuba diving), in the air (on an airplane, or to/from a satellite), and in multiple environments, including cities, forests and even possibly deserts.
The use of wireless communication in the forest, for both military and commercial applications, is of current interest. The forest terrain will affect the distance over which wireless communication can effectively take place, and similarly, forest objects such as trees and shrubs will affect the wireless channel characteristics. As for applications in the forest channel, it may be important for transferring both voice and data for forestry service applications and for military applications. In addition, wireless communication can be used in detective sensors to monitor environmental effects such as rainfall, water flow, smoke, weather parameters, and animal movements. As a result of inefficiencies of past forest communication systems, even though forest workers in the forest tower might detect a fire, without an effective communication system the fire event might not be communicated promptly and this could delay efforts to save the forest’s natural resources. As wireless communication has developed, wireless communication systems have become a vital link to help coordinate resources to extinguish forest fires.

The military often obtains exclusive use of different frequency bands and uses these frequency bands anywhere, including the forest environment. In addition to the above-mentioned civilian applications, military uses in the forest could be for voice when patrolling, and for transmitting digital data which contains various types of information such as graphs and images.
1.3 The Importance of Channel Characterization

The 3G systems were able to provide increased data rates because 3G systems were designed carefully, taking the mobile wireless channel into account. If a precise channel characterization is available, this can help us estimate the channel capacity and by knowing the channel’s dispersion and time variation characteristics, this enables engineers to design appropriate channel countermeasures so that high data rate services like multi-media services can be provided. For example, multi-media services demand precise frequency synchronization between video and audio, and a well-designed system decreases the possible loss of synchronization between video and audio. For a direct-sequence spread spectrum system (used in CDMA), a rake receiver can be designed to collect the energy distributed within multipath components and therefore the receiver can be used to alleviate the multipath fading influence [2]. If we want to design this rake receiver, we need accurate knowledge of these multipath components, their fading rate and Doppler spread.

Channel characterization gives us the knowledge to design various channel adaptive processing schemes in both the transmitter and receiver. Thus, we can say that channel characterization is an important step required to understand the performance of any communication system [5]. We can use precise channel models to ensure that we use the frequency spectrum in the most efficient manner. This design approach could also result in more economical system components.
1.4 Thesis Scope

In this thesis, we took measurements of the wireless channel in a forest environment located at Stroud’s Run State Park, in Athens, OH. We used a spread spectrum stepped correlator channel sounder to gather wideband (50 MHz) forest propagation measurement data at 5 GHz. From this data we can obtain key parameters of the forest channel, including delay dispersion and frequency correlation.

In Chapter 2, we discuss the related literature on forest channel modeling. We describe general propagation mechanisms such as direct waves, reflected waves and scattered waves in line-of-sight (LOS) and non-LOS (NLOS) propagation. We also discuss path loss, shadowing effects, and multipath fading. Chapter 3 describes the Stroud’s Run forest environment, measurements taken in the forest environment, and the procedures followed in using the wireless channel test set (the “channel sounder”). In Chapter 4 we provide measurement results in the form of channel statistics. We also provide statistical channel models based upon these measurements. Finally in Chapter 5 we conclude the thesis by summarizing the results and providing suggestions for future work.
Chapter 2

Overview of Propagation Modeling Theory

2.1 Introduction

When engineers evaluate how electromagnetic waves propagate in a specific environment, they often set up a model of the local terrain and geographic environment of the area of interest [6]-[8]. One modern approach is to use ray tracing to characterize all possible paths from the transmitter to receiver and then calculate reflections, refractions, and scattering effects in the paths. Using local environment information, the frequency of transmission, antenna characteristics, and theoretical propagation formulas then enables estimation of signal propagation loss in the area. Depending on the accuracy of the environment data this can yield models with a range of accuracy. Also, this type of “full wave” electromagnetic solution is computationally intensive, so measurements are also often used to augment these analytical techniques.

One key measure in radio propagation studies is path loss [9]. Path loss can be defined as the loss in power of the electromagnetic wave between the transmitter and the receiver. Popular empirical path loss estimation models for built-up terrestrial environments include those of Okumura [10] and Hata [6]. To predict the characteristics of
communication systems accurately, we have to understand the channel model and we need to consider some key points:

(1) When calculating the system coverage, we need an accurate path loss model for the environment of interest.

(2) When estimating system performance, particularly for wideband systems, we need a good model for multipath propagation

2.2 Propagation Mechanisms

Today, estimating the effective range of wireless transmitters is still important research because we need to ensure that each receiver obtains adequate radio frequency (RF) energy in the service area. Thus, researchers have developed many different radio wave propagation models to estimate propagation path loss and other wireless channel characteristics. To develop a useful wireless communication channel propagation model, we must account for the various physical mechanisms that affect propagation between a base transmitter and receiver in the environment of interest. In addition to a possible direct wave, a transmitted signal can reach a receiver by three additional “modes,” reflection, diffraction, and scattering. These “modes” are also related to the physical presence or absence of a line-of-sight (LOS) propagation path; its absence is termed non-line-of-sight (NLOS) propagation [11]. In subsequent sections we describe the main propagation mechanisms.
2.2.1 Direct Waves

If a signal is sent from transmitter (Tx) to receiver (Rx) and there are no obstructions between Tx and Rx, it is called a direct wave. When the medium is well modeled as a vacuum ("free space"), the received signal power can be expressed as follows [12]

\[ P_t(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \]  

(2.1)

where \( P_t \) is the transmitted power, the \( G \)'s are the antenna gains at transmitter and receiver, \( d \) is the direct path distance, and \( \lambda \) is the signal wavelength. The antenna gain is given by [12]

\[ G = \frac{4\pi A_e}{\lambda^2} \]  

(2.2)

with \( A_e \) the effective antenna aperture. The signal wavelength is

\[ \lambda = \frac{c}{f} \]  

(2.3)

with \( c \) the speed of light and \( f \) the signal (carrier) frequency. Equation (2.1) tacitly assumes narrowband transmission. The parameter \( L \) is the "system loss factor," which
means that \( L > 1 \) accounts for the attenuation of transmission lines and losses of filters in the communication system.

The attenuation or “path loss” is the ratio of transmitted to received power:

\[
PL(dB) = 10 \log \frac{P_t}{P_r} = -10 \log \left\{ \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2} \right\}
\]

\[
= -10 \log G_t - 10 \log G_r - 20 \log \left( \frac{c/ f}{4\pi d} \right)
\]

\[
= -10 \log G_t - 10 \log G_r + 20 \log f + 20 \log d - 147.56 dB
\]

If we exclude the antenna gains we have

\[
PL(dB) = 10 \log \frac{P_t}{P_r} = -10 \log \left\{ \frac{\lambda^2}{(4\pi)^2 d^2} \right\}
\]

\[
= -10 \log \left( \frac{c^2}{(4\pi)^2 d^2 f^2} \right)
\]

Equation (2.5) shows that free space path loss is proportional to the square of the distance between \( T_x \) and \( R_x \). Also, it is proportional to the square of the frequency \( f \) [12].
2.2.2 Reflected Waves

Reflection occurs when signals collide with a large object, whose area is much larger than the wavelength; examples of such objects include buildings and mountains for signals in the VHF band and higher. If the object is a perfect conductor, the signal is reflected without loss, otherwise the signal is partially attenuated upon reflection.

In principle if we know the distance from the Tx to the reflection site and from the reflection site to the Rx, we can calculate the path loss of the reflected signal. From this path loss and the signal loss from the reflection itself, we can estimate the total loss of the reflected wave from transmitter to receiver. Figure 2.1 shows a ground reflection or so-called two-ray model. This model is suitable for use in estimating the large-scale signal power over distance for a narrowband signal, in which $E_{LOS}$ is the energy of the LOS component, $E_i$ is the energy of the wave going from the transmitter to ground, and $E_g$ is the energy of the wave from ground to the receiver, $h_t$ is the height of transmitter antenna and $h_r$ is the height of receiver antenna. It can be shown that [12]:

\[
P_t = P_i G_t G_r \frac{h_t^2 h_r^2}{r^4}
\]

\[=> PL(dB) = 40 \log r - (10 \log G_t + 10 \log G_r + 20 \log h_t + 20 \log h_r) \]

(2.6)
2.2.3 Scattered Waves

Scattering occurs when electromagnetic waves hit small objects, whose dimensions are smaller than the wavelength. When electromagnetic waves hit into a rough surface, the reflected direction is difficult to predict, as shown in Figure 2.2.

Figure 2.1 Ground Reflection Model.
2.3 Wireless Signal Attenuation

There are many kinds of obstructions in the propagation of radio waves in terrestrial environments, such as buildings, mountains, and foliage. These obstructions may cause reflection, absorption and scattering. Many obstructions not only cause significant energy loss but also cause the resulting “departing” wave to propagate in different directions. When a signal travels multiple paths to reach a receiver, this is called multipath propagation. When the multiple signals are delayed relative to one another, this can cause destructive cancellation of the total received signal. The factors affecting signal attenuation include the distance between transmitter and receiver and the relative amplitudes and phases of the multipath interference between many delayed component signals. Generally, signal attenuation can be divided into three types: path loss, shadowing, and multipath fading, as shown in Figure 2.3.
2.3.1 Path Loss

Path loss is the reduction in power from the transmitter antenna to the receiver antenna [7]. This occurs because the electromagnetic wave spreads in volume as it propagates between transmitter and receiver. Path loss is affected by several factors, such as antenna height, terrain, and so on. Here, we consider only two models for such losses:
(a) Free Space Loss

Free space loss is due to the spatial spreading of the electromagnetic wave as it propagates through space; strictly this type of propagation holds only in space (outside planetary atmospheres), but is a good model for propagation in the earth’s atmosphere. In this case, the traveling electromagnetic wave is not affected by any reflection, diffraction or scattering. As in the prior section, free space path loss is given by [13]:

\[
L_{fs} = \left(\frac{4\pi r}{\lambda}\right)^2 G_{tx} G_{rx}
\]  

(2.7)

where again \(\lambda\) is the wavelength, and \(r\) is distance.

(b) Plane Earth Loss

As shown in Figure 2.1, in the plane earth model, we assume that the signal not only propagates from Tx to Rx directly, but also is reflected by the ground. Because propagation distances between these two paths are not the same, the power of the signal from path \(R_1\) should be stronger than that from path \(R_2\). Reference [12] also shows that when \(r >> h_{tx}, h_{rx}\), and the distance \(r\) is much smaller than the earth radius, that path loss is given by [13]:
\[ L_{PE} = \frac{r^4}{(h_{Tx}, h_{Rx})^2} G_{Tx} G_{Rx} \]  \hspace{2cm} (2.8)

where \( h_{Tx} \) is the height of the transmitter antenna and \( h_{Rx} \) is the height of the receiver antenna. As the formula shows, path loss in this model increases as distance to the fourth power, rather than to the second power, as in the free space model. Also, the plane earth model is independent of frequency.

### 2.3.2 Shadowing

Shadowing is another important phenomenon in large scale terrestrial propagation models. It is also known as obstruction. Generally, we model shadowing as random, and often the log-normal distribution is used to model its variation.

Sometimes the shadowing effect is called slow fading. Shadowing effects occur mainly around the receiver when there are large sized obstructions from tens of meters to more than one hundred meters away, such as buildings, hills foliage and so on.

### 2.3.3 Multipath Fading
In addition to path loss and shadowing, the other main propagation effect in terrestrial environments is multipath fading. Multipath fading occurs when signals travel from transmitter to receiver through multiple propagation paths, and these signals may encounter all three propagation mechanisms. Signal strength variation arises because the path lengths of the various multipath components are all different, and this can cause destructive cancellation of the signal in space or time. We often use Rayleigh and Rician distributions to model multipath fading.

### 2.3.3.1 Small Scale Fading

Small-scale fading describes changes in the wireless channel that occur over distances on the order of one-half wavelength. Small-scale fading may not occur in all wireless systems, e.g., not in non-mobile ones with all objects in the environment motionless.

Small-scale fading is caused by multipath propagation. This will cause the channel impulse response (CIR) to have multiple delayed components, which will vary in time in a dynamic environment. For the channel impulse response, if we consider a band-pass signal \( s(t) \) to be transmitted, then we have [1]:

\[
s(t) = \text{Re}[\tilde{s}(t)e^{j2\pi f_c t}]
\]  

(2.9)
where $\tilde{s}(t)$ is the complex envelope of the transmitted signal, and $f_c$ is the carrier frequency. If the channel has $N$ propagation paths, then the noiseless received band-pass signal waveform is [1]

$$r(t) = \text{Re} \left[ \sum_{n=0}^{N-1} C_n(t) e^{j2\pi(f_c+f_d)(t-\tau_n(t))} \tilde{s}(t-\tau_n(t)) \right]$$ \hspace{1cm} (2.10)

Where $C_n$ and $\tau_n$ are the amplitude and time delay, respectively, associated with the $n$th propagation path. Then the received band-pass signal $r(t)$ is

$$r(t) = \text{Re} \left[ \tilde{r}(t)e^{j2\pi f_d t} \right]$$ \hspace{1cm} (2.11)

and the base-band equivalent received signal has the form:

$$\tilde{r}(t) = \sum_{n=0}^{N-1} C_n(t) e^{-j\phi_n(t)} \tilde{s}(t-\tau_n(t))$$ \hspace{1cm} (2.12)

thus, we can extract the channel impulse response as

$$g(t,\tau) = \sum_{n=0}^{N-1} C_n(t) e^{-j\phi_n(t)} \delta(\tau-\tau_n(t))$$ \hspace{1cm} (2.13)

$$\phi_n(t) = 2\pi \left\{ (f_c+f_d)\tau_n - f_d t \right\}$$ \hspace{1cm} (2.14)
where $g(t, \tau)$ is the response of the channel at time $t$ to an impulse input at time $t-\tau$. Each channel impulse generally has a different amplitude, phase, and time delay. When the delay range of the multipath components is significant (in comparison to a signal symbol time), this is called delay dispersion, which “smears” adjacent transmitted symbols together. In addition to multipath delay dispersion, another important small-scale fading effect is Doppler shift and spread. It can be shown that Doppler shift $f_d$ is given by [7]:

$$f_d = \frac{v}{\lambda} \cos \alpha = f_m \cos \alpha \tag{2.15}$$

where $v$ is the relative velocity between transmitter and receiver, and $\alpha$ is the angle between the direction of motion and the arriving wave, as shown in Figure 2.4:

![Figure 2.4 Doppler Effect [7].](image)
As signals propagate by multiple paths, it can be seen that different paths will cause different Doppler shifts. The range of Doppler shifts is called the Doppler spread. Generally, we define the range of Doppler spread as \((f_c - f_m) \leq f \leq (f_c + f_m)\)

### 2.3.3.2 Rayleigh Fading

Two commonly used distributions for small scale fading are the Rayleigh fading distribution, generally used for NLOS settings, and the Rician fading distribution, generally for LOS settings [14]. Here we focus on Rayleigh fading. The Rayleigh fading channel is one kind of statistical model used in the wireless communication environment. We assume that the signals propagating through the wireless channel have amplitudes that are approximately equal, and the phases are approximately uniformly distributed. Via the Central Limit Theorem, when there are large numbers of approximately equal strength paths, the signal envelope \(\alpha(t) = |g(t)|\) has a Rayleigh distribution at any time [1]. This distribution is

\[
p_{\alpha}(x) = \frac{x}{b_0} \exp\left(-\frac{x^2}{2b_0}\right)
\]

where \(b_0\) is one-half the average envelope power, \(E[\alpha^2] = \Omega_p = 2b_0\).
Also, the corresponding Rayleigh fading squared envelope is $\alpha^2(t) = |g(t)|^2$, which has a chi-squared distribution:

$$p_{\alpha^2}(x) = \frac{1}{\Omega_p} \exp\left\{-\frac{x}{\Omega_p}\right\}$$  \hspace{1cm} (2.17)

Rayleigh fading is a suitable model for wireless channels which have no strong LOS path, and where numerous multipath components are present, e.g., in areas where buildings or forests are highly concentrated. In [15], the author showed that the channel amplitude in forest area fit the Rayleigh model, although large departures from the Rayleigh distribution occurred.

Usually, we use the following main channel impulse response parameters to describe the characterization of fading multipath channels

(1) Delay spread (RMS value $\sigma_\tau$) or coherence bandwidth ($B_c$): The coherence bandwidth is a statistical measurement of the frequency range over which the channel amplitude response can be considered “Flat.” We will describe the RMS-DS in section 4.2.1

(2) Doppler spread ($f_D$) or coherence time ($t_c$): The coherence time is a statistical measure of the time duration over which the channel impulse response is practically invariant. It also quantifies the similarity of channel response at different times. The
approximate relationship is \( f_D \sim 1/t_c \).

(3) Power delay profile (PDP): This is a function that shows the distribution of received power as a function of time delay. Collecting PDPs over time can also illustrate the dynamic behavior of different multipath components, as shown in Figure 2.5 [18].

![Figure 2.5 Diagram of CIR for two different times.](image)

The channel impulse response parameters can completely describe the communication channel. These parameters can also aid designers in system planning, such as selecting transmitter and receiver locations, and determining features of antennas appropriate for the channel [24]. Reference [22] used these channel parameters to build
channel models for vehicle-to-vehicle communications. We will describe more PDPs in detail in section 4.2.

2.4 Literature Review

In section 1.2, we described several applications of forest channel characterization. In this section, we will describe some text books and papers related to the work in this thesis.

In [1], the author provides general information about mobile communication which includes background on wireless communications, wireless propagation, modulation methods and CDMA systems, etc. This text book also describes some multipath fading channel models that we described in this chapter. In another text book [25], the author discusses propagation in different regions and the multipath characterization in these different regions, such as wideband channel and multipath phenomena and so on.

Some references on wireless channel characterization in the 5 GHz band are pertinent. In [26], the authors provide information on the statistical analysis of time-variant mobile channels in the 5 GHz band in several different regions, such as rural, suburban, and so on. The transmitter was mobile and the channel receiver employed a constant linear array of eight antenna elements. In this reference, the author provides channel statistics in terms of RMS delay spread (RMS-DS) which had a maximum value of 40 ns when the distance between the transmitter and the receiver was only 5 meters.
The author also found that for a link distance of 250 meters, the maximum value of RMS-DS was approximately 180 ns.

The author in [27] characterized some forest wideband channels in the 1900 MHz frequency band. Reference [27] used a channel transmitter and receiver placed directly on the ground and reported time domain measurements. The author analyzed PDPs by using two kinds of antennas: omni-directional and directional. The link distance in the forest was between 50-400 meters. For a distance of 100 meters, the mean value of RMS-DS was 116.59 ns with the omni-directional antenna, and was 54.04 ns with the directional antenna. For a 200 meters link distance, the mean values of RMS-DS were 148.88 ns using the omni-directional antenna and 103.39 ns using the directional antenna. This shows that RMS-DS increased as transmitter-receiver distance increased, as expected.

Reference [28] concentrated on outdoor wideband channels. The author described channel models in the 5.3 GHz band. The outdoor environments the author considered were urban and suburban areas. In this work, the author quantified the parameters mean excess delay (MED) and RMS delay spread (RMS-DS) with omni-directional antennas. The link distance was 300 meters, and the maximum mean value of RMS-DS was 88 ns for the urban area and the maximum mean value of RMS-DS was 25 ns for the suburban area. The maximum value of MED was 102 ns for urban areas and 36 ns for suburban areas.
Reference [15] described the statistical descriptions of the time delays and Doppler shifts associated with multipath propagation in the suburban environment. The author used a frequency of 910 MHz for measurements, and the distance between transmitter and receiver was 60 meters. Seven average profile were reported, and the average delay spread was $0.24 \mu s$. This value of RMS-DS is larger than the other that found in the other references cited because the propagation path loss at 910 MHz is smaller than that at 5 GHz.

In this thesis, we not only compute the RMS delay spread of the power delay profiles for our forest channels but we also compute frequency correlation estimates (FCE). From our sets of measured PDPs we also construct models for the channel impulse response (CIR). The models we construct specify the number of taps, the probability of tap existence, and tap energies. We also obtain the tap amplitude distributions, using both Weibull and Nakagami probability densities for construction of complete 10 MHz bandwidth models, which provide a comprehensive description of the forest channel in the 5 GHz band.
Chapter 3

Forest Measurements

In this chapter, we discuss the measurements made in the forest environment. First, we start with a brief description of the equipment we used to measure the channel impulse response. Next, we describe the forest environment setting of the measurements. We show some example photographs to illustrate the forest environment, and finally, we provide a description of the measurement procedures. This description of procedures consists of the channel sounder (transmitter and receiver) training, actual data collection, and use of the software to import PDP data into Matlab to compute forest channel parameters.

3.1 Equipment Description

The main equipment used in our measurement is the channel sounder, manufactured by Berkeley Varitronics Systems (BVS) [16]. The BVS spread spectrum stepped correlator was designed to operate in the 5 GHz spectrum. The channel sounder consists of the set of transmitter and receiver. Both the transmitter and receiver are powered by 12 V DC power supplies; the receiver is powered by a small battery pack and the transmitter by a larger vehicle (marine) battery. The primary measurement equipment used is as follows:
• BVS Wireless Channel Sounder: this consists of the receiver (Rx) and transmitter (Tx) units, each approximately the size of a small suitcase, as shown in Figure 3.1. The center frequency is adjustable between 5.095- to 5.25 GHz. For the forest measurements we used 5.12 GHz as the carrier frequency. The power level of the transmitter can be adjusted from 5 dBm to 33 dBm. There are two chip rates, 25 Mcps and 50 Mcps. The sounder’s chip rate was set to 50 Mcps. The receiver also operates between 5.095- to 5.25 GHz, and has the same two chip rates.

• Laptop Computer : in order to configure and record data from the channel sounder, it is necessary to use a laptop computer, which is connected to the receiver via an RS-232 cable.

• Battery Pack : this is a portable battery for the receiver, carry-able by hand. The battery pack can be utilized to power the receiver for about 3 hours.

• Vehicle battery : this battery is used to power the transmitter, and is larger than the receiver portable battery pack, since the transmitter RF power amplifier, outputting a maximum of 2 watts, requires more power than the Rx (see Figure 3.2).

• Antennas : in this measurement, for both transmitter and receiver, the antennas we used were omnidirectional monopoles. The gain of the monopoles is approximately 1.5 dBi.
Figure 3.3 shows the omnidirectional antennas, which are covered by hemispherical radomes.

Other essential equipment for the measurements included a backpack for carrying the receiver and its antenna, a vehicle inverter to power equipment during transport from the laboratory to the measurement sites, and various RF connectors and cables. Two Motorola “Talkabout” T5200 walkie-talkies were also used to enable voice communication between the transmit and receiver teams, and a digital camera was used for photographs.

Figure 3.1 Channel sounder hardware: (left) Tx and (right) Rx.
Figure 3.2 Vehicle Battery for powering sounder Tx.

Figure 3.3 Omnidirectional antennas.
3.2 Forest Environment Description

Before we took our measurements, we had to select appropriate locations in the forest. The forest measurement environment we selected is Stroud’s Run State Park located in Athens, Ohio. This was selected for convenience and its relative isolation from populated areas. Figure 3.4 shows a plan view of the three measurement locations. There are trails around the lake (Dow Lake), including hiking trails and bridle trails. There are also large forest areas surrounding the lake, so this provided us a setting to measure multipath effects through foliage in this forest environment. The trees within the forest are primarily deciduous trees, but some evergreens are also present. During our measurements, on September 26 and 29, 2008, the trees were partially in leaf, but some of the trees were almost bare. The measurement spots we chose were the forest trails next to the camp areas.

The first set of forest measurement was generated on Vista Point Trail (VPT), which is a sloped trail leading up from the trail head near CR 20. For measurements on this trail, shown in Figure 3.5, we set up the transmitter at the bottom of the slope in the parking area, and carried the backpack with the sounder receiver and Rx antenna inside. On the VPT, we walked along the path for approximately 100 meters, then doubled back along this path to another path that led back to the transmitter location. Figure 3.6 shows a diagram of the path walked to record the data.
Figure 3.4 Plan of Stroud’s Run State Park, showing measurement locations.
Figure 3.5 View of the Vista Point Trail.

Figure 3.6 Diagram of walking path in Vista Point Trail.
To gather additional data, two measurement locations were chosen near the camping area: the Homestead Trail (HT) and Camp Hiking Trail (CHT). Figure 3.7 shows the HT entrance and Figure 3.8 shows the CHT. In the HT spot, we crossed the bridge and set up the transmitter on the trail, then carried the backpack and walked along the path to record the data. Figure 3.9 shows the path directions traveled for the two paths on and near the Homestead trail. Figure 3.10 shows a photo looking up the hill for trail 2.

The CHT is a small hill trail that lies across the road from the HT. For this set of measurements, we placed the sounder transmitter on top of a van in the parking lot area, and the receiver team walked across the road then up the CHT.

Figure 3.7 View of the Homestead Trail entrance.
Figure 3.8 View of the Camp Hiking Trail.

Figure 3.9 Diagram of the two travel paths on the Homestead Trail.
3.3 Description of Measurement Procedures

3.3.1 Training

Before we conducted any actual forest measurements in Stroud’s Run Park, we needed to initialize and train the Tx and Rx. This was done in the Multiuser Mobile Communications Laboratory (MMCL) at Ohio University. The Tx and Rx calibration period is called “training,” and this is done to synchronize the Tx and Rx oscillators so that they do not drift during measurements. The training was conducted overnight in the laboratory.
In the training mode, we connected the Tx to the Rx via an RF cable and a 40 dB attenuator, to ensure the received power is equal to or less than -10 dBm. After connecting the equipment, we set the Tx carrier frequency to 5.12 GHz and set for Tx output power (P_{Tx}) to +5 dBm for training; the maximum P_{Tx} value of 33 dBm was used for sounding. We also set the Tx chip rate (Rc) to 50 Mcps.

Once training was begun, we checked all equipment again. Table 3.1 (from [17]) summarizes the procedures used in the training and channel sounding phases.

Table 3.1. Test procedure for initialization and training phase (from [17])

<table>
<thead>
<tr>
<th>#</th>
<th>Procedure Description</th>
<th>Estimated Duration (minutes)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><em>Initialization and Training</em></td>
<td>45-105</td>
<td>Training (step 13) could be conducted overnight</td>
</tr>
<tr>
<td>1</td>
<td>Position Tx platform, Tx and its power supply, and connect</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Turn on Tx power (not RF), and warm up</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Connect laptop to Rx, and power up laptop</td>
<td>0</td>
<td>During Tx warmup</td>
</tr>
<tr>
<td>4</td>
<td>Connect power (battery) to Rx</td>
<td>0</td>
<td>During Tx warmup; AC power provided through vehicle battery if training in location not actual transmission location</td>
</tr>
<tr>
<td>5</td>
<td>Turn on Rx power</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Connect RF cable from Tx to Rx, through attenuator</td>
<td>1</td>
<td>Use 40 dB attenuation, minimum, and ensure received power ≤ -10 dBm</td>
</tr>
<tr>
<td>7</td>
<td>Set Tx RF ( f_c )</td>
<td>0.25</td>
<td>( f_c = 5120 ) MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Set Tx output power $P_{Tx}$</td>
<td>0.25</td>
<td>Use $P_{Tx} = +5, \text{dBm}$ for training; the MAX value 33 dBm is used for sounding</td>
</tr>
<tr>
<td>9</td>
<td>Set Tx chip rate $R_c$</td>
<td>0.25</td>
<td>$R_c = 50, \text{Mcps}$</td>
</tr>
<tr>
<td>10</td>
<td>Turn on Tx RF power output</td>
<td>0.25</td>
<td>Again: $P_{Tx} \sim +5, \text{dBm}$, with $\geq 40, \text{dB}$ attenuator between Tx and Rx for training</td>
</tr>
<tr>
<td>11</td>
<td>Invoke Raptor SW on Rx, and make sure display indicates “Raptor Stable,” “Raptor Locked,” and received power $P_{Rx} &gt; -3, \text{dB}$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Configure Raptor Rx SW</td>
<td>1</td>
<td>During training, do NOT change any settings or display on laptop</td>
</tr>
</tbody>
</table>
|   | a. set $f_c$ and $R_c$ to match those of Tx  
|   | b. initiate training |   |   |
| 13 | Train for desired duration, depending upon desired measurement duration | 30-90+ | Measurement duration displayed via max(Current Count, Last Count) |

### 3.3.2 From Training to Forest Measurement

It took us approximately 20 minutes to drive from the MMCL to Stroud’s Run, therefore during driving we kept the sounder in training mode to gain more measurement time (generally speaking, the longer the training time, the better the synchronization between Tx and Rx, and this means a longer measurement time).
After arriving at Stroud’s Run, we finished training, then disconnected the Tx and Rx to prepare for measurement. We then put the Rx into the backpack and connected the antenna to the Rx through RF cable. We removed the 40 dB attenuator from the Tx RF input, and we connected the other antenna to the Tx. Table 3.2 (from [17]) shows the details of the procedure for transition from training to measurement.

Table 3.2. Test procedure for transition from training to measurement (from [17])

<table>
<thead>
<tr>
<th>#</th>
<th>Procedure Description</th>
<th>Estimated Duration (minutes)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Transition and Sounding</td>
<td>95-110</td>
<td>Begin this procedure after desired training duration, when ready to begin mobile tests.</td>
</tr>
<tr>
<td>2</td>
<td>Ensure that the Rx is connected to the charged battery pack</td>
<td>0.5</td>
<td>Secure the battery pack cable connection to the 4-pin cable leading to Rx via tape</td>
</tr>
<tr>
<td>3</td>
<td>At the Rx laptop pc, click on the box to “accept” the Raptor training value</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>At the Tx, turn off the RF transmission power and disconnect RF cable from sounder Rx</td>
<td>0.5</td>
<td>Keep Tx powered up</td>
</tr>
<tr>
<td>5</td>
<td>Rx Team: Gather battery pack and Rx cables together for imminent transport; also gather laptop pc</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Rx Team: Connect charged battery pack to Rx through 4-pin cable, then disconnect the AC power supply from the Rx. Put Rx into backpack, then connect laptop pc to Rx</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Tx Team: Keep Tx powered via vehicle battery</td>
<td>5</td>
<td>ENSURE Tx stays powered</td>
</tr>
<tr>
<td>8</td>
<td>Tx Team: Remove 40 dB attenuator from Tx RF input, and connect desired antenna to Tx</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3.2. Continued

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Tx Team: ENSURE $f_c$ and $R_c$ are correct, then await instructions to begin transmission from Rx team; set transmit power to MAX value (33 dBm), but still RF off</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Rx Team: Set up Rx and laptop in</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>Rx Team: Connect antenna cable to Rx RF input</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Rx Team: Invoke the “Chameleon” SW and prepare to log data</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.3.3 Forest Measurement Procedures

After completing training and connecting antennas, we began transmission for measurements. The transmitter power was set to its maximum value of 33 dBm. The Rx was carried in the backpack along with the antenna, as shown in Figure 3.11
Once at the trail beginning, we invoked the “Chameleon” SW from the laptop and prepared to log actual measurement data. Then with the Rx and laptop ready to log data, we carried the backpack and walked along the hiking and bridle trails. To collect data, we recorded in two separate files on the Vista Point Trail, Homestead Trail-trail 1 and Homestead Trail-trail 2; we also recorded one file on the Camp Hiking Trail. In our measurements, the distance we walked along the Vista Point Trail was approximately 120 meters. The total round-trip distance along the Homestead Trail-trail 1 was approximately 150.4 meters, for Homestead Trail-trail 2 it was approximately 136 meters. The distance along the Camp Hiking Trail was approximately 109.2 meters. The measured power delay profiles were stored as several files. Table 3.3 [17] shows the test procedure for measurements.
Table 3.3 Test procedure for measurement in the forest environment (from [17])

<table>
<thead>
<tr>
<th>#</th>
<th>Procedure Description</th>
<th>Estimated Duration (minutes)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rx Team: Communicate readiness to log data to Tx team verbally, and proceed to measurement point</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Tx Team: Upon receipt of message from Rx Team indicating readiness to transmit, turn on Tx RF power ($P_{tx}=33$ dBm)</td>
<td>1</td>
<td>Take photos of mobile van, and several views of Stroud’s Run Lake environment</td>
</tr>
<tr>
<td>3</td>
<td>Rx Team: With Rx and laptop ready to log data, move to measurement location point 1</td>
<td>1-5</td>
<td>If possible, during 1st measurement run, mark location points for repeatability</td>
</tr>
<tr>
<td>4</td>
<td>At Rx, configure Raptor SW to measure delay span of $N_p$ points. Record location 1 profile, and capture reference RSSI</td>
<td>5</td>
<td>Begin with $N_p$ on the order 300 except for full-delay-span initial measurement run. As distance increases, and/or more large-delay multipath is observed, $N_p$ can be increased</td>
</tr>
<tr>
<td>5</td>
<td>At Rx, set up log file for initial course. Rx Team should communicate readiness to begin to Tx Team</td>
<td>5</td>
<td>File names include data, area (e.g., Stroud’s Run), antenna types, LOS or NLOS, and terminal points</td>
</tr>
<tr>
<td>6</td>
<td>Begin to move from Tx site (point 1) and walk along the trail until Rx signals are weak (point 2). Then Rx team goes back along the original trail, as shown in Figure 3.6 &amp; 3.9</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>When trail point 2 reached, stop and end PDP logging</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Create new Rx log file, and move from next trail, and log PDPs</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Repeat steps 7-8 for the remaining measurement location points</td>
<td>~45</td>
<td></td>
</tr>
</tbody>
</table>
### 3.3.4 Measurement Data Conversion

The recorded data was kept in several log files, and these are in a proprietary .rap format. For this reason, we have to convert these data files after finishing the measurements. We used the BVS Raptor “Chameleon Data Convertor” software to provide magnitude, phase, and received signal strength information (RSSI). This software converts the .rap file to a .out file, which is in ASCII file format. Then we used the .out file and read this into MATLAB using the `csvread` command [18]. A screen shot of the BVS Raptor “Chameleon Data Convertor” software which we used for our data conversion is shown in Figure 3.12 [19].

The final procedure in our forest measurement is to use the imported files in MATLAB to compute statistical channel parameters from the measured PDPs (Channel Impulse Response).
Figure 3.12 Screen shot of BVS Raptor ‘Chameleon Data Convertor’ software.
Chapter 4

Forest Measurement Results

In this chapter, we will describe the channel models we have developed from the forest wireless channel measurement at Stroud’s Run Park. We will begin with a description of the data preprocessing required to obtain channel impulse response estimates.

4.1 Data Preprocessing

In Chapter 3, we described the procedures to obtain measured power delay profiles. As noted, we need to convert the data collected from the channel sounder to an ASCII format. Two other steps required for the data preprocessing are noise thresholding and multipath thresholding.

4.1.1 Noise Thresholding

In any real communication system, thermal noise affects the received signal. Due to this, we need to account for the effects of thermal noise. We use a noise threshold algorithm to separate out the noise from the multipath components. As in [20], we
determine a noise threshold for the $i^{th}$ PDP which provides a constant false alarm probability for each PDP. The thermal noise is assumed to be Gaussian, thus the amplitude of the thermal noise has a Rayleigh distribution [20]. The probability density function for the thermal noise amplitude is as follows:

$$P(n_0) = \exp\left(-\frac{n_0^2}{2(\sigma_x^i)^2}\right)$$

(4.1)

where $\sigma_x^i$ is the noise standard deviation for the $i^{th}$ PDP. For the $i^{th}$ PDP, the estimated median noise level can be obtained by setting $n_0 = \sigma_m^i$, and setting equation (4.1) to 1/2 for the estimated median, we obtain

$$\sigma_x^i \approx 0.8493\sigma_m^i$$

(4.2)

With the constant false alarm algorithm, the probability that any noise sample is mistaken for a valid multipath echo is

$$P(\eta) = \exp\left(-\frac{\eta^2}{2}\right)$$

(4.3)

where $\eta$ is a constant. If we use equation (4.3), for example, we have 510 samples in the 50 MHz mode for the full span, we can obtain $\eta = 3.52$. The noise threshold is [20]
\[ NT_i = \eta \sigma_s^i \] (4.4)

We first separate the noise samples from the multipath components then use equation (4.2) and compute \( \sigma_m^i \) for each PDP to obtain the noise standard deviation \( \sigma_s^i \). Here we select a threshold of 25 dB which assumes that the noise samples are below 25 dB from the maximum value in a PDP [20].

Using a threshold of 25 dB, with \( \sigma_m^i \), we use (4.2)-(4.4) to calculate \( NT_i \). Then in the \( i^{th} \) PDP, all samples below \( NT_i \) are set to be the minimum value, which is -130 dBm. This step can be repeated for each PDP [23].

4.1.2 Multipath Thresholding

According to the path taken by the multipath components to arrive at the receiver, the multipath components may be strong or weak. When the components are extremely weak and add very little energy to the PDP, it is not usually necessary to include them in computing CIR statistics. As a compromise between accurate modeling and reasonable model complexity, we hence use a second threshold to remove the weakest components. Reference [29] chose to use a multipath threshold of 25 dB. Reference [23] describes the rationale for this selection in detail. So, for a given PDP, any component that remains after noise thresholding, but which is below 25 dB from the largest multipath component is set to a minimum value of -130 dBm.
4.2 Statistical Channel Parameters

4.2.1 Parameters from PDPs

The following parameters can be obtained directly from the PDPs.

1. Mean Excess Delay (MED) ($\mu_\tau$): The MED is the mean value of the PDP’s energy delay. The MED is the normalized first moment of a PDP [22]:

$$\mu_\tau = \frac{\int_0^\infty \tau \phi_g (\tau) d\tau}{\int_0^\infty \phi_g (\tau) d\tau}$$

(4.4)

where $\phi_g (\tau)$ is the PDP, and $\int_0^\infty \phi_g (\tau) d\tau$ is the normalization factor, equal to the total power in the PDP.

2. Root Mean Square Delay Spread (RMS-DS) ($\sigma_\tau$): the RMS-DS is the square root of the normalized second central moment of the PDP [21]:

$$\sigma_\tau = \sqrt{\frac{\int_0^\infty (\tau - \mu_\tau)^2 \phi_g (\tau) d\tau}{\int_0^\infty \phi_g (\tau) d\tau}} \approx \sqrt{\frac{\sum_k \tau_k^2 \alpha_k^2}{\sum_k \alpha_k^2} - (\mu_\tau)^2}$$

(4.5)
The RMS-DS is a popular measure of the spread of the signal in time. Figure 4.1 shows an example histogram of RMS-DS in VPT at Stroud’s Run State Park, and Figure 4.2 shows an example time-series of RMS-DS values. As we can see, the values of RMS-DS for the first half of the plot increase to a maximum when the link distance was largest, then decreases again for the last half of the plot. Table 4.1 provides the RMS-DS statistics for a 10 MHz bandwidth channel, with the minimum, mean and maximum values of RMS-DS for all locations at Stroud’s Run.

Figure 4.1 RMS-DS distribution in VPT at Stroud’s Run Park.
Figure 4.2 RMS-DS vs. time plot for total trip along the Vista Point Trail.

Table 4.1 Measured RMS-DS values for four regions at Stroud’s Run State Park

<table>
<thead>
<tr>
<th>Location</th>
<th>RMS-DS<a href="ns">min</a></th>
<th>RMS-DS<a href="ns">mean</a></th>
<th>RMS-DS<a href="ns">max</a></th>
</tr>
</thead>
<tbody>
<tr>
<td>VPT</td>
<td>0.0523</td>
<td>63.7751</td>
<td>359.3289</td>
</tr>
<tr>
<td>HT trail-1</td>
<td>0.0701</td>
<td>76.8147</td>
<td>354.6679</td>
</tr>
<tr>
<td>HT trail-2</td>
<td>0.0225</td>
<td>86.9802</td>
<td>357.1271</td>
</tr>
<tr>
<td>CHT</td>
<td>0.2252</td>
<td>71.1197</td>
<td>367.1539</td>
</tr>
</tbody>
</table>

3. Delay Window \((W_D)\) : The delay window is the width of the middle section of a PDP, which includes \(D\%\) of the total energy in the PDP[18]. Figure 4.3 shows an example histogram for the delay window with \(D=90\) for HT-Trail 1.
4.2.2 Parameters obtained from Fourier Transform of the PDPs

Channel Transfer Function [23]: We can utilize the Fourier transform of the Impulse Response Estimate (IRE) to obtain the channel transfer function. The channel transfer function can be expressed as:

\[
H(f; t) = F\{h(\tau; t)\} = \int_{-\infty}^{\infty} h(\tau; t)e^{-j2\pi ft}\, d\tau
\]  

(4.6)

where \(H(f; t)\) is the time-varying channel transfer function (CTF). The CIRs are discrete in the time domain. Therefore, we can use the fast Fourier transform (FFT)
algorithm to obtain the CTF. We denote the samples of the CTF “complex amplitudes” at different frequency values.

Frequency correlation estimate (FCE) : We can use frequency correlation functions to compute the coherence bandwidth. These provide a quantitative measure of the correlation between channel effects at a given frequency separation, and hence can be useful for developing channel models in the frequency domain. From initial data processing, we suspect that we have some correlated scattering in the measurements. Thus, the Wide Sense Stationary Uncorrelated Scattering (WSSUS) can not be assumed. Therefore, we can use the formula from [23] to compute the FCE, which enables estimation of the coherence bandwidth :

\[
FCE = \frac{\gamma_H(a_{ref}, a_i)}{\sqrt{\gamma_H(a_{ref}, a_{ref}) \gamma_H(a_i, a_i)}}
\]  

\[
\gamma_H(a_{ref}, a_i) = \frac{1}{N} \sum_{j=1}^{N} a_{ref,j} a_{i,j}^*  
\]

where \( \gamma_H(a_{ref}, a_i) \) is the cross-correlation; \( a_i \) is the complex amplitude at frequency index \( i \); \( a_{ref} \) is the complex amplitude at the reference frequency; \( a_{i,j} = H(f_i, t_j) \), and \( j \) is the time index. Figure 4.4 shows example FCEs for our 10 MHz bandwidth for our forest measurements.
Figure 4.4 Frequency Correlation Estimates for all locations.

The FCE gives a measure of the channel frequency selectivity. In comparison to these four trails in 10 MHz bandwidth, we can see that the FCE in HT trail-1 is wider than other three forest locations. The narrowest FCE of CHT indicates that this location’s channel is more frequency selective than the others. For example, for a correlation coefficient of 0.4; the correlation bandwidth is approximately 6.5 MHz for the CHT channel and approximately 8 MHz for the VPT channel.
4.3 Channel Impulse Response Model Development

In order to discuss the channel models we developed for Stroud’s Run Park in the 5 GHz band, we first give a concise explanation of the tapped delay line (TDL) channel model. Then we provide channel models in TDL form which include relative tap energies, tap amplitude distributions, and probability of a tap existence for a 10 MHz channel bandwidth.

4.3.1 Tapped Delay Line Model

The tapped delay line model is the most common model for wireless channels. It is a linear, finite IR filter model for the channel impulse response, and has tap weights [24] that are modeled as stochastic processes. The tapped delay line model can be seen in Figure 4.5
where $x_k$ is the $k^{th}$ input symbol, $y_k$ is the $k^{th}$ output symbol, $\tau$ indicates delays, and the $h_k(t)$'s express the time variant impulse complex response components [18]. For the $k^{th}$ tap, $h_k(t)$ is given by

$$h_k(t) = z_k(t)\alpha_k(t)e^{j\phi_k(t)} \quad (4.9)$$

where $z_k$ is the time varying tap persistence process, $\alpha_k$ is the fading amplitude process, and $\phi_k$ is the phase.
4.3.2 Number of Channel Taps

We often use RMS-DS as an important measure of the channel dispersion. We can also determine the number of required taps based on the value of RMS-DS. Here we select the mean value of RMS-DS for determining the number of taps. Because the RMS-DS changes in different areas such as in line-of-sight and non-line-of-sight areas, we could calculate different numbers of taps in these two areas, but here we do not create such separate models. The formula we use to determine the number of taps is:

\[
L = \left\lceil \frac{\text{mean}(RMS-DS)}{T_c} \right\rceil + 1
\]  

(4.10)

In (4.10), \( L \) is the number of taps, \( T_c \) is the equivalent chip time (100 ns for our 10 MHz bandwidth), and \( \lceil x \rceil \) indicates the ceiling function, which is the smallest integer greater than or equal to \( x \) [19]. Here, considering the PDPs from all forest locations, the number of taps is \( L=4 \).
4.3.3 Tap Energies

In a dense scattering environment, the channel sounder produces a single amplitude for each multipath component within the 20 ns “delay bin,” but this single amplitude is very likely the aggregate of multiple rays that arrive at the receiver within the finite delay bin. The average tap energy is computed by dividing the sum of total energy collected over all PDPs for a given tap by the number of PDPs. Every tap is an effective multipath component. Figure 4.6 illustrates the relative tap energy associated with each tap for the data collected at four forest locations at Stroud’s Run State Park. We can see how the energy decreases as tap index increases.

Figure 4.6 Relative tap energy in dB vs tap index for all locations.
4.3.4 Probability of Tap Existence

As previously noted, sometimes taps are not present (either due to severe obstruction or very deep fading below our threshold—25 dB below the strongest tap). We capture this effect by computing each tap’s probability of existence. Figure 4.7 illustrates the four taps’ probability of existence versus tap index. As tap index increases, the probability of existence decreases. This is because the higher tap index components have longer delay (travel longer paths), and likely incur multiple reflections, and hence are weaker than the low index taps even when present.

Figure 4.7 Probability of existence tap vs. tap index for all locations.
We use a Markov chain to model the tap persistence processes [19]. The 1st-order homogeneous Markov chain for each tap is described by two matrices, the transition matrix (TS) and the steady state matrix (SS). For any multipath component (tap), there are two states: the “on” state, which means \( z_k(t) = 1 \) and the tap is above threshold, and the “off” state, which means \( z_k(t) = 0 \), and the tap is below threshold. The 2 x 2 TS matrix is shown in (4.11)

\[
TS = \begin{bmatrix} P_{00} & P_{01} \\ P_{10} & P_{11} \end{bmatrix}
\]

(4.11)

where \( P_{ij} \) is the probability of going from state \( i \) to state \( j \). The SS matrix indicates the percentage of time which a tap is present \( (z_k(t) = 1) \) or absent \( (z_k(t) = 0) \) [19]. Hence we have a 2 x1 SS matrix, as shown in (4.12)

\[
SS = \begin{bmatrix} P_0 \\ P_1 \end{bmatrix}
\]

(4.12)

where \( P_i \) is the steady probability associated with state \( i \). Tables 4.2-4.5 illustrate the Markov chain matrices for the forest channels, for the four different forest locations.
Table 4.2 Markov matrix for VPT location

<table>
<thead>
<tr>
<th>Tap Energy</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{01}$</th>
<th>$P_{10}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Na</td>
<td>Na</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.0259</td>
<td>0.9705</td>
<td>0.0614</td>
<td>0.9386</td>
<td>0.0285</td>
<td>0.9715</td>
</tr>
<tr>
<td>3</td>
<td>0.1627</td>
<td>0.8373</td>
<td>0.2456</td>
<td>0.7544</td>
<td>0.1466</td>
<td>0.8534</td>
</tr>
<tr>
<td>4</td>
<td>0.5522</td>
<td>0.4478</td>
<td>0.6201</td>
<td>0.3799</td>
<td>0.4684</td>
<td>0.5316</td>
</tr>
</tbody>
</table>

Table 4.3 Markov matrix for HP-Trail 1 location

<table>
<thead>
<tr>
<th>Tap Energy</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{01}$</th>
<th>$P_{10}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Na</td>
<td>Na</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.0307</td>
<td>0.9692</td>
<td>0.0564</td>
<td>0.9435</td>
<td>0.0299</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>0.1614</td>
<td>0.8385</td>
<td>0.2353</td>
<td>0.7646</td>
<td>0.1472</td>
<td>0.8527</td>
</tr>
<tr>
<td>4</td>
<td>0.5097</td>
<td>0.4902</td>
<td>0.6037</td>
<td>0.3962</td>
<td>0.4188</td>
<td>0.5881</td>
</tr>
</tbody>
</table>

Table 4.4 Markov matrix for HT-Trail 2 location

<table>
<thead>
<tr>
<th>Tap Energy</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{01}$</th>
<th>$P_{10}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Na</td>
<td>Na</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.0354</td>
<td>0.9645</td>
<td>0.1207</td>
<td>0.8792</td>
<td>0.0323</td>
<td>0.9676</td>
</tr>
<tr>
<td>3</td>
<td>0.1493</td>
<td>0.8506</td>
<td>0.295</td>
<td>0.7049</td>
<td>0.1238</td>
<td>0.8761</td>
</tr>
<tr>
<td>4</td>
<td>0.4608</td>
<td>0.5391</td>
<td>0.6178</td>
<td>0.3821</td>
<td>0.3267</td>
<td>0.6732</td>
</tr>
</tbody>
</table>
Table 4.5 Markov matrix for CHT location

<table>
<thead>
<tr>
<th>Tap Energy</th>
<th>$P_0$</th>
<th>$P_1$</th>
<th>$P_{00}$</th>
<th>$P_{01}$</th>
<th>$P_{10}$</th>
<th>$P_{11}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>Na</td>
<td>Na</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>0.028</td>
<td>0.972</td>
<td>0.0843</td>
<td>0.9157</td>
<td>0.0264</td>
<td>0.9736</td>
</tr>
<tr>
<td>3</td>
<td>0.1311</td>
<td>0.8689</td>
<td>0.2553</td>
<td>0.7447</td>
<td>0.1124</td>
<td>0.8876</td>
</tr>
<tr>
<td>4</td>
<td>0.4094</td>
<td>0.5906</td>
<td>0.5497</td>
<td>0.4503</td>
<td>0.312</td>
<td>0.688</td>
</tr>
</tbody>
</table>

### 4.3.5 Distributions of Tap Amplitude

Here, we provide the tap amplitude models for our 10 MHz forest channels. Tables 4.6 to 4.9 show the tap amplitude parameters for VPT, HT trail-1, HT trail-2 and CHT regions. The parameters in these tables contain the fading amplitude factor ($b$) and the average energies for all four taps. The fading amplitude parameter $b$ pertains to the Weibull probability density, and this factor is analogous to a Ricean $k$-factor. When $b=2$, the Weibull density is the Rayleigh, and if $b<2$, the fading is more severe than Rayleigh.

Table 4.6 Tap amplitude parameters for VPT location

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Tap Energy</th>
<th>Weibull Factor ($b$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8172</td>
<td>2.9883</td>
</tr>
<tr>
<td>2</td>
<td>0.1416</td>
<td>1.7986</td>
</tr>
<tr>
<td>3</td>
<td>0.0371</td>
<td>1.767</td>
</tr>
<tr>
<td>4</td>
<td>0.0042</td>
<td>1.9359</td>
</tr>
</tbody>
</table>
Table 4.7 Tap amplitude parameters for HT-Trail 1 location

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Tap Energy</th>
<th>Weibull Factor (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.811</td>
<td>2.4206</td>
</tr>
<tr>
<td>2</td>
<td>0.1427</td>
<td>1.7061</td>
</tr>
<tr>
<td>3</td>
<td>0.0395</td>
<td>1.7297</td>
</tr>
<tr>
<td>4</td>
<td>0.0067</td>
<td>2.0498</td>
</tr>
</tbody>
</table>

Table 4.8 Tap amplitude parameters for HT-Trail 2 location

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Tap Energy</th>
<th>Weibull Factor (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8048</td>
<td>2.1504</td>
</tr>
<tr>
<td>2</td>
<td>0.14</td>
<td>1.6159</td>
</tr>
<tr>
<td>3</td>
<td>0.0449</td>
<td>1.7528</td>
</tr>
<tr>
<td>4</td>
<td>0.0102</td>
<td>2.0686</td>
</tr>
</tbody>
</table>

Table 4.9 Tap amplitude parameters for CHT location

<table>
<thead>
<tr>
<th>Tap Index</th>
<th>Tap Energy</th>
<th>Weibull Factor (b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8029</td>
<td>2.8593</td>
</tr>
<tr>
<td>2</td>
<td>0.1408</td>
<td>1.8618</td>
</tr>
<tr>
<td>3</td>
<td>0.0462</td>
<td>1.8382</td>
</tr>
<tr>
<td>4</td>
<td>0.01</td>
<td>2.0124</td>
</tr>
</tbody>
</table>

Even though the Rayleigh distribution model is commonly used, in some cases our fading tap amplitude distributions in the forest are slightly worse than Rayleigh. Figures 4.8 to 4.11 show examples of the 1st tap’s fit to two types of probability density functions, the Weibull and the Nakagami.
Figure 4.8 Probability density function and Histograms fits for 1st tap of VPT.

Figure 4.9 Probability density function and Histograms fits for 1st tap of HT-Trail 1.
Figure 4.10 Probability density function and histograms fits for 1\textsuperscript{st} tap of HT-Trail 2.

Figure 4.11 Probability density function and histograms fits for 1\textsuperscript{st} tap of CHT.

Figures 4.12 to 4.15 show example fits for the 2\textsuperscript{nd} taps for all locations. From these example fits, we can see that the Weibull and Nakagami distributions provide good fits.
for the tap amplitude distributions. Also, as noted from Tables 4.6-4.9, some of the
can be so great, but most of the channel taps are nearly
Rayleigh or better than Rayleigh. Our distribution fits the maximum likelihood fitting
technique, via the “distribution fitting tool” in MATLAB. This tool computes log
likelihood (LL) for each hypothesized distribution, and the LL value is the metric used to
compare one distribution fit to another. For example, for the 1st tap of the VPT model, the
Weibull LL is $LL_w = -6001.41$, whereas the LL for the Nakagami distribution is $LL_N =
-6016.57$. This indicates that the Weibull fits better than the Nakagami for this tap’s
amplitude distribution. In contrast, for the 2nd tap of the VPT model, we found $LL_w =
-2055.77$, and $LL_N = -1874.51$, which indicates the Nakagami is the better fit. Over all
taps and all models though, the Weibull distribution generally fits better. For convenience
in simulations, one prefers to use only one type of random variable, hence we propose the
use of the Weibull distribution throughout for all our models.
Figure 4.12 Probability density function and Histograms fits for 2\textsuperscript{nd} tap of VPT.

Figure 4.13 Probability density function and Histograms fits for 2\textsuperscript{nd} tap of HT-Trail 1.
As we know, Rayleigh and Rician distributions are commonly used. In this thesis, we found the best fits with the Weibull and Nakagami fading distributions [30];
even though the Rayleigh fits for some taps, and the Ricean for others, the flexible Weibull distribution can be used for all.
Chapter 5

Summary, Conclusions & Future Work

5.1 Summary

We have described a wireless channel characterization effort for the 5 GHz band in a forest environment. We provided background and motivation for this work, described the equipment and measurement procedures, and gave examples of some of the measurement results. Statistics for RMS-DS were provided, along with example frequency correlation estimates (FCE). Our literature search revealed that only a few channel models for the forest environment exist, and we found no such models for the 5 GHz band. Hence we also developed statistical channel models for a 10 MHz bandwidth based upon the measurements.

5.2 Conclusions

From our results for RMS-DS for the four different measurement locations in Stroud’s Run Park, we found that the distributions for the four locations were mostly similar, except that the mean RMS-DS of HT trail-2 is larger than the others. This
indicates that the channel for the HT trail-2 is more dispersive, likely because the density of trees was larger than in the other areas.

For the frequency domain, the FCE plots show that the channel is most selective for the CHT channel model. The Markov chain illustrates the dynamic tap behavior. We found, as in prior studies, that the larger the tap index, the more probable the tap is “off”. This is in keeping with the finding that the tap energy decreases as tap index increases. The rate of the tap energy decrease for the VPT location is larger than for the other three forest locations, and this is likely due to the greater duration of a LOS component on that trail than on the others For the tap amplitude distributions, we used the Weibull and the Nakagami distributions to fit the tap amplitude fading, and found that on occasion, some of the weaker taps showed severe fading. This severe fading is likely from multiple scattering. In our forest channel models, we found that most tap amplitudes are better than Rayleigh.

**5.3 Future Work**

In this thesis, the measurements we conducted were in early fall on a sunny day. More data could possibly be gathered during other seasons and in other weather conditions to obtain a set of channel models for those conditions. We could also gather more data in different types of forest environments, and also investigate the effect of changing the heights of the Tx and/or Rx antennas. Finally, we could develop channel models for different values of channel bandwidth.
REFERENCES


APPENDIX: MATLAB CODE

% -----------These programs were developed by Indranil Sen [23], and modified for this thesis. This code generates the PDPs, RMS-Delay Spreads, Mean Envelope Delays, FCEs, tap amplitude statistical fits and correlation matrices for forest channel models in Vista Point Trail (VPT)-----------%

clc
clear
close all

Update = 1;
USDR = 25;
BW = input('Please enter the BW in MHz');
NAvg = 1;

lastcountR = 0;
lastcountL2 = 0;
lastcountNL1 = 0;
precount = 0;
corrcountNL1 = 0;
corrcountL2 = 0;
NumPDPSeg_NLOSS = zeros(1,22);

MaxRMSL2 = 285;
Dx = 10*(100/BW);
nTapL2 = ceil(MaxRMSL2/Dx) + 1;
Ns = (1/BW)/0.01;
Tinc = Ns*(10e-9);

f = [1:2];

for toti = 1:length(f)
toti;
f(toti)
flagL2 = 0; flagNL1 = 0;

%%% Reading measurement data file for particular segment
%%% Note: 'str1' will be different for different regions
str1 = 'C:\MATLAB7\work\VTV_July_2007\ForestSept26\ForestSept26_';
str2 = strcat(str1,num2str(f(toti)),'.out');
semp = csvread(str2,2,1);
numC = (siz_temp(2)-1)/2;

for jj = 1:siz_temp(1)
RSSI(jj)=semp(jj,siz_temp(2));
tempR_dBM_Rad=reshape (semp(jj,1:2*numC),2,numC);
TempR_dBm(jj,:)=tempR_dBM_Rad(1,:);
    TempR_Rad(jj,:)=tempR_dBM_Rad(2,:);
end

%% Collecting Phase values for each sample of the measured data
le= length(TempR_Rad(1,:));
tempp = reshape (TempR_Rad,1,siz_temp(1)*le);
AllAngle( precount+1 : precount+ (siz_temp(1)*le)) = tempp;
precount = length (AllAngle);

if(UpDate==1)
    PowerRecord(:,1:100)=TempR_dBm(:,1:100);
    PhaseRecord(:,1:100)=TempR_Rad(:,1:100);
end
if(UpDate==2)
    PowerRecord=TempR_dBm;  \%\%PowerRecord has the power of each PDP
    PhaseRecord=TempR_Rad;  \%\%PhaseRecord has the phases of each PDP
end

[PowerImpNoiThr,Angle,RssI]=RemImp1(PowerRecord,PhaseRecord,RSSI);

[powerdBMN]=NoiseThresh1(PowerImpNoiThr,USDR);
siz_temp1=size(powerdBMN);

AmpN=sqrt(10.^(-3+powerdBMN./10));
for jj=1:siz_temp1(1)
    Idata(jj,:)=AmpN(jj,:).*cos(Angle(jj,:));       Qdata(jj,:)=AmpN(jj,:).*sin(Angle(jj,:));
end

[PowerdBMN1,Angle1]=AddSampVecAngleFinal(Idata,Qdata,Ns);

\%\% Generate the delay vector for the PDP
siz_temp2=size(PowerdBMN1);
time=1:siz_temp2(2);
Del=(Tinc.*time);
DelX=(Tinc.*time)/(10^-6);
UpRate=floor((11e-3+2*siz_temp2(2)*0.4e-3)^-1);

for lj=1:siz_temp2(1)
    PowerdBMN2(lj,:)=PowerdBMN1(lj,:)-max(PowerdBMN1(lj,:));
    for lk = 1:siz_temp2(2)
if ( abs(PowerdBMN2(lj,lk))<= 25)  
    PowerdBMN(lj,lk)= PowerdBMN1(lj,lk);  
else  
    PowerdBMN(lj,lk)= -125 ;  
end  
end  
end  

ld=length(PowerdBMN(:,1)); % Number of PDPs in time  
tplot=PowerdBMN(1:ld,:);  
clear PowerdBMN;  
for jj=1:ld  
    [MaxT IndT]=max(tplot(jj,:));  
    flag=0;  
    I=1;  
    for kk= IndT:-1:1  
        if ((tplot(jj,kk)< (MaxT-25))&(flag==0))  
            I=kk;  
            flag=1;  
        end  
    end  
    PowerdBMN(jj,:)=[tplot(jj,I:end) tplot(jj,1:I-1)];  
end  

%%%% Calculating the RMS-DS,Mean Envelope Delay and Delay Window for 90% energy  
[RMSDelSpr,MED]= (Stat_RMS_DS(PowerdBMN,Del,siz_temp2(1)));  
[DW90] = DelayWindow1(PowerdBMN,Del,0.9);  
RMSDelSpr = RMSDelSpr/((10^-9));  
MED = MED/((10^-9));  
DW90 = DW90/((10^-9));  
AvgRMSDelSpr=mean(RMSDelSpr)  

[PowerdBMN_NP,FinalAngle1]= NormPeakAngle(PowerdBMN,Angle1);  
siz_temp3=size(PowerdBMN_NP);  

%%%%% Determining PathLoss in dB for each PDP  
AntGain=2*1.36;  
CableTx= 2.4;  
CableRx= 4.2;  
CableLoss = (AntGain)-(CableTx)-(CableRx);  
ActualPLdB= 33 - RssI + CableLoss;  

%%%% Determining the amplitude for each tap after removing PathLoss or  
%%%% "large scale fading" component
for ii=1:nTapL2
    k1=PowerdBMN_NP(:,ii)';
    k2=ActualPLdB(1,:);
    k3=30.*ones(1,siz_temp3(1));
    TempdB(ii,:)=k1-k3+k2;
    demp(ii,:)=10.^(TempdB(ii,:)/10);
    dempSqr(ii,:)=sqrt(demp(ii,:));
    dempSqrdb(ii,:)=10*log10(dempSqr(ii,:));
    t1 = FinalAngle1(:,ii);
    TempAngle1(ii,:)= t1;
end
lastcount=siz_temp2(1);
DempSqrdb= dempSqrdb;
DempSqr= dempSqr;
Demp= demp;

%% Determining transfer function and |H(f,t)|.^2 for each PDP
%% Refer to report Section 4.3.2 for more details
ss1=256; %% Number of frequencies considered
Finc=BW/ss1; %%%Frequency bin size
ff= -BW/2:Finc:(BW/2)-Finc;%% Frequency vector
iNL1=1;
iL2=1;
for ii=1:siz_temp2(1)
    PowerN=10.^(3+PowerdBMN(ii,:)/10);
    SigN_Sadd=sqrt(PowerN);
    Phase = exp(-j.*FinalAngle1(ii,:));
    Comp_SigN_Sadd = SigN_Sadd.*Phase;
    FSigN_Sadd=fftshift(fft(Comp_SigN_Sadd,ss1));
    FPowerN_Sadd=abs(FSigN_Sadd).^2;
    FPowerNdB_Sadd(ii,:)=10*log10(FPowerN_Sadd./max(FPowerN_Sadd));
    FSig(ii,:)=FSigN_Sadd;
end

%% Separating RMS-DS, Tap Amplitudes and Phases, DW90, Spectral line amplitudes
%% for NLOS-S and NLOS regions
cl=1;
cn=1;
cl2=1;
for ii=1:length(RMSDelSpr)
    flagL2=1;
    L2RMS(cl2)=RMSDelSpr(ii);
    L2MED(cn2) = MED(ii);
    L2DW90(cl2) = DW90(ii);
FSigL2(cl2,:) = FSig(ii,:);
for mm = 1:nTapL2
    t_L2(mm,cl2)=DempSqr(mm,ii);
    LOS2Angle1(mm,cl2)=TempAngle1(mm,ii);
end
cl2=cl2+1;
end

%% Identifying the number of PDPs in the region for a specific segment
if (flagL2==1)
    NumPDPSeg_NLOSS(toti) = length(L2RMS);
end

%% Creating persistence process vector(0: Multipath absent, 1: Multipath present) for each tap in the region. MT is 25 dB
for lj = 1:siz_temp3(1)
    MarAmp(lj,:) = PowerdBMN_NP(lj,:)-max(PowerdBMN_NP(lj,:));
    for lk = 1:siz_temp3(2)
        if ( abs(MarAmp(lj,lk)) <= 25)
            Markov1(lj,lk) = 1;
        else
            Markov1(lj,lk) = 0;
        end
    end
end
CountL2 = 0;
CountNL1 = 0;
for mm = 1:length(RMSDelSpr)
    CountL2 = CountL2 +1;
    for ii = 1:nTapL2
        c_marL2(ii, CountL2) = Markov1(mm,ii);
    end
end
csptic = 0;
if ( flagL2 == 1)
    for JJ = 1:nTapL2
        for jj=1:nTapL2
            cvec = 0;
            cpre = 0;
            for xx= 1:length(t_L2(1,:))
Identifying the PDPs when both the taps are present
if (c_marL2(JJ,xx)==1 && c_marL2(jj,xx)==1)
cvec = cvec + 1;
cpre = 1;
fvec(cvec) = t_L2(JJ,xx);
svec(cvec) = t_L2(jj,xx);
end
end
csptic = csptic + 1;

Determining the correlation coefficient only if there are
PDPs which have both the taps ON at the same time, else the
correlation coefficient is 0.
if( cpre ~=0)
temp12 = corrcoef(fvec,svec);
clc;
lfvec = length(fvec);
else
temp12= [0 0 ; 0 0 ];
lfvec =0 ;
end

Creating the 3D crosscorrelation coefficient matrix
if ( length(temp12)~=1)
    CrossCorr3DL2 (toti,JJ,jj)= temp12(1,2);
    NumProCorr3DL2 (toti,JJ,jj ) = lfvec;
    if(JJ == 1)
        CrossCorrL2(toti,jj)=temp12(1,2);
        NumProCorrL2(toti,jj)= lfvec;
    end
else
    CrossCorr3DL2 (toti,JJ,jj)= temp12(1);
    if(JJ == 1)
        CrossCorrL2(toti,jj)=temp12(1);
    end
end
clear fvec;
clear svec;
clear cvec;
end
end
clear fvec;
clear svec;
clear cvec;
clear csptic;
clear Markov1;
%% Creating single set of statistically determined parameters in region
%% region for all measurement segments
if(flagL2==1)
    sizL2 = size(t_L2);
    curcountL2 = sizL2(2);
    FL2((lastcountL2+1):(lastcountL2+curcountL2),:) = FSigL2;
    for mp=1:sizL2(1)
        TapL2(mp,(lastcountL2+1):(lastcountL2+curcountL2)) = t_L2(mp,:);
        PerSis_L2(mp,(lastcountL2+1):(lastcountL2+curcountL2)) = c_marL2(mp,:);
        NLOSSAngle1(mp,(lastcountL2+1):(lastcountL2+curcountL2)) =
        LOS2Angle1(mp,:);
    end
    LOS2RMS(1,(lastcountL2+1):(lastcountL2+curcountL2)) = L2RMS;
    LOS2MED(1,(lastcountL2+1):(lastcountL2+curcountL2)) = L2MED;
    LOS2DW90(1,(lastcountL2+1):(lastcountL2+curcountL2)) = L2DW90;
    lengthNLOSS(toti) = length(L2RMS);
    lastcountL2 = length(TapL2(1,:));
end

FinalTapL2 = TapL2.*PerSis_L2;

for jw= 1:sizL2
    SortTapNLOSS(jw,:) = sort(FinalTapL2(jw,:));
end

for jj=1:nTapL2
    flag = 0;
    for jk = 1:length(SortTapNLOSS(1,:))
        if((flag == 0) && (SortTapNLOSS(jj,jk) ~= 0))
            ampThreshL2(jj) = jk;
            flag = 1;
        end
    end
end

for jj = 1:nTapL2
    TempStat = SortTapNLOSS(jj,ampThreshL2(jj)+1:end);
    parameter = wblfit(TempStat);
    Weibull_L_B(jj) = parameter(2);
    clear TempStat;
    clear parameter;
end
%% Finding the FCE using the formula from paper by Bultitude

RefSendL2=FL2(:,ss1/2+1);

for ii=1:ss1
    FreqSendL2=FL2(:,ii);
    FrCoEsNLOSS(ii) = FCE(RefSendL2,FreqSendL2);
end

%% Determining Worse Case Correlation matrix for region
for jj=1:nTapL2
    for jk = 1:nTapL2
        ct = 0;
        if(jj~=jk)
            for kj = 1:length(f)
                if(NumProCorr3DL2(kj,jj,jk)>= 5)
                    ct= ct+1;
                    cova(ct) = CrossCorr3DL2 (kj,jj,jk);
                    prva(ct)= kj;
                end
            end
            CrosscorrelationMatrixL2(jj,jk) = max(cova);
            posi = find(cova == max(cova));
            NumProMaxCorrL2(jj,jk) = NumProCorr3DL2(prva(posi),jj,jk);
        else
            CrosscorrelationMatrixL2(jj,jk) = 1;
            NumProMaxCorrL2(jj,jk) = 1;
        end
        clear cova;
        clear posi;
        clear prva;
    end
end

%% Determining "Maximum Confidence" Correlation matrix for region
for jj=1:nTapL2
    for jk = 1:nTapL2
        ct = 0;
        if(jj~=jk)
            for kj = 1:length(f)
                if(NumProCorr3DL2(kj,jj,jk)>= 5)
                    ct= ct+1;
                    cova(ct) = NumProCorr3DL2(kj,jj,jk);
                end
            end
        else
            clear cova;
        end
    end
end
    prva(et) = kj;
    end
end
posi = find(cova == max(cova));
NumProMaxConfL2(jj,jk) = max(cova);
MaxConfCrosscorrelationMatrixL2(jj,jk) = CrossCorr3DL2(prva(posi(1)),jj,jk);
else
    MaxConfCrosscorrelationMatrixL2(jj,jk) = 1;
    NumProMaxConfL2(jj,jk) = 1;
end
clear cova;
clear posi;
clear prva;
end
end

AbsSumCorrSegL2 = zeros(1,length(f));
AbsSumProSegL2 = zeros(1,length(f));
maxNumProL2 = max(max(max(NumProCorr3DL2))); for kl = 1:length(f)
    sumCo = 0;
    sumPr = 0;
    for jj= 1:nTapL2
        for jk = 1:nTapL2
            if(jj ~= jk)
                sumCo = sumCo + abs(CrossCorr3DL2(kl,jj,jk));
                sumPr = sumPr + (NumProCorr3DL2(kl,jj,jk))/maxNumProL2;
            end
        end
    end
    AbsSumCorrSegL2 (kl) = sumCo;
    AbsSumProSegL2 (kl) = sumPr;
end

figure(1)
plot(ff,abs(FrCoEsNLOSS),'--or','Linewidth',2);
title('Frequency Correlation Estimate');
xlabel('Frequency in MHz');
ylabel('Correlation Coefficient');
grid on;
% ----------- These programs were developed by Indranil Sen [23], and modified for this thesis. This code compute tap energies and parameters for persistence processes for forest channel models in Vista Point Trail (VPT).

clc;
clear all;
close all;

UpDate= 1; %Option is 1 if IRE is full-span
USDR = 25 ; %User Selectable Dynamic Range (USDR) for Noise Thresholding
BW=input('Please enter the BW in MHz');
NAvg= 1; % Number of IRE's for Averaging to determine statistics of channel parameters
MT = 25;

MaxRMSL2=285
Dx= 10*(100/BW);
nTapL2=ceil ( MaxRMSL2/Dx) + 1;
Ns=(1/BW)/0.01;
Tinc=Ns*(10e-9);

corrcountNL1=0;
corrcountL2=0;
corrcountL1=0;
lastcountR=0;
precount = 0 ;
cntL1 = 1 ;
cntL2 = 1;
counterL2 = 0;
counterNL1 = 0;
cntNL1 = 1;
lastcountL2=zeros(1,nTapL2);
TotCountMultiL2 = zeros (1,nTapL2);
TotNumProL2 =zeros(1,1);

Sum11_L2 = zeros(1,nTapL2);
Sum10_L2 = zeros(1,nTapL2);
Sum01_L2 = zeros(1,nTapL2);
Sum00_L2 = zeros(1,nTapL2);
prevCountL2 = zeros(1,nTapL2);
RegCount = 0 ;

f = [1:2];
for toti=1:length(f)
    toti;
    f(toti)
    flagL2=0;flagNL1=0;
    str1=C:\MATLAB7\work\VT2July_2007\ForestSept26\ForestSept26_,';
    str2=strcat(str1,num2str(f(toti)),'.out');
    semp=csvread(str2,2,1);
    siz_temp=size(semp)
    numC=(siz_temp(2)-1)/2;

    for jj=1:siz_temp(1)
        RSSI(jj)=semp(jj,siz_temp(2));
        tempR_dBm_Rad=reshape (semp(jj,1:2*numC),2,numC);
        TempR_dBm(jj,:)=tempR_dBm_Rad(1,:);
        TempR_Rad(jj,:)=tempR_dBm_Rad(2,:);
    end

    %% Storing Phase values for each sample
    le= length(TempR_Rad(1,:));
    tempp = reshape (TempR_Rad,1,siz_temp(1)*le);
    AllAngle( precount+1 : precount+ (siz_temp(1)*le)) = tempp;
    precount = length (AllAngle);

    if(UpDate==1)
        PowerRecord(:,1:100)=TempR_dBm(:,1:100);
        PhaseRecord(:,1:100)=TempR_Rad(:,1:100);
    end

    if(UpDate==2)
        PowerRecord=TempR_dBm;
        PhaseRecord=TempR_Rad;
    end

    [PowerImpNoiThr,Angle,RssI]=RemImp1(PowerRecord,PhaseRecord,RSSI);
    [powerdBmN]=NoiseThresh1(PowerImpNoiThr,USDR);
    siz_temp1=size(powerdBmN);

    AmpN=sqrt(10.^(-3+powerdBmN./10));
    for jj=1:siz_temp1(1)
        Idata(jj,:)=AmpN(jj,:).*cos(Angle(jj,:));
        Qdata(jj,:)=AmpN(jj,:).*sin(Angle(jj,:));
    end

    [PowerdBMN1,Angle1]=AddSampVecAngleFinal(Idata,Qdata,Ns);
%% Generate the delay vector for the PDP
siz_temp2=size(PowerdBMN1);
time=1:siz_temp2(2);
Del=(Tinc.*time);
DelX=(Tinc.*time)/(10^-6);

UpRate=floor((11e-3+2*siz_temp2(2)*0.4e-3)^-1);

for lj=1:siz_temp2(1)
    PowerdBMN2(lj,:)=PowerdBMN1(lj,:)-max(PowerdBMN1(lj,:));
    for lk = 1:siz_temp2(2)
        if ( abs(PowerdBMN2(lj,lk))<= 25)
            PowerdBMN(lj,lk)= PowerdBMN1(lj,lk);
        else
            PowerdBMN(lj,lk)=-125;
        end
    end
end

%% Adjusting the PDPs to remove the absolute delay from each PDP.
ld=length(PowerdBMN(:,1)); % Number of PDPs in time
tplot=PowerdBMN(1:ld,:);
clear PowerdBMN;
for jj=1:ld
    [MaxT IndT]=max(tplot(jj,:));
    flag=0;
    I=1;
    for kk= IndT:-1:1
        if ((tplot(jj,kk)< (MaxT-25))&(flag==0))
        I=kk;
        flag=1;
        end
    end
    PowerdBMN(jj,:)=tplot(jj,I:end) tplot(jj,1:I-1);
end

%% Calculating the RMS-DS and Delay Window for 90% energy
[RMSDelSpr,MED]=(Stat_RMS_DS(PowerdBMN,Del,siz_temp2(1)));
RMSDelSpr = RMSDelSpr./(10^-9);

for rf = 1:siz_temp2(1)
    counterL2 = counterL2 +1;

promax = max(PowerdBMN(rf,:));
tromax = PowerdBMN(rf,:) - max(PowerdBMN(rf,:));
NumTapProL2(counterL2) = length(find(tromax>= -25));
clear tromax;
clear promax;
end

[PowerdBMN_NP,FinalAngle1] = NormPeakAngle(PowerdBMN,Angle1);
siz_temp3 = size(PowerdBMN_NP);
for lj=1:siz_temp3(1)
    MarAmp(lj,:) = PowerdBMN_NP(lj,:)-max(PowerdBMN_NP(lj,:));
    for lk = 1:siz_temp3(2)
        if (abs(MarAmp(lj,lk))<= 25)
            Markov1(lj,lk) = 1;
        else
            Markov1(lj,lk) = 0;
        end
    end
end
CountL2 = 0;
CountNL1 = 0;
for mm = 1:length(RMSDelSpr)
    CountL2 = CountL2 +1;
    RegCount = RegCount +1;
    RegStatus(RegCount) = 2;
    for ii = 1:nTapL2
        c_marL2(ii, CountL2 + prevCountL2) = Markov1(mm,ii);
    end
end
prevCountL2 = prevCountL2 + CountL2;

%% Determining PathLoss in dB for each PDP
AntGain=2*1.36;
CableTx= 2.4; %%% ReSh : Cable Loss for short red cable
CableRx= 4.2; %%% BlLo : Cable Loss of black long cable
CableLoss = (AntGain)-(CableTx)-(CableRx);
ActualPLdB= 33 - RssI + CableLoss;
coNL1=0;
coL1=0;
coL2=0;
CountMultiL2=zeros(1,nTapL2);

PowerN_NP_L2eq = zeros(nTapL2,siz_temp3(1));

for jj=1:siz_temp3(1)
    PowerdBMN_NPmax(jj,:)=PowerdBMN_NP(jj,:)-max(PowerdBMN_NP(jj,:));
    TempdB(jj,:) = PowerdBMN_NP(jj,:) - 30 + ActualPLdB(jj);
    PowerN_NP(jj,:)=10.^(TempdB(jj,:)./10);
    PowerN_NPeq(jj,:)=PowerN_NP(jj,:)./sum(PowerN_NP(jj,:));

    for ii=1:nTapL2
        if (abs(PowerdBMN_NPmax(jj,ii))<= MT)
            PowerN_NP_L2eq(ii,jj)= PowerN_NPeq(jj,ii);
            CountMultiL2(ii)=CountMultiL2(ii)+1;
        end
    end
end

mean(RMSDelSpr);
for mn=1:n TapL2
    TotCountMultiL2(mn)=TotCountMultiL2(mn) + CountMultiL2(mn);
    rt=siz_temp3(1);
    PowerL2(mn,((lastcountL2(mn)+1):(lastcountL2(mn)+rt)))= PowerN_NP_L2eq(mn,:);
    lastcountL2(mn) = length (PowerL2(mn,:));
end
TotNumProL2=TotCountMultiL2(1);
totMarL2 = length(c_marL2(1,:));
for ii = 1: nTapL2
    ProbSte1_L2(ii) = sum(c_marL2(ii,:))/length(c_marL2(ii,:));
    ProbSte0_L2(ii) = 1- ProbSte1_L2(ii);

    for jj = 1:totMarL2
        if(jj==1)
            if((c_marL2(ii,jj-1)==1) &&(c_marL2(ii,jj)==0))
                Sum10_L2(ii) = Sum10_L2(ii) + 1;
            end
            if((c_marL2(ii,jj-1)==1) &&(c_marL2(ii,jj)==1))
                Sum11_L2(ii) = Sum11_L2(ii) + 1;
            end
            if((c_marL2(ii,jj-1)==0) &&(c_marL2(ii,jj)==0))
                Sum00_L2(ii) = Sum00_L2(ii) + 1;
            end
            if((c_marL2(ii,jj-1)==0) &&(c_marL2(ii,jj)==1))
                Sum10_L2(ii) = Sum10_L2(ii) + 1;
            end
            if((c_marL2(ii,jj-1)==1) &&(c_marL2(ii,jj)==0))
                Sum00_L2(ii) = Sum00_L2(ii) + 1;
            end
            if((c_marL2(ii,jj-1)==0) &&(c_marL2(ii,jj)==1))
                Sum11_L2(ii) = Sum11_L2(ii) + 1;
            end
        end
    end
end
Sum01_L2(ii) = Sum01_L2(ii) + 1;
end
end
end

ProbTran10_L2 = Sum10_L2./(Sum10_L2+Sum11_L2);
ProbTran11_L2 = Sum11_L2./(Sum11_L2+Sum10_L2);
ProbTran01_L2 = Sum01_L2./(Sum01_L2+Sum00_L2);
ProbTran00_L2 = Sum00_L2./(Sum01_L2+Sum00_L2);
for mn=1:nTapL2
    PowerTapAvgL2(mn)= (sum(PowerL2(mn,:))/TotNumProL2);
    ProbL2(mn)=TotCountMultiL2(mn)/TotNumProL2;
end
CF1_L2 = ProbL2.*PowerTapAvgL2;
CF_L2=CF1_L2./sum(CF1_L2);
CF_L2dB = 10*log10(CF_L2./max(CF_L2));
PowerInTapL2 = PowerTapAvgL2./sum(PowerTapAvgL2);
PowerInTapL2dB = 10*log10( PowerInTapL2./max(PowerInTapL2));
TapL2= 1:1:nTapL2;
for jj=1:length(CF_L2)
    if(jj==1)
        TotE_L2(jj)= TotE_L2(jj-1) + CF_L2(jj);
    else
        TotE_L2(jj)= CF_L2(jj);
    end
end

for ii=1:nTapL2
    MarkovMatrixL2 (ii,1) = ProbSte0_L2(ii);
    MarkovMatrixL2 (ii,2) = ProbSte1_L2(ii);
    MarkovMatrixL2 (ii,3) = ProbTran00_L2(ii);
    MarkovMatrixL2 (ii,4) = ProbTran01_L2(ii);
    MarkovMatrixL2 (ii,5) = ProbTran10_L2(ii);
    MarkovMatrixL2 (ii,6) = ProbTran11_L2(ii);
end
sumL2 = 0;
for jj=1:4
    sumL2 = sumL2 + PowerInTapL2(jj).* MarkovMatrixL2(jj,2);
end
for jj=1:4
    AverageTapEnergyL2(jj) = PowerInTapL2(jj).* MarkovMatrixL2(jj,2)./sumL2;
end
figure(1)
plot(TapL2,CF_L2dB,'-.dg','Linewidth',2);
xlabel('Tap-Index');
ylabel('Power');
title('Cumulative energy as a function of Taps ');
grid on;
%
figure(2)
plot(TapL2,ProbL2,'-.dg','Linewidth',2);
xlabel('Tap-Index');
ylabel('Probability of having tap');
title('Probability for existence of tap ');
grid on;