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RADIO CHANNEL MODELING FOR MOBILE AD HOC WIRELESS NETWORKS

by

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June 2004

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The radio channel places fundamental limitations on the performance of mobile ad hoc wireless networks. In the mobile radio environment, fading due to multipath delay spread impairs received signals. The purpose of this thesis is to develop a radio channel model and examine the effect of various parameters on channel behavior that is representative of environments in which mobile ad hoc wireless networks operate. The various physical phenomena considered are outdoor environments, fading and multipath propagation, type of terrains, and mobility (Doppler shift). A channel model based on a Tapped Delay Line (TDL) structure was developed and implemented in the MATLAB programming language, and the performance of the time-varying channel was studied by plotting the signal constellations. The simulation results indicate that the number of taps required in the TDL is 8 or less and the carrier frequency did not influence the performance significantly. The Jakes Doppler spectrum should be used in urban environments with high mobility; the Gaussian Doppler spectrum is the choice for low mobility urban environments and for the hilly terrain under both low and high mobility.

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RADIO CHANNEL MODELING
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Submitted in partial fulfillment of the
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ABSTRACT

The radio channel places fundamental limitations on the performance of mobile ad hoc wireless networks. In the mobile radio environment, fading due to multipath delay spread impairs received signals. The purpose of this thesis is to develop a radio channel model and examine the effect of various parameters on channel behavior that is representative of environments in which mobile ad hoc wireless networks operate. The various physical phenomena considered are outdoor environments, fading and multipath propagation, type of terrains, and mobility (Doppler shift). A channel model based on a Tapped Delay Line (TDL) structure was developed and implemented in the MATLAB programming language, and the performance of the time-varying channel was studied by plotting the signal constellations. The simulation results indicate that the number of taps required in the TDL is 8 or less and the carrier frequency did not influence the performance significantly. The Jakes Doppler spectrum should be used in urban environments with high mobility; the Gaussian Doppler spectrum is the choice for low mobility urban environments and for the hilly terrain under both low and high mobility.

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EXECUTIVE SUMMARY

The next generation of wireless systems is moving towards ad hoc operations. With wireless ad hoc networks, seamless communications infrastructure could be deployed quickly on the battlefield to increase combat effectiveness and mobility of the force. Military planners value mobile ad hoc wireless networking because they are flexible and can be quickly deployed. It is also often desirable to make the communications network operable while the command vehicle is on the move. This research was thus carried out from the perspective of an outdoor mobile radio communications environment for military operations.

However, the mobile radio channel places fundamental limitations on the performance of mobile ad hoc wireless networks. In the mobile radio environment, fading due to multipath delay spread impairs received signals. Movement of the receiver causes the multipath components as well as their phase and propagation delays to vary with time, and the speed of motion impacts how rapidly the signal level fades.

The focus of channel characterization in this thesis is studied based on the following physical phenomena: multipath propagation, type of terrains, and Doppler shift due to motion of the mobile. The purpose is to develop a radio channel model and examine the effect of various parameters on the channel behavior that is representative of environments in which mobile ad hoc wireless networks operate.

A channel model based on a Tapped Delay Line (TDL) structure was developed and implemented in the MATLAB programming language to determine the signal performance under varying channel conditions. It has been demonstrated that the number of tap gains of the TDL channel model should generally be small since higher-order tap gain values are not significant.

There are several combinations of the parameter variations that were examined. The simulation results included plots of the Doppler power spectrum, delay profile, TDL gain coefficients and the signal constellations. The simulation results indicated that the flat Doppler spectrum is not suitable for both the urban environments and the hilly terrain

and suffers the most distortion. The Jakes spectrum is found to be suitable for the high mobility urban areas, and the Gaussian spectrum is appropriate for the low mobility urban areas and the hilly terrain.

I. INTRODUCTION

Military planners value mobile ad hoc wireless networking because they are flexible and can be quickly deployed [1]. Figure 1 shows a mobile ad hoc network. While in principle, the communications among the nodes is on a peer to peer basis, one of the nodes may be elected to become a gateway for coordination of external connectivity. In general, in a mobile ad hoc network, there are no fixed *points of failure* like base stations that can be disabled by a strike. Ad hoc networks self-organize by adjusting themselves as users join, leave, or move.

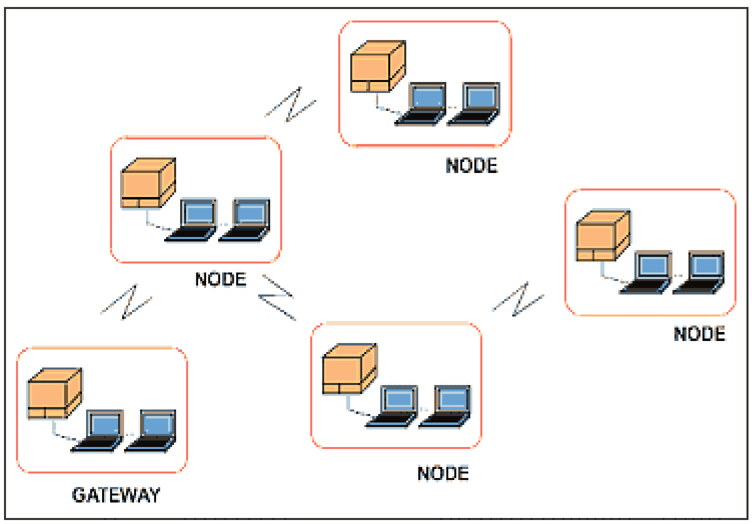

Figure 1. Mobile ad hoc networks are internetworks formed by mobile wireless nodes (From Ref. [1].).

Ad hoc networking enables its users to roam about freely, but its radio channel presents a hostile environment to a transmitted signal as compared to transmission on a fixed wireless link. As radio waves propagate through space, multiple corruptions due to morphology, temperature and humidity of the environment through which they are traveling can occur. As a consequence, mobile radio transmissions usually suffer large fluctuations in both time and space.

A major limitation on the performance of a mobile communications system is the attenuation undergone by the signal as it travels from the transmitter to the receiver. The path (from the transmitter to the receiver) taken by the signal can follow the Line-of-

Sight (LOS) in which the signal loss may not be severe. In typical operational surroundings, indirect paths also exist and the signal reaches the receiver through the processes of reflection, diffraction, refraction, and scattering from buildings, structures, and other obstructions in the path. These are examples of Non-Line-of-Sight (NLOS) propagation.

A. OBJECTIVE AND TECHNICAL APPROACH

The objective of this research was to develop a radio channel model and examine the effects of various parameters on the channel behavior that is representative of the environments in which mobile ad hoc wireless networks operate. The various physical phenomena and parameters considered in this modeling are outdoor environments, fading and multipath propagation, type of terrains, mobility (Doppler shift) and effects of the weather.

In order to meet the objective of the thesis, a channel model based on a Tapped Delay Line (TDL) structure was developed and implemented in the MATLAB programming language, and results of the simulation are presented.

B. THESIS OUTLINE

The thesis is organized as follows. Chapter II describes the various physical phenomena and parameters of wireless channels that contribute to the underlying structure of the channel model. It also provides a description of the Additive White Gaussian Noise (AWGN) channel. Chapter III covers two types of multipath fading channel model, diffuse and discrete. The second part of this chapter deals with the TDL model for random time-varying channels. Chapter IV describes the simulation methodology and presents the results of the simulation. Chapter V summarizes this thesis research and offers several suggestions for future research. Finally, the appendix contains the MATLAB code.

II. WIRELESS CHANNEL CHARACTERISTICS

Reliable operation of a wireless communications system is dependent upon the propagation channel over which the system operates as the channel is the primary contributor to many of the problems and limitations that plague wireless communications systems [2]. This has prompted a need for a deeper understanding of the wireless channel characteristics. Such an understanding will lead to developing viable solutions to such problems as dropped or lost packets, interference, and coverage. This chapter discusses the main characteristics of wireless channels that form the underlying structure of the channel model developed in the thesis.

A. OPERATING ENVIRONMENT

The operating environment of wireless communications usually encompasses indoor or outdoor forms where a radio transmitter or receiver is capable of moving (regardless of whether it actually moves or not).

1. Types of Terrain

Propagation characteristics differ with the environment through and over which the radio waves travel. In general, several types of environment can be identified and classified according to the following parameters [2]:

- Antenna heights and transmission frequency (or wavelength);
- Vegetation density;
- Diffraction loss due to mountains;
- Buildings, density and heights; and
- Open areas, road shape, lakes, water surfaces.

Depending on the type of environment, the signal will be reflected or absorbed by the obstacles it encounters. The above-mentioned parameters are important considerations in a military operating environment, e.g., a command vehicle carrying mobile command posts moving through an area where the radio wave could be reflected by any kind of obstacle, such as a mountain or building.

2. Typical Propagation Environments

In 1984, the European working group, European Cooperation in the Field of Scientific and Technical Research (COST 207) [3] was established by the Conference of

European Posts and Telecommunications Administrations (CEPT). At that time, this working group developed suitable channel models for typical propagation environments. Numerous measurements have been made under various conditions. The typical propagation environments of COST 207 are classifiable into areas with rural character, areas typical of cities and suburbs, densely built urban areas with bad propagation conditions and hilly terrains.

Two models that are widely used in system performance evaluation [4] are urban areas and hilly terrain. In urban areas, typical values of multipath spread range from 1 to 10 μs and governed by the following equation:

$$P_m(\tau) = \begin{cases} \exp(-\tau) & \text{for } 0 < \tau < 7\ \mu\text{s} \\ 0 & \text{elsewhere} \end{cases} \tag{1}$$

where $P_m(\tau)$ is the received power as a function of the delay τ.

In rural mountainous areas, the multipath spreads are much greater, with typical values in the range of 10 to 30 μs as given by

$$P_m(\tau) = \begin{cases} \exp(-3.5\tau) & \text{for } 0 < \tau < 2\ \mu\text{s} \\ 0.1\exp(15-\tau) & \text{for } 15 < \tau < 20\ \mu\text{s} \\ 0 & \text{elsewhere.} \end{cases} \tag{2}$$

B. MULTIPATH PROPAGATION

For most practical channels, where signal propagation takes place in the atmosphere and near the ground, the free-space propagation model is inadequate to describe the channel [5]. In a wireless mobile communications system, a signal can travel from the transmitter to the receiver over multiple reflective paths; this phenomenon is known as multipath propagation. This effect can cause fluctuations in the received signal's amplitude, phase, and angle of arrival, known as multipath fading. Fading is caused by interference between two or more versions of the transmitted signal that arrive at the receiver at slightly different times [6].

An overview of the fading channel manifestations [5] is as shown in Figure 2. It shows that there are two main types of fading effects that characterize mobile communications, large-scale fading and small-scale fading. A mobile radio roaming over a large area must process signals that experience both types of fading, small-scale fading superimposed on large-scale fading.

Large-scale fading is represented in blocks 1, 2 and 3 in Figure 2. This phenomenon is affected by prominent terrain contours (e.g., hills, forests, clumps of buildings, etc.) between the transmitter and the receiver [5]. Small-scale fading refers to the rapid fluctuations in signal amplitude and phase that can be experienced as a result of small changes in the spatial separation between a receiver and a transmitter and is represented in blocks 4, 5, and 6. Small-scale fading manifests itself in two mechanisms, namely, time-spreading of the signal and time-variation of the channel. For mobile radio applications, the channel is time-varying because motion between the transmitter and the receiver results in propagation path changes.

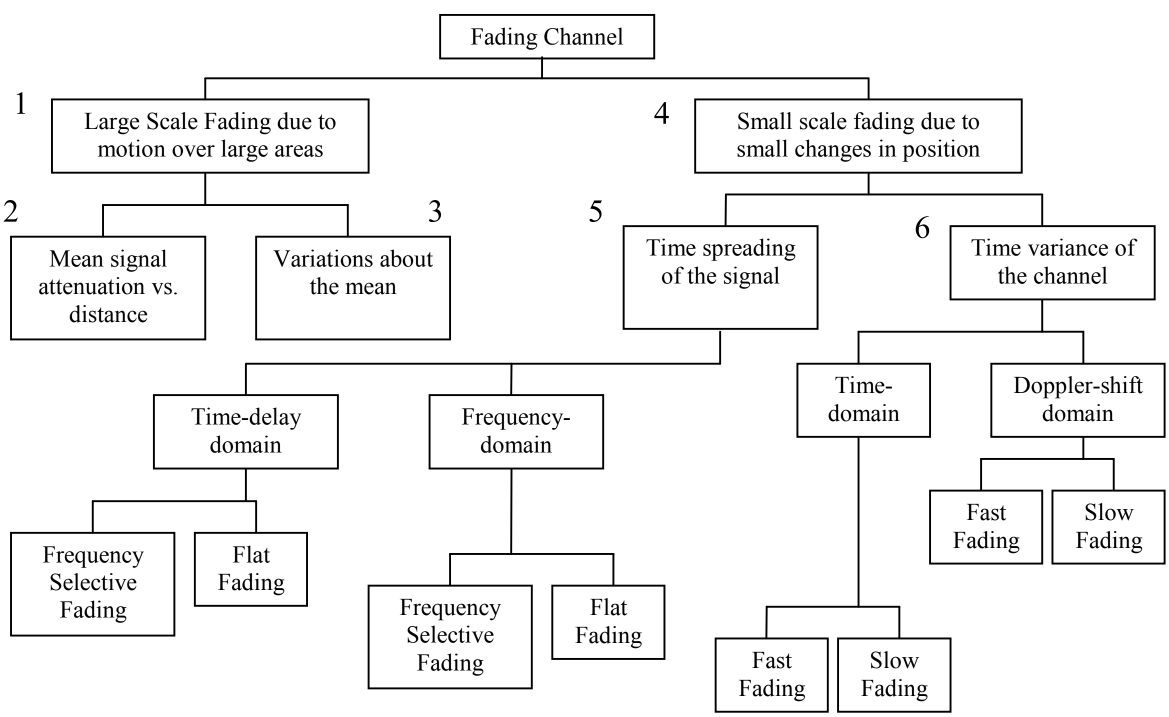

Figure 2. Fading channel manifestations (After Ref. [5].).

1. Small-Scale Multipath Propagation

Multipath in the radio channels creates small-scale fading effects. The three most important effects are:

- Rapid changes in signal strength over a small travel distance or time interval;
- Random frequency modulation due to Doppler shifts on different multipath signals; and
- Time dispersion caused by multipath propagation delays.

In built-up urban areas, fading occurs because the height of the mobile antennas is well below the height of the surrounding structures, so there may not be a single LOS path to the transmitter. Even when a LOS exists, multipath still occurs due to the reflections from the ground and the surrounding structures. Multiple reflections thus produce many paths between the transmitter and the receiver as illustrated in Figure 3.

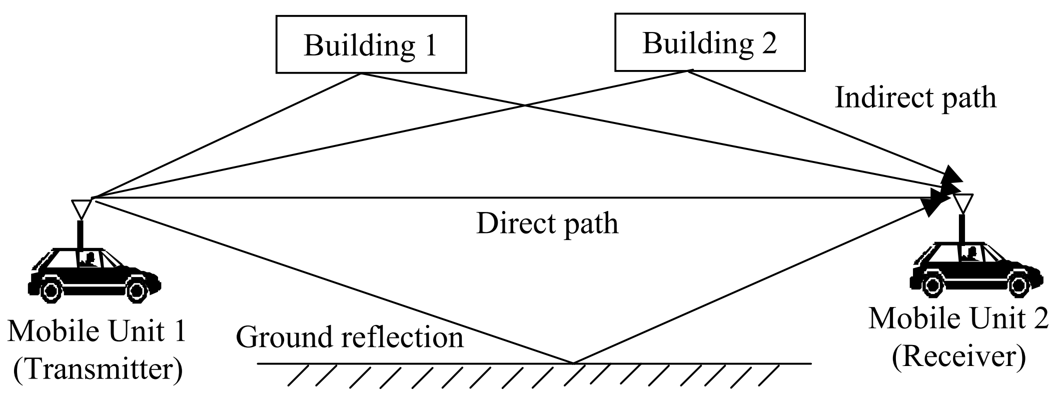

Figure 3. The multipath concept.

The main advantage of the multipath propagation is that it enables communications even when the transmitter and the receiver are not in the LOS conditions. Multipath propagation allows radio waves to effectively overcome obstacles (e.g., mountains, buildings, tunnels, underground parking lots, etc.) by getting around them and help ensure more or less continuous radio coverage. However, multipath propagation also causes many signal impairments. The three main ones are delay-spread, interference between paths coming from the transmitter, which create fast fluctuations of the signal (Rayleigh fading), and random frequency modulation due to Doppler shift on the different paths.

2. Propagation Mechanisms

The mechanisms that govern radio propagation can generally be attributed to three basic propagation methods: (1) reflection, (2) diffraction, and (3) scattering [7]. As a result of these three propagation mechanisms, the received signal strength can be roughly characterized by three nearly independent phenomena of large-scale path loss, large-scale shadowing, and multipath fading. Small-scale fading and multipath propagation may also be described by the physics of these three basic propagation mechanisms. Links in urban environments are subjected to severe degradation due to the combination of these three propagation effects.

a. Reflection

A radio signal radiates in all directions and, depending on the nature of the environment, will be reflected or absorbed by the obstacles it encounters. Reflection occurs when a propagating electromagnetic wave impinges upon an object whose dimensions are large compared to the wavelength of the propagating wave [8]. The radio wave could be reflected by any kind of obstacle, such as mountains, buildings, vehicles, aircraft, or even a discontinuity in the atmosphere (e.g., ducting). Reflection may occur at the wall of a building as shown in Figure 4. Typically, more reflections occur in an urban environment than in a rural area because the number of reflectors is higher in a dense urban locality.

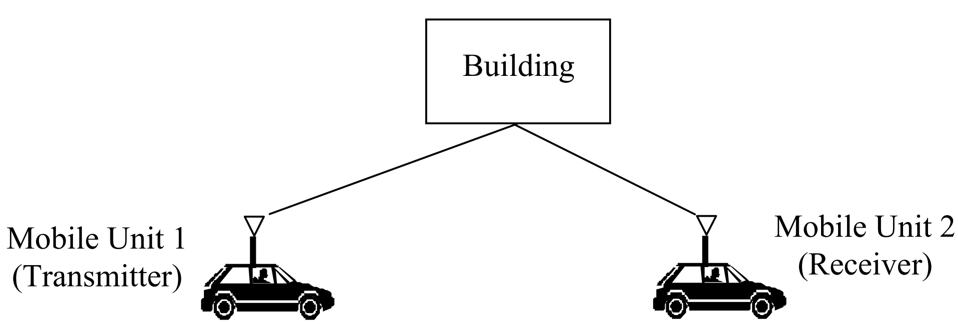

Figure 4. Reflection of the electromagnetic wave.

b. Diffraction

Diffraction occurs when the radio path between the transmitter and the receiver is obstructed by a surface that has irregularities [8]. This gives rise to a bending of waves around the obstacle as shown in Figure 5, making it possible to receive the signal even when a LOS path does not exists between the transmitter and the receiver. At high frequencies, diffraction, like reflection, depends on the geometry of the object as well as the amplitude, phase, and polarization of the incident wave at the point of diffraction.

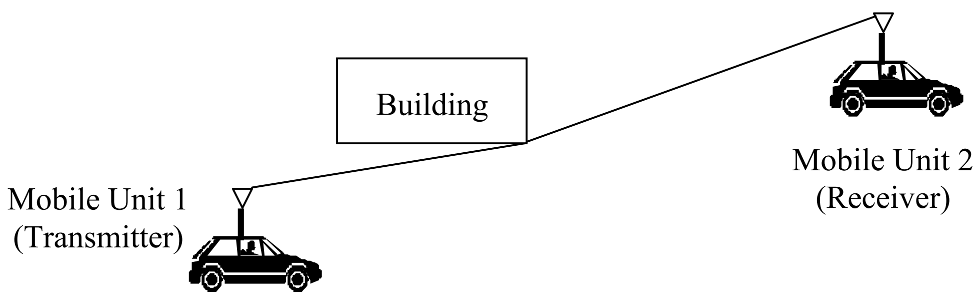

Figure 5. Diffraction of the electromagnetic wave.

c. Scattering

Scattering occurs when the medium through which the wave travels consists of a large number of objects whose dimensions are small compared to the wavelength [8]. Scattered waves are produced by rough surfaces, small objects, or by other irregularities in the channel. The wave is scattered in all directions as shown in Figure 6. In practice, foliage, street signs, and lamp posts induce scattering in a mobile communications system. Scattering local to the mobile unit is caused by buildings and other scatterers in the vicinity of the mobile unit (within a few tens of meters). Mobile motion and local scattering give rise to Doppler spread, which causes time-selective fading.

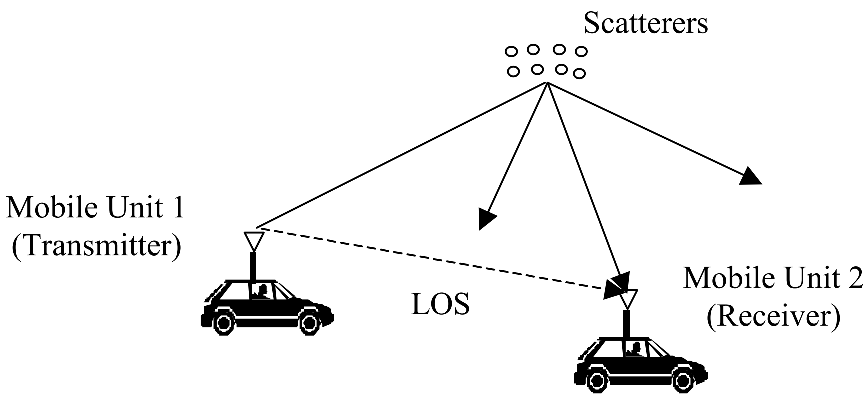

Figure 6. Scattering of the electromagnetic wave.

3. Delay Spread

The reflected paths are usually longer than the direct path, which means that these signals reach the receiver later than those from the direct path [2]. As a consequence, the signals from different paths can arrive at the receiver with different delays and at different times as shown in Figure 7. The delay spread is thus defined as the maximum time difference between the arrival of the first and last multipath signal seen by the receiver and is a function of the transmission environment.

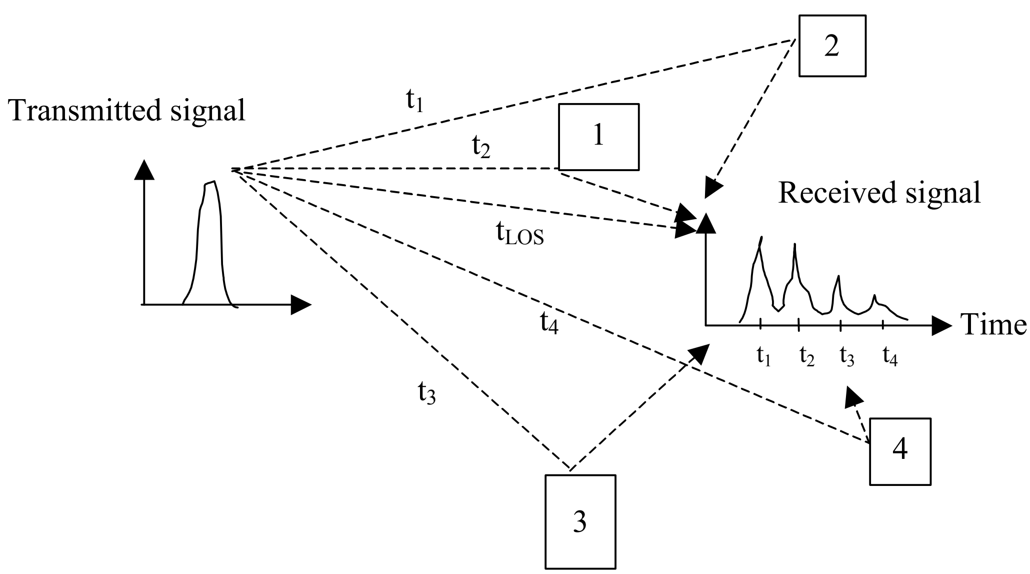

Figure 7. Illustration of multipath delay-spread.

In order to compare different multipath channels, parameters that quantify the multipath channel are used [6]. The mean excess delay and rms delay spread are the multipath channel parameters that can be determined from a power delay profile. The mean excess delay is the first moment of the power delay profile and is defined to be

$$\overline{\tau} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} \tag{3}$$

where a_k is the amplitude of the k^{th} signal, τ_k is the time of the k^{th} signal, and $P(\tau_k)$ is the absolute power level of the k^{th} signal. The rms delay spread is the square root of the second central moment of the power delay profile and is defined [6] to be

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2} \tag{4}$$

where

$$\overline{\tau^2} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)}. \tag{5}$$

The channel delay spread depends on physical factors, such as the direction, reflectivity and distance between the reflecting objects (e.g., buildings, mountains, walls, and vehicles). Typical values of the rms delay spread are on the order of microseconds in outdoor mobile radio channels and on the order of nanoseconds in indoor radio channels [6].

High delay values are due to the presence of significant multipath components and depend on the received signal-to-noise ratio. Low excess loss and low delay spread correspond to a less dispersive and less attenuated channel. High delay spread but low excess path loss corresponds to clear LOS receiver locations at larger distances. High delay spread and high excess loss correspond to the partially blocked nearby receiver locations surrounded by high-rise buildings.

4. Rayleigh and Ricean Fading

The signal at the receiver suffers magnitude and phase variations due to the multiple propagation paths that interfere either constructively or destructively [2]. If there is no single dominant signal contribution to the receiver, the signal will follow a Rayleigh distribution. If there is a dominant signal contribution to the receiver, such as a LOS signal, the signal will follow a Ricean distribution.

a. Rayleigh Distribution

Small-scale fading is also known as Rayleigh fading [2] when the multiple reflective paths are large in number and there is no LOS signal component. Figure 8 shows a simple illustration of multipath channel with NLOS signal. The signal from the transmitter reaches the receiver via other paths that could be a result of reflection, diffraction or scattering from an obstacle. There is no direct LOS path from the transmitter to the receiver. The envelope of the received signal is statistically described by a Rayleigh probability density function (pdf), given by

$$f_R(r) = \begin{cases} r/\sigma^2 \exp\left[-r^2/2\sigma^2\right] & \text{for } r \geq 0 \\ 0 & \text{for } r < 0 \end{cases} \tag{6}$$

where r is the envelope amplitude of the received signal and σ is the rms value of the received voltage signal before envelope detection.

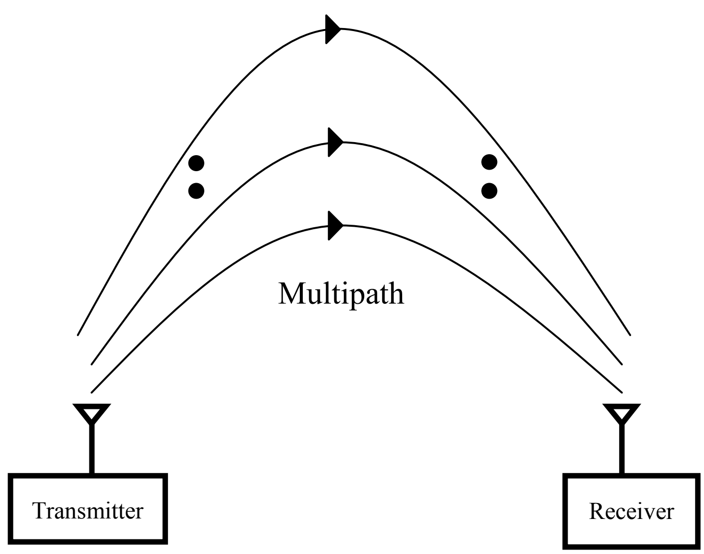

Figure 8. Simple illustration of multipath channel with NLOS signal.

b. Ricean Distribution

Rayleigh fading [8] is not the only consequence of the multipath phenomenon. In addition to a number of random paths taken by the signal, it is possible to have a LOS signal from the transmitter to the receiver as shown in Figure 9.

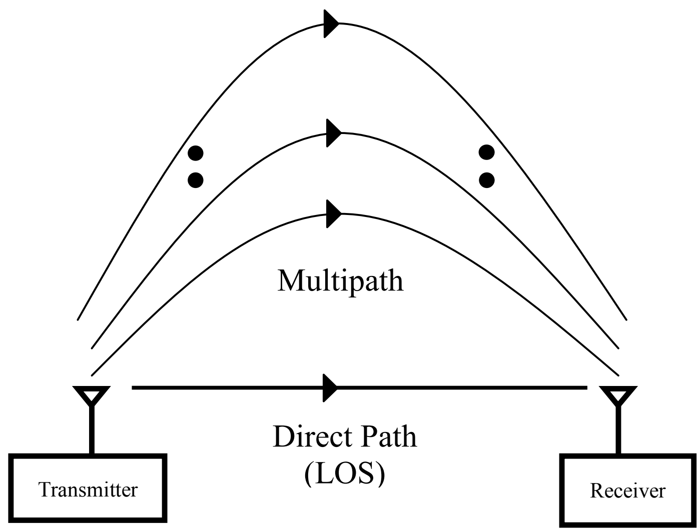

Figure 9. Simple illustration of multipath channel with LOS signal.

This LOS signal adds a deterministic component to the multipath signal and has a pdf given by

$$f_R(r)=\begin{cases} r/\sigma^2 \exp-(r^2+A^2)/2\sigma^2\, I_0\left(Ar/\sigma^2\right) & \text{for } A\geq 0, r\geq 0 \\ 0 & \text{for } r<0 \end{cases} \tag{7}$$

where A is the peak amplitude of the dominant signal and I_0 is the modified Bessel function of the first kind and zero-order.

The contribution of the random scatterers is referred to as the diffuse component and the contribution of the LOS component is referred to as the direct component [8]. Therefore, Ricean fading is the result of the presence of a direct component along with the diffuse components. The Ricean distribution is often characterized by the ratio of the power of the direct component to the power of the diffuse component in terms of the Ricean factor, K, given by

$$K\,(\text{dB})=10\log\left[A^2/2\sigma^2\right]. \tag{8}$$

When the peak amplitude A approaches zero, K becomes infinity, we have no direct path and the Ricean distribution becomes Rayleigh. The LOS component of the Ricean distribution provides a steady signal and serves to reduce the effects of fading.

C. MOBILITY

For mobile radio applications, the channel is time-varying because motion between the transmitter and receiver results in propagation path changes. The Doppler effect is a phenomenon caused by the relative velocity between the receiver and the transmitter [6]. When a wave source and a mobile are moving relative to one another, the motion leads to a frequency variation, f_d, of the received signal known as Doppler shift and can be written as

$$f_d = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = \frac{v}{\lambda}\cos\theta \tag{9}$$

where $\Delta\phi$ is the phase variation during time Δt, v is the mobile unit velocity, λ is the wavelength of the incident wave, and θ is the angle of incidence.

Equation (9) relates the Doppler shift to the mobile velocity and the spatial angle between the direction of motion of the mobile unit and the direction of the wave. If the mobile receiver is moving towards the direction of arrival of the wave, the Doppler shift is positive (i.e., the apparent received frequency is increased). However, if the mobile is moving away from the direction of arrival of the wave, the Doppler shift is negative (i.e., the apparent received frequency is decreased). Multipath components from a Continuous Wave (CW) signal that arrives from different directions contribute to the Doppler spreading of the received signal, thus increasing the signal bandwidth.

D. EFFECTS OF WEATHER

For most practical channels in which the signal propagates through the atmosphere, the free-space propagation channel assumption is usually not enough. The first effect that must be included is the atmosphere, which causes absorption, refraction and scattering. Signal attenuation through the atmosphere is mainly due to molecular absorption by oxygen for frequencies ranging between 60 and 118 GHz and due to water vapor in the 22, 183 and 325-GHz bands [2]. Rain has the most significant impact since the size of the rain drops is on the order of the wavelength of the transmitted signal. It results in energy absorption by the rain drops themselves, and as a secondary effect, energy is scattered by the drops.

The frequency selective absorption characteristics of the atmosphere can be approximated by a transfer function of the form [9]:

$$H(f)=H_0 \exp\left\{j0.02096 f\left[10^6+N(f)\right]l\right\} \tag{10}$$

where H_0 is a constant and $N(f)$ is the complex refractivity of the atmosphere in parts per million.

E. ADDITIVE WHITE GAUSSIAN NOISE

In addition to the impairments experienced by the signal as a result of the multipath propagation phenomena, a channel can also be affected by Additive White Gaussian Noise (AWGN). It can be considered one of the limiting factors in a communications system's performance. AWGN affects each transmitted symbol independently. The term "additive" means that the noise is superimposed or added to the signal and there are no multiplicative mechanisms involved.

The simplest practical model of a mobile radio channel is that of an AWGN channel [10]. The system can be represented by the block diagram shown in Figure 10. The path loss is indicated by a loss represented by *A*, and the noise is added to the signal to represent the received signal $y(t)$ as given by

$$y(t)=Au(t)+n(t) \tag{11}$$

where $n(t)$ is the noise waveform, $u(t)$ is the modulated signal and *A* is the overall path loss.

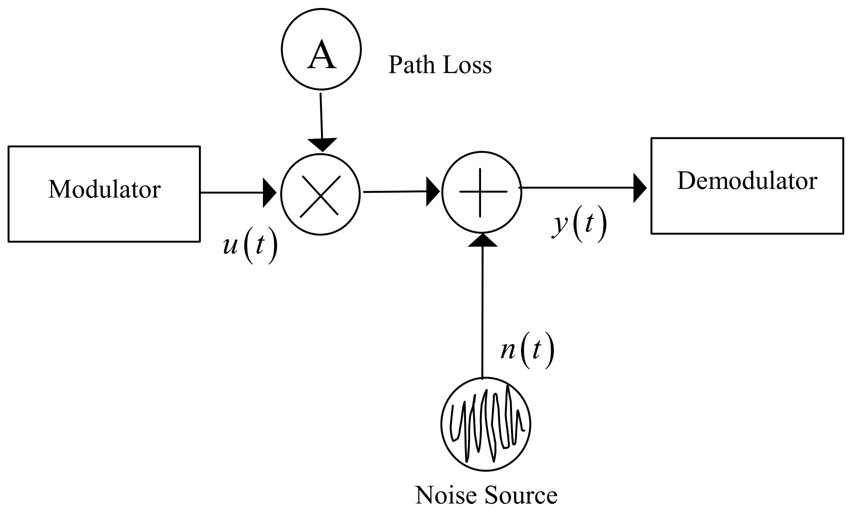

Figure 10. The AWGN channel.

In this chapter, we have discussed several important channel characteristics that form the basis for performance evaluation of using the wireless channel as a transmission medium in mobile radio communications system. Wireless channels in terrestrial communications are typically modeled as multipath channels because of signal propagation over multiple paths. The next chapter will discuss the channel models typically used in wireless channel simulations.

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III. CHANNEL MODELS

The generic architecture of a communications system [11] is illustrated in Figure 11. When an information source attempts to send information to a destination, the data are converted into a signal suitable for sending by the transmitter and are sent through the channel. The channel itself modifies the signal in ways, which may be more or less unpredictable to the receiver. The receiver must, therefore, be designed to overcome these modifications and be able to deliver the information to its final destination with as few errors or distortions as possible. This representation applies to all types of systems, whether wired or wireless.

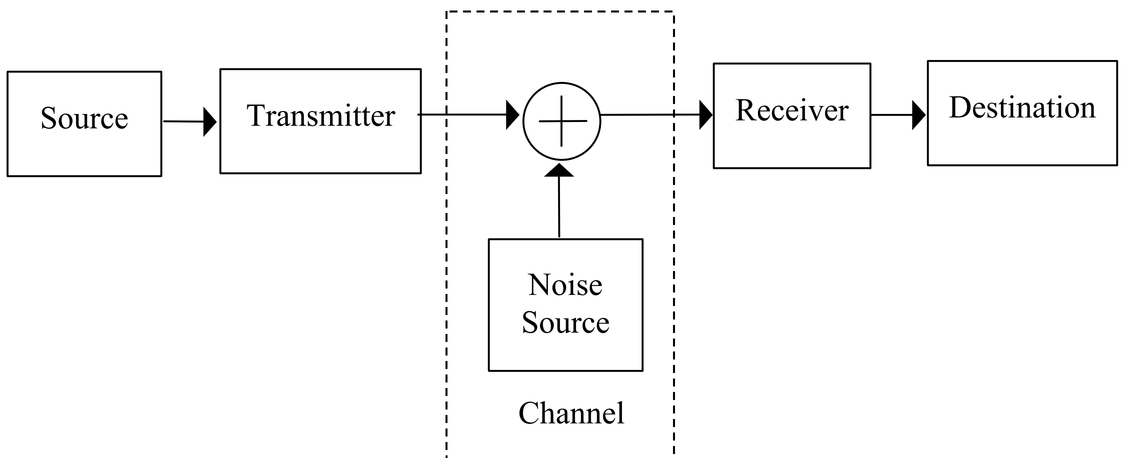

Figure 11. Architecture of a generic communications system.

In this chapter, we shall outline two channel models, the discrete and diffuse multipath channels, which describe the medium through which the signal has to travel in most existing and emerging wireless applications. The second part of the chapter covers the Tapped Delay Line (TDL) model for time-varying channels.

A. MULTIPATH FADING CHANNEL MODEL

A variety of models have been proposed for characterizing multipath channels, and almost all of them involve using random process models to characterize fading. The mobile wireless radio channel may be regarded as random, time-variant linear channel since changes in the environment due to movement of foliage, reflectors and scatterers, changes in atmosphere and changes due to mobility (i.e., relative movement of the transmitter and the receiver) can cause the received signal to change as a function of time.

There are two classes of channel models for describing multipath, the diffuse multipath channel and the discrete multipath channel. The multipath signals are made up of a relatively small and identifiable number of components reflected by small hills, houses, and other structures encountered in open areas and rural environments [12]. This results in a channel model with a finite number of multipath components. Such a channel is referred to as a discrete multipath channel and is applicable mostly to a rapidly changing environment.

In some mobile radio channels, it is more appropriate to view the received signal as a continuum of multipath components [12]. Such channels can be caused by scattering and reflections from very large terrain features, such as mountain ranges. This type of channel is referred to as diffuse multipath channel.

For both cases, the channel is modeled as a linear time-varying system with a complex lowpass impulse response, $\tilde{c}\left(\tau,t\right)$ [12]. If there are *N* discrete multipath components, the output of the channel consists of the sum of *N* delayed and attenuated versions of the transmitted signal as given by

$$\tilde{y}\left(t\right)=\sum_{k=1}^{N(t)}\tilde{h}_k\left(t\right)\tilde{s}\left(t-\tau_k\left(t\right)\right) \tag{12}$$

where $\tilde{h}_k\left(t\right)$ are the complex attenuation coefficients, $\tilde{s}\left(t\right)$ is the transmitted signal, $\tau_k\left(t\right)$ is the delay of the k^{th} multipath at time *t*, and $N\left(t\right)$ is the number of multipath components.

The impulse response of this representation can be represented by

$$\tilde{c}(\tau,t)=\sum_{k=1}^{N}\tilde{h}_k(t)\,\delta\big(\tau-\tau_k(t)\big). \tag{13}$$

Both diffuse and discrete multipath approaches have been used for the mobile radio channel, and a variety of models have been devised under various assumptions or operating environments [12]. Both types of models are topologically identical in that they consist of tapped delay lines whose gains are complex Gaussian random processes. The difference between these two approaches lies in the number of taps, the tap spacing, the average power, and the power spectral density (PSD) associated with each tap gain. In this thesis, we shall only consider the discrete multipath channel model.

B. TAPPED DELAY LINE (TDL) CHANNEL MODEL

Modeling mobile radio channels by using a TDL structure with time-varying coefficients [12], as shown in Figure 12, provides an insight into the channel distortions caused by scattering components with different propagation delays. The received signal is composed of an infinite number of delayed and weighted replicas of the transmitted signal. The notation of Figure 12 is as follows: $\tilde{s}(t)$ is the transmitted signal, $\tilde{h}_k(t)$ are the complex attenuation coefficients, τ_k is the delay of the k^{th} multipath at time *t*, and $\tilde{y}(t)$ is the output signal.

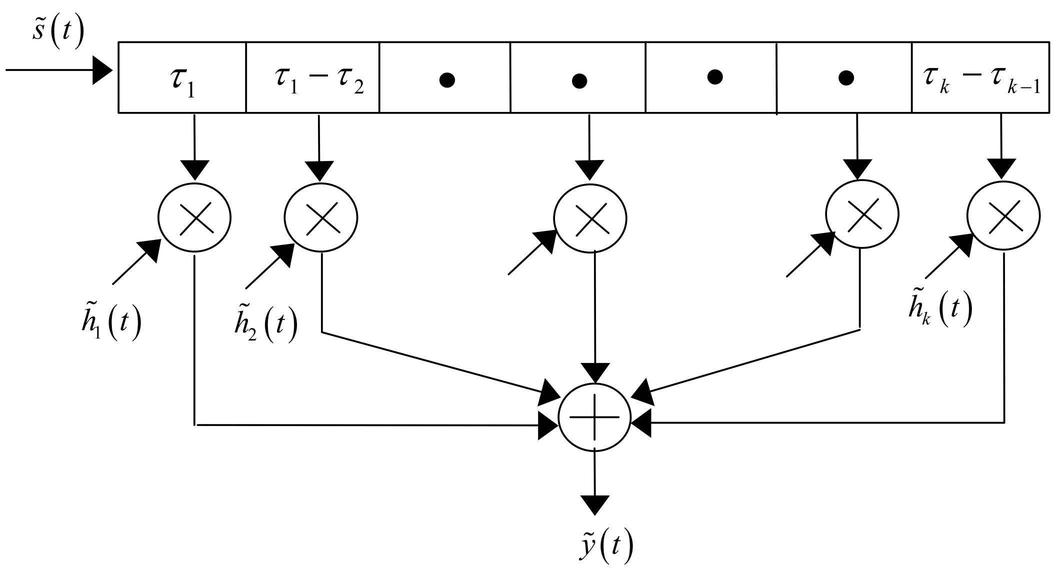

Figure 12. Variable-delay TDL model for discrete multipath channels.

1. Uniformly Spaced TDL Model

While the implementation of the variable-delay TDL model can be straightforward, it poses a problem when the delays differ by very small time offsets compared to the sampling time T_s or when the delays are not integer multiples of T_s [12]. As a consequence, the sample time must be very small, and this will lead to excessive sampling rates, resulting in an unacceptable computational burden.

The problem can be avoided by bandlimiting the channel to obtain better simulation properties, namely a uniformly spaced TDL as shown in Figure 13. The bandlimiting filter is an ideal rectangular filter with bandwidth equal to that of the signal. Applying the bandlimiting method, we obtain the tap gains of a uniformly spaced TDL given by

$$\tilde{h}_n(t) = \int_{-\infty}^{\infty} \tilde{c}(\tau, t)\operatorname{sinc}\big(B(\tau - nT)\big)\,d\tau \tag{14}$$

where B is the signal bandwidth.

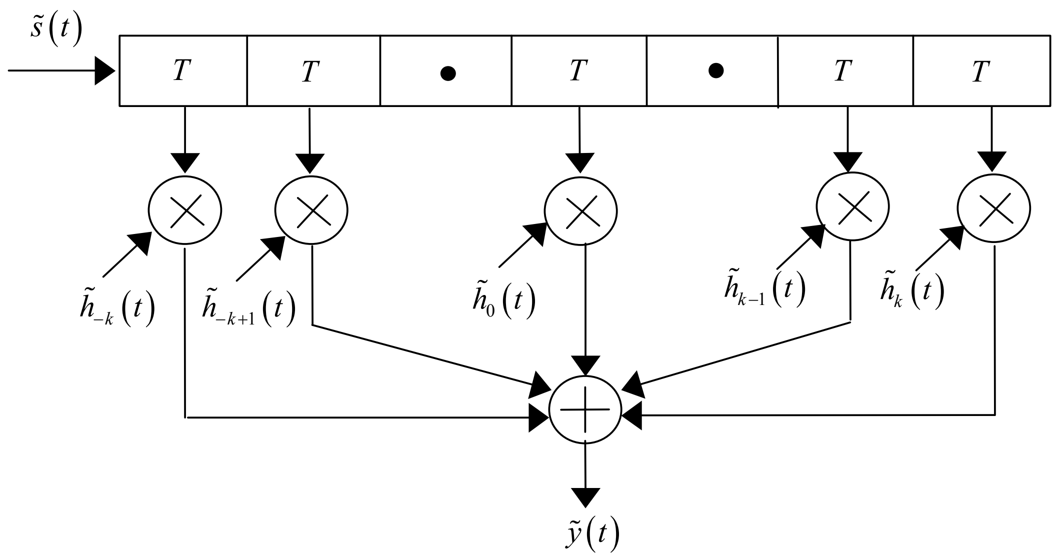

Figure 13. Uniformly spaced TDL model for discrete multipath channels.

Substituting the impulse response of the multipath channel given in Equation (13) into Equation (14), the tap gains can be represented as:

$$\tilde{h}_n(t) = \int_{-\infty}^{\infty} \sum_{k=1}^{N} \tilde{a}_k(t)\,\delta(\tau - \tau_k)\,\mathrm{sinc}\big(B(\tau - nT)\big)\,d\tau \tag{15}$$

and performing integration on Equation (15) yields the following equation:

$$\tilde{h}_n(t) = \sum_{k=1}^{N} \tilde{a}_k(t)\,\mathrm{sinc}(\tau_k - nT) = \sum_{k=1}^{N} \tilde{a}_k(t)\,\alpha(k,n) \tag{16}$$

where

$$\alpha(k,n) = \mathrm{sinc}\big((\tau_k/T) - n\big) \tag{17}$$

and T is the sampling period.

2. Generation of Tap-Gain Processes

The tap gain processes are stationary random processes with a given probability density function and power spectral density [12]. There are two main steps involved in the implementation of the discrete multipath model describe in the previous section. First, a set of white (discrete-time) Gaussian processes have to be generated since the simplest model for the tap gain processes assumes them to be uncorrelated, complex, zero-mean Gaussian processes. The tap gain processes can then be generated by filtering the Gaussian processes using a Doppler filter as shown in Figure 14. Therefore, the next step is to shape the power spectral density of these processes to that of the Doppler spectrum at each tap location.

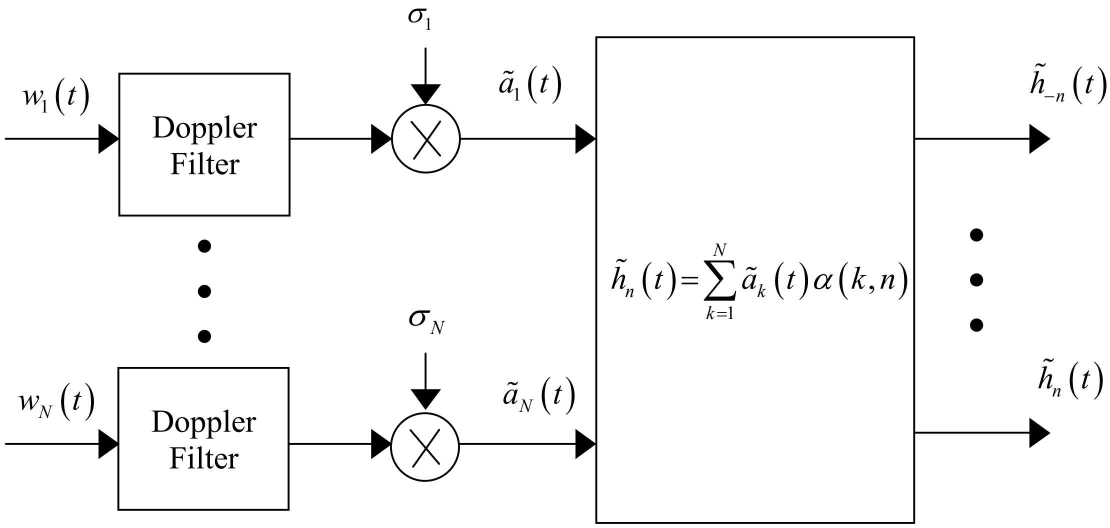

Figure 14. Generation of the tap gain processes.

3. Doppler Power Spectrum

The common Doppler spectral shape is an even function of frequency, meaning that only a real-valued filter is necessary to do the shaping [12]. Therefore, the shaping filter's amplitude transfer function can be expressed as

$$|H(f)| = \sqrt{S(f)} \tag{18}$$

where $S(f)$ is the Doppler power spectrum of the filter. Depending on the physical environment, three Doppler spectra can be specified: flat, Gaussian and Jakes.

a. Flat Spectrum

The flat spectrum has a rectangular shape as shown in Figure 15. In order to obtain the desired process bandwidth, proper scaling and bandlimiting is required [12]. The flat spectrum is described by

$$S_f(f)=\begin{cases}\sigma^2/f_d & -f_d<f<f_d\\ 0 & \text{otherwise}\end{cases} \tag{19}$$

where σ^2 is the total signal power and f_d is the maximum Doppler frequency. After substitution into Equation (18), the filter response is given by

$$H_f(f)=\begin{cases}\sigma\big/\sqrt{f_d} & -f_d<f<f_d\\ 0 & \text{otherwise.}\end{cases} \tag{20}$$

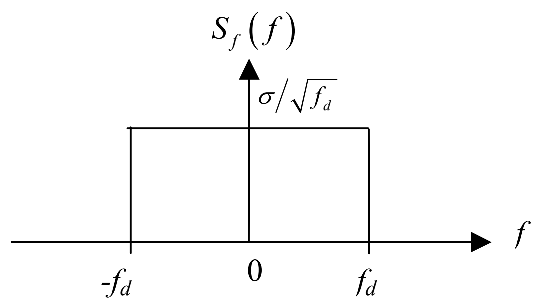

Figure 15. Flat power spectrum.

b. Gaussian Spectrum

The Gaussian spectrum is illustrated in Figure 16 and is mathematically described by [12]

$$S_G(f)=\left(2\sigma^2\Big/\sqrt{\pi(f_d)^2}\right)\exp\left\{-(f/f_d)^2\right\} \tag{21}$$

where σ^2 is the total signal power and f_d is the maximum Doppler frequency. The corresponding shaping filter response function is given by

$$H_G(f)=\left(\sqrt{2}\sigma\big/f_d\pi^{1/4}\right)\exp\left(-f/f_d\right). \tag{22}$$

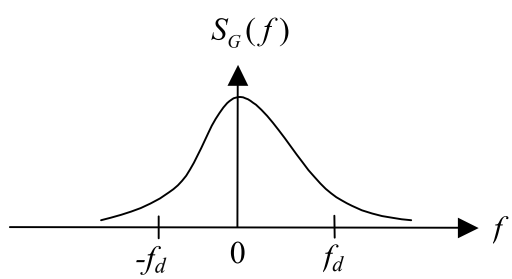

Figure 16. Gaussian power spectrum.

c. *Jakes Spectrum*

The classical Jakes Doppler spectrum was used by Jakes and others at Bell Laboratories to derive the first comprehensive mobile radio channel model for Doppler effects [13]. The Jakes spectrum that characterizes a mobile radio channel is described by

$$S_J(f) = \begin{cases} 1 \Big/ \pi f_d \sqrt{1-(f/f_d)^2} & |f| \le f_d \\ 0 & \text{otherwise.} \end{cases} \tag{23}$$

The shaping filter function is given by

$$H_J(f) = \left[S_J(f)\right]^{1/2} = \begin{cases} A^{1/2} \Big/ \left[1-(f/f_d)^2\right]^{1/4} & |f| \le f_d \\ 0 & \text{otherwise.} \end{cases} \tag{24}$$

A plot of the Jakes power spectrum is shown in Figure 17, which shows that most of the energy is concentrated around the maximum Doppler shift, f_d.

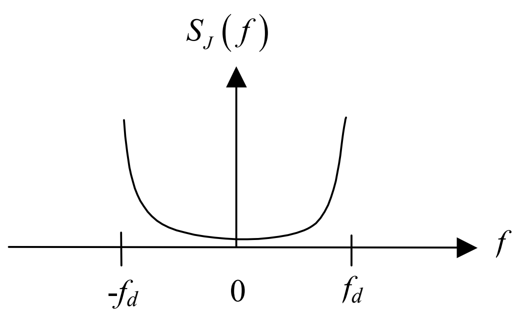

Figure 17. Jakes power spectrum.

In summary, mobile radio communications channels have two types of channel models to account for the multipath effect and the time-variations (fading) in the channel characteristics. The simulation model for multipath fading channels has the structural form of a TDL with time-varying tap gains, which are modeled as stationary random processes. For mobile applications, fading in the communication channel is characterized by complex Gaussian processes with appropriate power spectral density functions. Three such functions discussed here are flat, Gaussian and Jakes.

The next chapter will describe the simulation model of a discrete TDL channel model in MATLAB and present the simulation results.

IV. SIMULATION AND RESULTS

This chapter discusses the simulation model used to represent the channel in wireless networks. The aim of the simulation was to study the system performance under different channel conditions. A simulation of the discrete TDL channel model was performed using MATLAB. The simulation results obtained for different combinations of the system parameters are discussed.

A. SIMULATION MODEL DEVELOPMENT

The focus of this thesis is on the mitigation of small-scale effects due to multipath propagation in outdoor mobile radio wireless channels. Outdoor mobile radio channels differ from the indoor wireless channels in several aspects. First, the multipath structure is of a much larger scale. Second, outdoor mobile radio channels experiences a higher Doppler effect than that of indoor wireless channels.

1. Models

The first step in developing a simulation is the development of a model for the system of interest which in this case is the wireless communications channel. The model is typically expressed in a mathematical form. In general, it is useful to consider two different types of models, analytical and simulation.

Analytical models typically take the form of equations that define the input-output relationship of the system; whereas the simulation model is usually a collection of algorithms that implements a numerical solution of the equations defining the analytical model. The techniques of the numerical analysis and digital signal processing are the tools used in the development of such a model [14].

2. Simulation of Channel Model

In general, the channel is the most difficult part of the system to model accurately. The process of establishing such a model is often complicated as the mobile radio channel introduces significant levels of interference, distortion and noise. Furthermore, the mobile radio channel is time-varying and undergoes fading. The next step was the implementation of a TDL channel model for mobile wireless ad hoc networks. Since the dominant noise type for the channel is AWGN, it is included in the simulation. Fading and multipath propagation, type of terrain and mobility (Doppler shift) are the other factors included in the model. Figure 18 illustrates the influence of these factors on the transmitted signal in the channel.

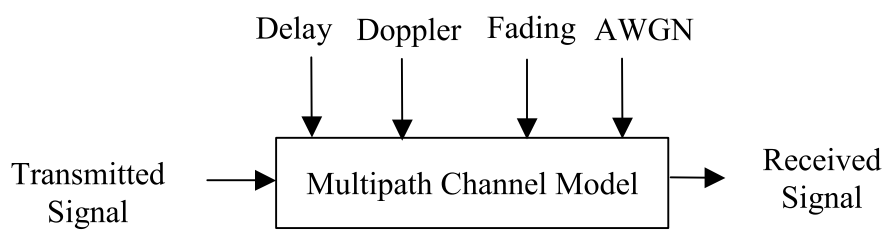

Figure 18. Multipath channel model.

3. Construction of Functional Blocks

The main components of the MATLAB code developed to simulate the channel are *channel.m*, *qpsk.m*, *doppler.m*, *pwrSpectrum.m* and *delayprofile.m*. Figure 19 shows the hierarchical representation of the m-files. Each of the functions is explained in the following sections.

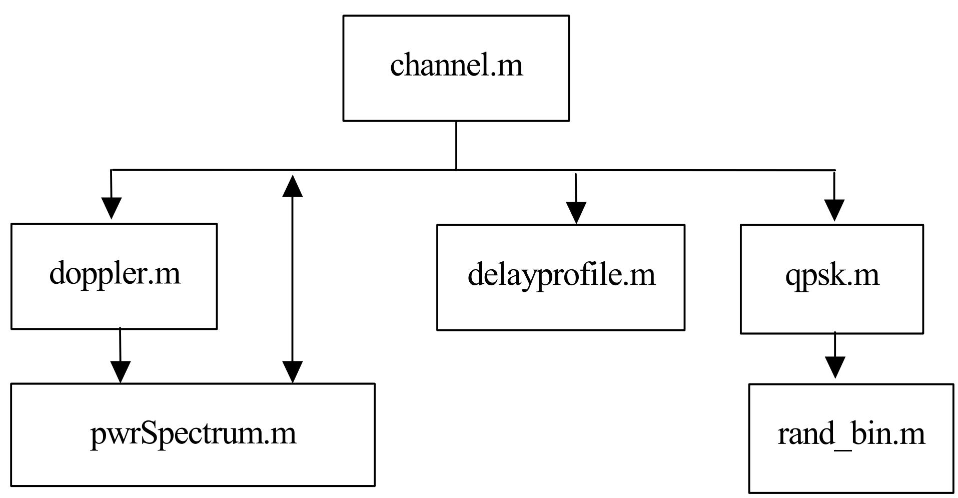

Figure 19. Hierarchical representation of the m-files.

a. *Channel.m*

This function models the multipath fading of the channel, which has a TDL structure. The channel characteristics are simulated by the m-file, *channel.m*. The function has five input arguments and a single output represented by *y_t* = *channel* (*L, area, v,* f_c*, model).*

The input parameter, *L*, ranging from 6 to 32, determines the number of taps for the TDL structure of the channel. The parameter, *area*, allows the selection of the type of terrain in which to operate. If *area* = 1, then the type of terrain selected is urban; if *area* = 2, the type of terrain is hilly. The input *v* is the mobile velocity and f_c is the carrier frequency, which will be further described in the function, *doppler.m*. The parameter *model* determines the filter response function for the Doppler spectrum. Select 1 for Jakes spectrum, 2 for flat spectrum, and 3 for Gaussian spectrum. The modulation scheme used is QPSK. The output *y_t* represents the received signal after it passes through the channel.

b. *Doppler.m*

This function calculates the Doppler frequency shift of a time-varying multipath channel. The input parameters are passed from the function, *channel.m*. The mobile velocities used in this thesis are 30 mph and 80 mph, and the carrier frequencies used are 2.4 GHz and 5.3 GHz. The output of this function is the maximum Doppler frequency based on the input values entered.

c. *PwrSpectrum.m*

This function generates the three types of power spectrum as described in Chapter III. Based on the input selection passed from the function, *channel.m* and the maximum Doppler frequency, the respective Doppler power spectrum is plotted. The values of the Doppler spectrum are then passed back to *channel.m* to compute the tap gain coefficients.

d. *DelayProfile.m*

This function implements two types of delay profile as described in Chapter II according to the type of terrain selected. The Ricean and Rayleigh effects are considered here by including the Ricean factor, *K*, which was defined in Chapter II. If *K* is zero, the channel is Rayleigh, and if *K* has a value greater than zero, the channel is Ricean.

e. QPSK.m

This function is used to generate the QPSK transmission signal. Each of the symbols could take on one of the four possible symbol states: $1+j, -1+j, -1-j, 1-j$. The number of levels on the *I* (In phase) axis and the *Q* (Quadrature) axis are assigned using a random binary number generator.

B. SIMULATION PARAMETERS

The key to successful channel characterization depends on whether the chosen parameters are closely related to the performance of the system under consideration. Therefore, a number of choices and considerations must be taken into account when building the model. In general, for a TDL model, the following parameters and functions must be specified: the number of taps, the Doppler spectrum of each tap, the Ricean factor *K*, and the power distribution of each tap.

Simulations were conducted for five different sets of parameters values consisting of number of taps, velocity in miles per hour (mph), frequency in MHz, terrain and the power spectrum as given in Table 1. For each scenario, the Doppler spectrum, delay profile, fading envelope, TDL gain coefficients, and the signal constellation diagram were plotted; the simulation results are presented in Section C.

Taps No.	Velocity (mph)	Frequency (MHz)	Terrain	Power Spectrum
8	30 or 80	2400 or 5300	Urban or Hilly	Jakes/ Flat/ Gaussian
10	30 or 80	2400 or 5300	Urban or Hilly	Jakes/ Flat/ Gaussian
16	30 or 80	2400 or 5300	Urban or Hilly	Jakes/ Flat/ Gaussian
24	30 or 80	2400 or 5300	Urban or Hilly	Jakes/ Flat/ Gaussian
32	30 or 80	2400 or 5300	Urban or Hilly	Jakes/ Flat/ Gaussian

Table 1. Parameters for the vehicular outdoor model.

The outdoor vehicular environment is most appropriate for the purpose of studying the effect of multipath fading on the wireless mobile radio channel for military applications. As the velocity of the vehicle or mobile unit (i.e., transmitter or receiver) contributes to the Doppler shift frequency, two different values were selected, a slow speed of 30 mph and a fast speed at 80 mph.

In the United States, the Federal Communications Commission (FCC) governs radio transmissions, including those employed in wireless networks. Other nations have corresponding regulatory agencies. Wireless networks are typically designed to operate in the unlicensed portions of the radio spectrum. In the U.S., most wireless networks broadcast over one of the ISM (Instrumentation, Scientific, and Medical) bands. These include 902-928 MHz, 2.4-2.483 GHz, 5.15-5.35 GHz, and 5.725-5.875 GHz. Since the IEEE 802.11 wireless standards are commonly adopted, carrier frequencies in the 2.4 GHz (802.11b or 802.11g) and 5 GHz (802.11a) bands are thus considered here.

The characteristics of the communications channel between the transmitter and the receiver are time-varying since the parameters of the channel, such as the attenuation and delay, are changing due to the relative motion between the transmitter and the receiver. The time-domain approach leads to a model consisting of a TDL structure with time-varying tap gains as described in Chapter III. The TDL model implemented here has a finite number of taps, ranging from 6 to 32. The total number of taps should be kept to a minimum in order to maximize the computational efficiency of the model.

As discussed in Chapter II, there are four general classifications of the radio propagation environments, and the multipath intensity profile of a mobile radio channel depends critically on the type of terrain. Since we are considering the outdoor vehicular environment for wireless communications system operations in military applications, the two most suitable operating environments are the urban area and rural mountainous terrain. As such, these two models are implemented to evaluate the channel performance in different operating environments.

The transmitted frequency undergoes Doppler frequency shifts due to the motion of the mobile (i.e., the transmitter and receiver) as well as the nature of the path. Hence, simulation of wireless systems where motion is present requires the generation of the Doppler spectrum to quantify the time-varying nature of the channel. It is most appropriate for dense scattering environments like the urban areas and is usually used to represent land mobile systems. Two other spectral shapes used for the Doppler power spectral densities including Gaussian and flat are also implemented here.

The modulation scheme plays a major role in how the channel affects the transmitted signal. In this simulation, the QPSK modulation scheme is used.

C. SCENARIOS AND SIMULATION RESULTS

In this section, we present the simulation results illustrating the effects of small-scale fading, AWGN, and Doppler on the transmission of QPSK signals over a discrete multipath channel of a wireless communications system. The MATLAB code for the simulation program is given in the appendix. The simulation results include plots of the Doppler power spectrum, delay profile, power spectral density (PSD), TDL gain coefficients and the received signal constellation.

In all subsequent simulations, the methodology shall remain the same and only the parameter values are changed. Only simulation results from selected combinations of parameters are examined here in particular. The effects of other combinations of parameters have on the channel that are not considered in this thesis can be easily examined by simply changing the input parameter values accordingly.

1. Simulation Conditions

As discussed in the previous section, we investigated the effect of the maximum Doppler frequency on the channel performance. It is known that Doppler frequency is directly related to how fast the mobile unit is moving with respect to the transmitter. Assuming that a mobile traveling at a velocity of 30 mph and a carrier frequency of 2.4 GHz (wavelength $\lambda = 0.125$m), the Doppler frequency can be obtained from Equation (9) as 108 Hz.

Table 2 lists the Doppler frequencies for two different speeds of the mobile units. The highest Doppler frequencies of 636 Hz occur at 80 mph in the 5.3 GHz band.

Speed (mph)	**Doppler Frequency (Hz) at 2.4 GHz**	**Doppler Frequency (Hz) at 5.3 GHz**
30	108	238.52
80	288	636.04

Table 2. Doppler frequencies at different mobile speed

The simulation of wireless system in which motion is present requires the generation of a process having the power spectral density to represent the effect of Doppler. As discussed in Chapter III, three types of Doppler spectrum are considered.

Figure 20 shows the Jakes spectrum [13] at a carrier frequency of 2.4 GHz and a mobile speed at 30 mph. Two related representations of flat and Gaussian spectra were also implemented in the simulation and are shown in Figures 21 and 22, respectively, for the carrier frequency of 2.4 GHz and a mobile speed at 30 mph. Note that as the Jakes spectrum suppresses the low frequencies, the Gaussian spectrum is predominantly low frequency in nature.

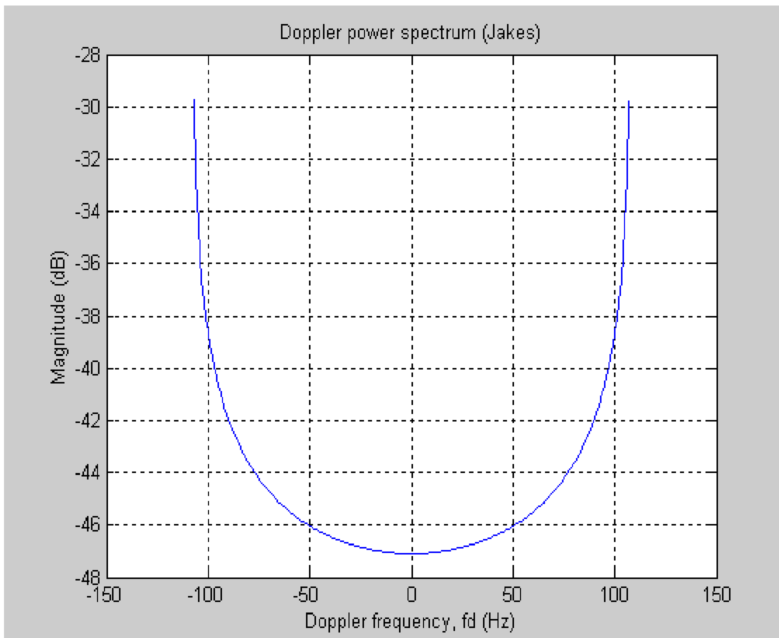

Figure 20. Jakes Doppler power spectrum at a mobile speed of 30 mph and a carrier frequency of 2.4 GHz.

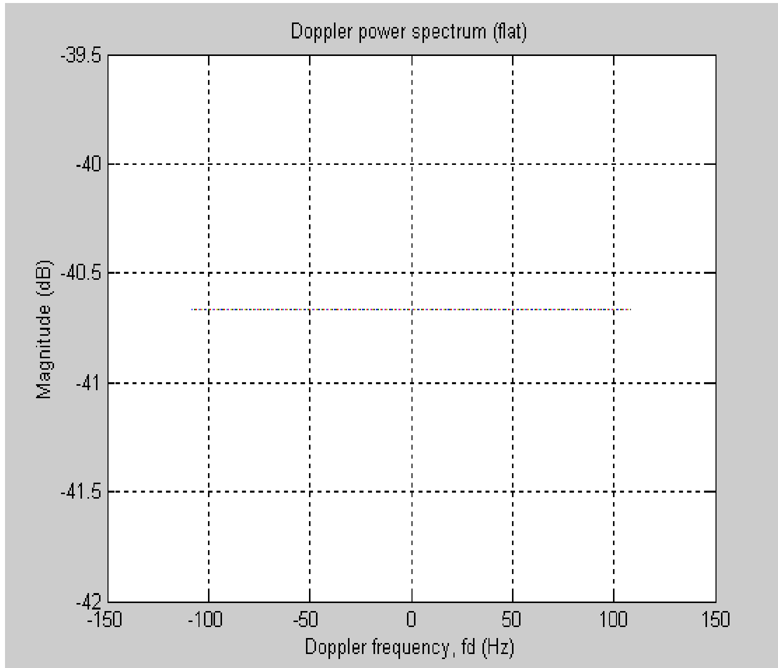

Figure 21. Flat Doppler spectrum at a mobile speed of 30 mph and a carrier frequency of 2.4 GHz.

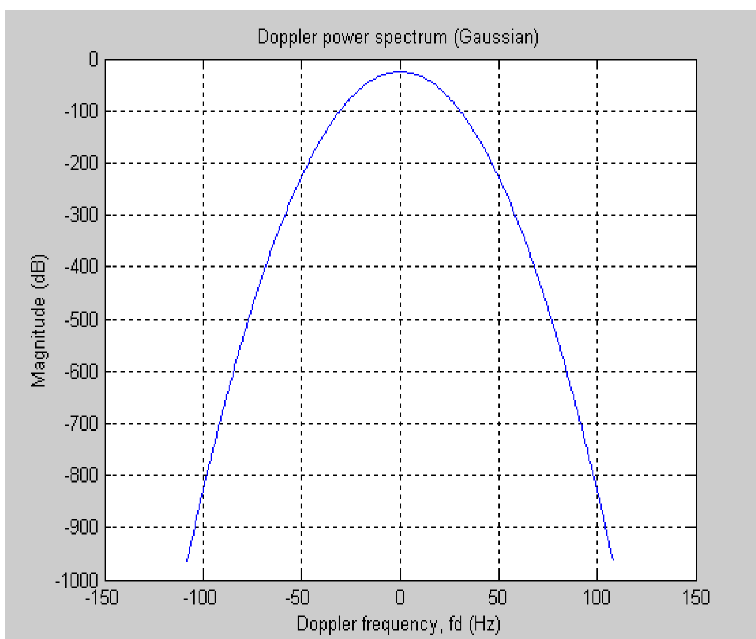

Figure 22. Gaussian Doppler spectrum at a mobile speed of 30 mph and a carrier frequency of 2.4 GHz.

The fading channel undergoes different types of fading according to the relation between the signal parameters and the channel parameters. In military operations, the receivers are usually surrounded by foliage and hilly terrains. Factors that affect the signal quality include attenuation by vegetation and blockage by adjacent buildings. In a practical application, channel measurements would be used to determine a power delay profile. However, in this simulation, it is important to note that the delay profile is explicitly specified and is dependent on the type of operating environment.

Two types of terrain [3] are generated according to Equation (1) and (2), and the resultant power delay profile graphs are shown in Figures 23 and 24. The delay spread in the urban environment extends to 7 μs. For hilly terrain, there are two regions over which the power is spread; together, the spread is much longer for hilly regions.

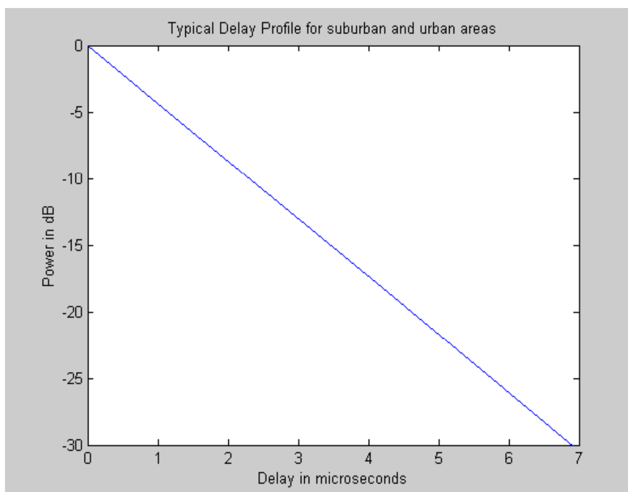

Figure 23. Delay profile for urban areas.

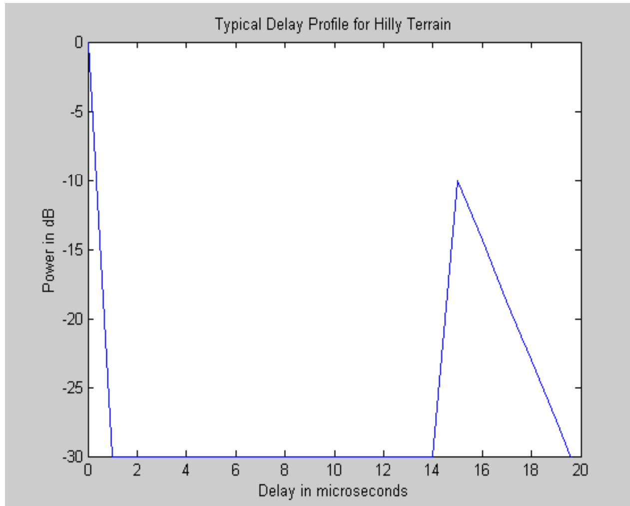

Figure 24. Delay profile for hilly terrain.

The choice of QPSK as the modulation technique for the transmission signal was because of its simplicity and to reduce problems with amplitude fluctuations due to fading since the amplitude of a QPSK signal is constant. Figure 25 shows a constellation diagram that provides a graphical representation of the complex envelope of the four possible symbol states: $1+j, -1+j, -1-j, 1-j$. The *x*-axis and *y*-axis of the constellation diagram represents the in-phase and quadrature components of the complex envelope. The distance between the signals relates to how different the modulation waveforms are and how well a receiver can differentiate between all possible symbols, which we shall examine in the following sections.

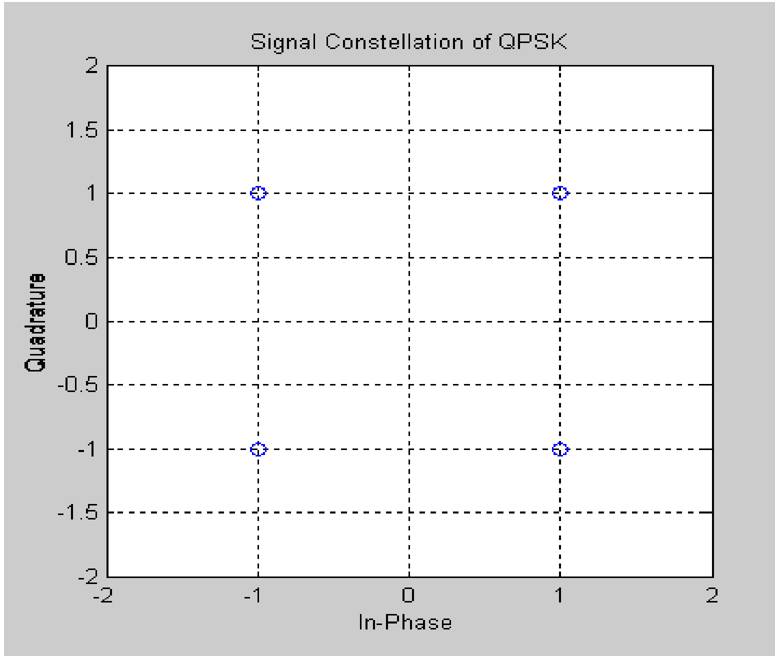

Figure 25. Signal constellation of QPSK at the transmitter.

2. Number of Taps

Simulations were performed assuming an urban environment, a carrier frequency of 2.4 GHz, keeping the velocity at 30 mph and varying the number of filter-taps. The effect of 8, 16, 24 and 32-taps were studied. The filter-taps are computed for the three different Doppler spectra: Jakes, flat and Gaussian. The PSD at the filter output using the Jakes spectrum is shown in Figure 26. Depending on the type of power spectrum used, it can be seen that the envelope corresponds to the shape of the respective power spectrum used. Figure 27 and Figure 28 show the PSD at the filter output for the flat and the Gaussian spectrum, respectively; the shape of both differs considerably from that of Jakes.

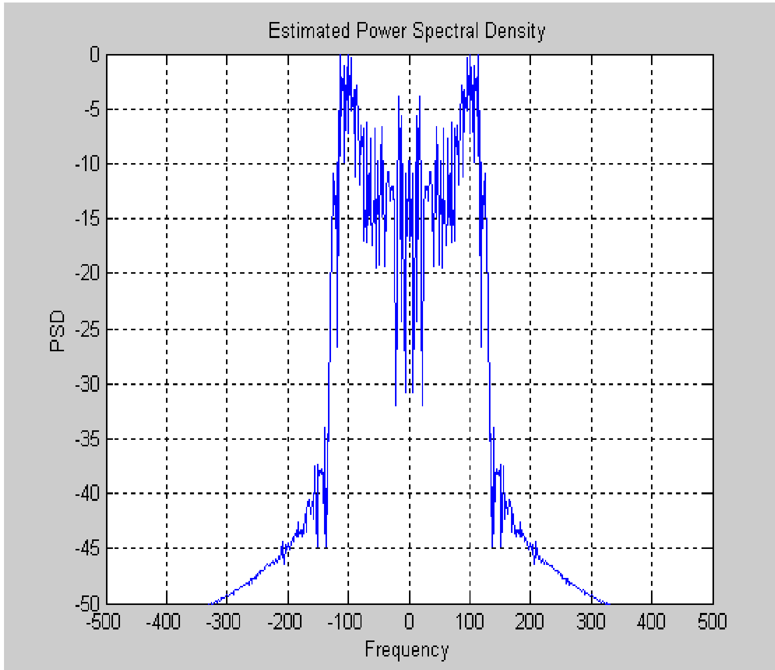

Figure 26. PSD at the filter output using Jakes spectrum.

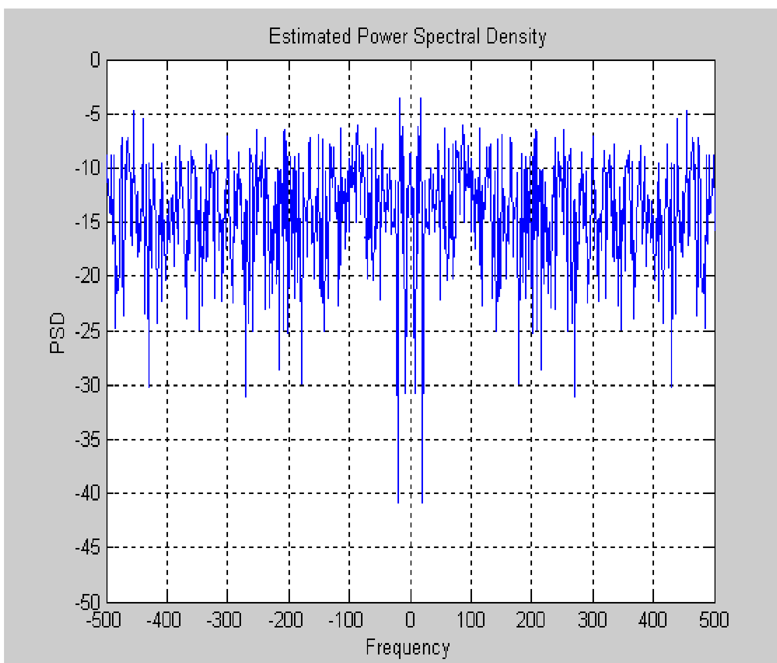

Figure 27. PSD at the filter output using flat spectrum.

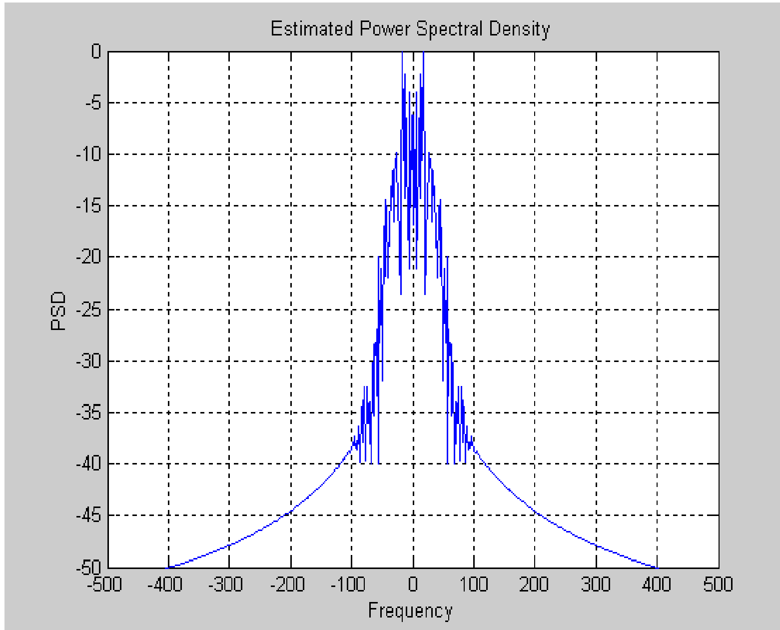

Figure 28. PSD at the filter output using Gaussian spectrum.

The channel tap coefficients obtained for 8, 16, 24 and 32-taps using the Jakes spectrum are shown in Figures 29, 30, 31 and 32, respectively. It can be seen from the graphs that the coefficients are negligible for higher-order tap gains and, hence, they can be ignored. Therefore, the number of taps required by the TDL model is generally small. We shall set the number of taps to 8 in subsequent simulations and study the effect by varying other parameters.

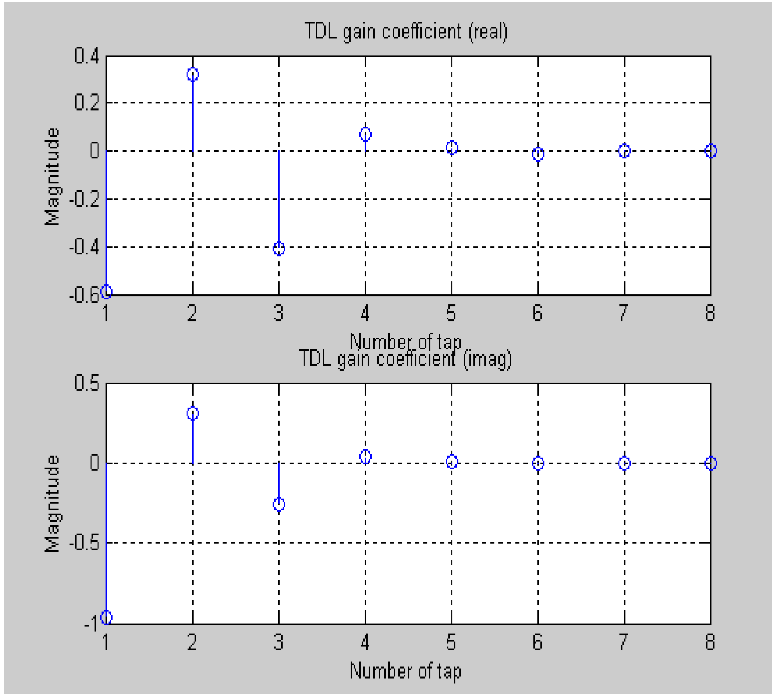

Figure 29. TDL gain coefficients for an 8-tap filter using Jakes spectrum.

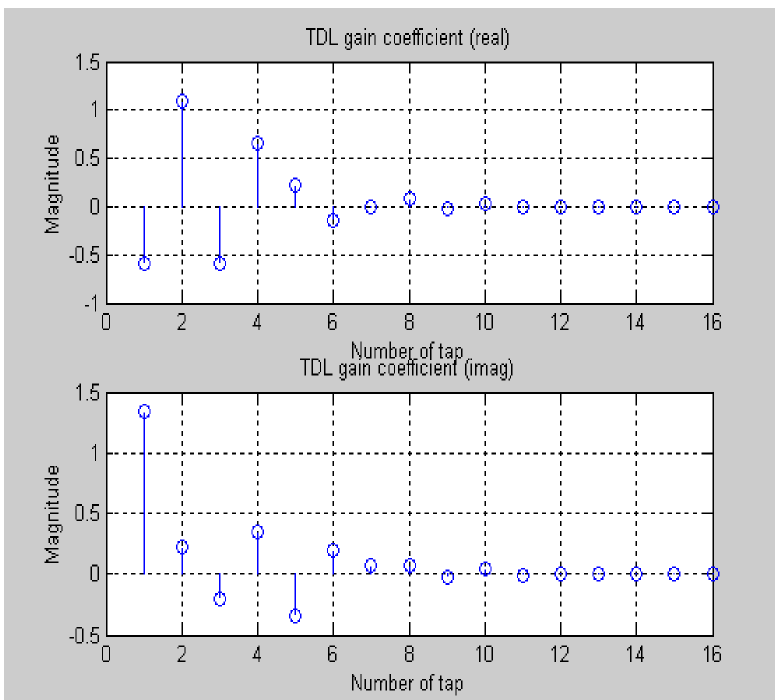

Figure 30. TDL gain coefficients for a 16-tap filter using Jakes spectrum.

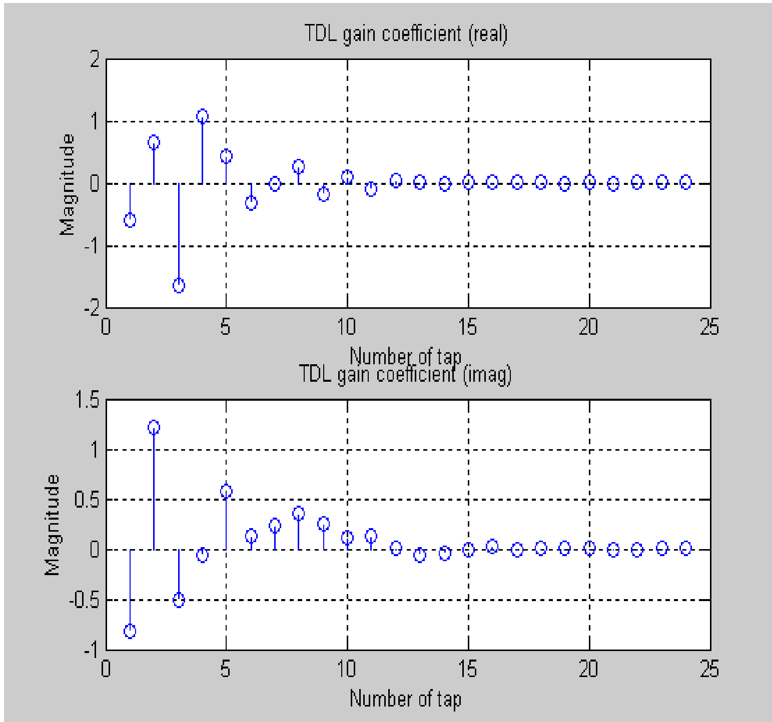

Figure 31. TDL gain coefficients for a 24-tap filter using Jakes spectrum.

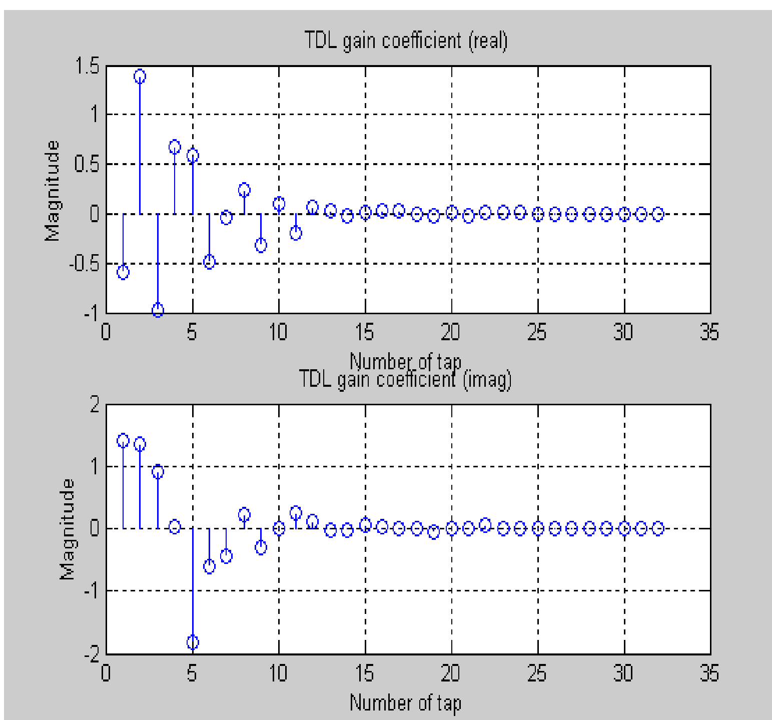

Figure 32. TDL gain coefficients for a 32-tap filter using Jakes spectrum.

3. Mobile Velocity and Doppler Spectrum

In this simulation, the carrier frequency is set at 2.4 GHz and, from the previous section, the number of taps for the TDL model was chosen to be 8. We carry on with our study by varying the mobile velocity since the Doppler spread is directly proportional to velocity and is regarded as the fading rate of the channel. At the same time, we also vary the spectra for the shaping filters to one of Jakes, flat or Gaussian. As system parameters are varied, the signal constellation for each scenario is presented here. It gives us a qualitative measure of the system performance

a. Velocity at 30 mph

The signal constellation plots for a mobile traveling at a speed of 30 mph are shown in Figures 33, 34 and 35. Figure 33 shows the transmitted signal through a channel with a shaping filter using the Jakes spectrum, Figure 34 shows the result of passing the signal through a channel with a shaping filter using the flat spectrum, and Figure 35 shows the result of passing the signal through a channel with a shaping filter using a Gaussian spectrum.

As a consequence of AWGN and multipath distortions within the channel causing constructive and destructive signal interference, it is observed that the received constellation points are scattered from their normal pre-transmitted region. We can see from Figure 34 that the channel using the flat spectrum has constellation points falling beyond the range of 0 to 2 into the region of 2 to 6. This severe distortion is expected since there is no conditioning of signal for a flat spectrum. Figure 35 shows less scattering than Figure 33, and the constellation points lie closer to the pre-transmitted region and are more densely packed. It is observed that Gaussian spectrum offers a better signal estimation than the Jakes spectrum in this situation.

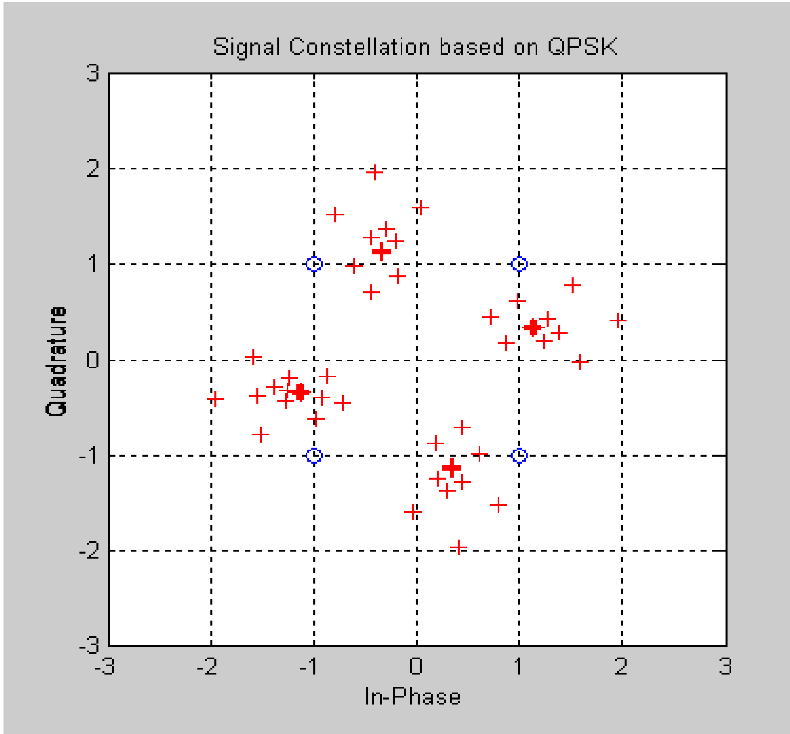

Figure 33. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 30 mph, urban area, and Jakes spectrum.

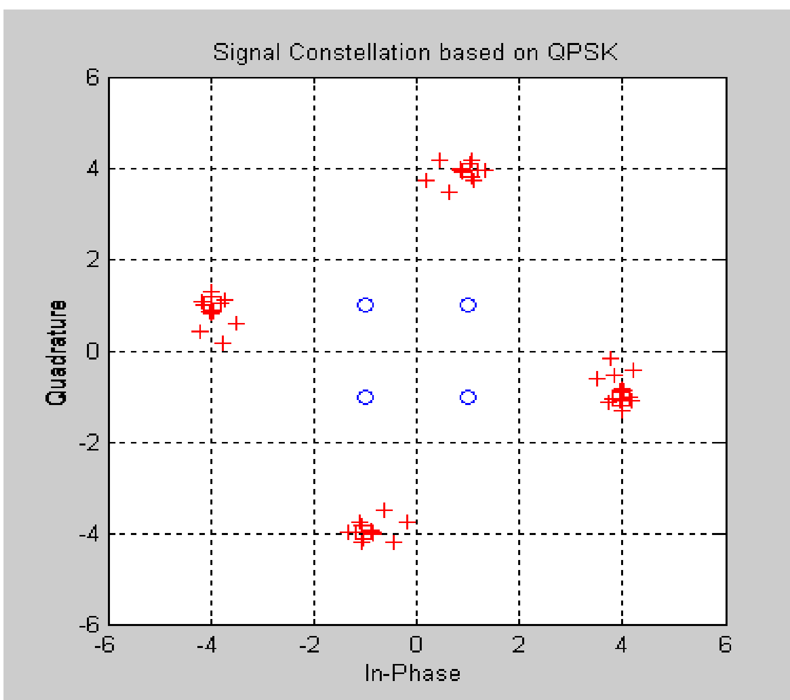

Figure 34. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 30 mph, urban area, and flat spectrum.

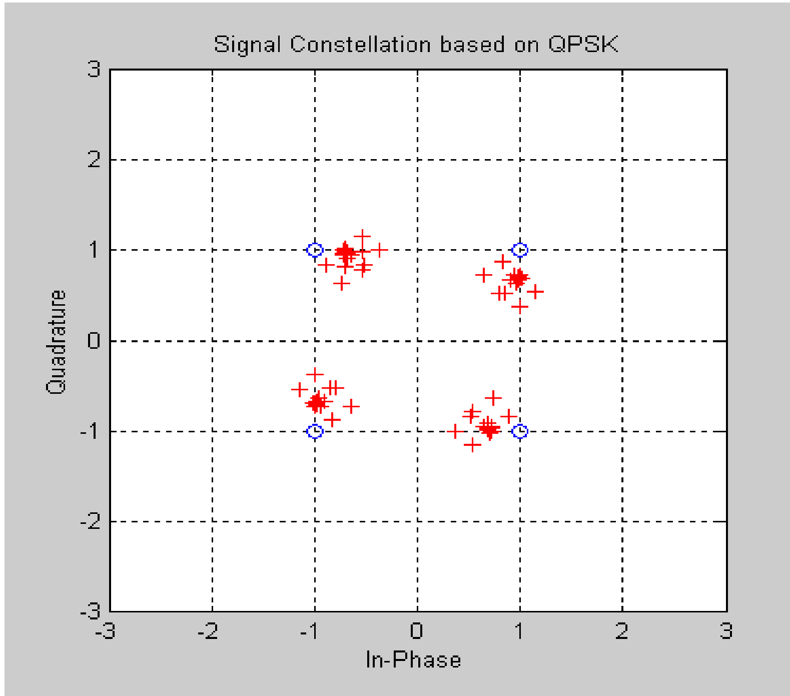

Figure 35. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 30 mph, urban area, and Gaussian spectrum.

b. Velocity at 80 mph

When the velocity of the mobile is increased, the Doppler frequency is higher. The fact that the mobile unit is now moving at a higher speed caused the channel to change accordingly. The constellation plots for a mobile traveling at a speed of 80 mph are shown in Figures 36, 37 and 38 for different Doppler spectra. Even though the Doppler frequency is higher, we see that there are signal points that are closer together and less scattered around. This indicates that the multipath components could be constructive instead of destructive in this case. The results reinforce the argument that that Gaussian and Jakes Doppler spectrum are more suitable for mobile radio channels as compared to the flat spectrum. By comparing Figures 33 to 35 with Figures 36 to 38, we may remark that, in the urban environment, the Gaussian spectrum is a better choice at low speeds and the Jakes spectrum is preferred at high speeds for determining the shaping filter for the parameters chosen here.

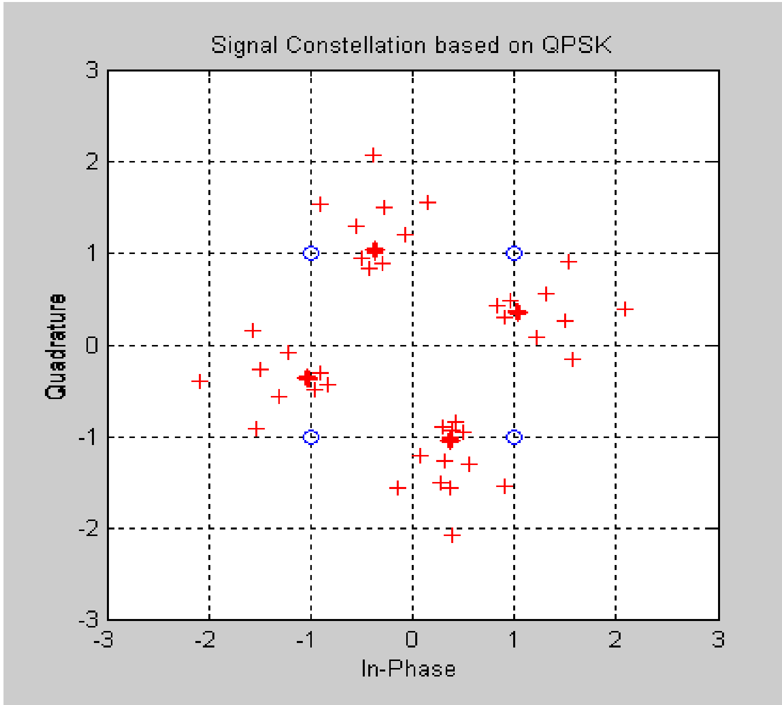

Figure 36. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 80 mph, urban area, and Jakes spectrum.

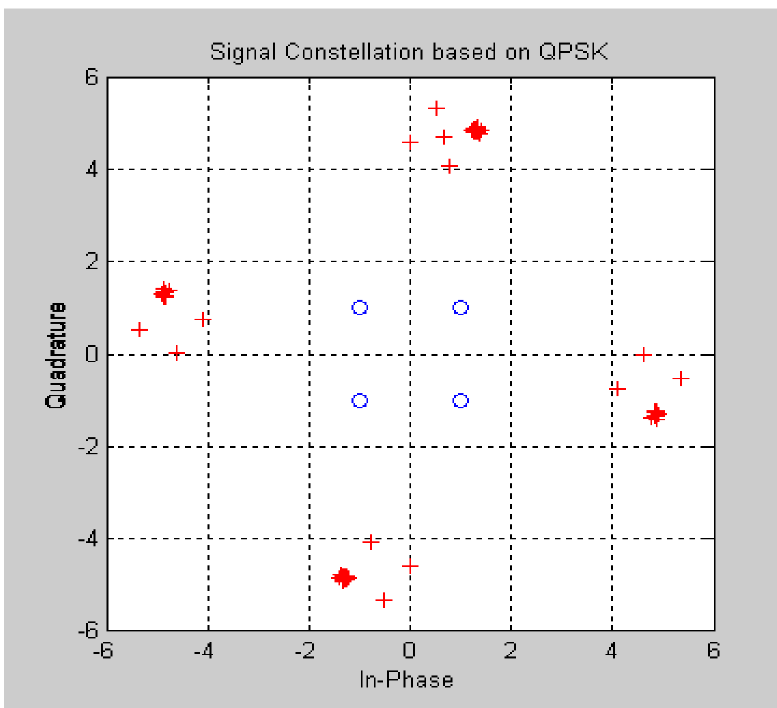

Figure 37. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 80 mph, urban area, and flat spectrum.

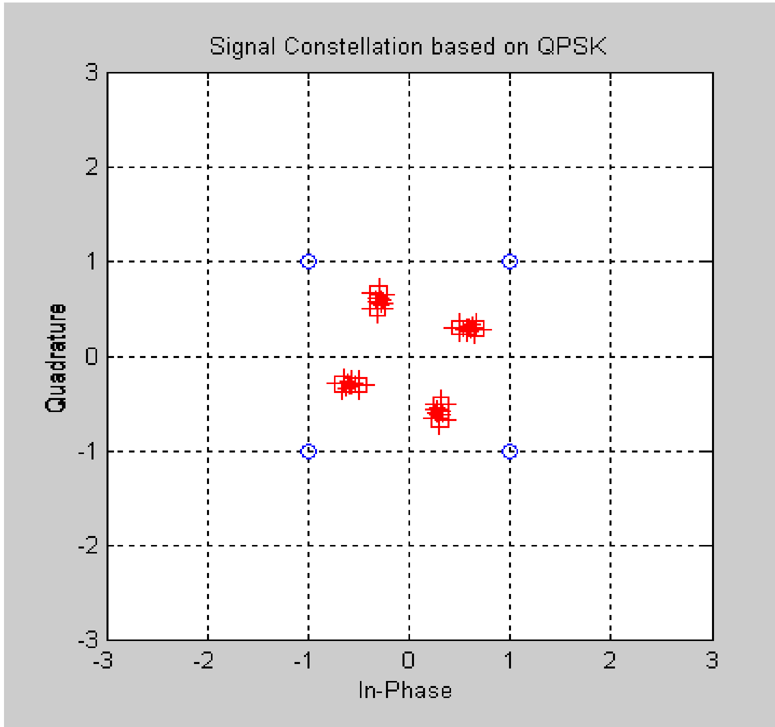

Figure 38. QPSK signal constellation for a channel model with the following parameter settings: 2.4 GHz, 80 mph, urban area, and Gaussian spectrum.

4. Carrier Frequency at 5.3 GHz

Modeling of radio channel at 5.3 GHz has increasing importance in the study of wireless systems. Since a TDL model operating at 2.4 GHz may not be the same for a TDL model at 5.3 GHz, we conducted the simulation for a carrier frequency of 5.3 GHz. The parameters used in the simulation are: 8-taps, 80 mph for the mobile velocity and Jakes, flat or Gaussian Doppler spectrum.

The constellation plots of the received symbols are illustrated in Figures 39, 40 and 41. Comparing the results to those in Figures 36 to 38, it is noticed that there is no significant difference between the carrier frequencies of 2.4 GHz and 5.3 GHz. We can also see that the Jakes model is more suitable than either the flat or Gaussian power spectrum in this case.

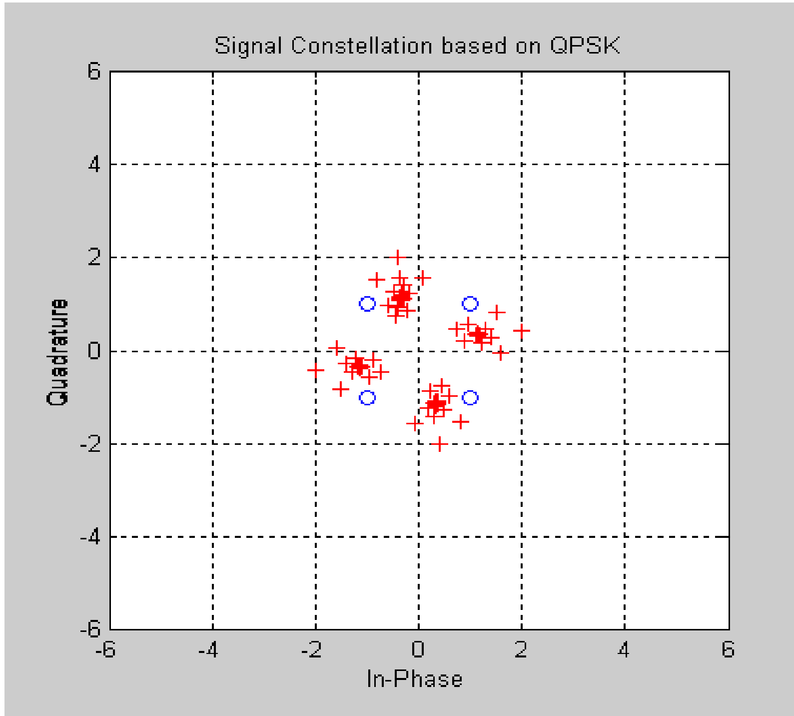

Figure 39. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 80 mph, urban area, and Jakes spectrum.

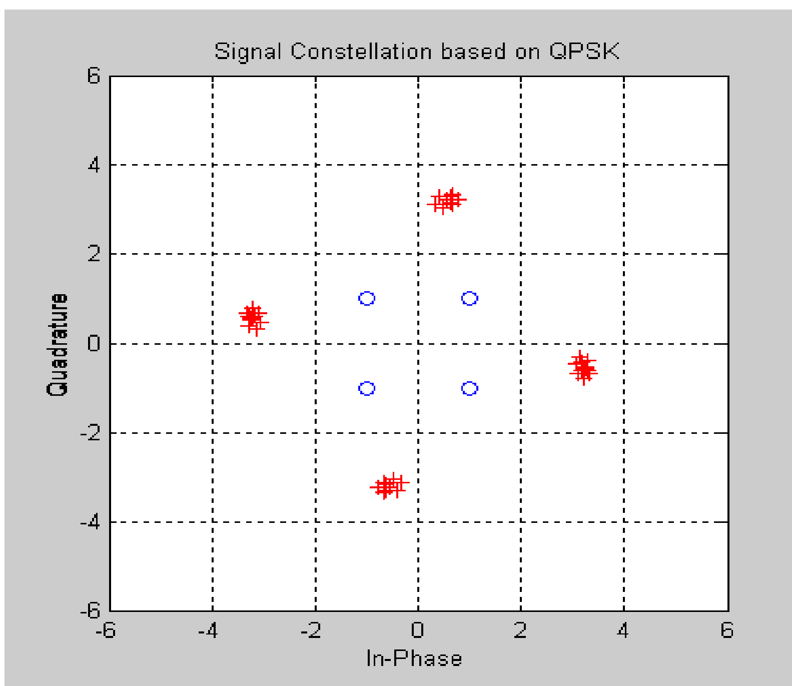

Figure 40. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 80 mph, urban area, and flat spectrum.

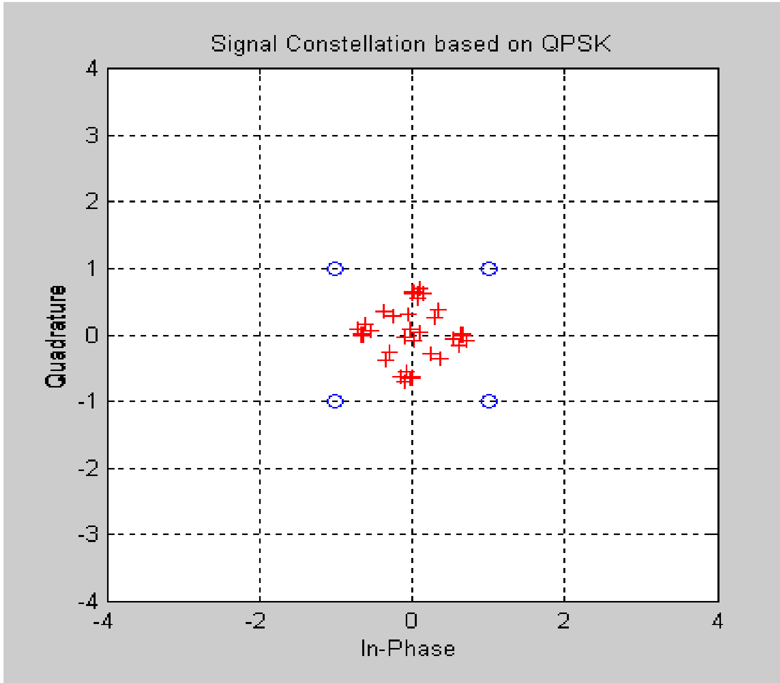

Figure 41. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 80 mph, urban area, and Gaussian spectrum.

5. Operating Environment

The amount of time-spreading of the transmitted signal depends on the amount of the multipath components present in the environment. More spreading of the signal takes place in highly cluttered areas, such as urban regions, than in open areas. Hence, simulations are repeated for transmitting the signal across a channel with the following parameters: 8-tap, 5.3 GHz, choice of 30 mph or 80 mph for the mobile velocity and Jakes or Gaussian Doppler spectrum and hilly terrain.

The signal constellation diagrams are shown in Figures 42, 43, 44 and 45. We have not included the flat spectrum as it is deemed not suitable in our previous analysis. It is also observed that the model produces better results when the carrier frequency is set to 5.3 GHz; hence the simulations for 2.4 GHz were not repeated here. In both cases, Figures 43 and 45 suggest that the channel implemented with the Gaussian spectrum suffers less distortion and scattering, and the received symbols are closer together as compared to the one implemented with Jakes model.

In the hilly environment, therefore, compared to the widely used Jakes spectrum, it is found to be more appropriate to use a Doppler power spectral density that is approximately Gaussian shaped. Additionally, it is observed that less distortion is encountered when the mobile unit is moving at a slower speed of 30 mph.

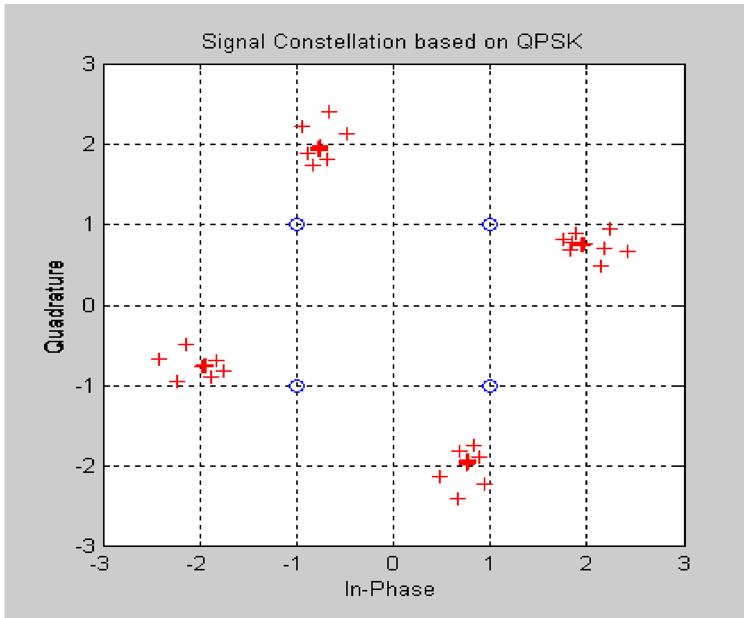

Figure 42. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 30 mph, hilly terrain, and Jakes spectrum.

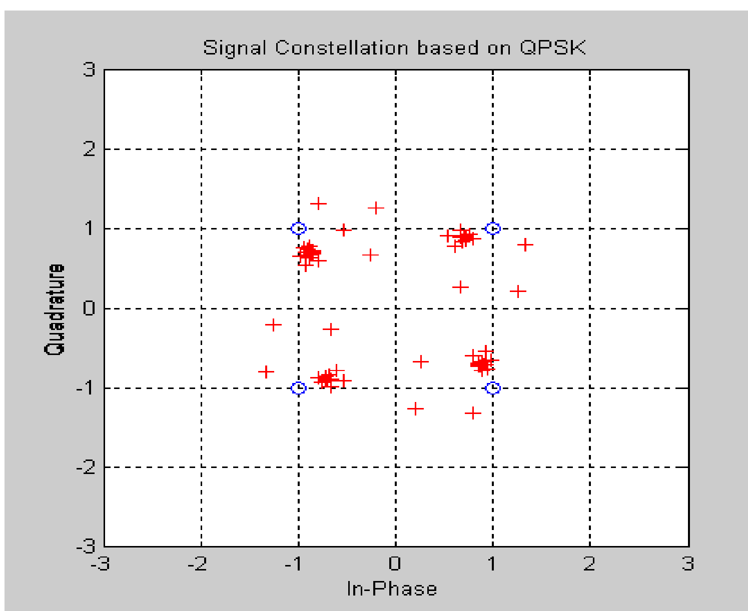

Figure 43. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 30 mph, hilly terrain, and Gaussian spectrum.

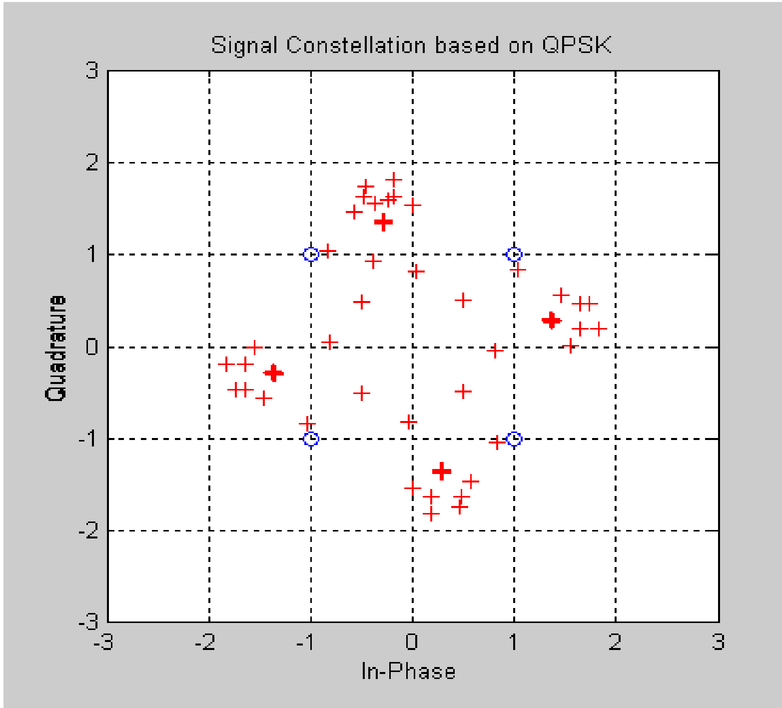

Figure 44. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 80 mph, hilly terrain, and Jakes spectrum.

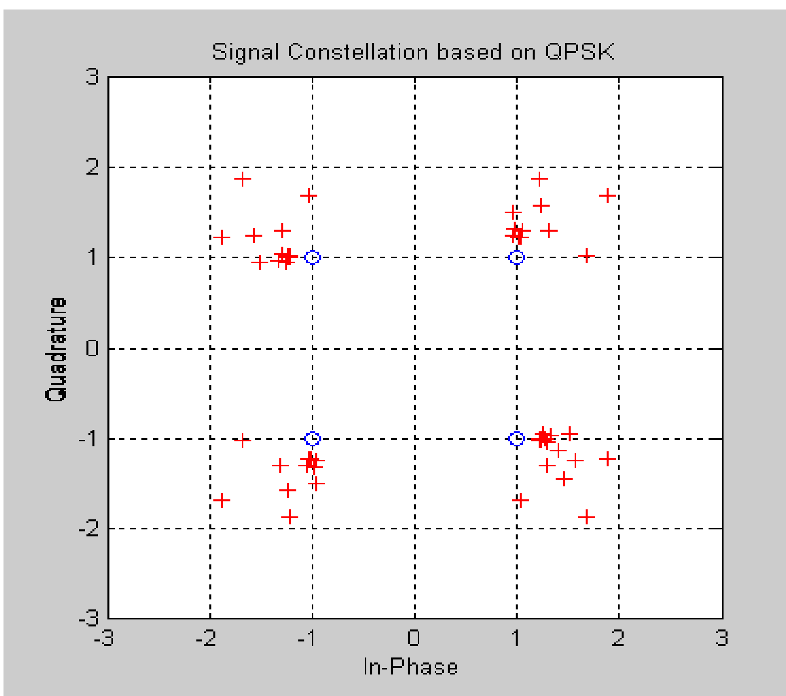

Figure 45. QPSK signal constellation for a channel model with the following parameter settings: 5.3 GHz, 80 mph, hilly terrain, and Gaussian spectrum.

D. SUMMARY

This chapter presented the simulation study of a time-varying mobile radio channel, arising from multipath and motion. A tapped delay line channel model was implemented, and the simulation results indicate that the number of tap gains should generally be small since higher-order tap gains can be ignored. By observing the changes in the signal constellation plots, we noticed that the scattering of constellation points is due to the effect of passing the signal through a channel causing signal impairment due to AWGN, multipath, Doppler shift, delay and TDL gain coefficient variations. The simulation results also showed that the flat spectrum is not suitable for both operating environments of urban and hilly terrains, and it suffers the most distortion. The Jakes spectrum was found to be suitable for the high-speed urban areas, and the Gaussian spectrum was appropriate for the low-speed urban areas and the hilly terrain. The next chapter summarizes the thesis and includes recommendations for follow-on research.

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V. CONCLUSIONS

The next generation of wireless systems is moving towards ad hoc operations. With wireless ad hoc networks, seamless communications infrastructure could be deployed quickly on the battlefield to increase combat effectiveness and mobility of the force. It is often desirable to make the communications network operable while the command vehicle is on the move. This research was thus carried out from the perspective of an outdoor mobile radio communications environment for military operations.

In real-world wireless communications systems, there are several limitations that affect communications over the underlying time-varying wireless channels. The focus of channel characterization in this thesis is studied based on the following factors: fading effect and multipath propagation, types of terrain, time-varying nature, and Doppler shift due to motion of the mobile. The simulation model of the multipath fading channel takes the structural form of a TDL with time-varying, tap gains that were modeled as random processes. Three Doppler power spectral densities, namely, Jakes, flat and Gaussian, were also implemented to quantify the mobility in the channel. The transmission signal modulation was QPSK.

The TDL channel model was developed and simulated in MATLAB. Mobile velocity, carrier frequency, the number of taps, type of terrain and the Doppler power spectrum were the parameters in the model. Several combinations of these parameters were used, and the simulation results included plots of the Doppler power spectrum, delay profile, filter output Power Spectral Density (PSD), TDL gain coefficients and the signal constellation. The signal constellation for each combination gives a qualitative measure of the system performance.

A. SIGNIFICANT RESULTS

It is widely known that a communication system's performance depends fundamentally on its channel characteristics. However, there is no generic way of specifying the parameters for simulating a wireless link. The overall performance of the wireless links is limited by the difficulty in modeling a large number of channel and system parameters. The TDL-based discrete channel model developed in this work is shown to characterize a mobile wireless channel in a comprehensive manner. This section summarizes the significant findings in this work.

The simulations results indicate that the number of tap gains of the TDL channel model should generally be small since higher-order tap gain values are not significant. In addition, it was noticed that the results obtained for two different carrier frequencies of 2.4 GHz and 5.3 GHz did not influence the performance significantly.

As Doppler shift is directly proportional to speed, two different mobile speeds of 30 mph and 80 mph were used in the simulation, representing a low and a high mobility scenario, respectively. The simulation results indicate that the Gaussian and Jakes are more suitable Doppler spectra for mobile radio channels than the flat spectrum.

Lastly, two types of environments (i.e., urban and hilly terrain) were considered in this work. The Jakes Doppler spectrum should be used in urban environments with high mobility; the Gaussian Doppler spectrum is the choice for low mobility urban environments and for the hilly terrain under both low and high mobility.

B. RECOMMENDATIONS FOR FUTURE WORK

The simulation model developed in this thesis was helpful in determining signal quality under certain channel conditions. The work reported here only covers a small portion of a mobile wireless radio channel, and many extensions could be incorporated to increase its usefulness. We now propose a few potential future directions for this work.

The accuracy of the simulation model developed in this thesis is limited by the accuracy of the underlying mathematical model and the associated assumptions. The equations, at best, provide a partial description of the system being modeled since only certain aspects of the system can be modeled. In order to develop a more accurate simulation model, it is recommended that field measurements of the environment being modeled should be made.

A variety of modulation techniques are used in mobile radio communications systems. The QPSK modulation scheme was chosen in this work. It is recommended that performance of other modulation schemes, such as QAM, GMSK, OFDM and spread spectrum techniques, be investigated. In this thesis, only the constellation plots are used to observe the performance of the communications system. It is further recommended that the receiver operating curves be measured to study the system performance.

Diversity is widely used to improve the communications system performance in fading channels. Multiple-input, multiple-output (MIMO) approaches are being considered for the next generation wireless networks. A potential area for a future effort will be to extend the channel modeling approach presented in this thesis to the MIMO and other diversity environments.

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APPENDIX. MATLAB SOURCE CODE

The MATLAB source code developed for channel simulation in this thesis is listed in this appendix.

```
% ----------------------------------------------------------------------
% Filename: Channel.m
% ----------------------------------------------------------------------
% Input parameters:
% L = number of taps (6 to 32)
% area = Type of terrains; 1 = urban and suburban; 2 = hilly terrain
% v = velocity of mobile (in mph)
% fc = carrier frequency (in MHz)
% model = Doppler Power Spectrum; 1 = Jakes; 2 = Flat; 3 = Gaussian
% ----------------------------------------------------------------------
% Output:
% sigout = channel output
% ----------------------------------------------------------------------

clear;

M = 2000;
B = 3000;
T=1/B;

L=input('Input no. of taps (6 to 32) : ');
if L < 6
   disp('The minimum no. of taps is 6');
   L=input('Please enter no. of taps again: ');
elseif L > 32
   disp('The maximum no. of taps is 32');
   L=input('Please enter no. of taps again : ');
end

disp(' ');
disp('Please select type of terrain');
disp('1 => Urban and Suburban');
disp('2 => Hilly Terrain');
area = input('Input terrain (1 or 2): ');

disp(' ');
v = input('Input velocity of mobile (in miles per hour) : ');
fc = input('Input carrier frequency (in MHz) : ');

[fdmax,fc3dB] = doppler(v,fc);
```

```
[S,model] = pwrSpectrum(fdmax,fc3dB);
[Pwr,tau,sigma2,alpha2,alpha,W] = delayprofile(area,L,M);

fs = 16*fdmax;
ts = 1/fs;
time = [1*ts:ts:128*ts];

if model == 1

   for p = 1:1:L
         %Doppler Filter

         %S_f = [S(2:end-1)];            % S(f) using Jakes model
         %H_f = sqrt(S_f);               % from S(f) to |H(f)|
         H_f = jakes(fdmax);
         filt = ifftshift(ifft(H_f));    % get impulse response
         filt = real(filt);              % a real-valued filter
         gn = fftfilt(filt,W);
         for m=1:M
            an(m,p) = gn(m,p).*(30*sigma2(p));
            gamma(:,p) = sinc((tau(p)*10^-6)/T);
            hn(:,p) = sum(an(m,p).*gamma(:,p));
         end
   end

elseif model == 2

   for p = 1:1:L
         %Doppler Filter
         S_f = S;                        % S(f) using Flat model
         H_f = sqrt(S_f);                % from S(f) to |H(f)|
         filt = ifftshift(ifft(H_f));    % get impulse response
         filt = real(filt);              % a real-valued filter
         gn = fftfilt(filt,W);
         for m=1:M
            an(m,p) = gn(m,p).*(30*sigma2(p));
            gamma(:,p) = sinc((tau(p)*10^-6)/T);
            hn(:,p) = sum(an(m,p).*gamma(:,p));
         end
   end

elseif model == 3

   for p = 1:1:L
         %Doppler Filter
         S_f = S;                        % S(f) using Flat model
```

```
        H_f = sqrt(S_f);                % from S(f) to |H(f)|
        filt = ifftshift(ifft(H_f));    % get impulse response
        filt = real(filt);              % a real-valued filter
        gn = fftfilt(filt,W);
        for m=1:M
            an(m,p) = gn(m,p).*(30*sigma2(p));
            gamma(:,p) = sinc((tau(p)*10^-6)/T);
            hn(:,p) = sum(an(m,p).*gamma(:,p));
        end
    end

end

envelope(H_f,ts,hn,L);

sigin = qpsk;
sigout = fftfilt(hn,sigin);

h = scatterplot(sigin,1,0,'bo'); grid on; hold on;
scatterplot(sigout,1,0,'r+',h); grid on;
axis([-6 6 -6 6]);
title('Signal Constellation based on QPSK');

% End of file: channel.m










% ----------------------------------------------------------------------
```

```
% Filename: doppler.m
% ---------------------------------------------------------------------
% Input parameters:
% v = velocity of mobile (in mph)
% fc = carrier frequency (in MHz)
% ---------------------------------------------------------------------
% Output:
% fdmax = max Doppler frequency
% ---------------------------------------------------------------------
%
% The model assumes a constant velocity mobile with doppler frequency = v/lambda
% where v = velocity of mobile, lambda = wavelength of carrier

function [fdmax,fc3dB]=doppler(v,fc)

disp(' ');

Rb = 54;
c = 3*10^8;
fc = fc*10^6;
Tb = 1/Rb*10^6;

lamda = c/fc;                     %calculate wavelength from the carrier frequency
v_mpers = (v*1.62*10^3)/(60*60);    %convert from miles/hr to meter/sec
fdmax = (v_mpers/lamda);           %calculate maximum doppler frequency, fd=v/lamda
fc3dB=sqrt(log(2)*fdmax);

% End of function file: doppler.m
```

```
% ---------------------------------------------------------------------
```

```
% Filename: pwrSpectrum.m
% ---------------------------------------------------------------------
% Input parameters:
% fdmax = max Doppler frequency
% ---------------------------------------------------------------------
% Output:
% S = Doppler spectral density
% model = (1)Jakes spectrum, (2)Flat spectrum, (3)Gaussian spectrum
% ---------------------------------------------------------------------
%
% plot Doppler power spectrum

function [S,model] = pwrSpectrum(fdmax,fc3dB);

disp(' ');
disp('Please select model');
disp('1 => Jakes spectrum');
disp('2 => Flat spectrum');
disp('3 => Gaussian spectrum');
model = input('Input model (1 to 3): ');

switch(model)
   case 1
      fd = -fdmax:fdmax;
      S = 1.5./((pi*fdmax).*sqrt(1-((fd/fdmax).^2)));
      mag = 20*log10(abs(S));

      figure;plot(fd,mag); grid on;
      xlabel('Doppler frequency, fd (Hz)');
      ylabel('Magnitude (dB)');
      title('Doppler power spectrum (Jakes)');

   case 2
      fd = -fdmax:fdmax;

      if fd <= fdmax
         S=1./fdmax;
      elseif fd >= -fdmax
         S=1./fdmax;
      else
         S=1;
      end

      mag = 20*log10(abs(S));
      figure;plot(fd,mag); grid on;
      xlabel('Doppler frequency, fd (Hz)');
```

```
        ylabel('Magnitude (dB)');
        title('Doppler power spectrum (flat)');

    case 3

        fd = -fdmax:fdmax;
        S=(1/fc3dB).*sqrt(log(2)/pi).*exp(-log(2)*(fd/fc3dB).^2);
        mag = 20*log10(abs(S));

        figure;plot(fd,mag);
        xlabel('Doppler frequency, fd (Hz)');
        ylabel('Magnitude (dB)');
        title('Doppler power spectrum (Gaussian)');grid on;

    break;
end

% End of function file: pwrSpectrum.m




% -----------------------------------------------------------------------
```

```
% Filename: delayprofile.m
% ----------------------------------------------------------------------
% Input parameters:
% L = number of taps (6 to 32)
% area = Type of terrains; 1 = urban and suburban; 2 = hilly terrain
% M = no of random realizations
% ----------------------------------------------------------------------
% Output:
% 1) Delay Profile for suburban and urban areas
% 2) Delay Profile for Hilly Terrain
% ----------------------------------------------------------------------

function [Pwr,tau,sigma2,alpha2,alpha,W] = delayprofile(area,L,M);

N=L-1;
s = 12; % seed parameter for random number generator

%Seed configurations to set the random# generator seed
randn('seed',s+2);
rand('seed',s+2);

if area == 1

   for c=0:1:N
      t1 = 0;
      t2 = 7;
      tau(c+1) = (t1 + (t2-t1))*(c/N); % for urban and suburban, tau ranges from 0 to 7
microsec
   end

   W = (randn(M,L) + i* randn(M,L))./sqrt(2); % Generate a set of complex white
Gaussian processes
   K= round(rand(1,L));

   %Average delay power profile for suburban and urban areas
   Pwr = exp(-tau);
   Pwr_dB = 10*log10(Pwr);
   figure;plot(tau,Pwr_dB);
   xlabel('Delay in microseconds');
   ylabel('Power in dB');
   title('Typical Delay Profile for suburban and urban areas');
   axis([0 7 -30 0])

   %Total power of each tap, P = alpha^2 + 2sigma^2
   % where sigma = variance
   % Ratio of powers, K = alpha^2/2sigma^2
```

```
  for a=1:L
    sigma2(:,a) = Pwr(:,a)./(K(:,a)+1);              % calculate variance
    alpha2(:,a) = Pwr(:,a).*[(K(:,a)./(K(:,a)+1))];    % calculate constant power
    alpha(:,a) = sqrt(alpha2(:,a));                   % calculate constant part
  end

elseif area == 2

  for tau = 0:2
    Pwr(tau+1) = (exp(-3.5*tau));
    Pwr_dB(tau+1) = 10*log10(Pwr(tau+1));
  end
  for tau = 15:20
    Pwr(tau+1) = (0.1*exp(15-tau));
    Pwr_dB(tau+1) = 10*log10(Pwr(tau+1));
  end

  W = (randn(M,L) + j* randn(M,L))./sqrt(2); % Generate a set of complex white
Gaussian processes
  K = round(rand(1,L));

  for c=0:1:N
    t1 = 0;
    t2 = 20;
    tau(c+1) = (t1 + (t2-t1))*(c/N);
  end

  Pwr_dB(2:15)=-30;
  figure;plot(0:20,Pwr_dB)
  xlabel('Delay in microseconds');
  ylabel('Power in dB');
  title('Typical Delay Profile for Hilly Terrain');
  axis([0 20 -30 0])

  for a=1:L
    sigma2(:,a) = Pwr(:,a)./(K(:,a)+1);           % calculate variance
    alpha2(:,a) = Pwr(:,a).*[(K(:,a)./(K(:,a)+1))]; % calculate constant power
    alpha(:,a) = sqrt(alpha2(:,a));              % calculate constant part
  end
end

% End of function file: delayprofile.m


% -------------------------------------------------------------------
```

```
% Filename: jakes.m
% ----------------------------------------------------------------------
% Input parameters:
% fdmax = max Doppler frequency
% ----------------------------------------------------------------------
% Output:
% impw = impulse response
% ----------------------------------------------------------------------

function [impw] = jakes(fdmax)

n = 512;
nn = 2*n;
fs = 0:fdmax/64:fdmax;
H = zeros(1,n);

for k=1:(n/8+1) %psd for k=1:65
    jpsd(k)=1/((1-((fs(k))/fdmax)^2)^0.5);
    if(jpsd(k))>1000
        jpsd(k)=1000;
    end
    H(k)=jpsd(k)^0.5;
end
for k=1:n
    H(n+k) = H(n+1-k);
end
[inv,time] = linear_fft(H,nn,fdmax/64);
imp = real(inv(450:577));
impw = imp.*hanning(128)';
energy = sum(impw.^2);
impw=impw/(energy^0.5);

%End of function file: jakes.m




% ----------------------------------------------------------------------
```

```
% Filename: qpsk.m
% ---------------------------------------------------------------------
%
% ---------------------------------------------------------------------
% Output:
% seq = QPSK signals
% ---------------------------------------------------------------------

function seq=qpsk;

%Establish QPSK signals
%
seq = rand_bin(256,16)+i*rand_bin(256,16);    %QPSK signal

%End of funtion file: qpsk.m
```

```
% ---------------------------------------------------------------------
```

```
% Filename: rand_bin.m
% ----------------------------------------------------------------------
% Input parameters:
% nbits, nsamples
% ----------------------------------------------------------------------
% Output:
% x, bits
% ----------------------------------------------------------------------

function [x,bits] = rand_bin(nbits,nsamples)

x=zeros(1,nbits*nsamples);
bits=round(rand(1,nbits));
for m=1:nbits
   for n=1:nsamples
      index = (m-1)*nsamples + n;
      x(1,index) = (-1)^bits(m);
   end
end

%End of function file: rand_bin.m
```

```
% ----------------------------------------------------------------------
```

```
% Filename: envelope.m
% --------------------------------------------------------------------
% Input parameters:
% H_f,ts,hn,L
% --------------------------------------------------------------------
% Output:
% Plots of Estimated Power Spectral Density;
% Fading Envelope;
% TDL Gain Coefficient(real); TDL Gain Coefficient(imag)
% --------------------------------------------------------------------

function envelope(H_f,ts,hn,L);

x = randn(1,1024);
y = filter(H_f,1,x);
[output_psd ff] = log_psd(y,1024,ts);

%Plot Estimated Power Spectral Density
figure;subplot(2,1,1)
plot(ff,output_psd);grid;
axis([-500 500 -50 0])
xlabel('Frequency'); ylabel('PSD');
title('Estimated Power Spectral Density');

z = randn(1,1024)+i*randn(1,1024);
zz = filter(H_f,1,z);
time = (0.0:ts:1024*ts);

%Plot Fading Envelope
zz = zz/max(max(abs(zz)));
subplot(2,1,2)
plot(time(1:1024),10*log10(abs(zz(1:1024))));grid;
axis([0.1 0.3 -20 0])
xlabel('Time'); ylabel('Log Amplitude')
title('Fading Envelope');

hn1 = real(hn);
hn2 = imag(hn);

%Plot TDL Coefficient
figure;subplot(2,1,1); stem(hn1,'o');
xlabel('Number of tap');
ylabel('Magnitude');
title('TDL gain coefficient (real)'); grid on;
subplot(2,1,2); stem(hn2,'o');
xlabel('Number of tap');
```

```
ylabel('Magnitude');
title('TDL gain coefficient (imag)'); grid on;

%End of function file: envelope.m
```

```
% ---------------------------------------------------------------------
```

```
% Filename: linfft.m
% ----------------------------------------------------------------------
% Input parameters:
% x,n,ts
% ----------------------------------------------------------------------
% Output:
% fftx,freq
% ----------------------------------------------------------------------

function [fftx,freq] = linear_fft(x,n,ts)

y=zeros(1,n);
for k=1:n
   freq(k) = (k-1-(n/2))/(n*ts);
   y(k) = x(k)*((-1.0)^(k+1));
end;
fftx = fft(y)/n;

%End of function file: linfft.m
```

```
% ----------------------------------------------------------------------
```

```
% Filename: log_psd.m
% ----------------------------------------------------------------------
% Input parameters:
% x,n,ts
% ----------------------------------------------------------------------
% Output:
% logpsd,freq,ptotal,pmax
% ----------------------------------------------------------------------

function [logpsd,freq,ptotal,pmax] = log_psd(x,n,ts)

y = zeros(1,n); %initialize y vector

h = waitbar(0,'For Loop in PSD Calculation');
for k=1:n
   freq(k)=(k-1-(n/2))/(n*ts);
   y(k)=x(k)*((-1.0)^k);
   waitbar(k/n)
end;

v = fft(y)/n;
psd = abs(v).^2;
pmax=max(psd);
ptotal=sum(psd);
logpsd = 10*log10(psd/pmax);

%Truncate negative values at -60dB

for k=1:n
   if(logpsd(k)<-60.0)
      logpsd(k) = -60.0;
   end
end
close(h)

%End of function file: log_psd.m
```

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