FADING CHANNEL CHARACTERIZATION AND MODELING

A graduate project submitted in partial fulfillment of the requirements
For the degree of Master of Science
in Electrical Engineering

By

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# Table of Contents

Signature Page ....................................................................................................................... ii

Abstract ........................................................................................................................................ iv

1. Introduction ............................................................................................................................... 1

2. Background................................................................................................................................. 2

   2.1 Large scale fading ............................................................................................................... 3

   2.2 Small scale fading ............................................................................................................... 4

       2.2.1 Time spreading of the signal ..................................................................................... 6

       2.2.2 Time variance of the channel .................................................................................... 7

   2.3 Performance over a slow and flat fading channel .............................................................. 9

   2.4 Modeling a BFSK and BPSK with Simulink ................................................................. 11

3. Rayleigh fading channel .......................................................................................................... 14

   3.1 Performance of Rayleigh fading channel ......................................................................... 14

   3.2 Modeling a Rayleigh fading channel with Simulink .................................................... 16

       3.2.1 Block descriptions ...................................................................................................... 16

       3.2.2 Bit Error Rate Tool in Simulink .............................................................................. 17

       3.2.3 System design .......................................................................................................... 22

4. Rician fading channel ............................................................................................................. 27

   4.1 Performance of Rician fading channel .............................................................................. 27

   4.2 Modeling a Rician fading channel with Simulink ...................................................... 29

       4.2.1 Block descriptions ...................................................................................................... 29

       4.2.2 Bit Error Rate Tool for Rician fading channel ................................................... 30

       4.2.3 System design .......................................................................................................... 32

5. Summary and Conclusion ....................................................................................................... 36

Bibliography ............................................................................................................................. 37
ABSTRACT

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Multipath fading is one of the significant factors that affect the performance of a wireless communications link. Theoretical results exist for calculating link performance in the presence of a fading channel for some modulation schemes and some types of fading. In other cases, link performance must be evaluated by simulation. Mathworks’ Simulink is one tool used for these simulations. Mathworks provides pre-constructed blocks for both Rician and Rayleigh fading which accept parameters defining these fading models. The proper use of these blocks to include the parameters that define fading channels has been described. These blocks make it easy to model complex fading systems. Simulation results for link performance obtained using these channel-modeling blocks in BPSK and BFSK systems correspond closely to the theoretical results. The work presented here should be of interest to others studying wireless communications.
1. Introduction

Multipath fading is one of the significant factors that affect the performance of a wireless communications link. Theoretical results exist for calculating link performance in the presence of a fading channel for some modulation schemes and some types of fading. In other cases, link performance must be evaluated by simulation. Mathworks’ Simulink is one tool used for these simulations. Mathworks provides pre-constructed blocks for both Rician and Rayleigh fading which accept parameters defining these fading models. This project studies the use of the various fading channel models available in Simulink.

Section 2 of this report provides theoretical background on large and small scale fading. Section 2 also introduces the use of Simulink as a tool for modeling communications links. Section 3 presents the theoretical model of a Rayleigh fading channel and its effect on link performance. These results are compared to those obtained from the Simulink model. Section 4 presents a similar comparison for a Rician fading channel. Section 5 presents the summary and conclusions.
2. Background

In wireless communications, a signal often undergoes reflection, diffraction and scattering from the buildings, trees, mountains, etc. when propagating from a transmitter to receiver. Therefore, multipath signals will arrive at a receiver with different amplitudes and phases. This phenomenon is referred to as multipath fading. Figure 1 characterizes two types of fading: large scale fading and small scale fading [1]. Large scale fading represents the path loss due to motion over large areas. Small scale fading refers to large changes in the amplitude and phase of a signal caused by a small change in the position of the transmitter or receiver. Small scale fading has two manifestations: time spreading of the signal and time variance of the channel.

![Fading manifestations diagram]

*Figure 1: Fading manifestations*
2.1 Large scale fading

Large scale fading represents the path loss of a signal affected by large objects, like hills, forests, buildings, etc. between a transmitter and receiver. It occurs when a mobile transmitter and/or receiver moves over long a distance, resulting in rapid fluctuations in the received signal’s envelope. In mobile communications, large scale fading occurs in urban, outdoor-to-indoor and indoor environments.

For both indoor and outdoor channels, the mean path loss $\bar{L}_p(d)$, as a function of distance, $d$, between a transmitter and receiver, is directly proportional to the $n$th power of the ratio of the distance from the transmitter to the receiver and a reference distance $d_0$, as shown in equation 2.1 [1]. This equation was developed based on Okumura’s path-loss measurements.

$$\bar{L}_p(d) \propto \left(\frac{d}{d_0}\right)^n$$  \hspace{1cm} \text{(equation 2.1)}

or, in decibels: $\bar{L}_p(d) = L_s(d_0) + 10n \log\left(\frac{d}{d_0}\right)$

where $L_s(d_0) = \left(\frac{4\pi d_0}{\lambda}\right)^2$ is the free space path loss between a transmitter and receiver and $n$ is the path loss exponent described below. The free path loss model assumes that the region between a transmitter and receiver is free of all objects that can absorb or reflect power. In addition, the atmosphere is assumed to be as a non-absorbing medium and its reflection coefficient is negligible.

Typically, the value of the reference distance, $d_0$, is 1km for large cellular radio cells, 100m for microcells, and 1m for indoor channels. The path loss exponent, $n$, depends on the frequency of the propagating signal, antenna height, and propagation environment (in free space $n = 2$). The value of $n$ can be higher than 2 if there are
obstacles between the transmitter and receiver. Table 1 shows the typical large scale path loss over some environments [2].

<table>
<thead>
<tr>
<th>Environment</th>
<th>Path Loss Exponent, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free space</td>
<td>2</td>
</tr>
<tr>
<td>Urban area cellular radio</td>
<td>2.7 to 3.5</td>
</tr>
<tr>
<td>Shadowed urban cellular radio</td>
<td>3 to 5</td>
</tr>
<tr>
<td>In building line-of-sight</td>
<td>1.6 to 1.8</td>
</tr>
<tr>
<td>Obstructed in building</td>
<td>4 to 6</td>
</tr>
<tr>
<td>Obstructed in factories</td>
<td>2 to 3</td>
</tr>
</tbody>
</table>

*Table 1: Path loss exponents for different environments*

### 2.2 Small scale fading

Small scale fading refers to large changes in the amplitude and phase of a signal caused by a small change in the position of the transmitter or receiver (on the order of half a wavelength). This effect is due to constructive and destructive interference of the transmitted signal that occurs at very high carrier frequencies (900 MHz or 1.9 GHz for cellular).

*Figure 2: Multipath fading*
Both Rayleigh and Rician fading are used to model small scale fading. Figure 2 illustrates multipath fading between a transmitter and receiver. There are line of sight (LOS) or direct paths and non-line of sight (NLOS) paths where the transmitted signal is reflected by obstacles. If there is no line of sight path among the multiple paths between a transmitter and receiver, a Rayleigh fading model is used. Rician fading is used when there is a strong line of sight path between the transmitter and receiver.

Small scale fading includes two phenomena: time spreading due to multipath delay and time variance due to motion between a transmitter and receiver (or Doppler spread). Both phenomena can be described in either the time domain or frequency domain, as indicated in figure 3 [2].

**Small scale fading based on multipath time delay spread**

- **Flat Fading**
  1. BW of signal < BW of channel
  2. Delay spread < Symbol period

- **Frequency Selective Fading**
  1. BW of signal > BW of channel
  2. Delay spread > Symbol period

**Small scale fading based on Doppler spread**

- **Fast Fading**
  1. High Doppler spread
  2. Coherence time < Symbol period
  3. Channel variations faster than baseband signal variations

- **Slow Fading**
  1. Low Doppler spread
  2. Coherence time > Symbol period
  3. Channel variations slower than baseband signal variations

*Figure 3: Type of small scale fading*
2.2.1 Time spreading of the signal

Time spreading of the signal due to small scale fading can be characterized in the time domain and in the frequency domain. This causes the transmitted signal to undergo either flat or frequency selective fading.

2.2.1.1 Signal time spreading viewed in the time domain

In a fading channel, the time delay is referred to the maximum excess delay, $T_m$. This is the time between the first and the last copies of transmitted signal. If $T_m$ is greater than the symbol period, $T_s$, the channel is said to be a frequency selective fading channel. Otherwise, the channel is said to be a frequency nonselective or flat fading channel, this means all multipath signals arrive at the receiver within a symbol period of the transmitted signal.

2.2.1.2 Signal time spreading viewed in the frequency domain

The coherent bandwidth of the channel, $f_0$, is the frequency range over which the channel will add the same amount of gain and linear phase to a transmitting signal. Two signals with a frequency separation greater than $f_0$ are affected differently by the channel.

The relationship between coherent bandwidth and the time delay is specified as: $f_0 \approx 1/T_m$.

A channel is said to be a frequency selective if the coherent bandwidth of the channel is small in comparison to the bandwidth $W$ of a transmitted signal ($f_0 < W$). In frequency selective fading, distortion is possible because many of the multipath components are resolvable by the receiver.

Flat fading occurs when $f_0 > W$. This implies that the coherent bandwidth of the channel is large in comparison to the bandwidth of the transmitted signal. Flat fading
channels are also known as amplitude varying channels or narrowband channels. There is no channel-induced distortion in flat fading. However, the signal still goes through performance degradation due to the loss in signal to noise ratio caused by the fading.

2.2.2 Time variance of the channel

For mobile radio communications, the channel is time variant because a propagation channel depends on the position of the transmitter and receiver. The time variant fading will be characterized in the time domain as a channel coherence time and in the Doppler shift frequency domain as a Doppler spread rate. The relative motion between transmitter, receiver and obstacles causes a Doppler shift.

2.2.2.1 Time variance viewed in the time domain

Channel coherence time, $T_0$, is the period of time during which the fading process is correlated. It can be measured in terms of either time or distance traversed. When the coherence time of the channel is smaller than the symbol period of the transmitted signal ($T_0 < T_s$), the channel is described as a fast fading channel. Fast fading causes distortion because the time period where the channel behaves in a correlated manner is less than the time duration of a symbol. On the other hand, if $T_0 > T_s$, the channel is said to be slow fading. It implies that channel characteristics vary slowly; hence, the distortion can be eliminated. The only thing that degrades the performance of the channel is the decrease in signal to noise ratio.
2.2.2.2 Time variance viewed in the Doppler shift domain

Doppler spread of the channel, \( f_d \), is a measure of the spectral broadening caused by the relative movement of the mobile and base station or by movement of objects in the channel, \( f_d \approx 1/T_0 \). If the mobile unit moves at speed, \( v \), making an angle of \( \alpha \) with the direction of the wave motion, the Doppler spread is \( f_d = \frac{vf}{c} \cos \alpha \) where \( f \) is the carrier frequency and \( c \) is the speed of light. The Doppler spread is maximized when the scattered signal is directly ahead of the moving antenna or directly behind it (\( \alpha = 0^\circ, 180^\circ \)) as described in figure 4. When the transmitter and receiver move toward each other, \( f_d \) is positive. When the transmitter moves away from the receiver, \( f_d \) is negative. The channel is referred to as fast fading when the bandwidth of the transmitted signal is smaller than the Doppler spread of the channel (\( W < f_d \)). Signal distortion increases when Doppler spread increases in relation to the bandwidth of the transmitted signal. On the other hand, slow fading occurs when the Doppler spread of the channel is much less than the bandwidth of the transmitted signal (\( f_d < W \)).

![Figure 4: Doppler Spread Detail](image)

Figure 4: Doppler Spread Detail
2.3 Performance over a slow and flat fading channel

This section will describe the theoretical bit error rate performance of binary phase shift keying (BPSK) and binary frequency shift keying (BFSK) when the signals are transmitted over a slow and flat fading channel.

A transmitted signal can be represented in general as:

\[ s(t) = Re\left[s_1(t)e^{j2\pi f_c t}\right] \quad [3] \]

where \( f_c \) is the carrier frequency and \( s_1(t) \) is the complex envelope.

With each multiple path arriving at the receiver, there is a propagation delay and an attenuation factor. Therefore, the received band-pass signal can be written in the form:

\[ x(t) = \sum_n \alpha_n(t)s(t - \tau_n(t)) = Re\left\{\left[\sum_n \alpha_n(t)e^{-j2\pi f_c \tau_n(t)}s_1(t - \tau_n(t))\right]e^{j2\pi f_c t}\right\} \]

where \( \alpha_n(t) \) is the attenuation factor on the \( n^{th} \) path and \( \tau_n(t) \) is the propagation delay for the \( n^{th} \) path.

The equivalent lowpass received signal is:

\[ r_1(t) = \sum_n \alpha_n(t)e^{-j2\pi f_c \tau_n(t)}s_1(t - \tau_n(t)) \]

And the equivalent lowpass time-variant impulse response is:

\[ c(\tau ; t) = \sum_n \alpha_n(t)e^{-j2\pi f_c \tau_n(t)}\delta(t - \tau_n(t)) \]

Where \( c(\tau ; t) \) is the response of the channel at time \( t \) due to an impulse applied at time \( t - \tau \).

If the signal is transmitted as an unmodulated carrier at frequency \( f_c \) then \( s_1(t) = 1 \) for all \( t \). Thus, the discrete multipath received signal will reduce to:

\[ r_1(t) = \sum_n \alpha_n(t)e^{-j2\pi f_c \tau_n(t)} = \sum_n \alpha_n(t)e^{-j\theta_n(t)} \quad \text{(equation 2.2)} \]

Where \( \theta_n(t) = 2\pi f_c \tau_n(t) \)
Therefore the received signal is the sum of n time variant vectors with amplitude $\alpha(t)$ and phase $\theta(t)$. When $\tau_n(t)$ changes by $1/f_c$, $\theta_n(t)$ will change by $2\pi$. The propagation delay $\tau_n(t)$ of each path can be described by a random variable. Hence the received signal $r_1(t)$ can be modeled as a random process. When there are multiple paths at the receiver, the central limit theorem can be applied. Therefore, the received signal $r_1(t)$ can be modeled as a complex valued, Gaussian random process.

In flat fading ($f_0 > W$), all frequency components of transmitted signal undergo the same attenuation and phase shift when travelling through the channel. Also, the multipath components in the received signal are not resolvable; the received signal arrives at the receiver via a single fading path. A slow fading channel implies that the amplitude and phase of the transmitted signal can be considered as a constant during at least one signaling interval. If the transmitted signal is $s_1(t)$, the received signal with the noise included in one symbol period is:

$$r_1(t) = \alpha_n(t)e^{-j\theta_n(t)}s_1(t) + n(t)$$

(equation 2.3)

$n(t)$: the complex valued white Gaussian noise.

Assume that the signal is transmitted over a flat and slow fading channel. A slow fading channel is independent of the phase shift. Hence, the received signal can be processed by passing it through a matched filter in BPSK or through a pair of matched filters in the case of BFSK. In addition, the flat fading implies that the received signal will arrive at the receiver through a single fading path.

One way to characterize the performance of a communications link over a fading channel is by using the probability of bit error. The probability of bit error for coherently detected BPSK is defined as: $P(\gamma_b) = Q(\sqrt{2\gamma_b})$ and the probability of bit error for
coherently detected binary orthogonal FSK is: \( P(\gamma_b) = Q(\sqrt{\gamma_b}) \) [3] where \( \gamma_b \) is a function of received signal to noise ratio \( \gamma_b = \frac{a^2 E_b}{N_0} \).

The probability of bit error on fading channel is:

\[
P = \int_0^\infty P(\gamma_b) p(\gamma_b) d\gamma_b
\]

Where \( P(\gamma_b) \) is the probability of bit error and \( p(\gamma_b) \) is the probability density function of \( \gamma_b \).

2.4 Modeling a BFSK and BPSK with Simulink

Mathworks’ Simulink will be used as the simulation tool for this project. Figure 5 is a Simulink block diagram for a link using binary frequency shift keying (BFSK). The data source is modeled by the “Random Integer Generator” block. The output of the Random Integer block is a unipolar binary sequence. After the data source has been generated, it is applied to an M-FSK modulator baseband block. This modulator block will output a baseband signal represented by I and Q values. The output of the baseband signal from the modulator block is applied to an AWGN channel block. This AWGN block takes as input the desired \( E_b/N_0 \) value, the signal power and bit duration. From the input, the block will add noise with the appropriate variance to the signal. Then, a coherent detector is used to demodulate the BFSK signal. In order to verify the proper operation of this simulation, the output of the demodulator is fed into an error rate calculator block as shown in figure 5. The error rate calculator block takes the received demodulated signal and the original data sequence signal as inputs and compares them. The error rate calculator will give a bit error rate for the received signal based on doing a bit to bit comparison. The waterfall curve in figure 6 is generated by performing this
simulation multiple times with different $E_b/N_0$. This is plotted along with the theoretical probability of error for BFSK: $P = Q\left(\sqrt{\frac{E_b}{N_0}}\right)$. These two curves match, verifying the correct operation of this simulation.

Figure 5: BFSK Transmitter Receiver System

Figure 6: BFSK BER Waterfall Curve Simulation vs Theory
For binary phase shift keying (BPSK), the block diagram will be the same as BFSK except that the BPSK modulator and BPSK demodulator blocks will be used. Figure 7 shows the BPSK simulation model. Figure 8 is the comparison between simulated bit error rate and the theoretical bit error rate for BPSK, which is given in equation: \( P = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \). Again, the simulated values match the theoretical values.

![BPSK Transmitter Receiver System](image)

**Figure 7: BPSK Transmitter Receiver System**

![BPSK BER Waterfall Curve Simulation vs Theory](image)

**Figure 8: BPSK BER Waterfall Curve Simulation vs Theory**
3. Rayleigh fading channel

3.1 Performance of Rayleigh fading channel

In urban areas with many buildings, vehicles and other large objects, transmitted signals arrive at the receiver over multiple paths as discussed in section 2. The combination of these multiple received signals causes fading. A Rayleigh fading channel occurs when there are many different signal paths between the transmitter and receiver, none of which is dominant. It means all the paths will fluctuate and have an effect on the overall signal at the receiver.

When the impulse response from section 2.3, \( c(\tau; t) \), is modeled as a zero-mean, complex valued, Gaussian process, the envelope of \( c(\tau; t) \) at any instant \( t \) is Rayleigh distributed and the phase is uniformly distributed in the interval \((0, 2\pi)\). In this case, the channel is said to be a Rayleigh fading channel. This is the simplest fading channel from the standpoint of analytical characterization.

The Rayleigh probability density function of the received signal envelope, \( p(r_0) \), is given by:

\[
p(r_0) = \frac{r_0}{\sigma^2} \exp \left( -\frac{r_0^2}{2\sigma^2} \right) \text{ when } r_0 \geq 0
\]  

(equation 3.1)

where \( r_0 \) is the envelope amplitude of the received signal, \( \sigma^2 \) is the variance of the random variable and \( 2\sigma^2 \) is the average power of the multipath signal [1].

In a Rayleigh fading channel, \( \alpha \) in equation 2.3 is Rayleigh distributed and \( \alpha^2 \) has a chi-squared distribution. Accordingly, \( \gamma_b \) is also a chi-squared distribution. Therefore, the probability density function of the instantaneous signal to noise ratio is given by:
\[ p(y_b) = \frac{1}{\overline{y}_b} e^{-y_b/\overline{y}_b}, y_b \geq 0 \]  \hspace{2cm} \text{(equation 3.2)}

Where \( \overline{y}_b \) is the average signal to noise ratio (SNR) per bit: \( \overline{y}_b = \frac{E_b}{N_0} E(\alpha^2) \) and \( E(\alpha^2) \) is the average value of \( \alpha^2 \).

From section 2, the bit error rate of BPSK is given as \( P(\gamma_b) = Q(\sqrt{2\gamma_b}) \). If this value of \( P(\gamma_b) \) and the value of the probability density function in equation 3.2 are substituted into equation 2.4, we obtain the probability of bit error rate in the presence of Rayleigh fading channel for BPSK to be: \( P = \frac{1}{2} (1 - \sqrt{\frac{y_b}{1 + y_b}}) \) [3]. The same method is used for BFSK. Since \( P(\gamma_b) = Q(\sqrt{\gamma_b}) \) for BFSK, the probability of bit error rate in the presence of Rayleigh fading channel is \( P = \frac{1}{2} (1 - \sqrt{\frac{y_b}{2 + y_b}}) \) [3]. Those equations show that the BER of BFSK is greater than the BER of BPSK with the same \( \gamma_b \).
3.2 Modeling a Rayleigh fading channel with Simulink

3.2.1 Block descriptions

The multipath Rayleigh fading channel block implements a baseband simulation of a multipath Rayleigh fading propagation channel. It can be found under the Communications System Toolbox /Channels/Multipath Rayleigh Fading Channel.

Figure 9: Multipath Rayleigh Fading Channel Block

Figure 9 shows the parameters of the block. The Doppler shift is the relative motion between the transmitter and receiver as defined in section 2. The discrete path delay vector is the propagation delay for each path. The average path gain vector is the gain of each path. The discrete path delay vector and the path gain vector must have the same length if they are vectors. If they are scalar, the larger length of either the discrete
path delay vector or the average path gain vector parameters will become the number of propagation paths at the receiver. The complex path gains port generates a port which includes the values of the complex path gains for each path. If the “Normalize gain vector to 0 dB overall gain” box is checked, the Multipath Rayleigh Fading Channel block will use a multiple of the average path gain vector so that the gain of all paths is 0 dB. If the box is unchecked, the average path gain vector will specify the gain of each path.

Figure 9.2 shows all the Doppler spectrum types which consist of Jakes, Flat, Gaussian, Rounded, Restricted Jakes, Asymmetrical Jakes, Bi-Gaussian, and Bell. It specifies the Doppler spectrum of the Rayleigh process.

3.2.2 Bit Error Rate Tool in Simulink

This tool generates the ideal theoretical BER results for AWGN and Rayleigh or Rician flat fading channel. It can generate BER for PSK, OQPSK, DPSK, PAM, QAM, FSK, MSK, and CPFSK modulation as indicated in figure 10.1. Figure 10.2 shows the order of modulation varies from 2 to 64. When diversity is used in Rayleigh and Rician fading channels, the SNR on each diversity branch is $\frac{E_b}{N_0}/\text{number of diversity branches}$. 


Bertool can be used to generate and analyze BER data via the semi-analytic technique as showed in figure 12. This technique uses a combination of simulation and analysis to determine the error rate of a communication system.

The theoretical BERs which are generated in Bertool for BFSK and BPSK Rayleigh fading channels are the same as the calculated BERs when using the formulas in section 3.1 with a given $\frac{E_b}{N_0}$. For example, if $\frac{E_b}{N_0} = 5 \text{ dB} = 3.162$, the theoretical BER for BPSK with a Rayleigh fading channel is:

$$P_B = \frac{1}{2} \left[ 1 - \sqrt{\frac{E_b}{N_0}} \right] = 0.06418$$

which equals to the BER obtained with the Bertool and shown in figure 11.
Figure 11: The theoretical BER of BPSK Rayleigh fading channel

Figure 12: Semi-analytic technique in the bit error rate analysis tool
In addition, Bertool can also be used in conjunction with Simulink models to generate and collect BER data on the Monte Carlo tab. Bertool will run the simulation MATLAB file or Simulink model for each value of $E_b/N_0$, and gather BER data as displayed in figure 13.

This report only uses the first tab of the bit error rate analysis tool to compare the theoretical BER of two modulations: BPSK and BFSK. The result is showed below in figure 14. It is clear that the waterfall curve of BFSK is above the curve of BPSK. It means that the BER of BFSK will be greater than the BER of BPSK at the same $E_b/N_0$ value which is similar to the prediction in section 3.1.
Figure 14: Comparison the theoretical value between BPSK and BFSK Rayleigh fading channel by using Bertool
3.2.3 System design

3.2.3.1 Binary Phase Shift Keying Model

In figure 15, the BPSK modulator baseband block is used to generate a BPSK signal (figure 16.1). After the transmitter signal is created, it is applied to a Rayleigh fading channel block. The output of the fading channel is shown in figure 16.2.

The remove phase block is used to remove all the phase distortion caused by multiple paths fading as indicated in figure 16.3. Since this report assumes that the fading channel is a flat and slow fading, the transmitted signal is independent on the phase shift as described in section 2.3. The output of the remove phase block is applied to an AWGN channel block. In order to verify this simulation, the output of the demodulator is fed into an error rate calculation block. The error rate calculator will give a bit error rate for the received signal.
Figure 16: the output of BPSK Rayleigh fading channel

16.1: BPSK signal
16.2: output of BPSK signal after going through Rayleigh fading block
16.3: output of Rayleigh fading channel after removing phase shift
16.4: output of BPSK Rayleigh signal after AWGN

Figure 17: Remove phase block
In figure 17, the output of the multipath Rayleigh fading channel is applied to input 1 of the removing phase block and the complex gain port is applied to input 2. Input 1 is fed into the complex to magnitude-angle block. The phase output of that block is applied to the gain block. Then, the signal is applied to the exponential function block. After that, the product block is used to combine the output of the exponential block and the complex gain port to create an output signal without the phase shift.

Figure 18: BER comparison between the theory and simulation of AWGN and Rayleigh in BPSK

Figure 18 shows that the theoretical and the simulated value of the probability of bit error for BPSK in Rayleigh fading channel match. The performance of the link with Rayleigh fading is worse when compared with the AWGN channel only (no fading).
3.2.3.2 Binary Frequency Shift Keying Model

Figure 19: BFSK Rayleigh fading channel

In figure 19, the BFSK modulator baseband block is used to generate a BFSK signal. After the transmitter signal is created, it is applied to a Rayleigh fading channel block. The output of the fading channel is put through an AWGN channel block. In order to verify this simulation, the output of the demodulator is fed into an error rate calculation block. The error rate calculator will give a bit error rate for the received signal.
Figure 20: BER comparison between the theory and simulation of AWGN and Rayleigh in coherent BFSK

Figure 20 shows that the theoretical and the simulated value of the probability of bit error for BFSK in Rayleigh fading channel match. The performance of the link with Rayleigh fading is worse than the AWGN channel only.
4. Rician fading channel

4.1 Performance of Rician fading channel

A Rician fading channel occurs when the received signal is a combination of a significant line of sight path and multiple fading paths between a transmitter and receiver. The line of sight path is the strongest signal path that travels directly from the transmitter to receiver. Because of the line of sight path, the effect of Rician fading on the transmitted signal will be less than in the case of Rayleigh fading.

The impulse response in equation 2.3 cannot be modeled as a zero mean complex valued Gaussian process when fixed scatterers and randomly moving scatterers exist in the environment between the transmitter and receiver. In this instance, the envelope of $c(\tau; t)$ has a Rice distribution. Hence, the channel is referred to as a Rician fading channel.

The Rician probability density function of the received signal envelope is given by:

$$p(r_0) = \frac{r_0}{\sigma^2} \exp \left[ -\frac{(r_0^2 + A^2)}{2\sigma^2} \right] I_0 \left( \frac{r_0A}{\sigma^2} \right) \text{ for } r_0 \geq 0, A \geq 0$$

Where $I_0(\cdot)$ is the modified Bessel function of zero order and $A$ is the peak magnitude of the line of sight signal component [1]. In Rician fading channel, the $K$-factor is one of the inputs that defines the ratio of the power of the line of sight component and the multipath components ($K = \frac{A^2}{2\sigma^2}$). When $K$ is zero, the Rician fading channel becomes Rayleigh fading channel. When $K$ increases, the Rician fading channel approximates a Gaussian distribution with mean value $A$. Figure 21 shows the Rician probability density function at three different values of $K$ [4].
In a Rician fading channel, the probability density function of the instantaneous signal to noise ratio is given by: [4]

$$pdf_{\gamma_b}(\gamma_b) = \frac{1 + K}{\bar{\gamma}_b} \exp(-\frac{\gamma_b}{\bar{\gamma}_b}(1 + K) + K\bar{\gamma}_b) I_0\left(\frac{4(1 + K)K\gamma_b}{\sqrt{\bar{\gamma}_b}}\right)$$

The BER for non-ideal coherent detection of BPSK in a Rician fading environment is given by:

$$P_b = \frac{1}{2} \left[ 1 - Q_1(\sqrt{a}, \sqrt{b}) + Q_1(\sqrt{a}, \sqrt{b}) - \frac{A}{2} \exp\left(-\frac{a + b}{2}\right) I_0(\sqrt{ab}) \right]$$

where $$\{a, b\} = \frac{1}{2} \left( \sqrt{\frac{K}{1 + K} G\bar{\gamma}} \mp \sqrt{\frac{K}{1 + K} G\bar{\gamma}} \right)^2$$

and $$A = \frac{\sqrt{G}}{1 + K\bar{\gamma}} \sqrt{\left(\frac{G}{1 + K\bar{\gamma}} + 1\right)\left(\frac{1}{1 + K\bar{\gamma}} + 1\right)}$$

G is a nonideal coherent parameter [5].

The formula for Rician fading channel is very complex. Therefore, the Bertool in MATLAB will be used to calculate the theoretical value of probability of bit error rate for Rician fading.
4.2 Modeling a Rician fading channel with Simulink

4.2.1 Block descriptions

The multipath Rician fading channel block implements a baseband simulation of a multipath Rician fading propagation channel. It can be found under the Communications System Toolbox/Channels/Multipath Rician Fading Channel.

Figure 22: Multipath Rician Fading Channel Block

Figure 22 shows the parameters of the block. Most of the parameters are the same as the Multipath Rayleigh Fading Channel Block which is described in section 3.2.1. If the K-factor parameter is a scalar, the first discrete path of the channel is a line of sight component while the remaining paths are non-line of sight components. If the K-factor parameter is a vector of the same size as discrete path delay vector, each discrete path is a
line of sight path with a given K factor. The Doppler shift(s) of line of sight component(s) and initial phase(s) of line of sight component(s) parameters must be the same size as the K-factor parameter.

A Rician fading channel has the same Doppler spectrum types as the Rayleigh fading channel. They include: Jakes, Flat, Gaussian, Rounded, Restricted Jakes, Asymmetrical Jakes, Bi-Gaussian, and Bell as indicated in figure 22.2. These types specify the Doppler spectrum of the Rician process.

4.2.2 Bit Error Rate Tool for Rician fading channel

Figure 23 shows the theoretical value of BPSK Rician fading channel with varying k-factor. The probability of bit error rate decreases when k-factor increases. With a large value of k (k = 500), the bit error rate curve with Rician fading channel matches with the theoretical value with AWGN only as predicted in section 4.1. It is the same with BFSK Rician fading channel which is shown in figure 24.

Figure 23: Theoretical value of BPSK Rician fading channel with different value of K-factor
Figure 24: Theoretical value of BFSK Rician fading channel with different value of K-factor

Figure 25: Comparison of the theoretical value of BPSK and BFSK Rician fading channel with K-factor = 1

Figure 25 shows that the BER of BFSK is larger than the BER of BPSK with Rician fading channel at the same $E_b/N_0$ which is the same with the case of Rayleigh fading channel.
4.2.3 System design

4.2.3.1 Binary Phase Shift Keying Model

The BPSK Rician fading model of figure 26 is similar to figure 15, which is a BPSK Rayleigh fading model. The only difference is the output of BPSK modulator baseband block being applied to the Rician fading channel block instead of Rayleigh fading channel block.

Figure 27 shows the output of BPSK signal (figure 27.1), the BPSK Rician fading channel output (figure 27.2), the BPSK Rician fading channel output after removing the phase shift (figure 27.3) and the noisy Rician channel output (figure 27.4).
Figure 27: the output of BPSK Rician fading channel

27.1: BPSK signal
27.2: output of BPSK signal after going through Rician fading block
27.3: output of Rician fading channel after removing phase shift
27.4: output of BPSK Rician signal after AWGN
Figure 28: BER comparison between the theory and simulation of AWGN and Rician (k-factor = 1) in BPSK

Figure 28 shows that the theoretical and the simulated value of the probability of bit error rate for BPSK in Rician fading channel match. In that case, the Rician K-factor is set to 1. The performance of BPSK Rician fading with a small value of k-factor is similar to the performance of BPSK Rayleigh fading (in section 3) when compared with the AWGN channel.

4.2.3.2 Binary Frequency Shift Keying Model

Figure 29: BFSK Rician fading channel
In figure 29, the BFSK Rician fading model is similar to figure 19 which is BFSK Rayleigh fading model. The only difference is the output of the BFSK modulator baseband block is applied to the Rician fading channel block instead of the Rayleigh fading channel block.

![BER for BFSK modulation in Rician channel](image)

*Figure 30: BER comparison between the theory and simulation of AWGN and Rician (k-factor = 1) in coherent BFSK*

Figure 30 shows that the theoretical and the simulated value of the probability of bit error for coherent BFSK in Rician fading channel are close. The BER of BFSK Rician fading channel with a small value of k-factor is much higher than the AWGN channel only.
5. Summary and Conclusion

The use of Simulink fading channel modeling blocks has been studied for both the Rayleigh and Rician fading channel models. The proper use of these blocks to include the parameters that define fading channels has been described. These blocks make it easy to model complex fading systems. Simulation results for link performance obtained using these channel-modeling blocks in BPSK and BFSK systems correspond closely to the theoretical results. The work presented here should be of interest to others studying wireless communications.

It would be useful to compare the theoretical and simulated results for modulation schemes using a combination of amplitude and phase modulation such as QAM.

This project is limited to the Rayleigh and Rician fading models. There are other fading models of interest such as the Nakagami-m, Nakagami-q, and log normal models. At this time Simulink does not include fading channel blocks for these models.
Bibliography


