Simulation of Flat Fading Using MATLAB for Classroom Instruction

Gayatri S. Prabhu and P. Mohana Shankar, *Senior Member, IEEE*

Abstract—An approach to demonstrate flat fading in communication systems is presented here, wherein the basic concepts are reinforced by means of a series of MATLAB (Mathworks, Inc., Natick, MA 01760–2098 USA) simulations. Following a brief introduction to fading in general, models for flat fading are developed and simulated using MATLAB. The concept of outage is also demonstrated using MATLAB. The authors suggest that the use of MATLAB exercises will assist the students in gaining a better understanding of the various nuances of flat fading.

Index Terms—Fading, MATLAB-based instruction, mobile communications, simulation of fading, wireless systems.

I. INTRODUCTION

WIRELESS communications is one of the fastest growing areas in electrical engineering. As a result, courses in wireless communications are being offered as a part of the electrical engineering curriculum at the undergraduate and graduate levels. With the incorporation of computers in the curriculum [1], [2], it has become much easier to bring some of the concepts of this new and exciting field of wireless communications into the classroom. MATLAB (Mathworks, Inc., Natick, MA 01760–2098 USA) is being used extensively in colleges and universities to accomplish this integration of computers and curriculum. In this paper, a MATLAB-based approach is proposed and implemented to demonstrate the concept of fading, one of the important topics in wireless communications.

Before delving into the details of how MATLAB is used as a learning tool, it is necessary to understand underlying principles of fading in wireless systems. These principles are discussed in Section II. Section III shows how MATLAB can be used to reinforce these concepts. The results obtained from the MATLAB simulations are discussed in this section. The use of these results in the calculation of outage probability is presented in Section IV. Finally, the concluding remarks are given in Section V.

II. FADING IN A WIRELESS ENVIRONMENT

Radio waves propagate from a transmitting antenna and travel through free space undergoing absorption, reflection, refraction, diffraction, and scattering. They are greatly affected by the ground terrain, the atmosphere, and the objects in their path,
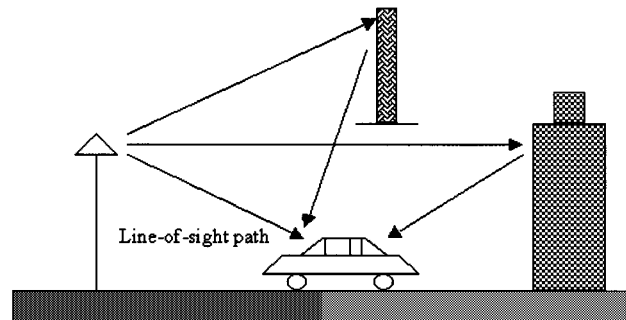
Fig. 1. Mechanism of radio propagation in a mobile environment. A number of indirect paths and an LOS path are shown.

such as buildings, bridges, hills, and trees. These multiple physical phenomena are responsible for most of the characteristic features of the received signal.

In most of the mobile or cellular systems, the height of the mobile antenna may be smaller than the surrounding structures. Thus, the existence of a direct or *line-of-sight* (LOS) path between the transmitter and the receiver is highly unlikely. In such a case, propagation comes from reflection and scattering from the buildings and diffraction over or around them. Thus, in practice, the transmitted signal arrives at the receiver via several paths, with different time delays creating a *multipath* situation, as shown in Fig. 1.

At the receiver, these multipath waves with randomly distributed amplitudes and phases combine to give a resultant signal that fluctuates in time and space. Therefore, a receiver at one location may have a signal that is much different from the signal at another location only a short distance away because of the change in the phase relationship among the incoming radio waves. This situation causes significant fluctuations in the signal amplitude. This phenomenon of random fluctuations in the received signal level is termed as *fading*.

Whereas the short-term fluctuation in the signal amplitude caused by the local multipath is called *small-scale fading*, and is observed over distances of about half a wavelength, long-term variation in the mean signal level is called *large-scale fading*. The latter effect is a result of movement over distances large enough to cause gross variations in the overall path between the transmitter and the receiver. Large-scale fading is also known as *shadowing* because these variations in the mean signal level are caused by the mobile unit moving into the shadow of surrounding objects, such as buildings and hills. Because of multipath, a moving receiver can experience several fades in a very short duration. In a more serious case, the vehicle may stop at a location where the signal is in deep fade; in such a situation,

maintaining good communication becomes an issue of great concern.

Small-scale fading can be further classified as flat or frequency selective, and slow or fast [3]. A received signal is said to undergo *flat fading* if the mobile radio channel has a constant gain and a linear phase response over a bandwidth larger than the bandwidth of the transmitted signal. Under these conditions, the received signal has amplitude fluctuations as a result of the variations in the channel gain over time caused by multipath. However, the spectral characteristics of the transmitted signal remain intact at the receiver. If the mobile radio channel has a constant gain and linear phase response over a bandwidth smaller than that of the transmitted signal, the transmitted signal is said to undergo *frequency selective fading*. In this case, the received signal is distorted and dispersed because it consists of multiple versions of the transmitted signal, attenuated and delayed in time. The result is time dispersion of the transmitted symbols within the channel arising from these different time delays bringing about *intersymbol interference* (ISI).

When there is relative motion between the transmitter and the receiver, Doppler spread is introduced in the received signal spectrum, causing frequency dispersion. If the Doppler spread is significant relative to the bandwidth of the transmitted signal, the received signal is said to undergo *fast fading*. This form of fading typically occurs for very low data rates. However, if the Doppler spread of the channel is much less than the bandwidth of the baseband signal, the signal is said to undergo *slow fading*.

The work reported here will be confined to flat fading. Results on shadowing or lognormal fading are also presented because of the existence of some general approaches, which incorporate short-term and long-term fading resulting in a single model. Details of these models are available elsewhere [3], [4] and will not be described in this work.

III. STATISTICAL MODELING OF FLAT FADING USING MATLAB

To fully understand wireless communications, the student must learn what happens to the signal as it travels from the transmitter to the receiver. As explained earlier, one of the important aspects of this path between the transmitter and receiver is the occurrence of fading. MATLAB provides a simple and easy way to demonstrate fading taking place in wireless systems. The radiofrequency (RF) signals with appropriate statistical properties can readily be simulated. Statistical testing can subsequently be used to establish the validity of the fading models frequently used in wireless systems. The different fading models and MATLAB-based simulation approaches will now be described.

A. Rayleigh Fading

The mobile antenna, instead of receiving the signal over one LOS path, receives a number of reflected and scattered waves, as shown in Fig. 1. Because of the varying path lengths, the phases are random and, consequently, the instantaneous received power becomes a random variable. In the case of an unmodulated carrier, the transmitted signal at frequency ω_c reaches the receiver via a number of paths, the ith path having an amplitude a_i and

a phase ϕ_i. If it is assumed that there is no direct path or LOS component, the received signal $s(t)$ can be expressed as

$$s(t) = \sum_{i=1}^{N} a_i \cos(\omega_c t + \phi_i) \tag{1}$$

where N is the number of paths. The phase ϕ_i depends on the varying path lengths, changing by 2π when the path length changes by a wavelength. Therefore, the phases are uniformly distributed over $[0, 2\pi]$. When there is relative motion between the transmitter and the receiver, (1) must be modified to include the effects of motion-induced frequency and phase shifts. The ith reflected wave with amplitude a_i and phase ϕ_i arrive at the receiver from an angle ψ_i relative to the direction of motion of the antenna. The Doppler shift of this wave is given by

$$\omega_{d_i} = \frac{\omega_c v}{c} \cos \psi_i \tag{2}$$

where v is the velocity of the mobile, c is the speed of light $(3 \times 10^8$ m/s$)$, and ψ_is are uniformly distributed over $[0, 2\pi]$. The received signal $s(t)$ can now be written as

$$s(t) = \sum_{i=1}^{N} a_i \cos(\omega_c t + \omega_{d_i} t + \phi_i). \tag{3}$$

Expressing the signal in inphase and quadrature form, (3) can be written as

$$s(t) = I(t) \cos \omega_c t - Q(t) \sin \omega_c t \tag{4}$$

where the inphase and quadrature components are respectively given as

$$I(t) = \sum_{i=1}^{N} a_i \cos(\omega_{d_i} t + \phi_i) \tag{5}$$

and

$$Q(t) = \sum_{i=1}^{N} a_i \sin(\omega_{d_i} t + \phi_i). \tag{6}$$

The envelope R is given by

$$R = \sqrt{[I(t)]^2 + [Q(t)]^2}. \tag{7}$$

When N is large, the inphase and quadrature components will be Gaussian [5]. The probability density function (pdf) of the received signal envelope $f(r)$ can be shown to be Rayleigh, given by

$$f(r) = \frac{r}{\sigma^2} \exp\left\{-\frac{r^2}{2\sigma^2}\right\}, \qquad r \geq 0 \tag{8}$$

where $2\sigma^2$ is the average power. The multipath faded signal was simulated using MATLAB to understand the relationship between the number of paths (N) and statistics of the received signal. The carrier frequency used was 900 MHz. The number of paths (no LOS) N was varied from four to 40. For each value of N, simulation was carried out for a time interval corresponding to 1250 wavelengths. This was repeated 50 times and averaged
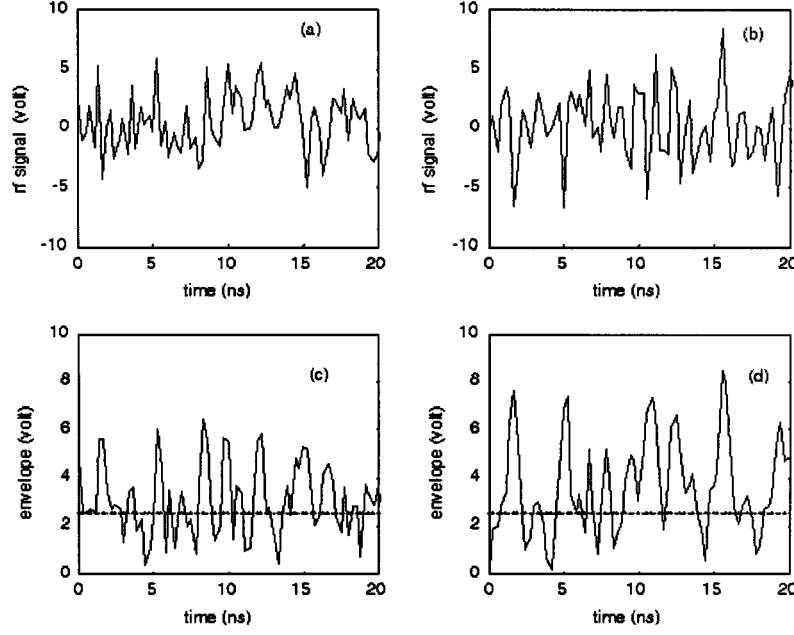
Fig. 2.   RF signals and envelopes for stationary mobile (a) Rayleigh-faded signal, (b) Rician faded signal, (c) Rayleigh envelope, and (d) Rician envelope.

for each N to get statistically meaningful results. For a given time instant, the received signal in the case of a stationary receiver was generated using (1). Generating the signal using (3) allowed the inclusion of Doppler effect induced by motion. The path amplitudes a_i were taken to be Weibull-distributed random variables and generated using the function $weibrnd$ from the Statistics Toolbox. The two-parameter Weibull distribution allowed the variation of the mean and variance of the scattering amplitudes. The phases ϕ_i were taken to be uniform in $[0, 2\pi]$ and were generated using the function $unifrnd$ from the Statistics Toolbox. The signal was then demodulated to get the in-phase and quadrature components, using the command $demod$ from the Signal Processing Toolbox. Subsequently, the envelope was calculated using (7). This envelope was tested against the Rayleigh distribution using the chi-square test described in Appendix II. The average chi-square statistic was computed. This value was compared with the chi-square value from tables [5] for 20 bins at the ninety-fifth percentile. If the computed average chi-square statistic is less than the corresponding value from the tables, the hypothesis is accepted. The chi-square tests were written as MATLAB functions and called in the main program.

Varying the number of paths, it can be seen that the fading envelope in the absence of an LOS path fits the Rayleigh distribution for as few as six paths. This result was established by conducting chi-square tests for different values of N. Fig. 2 shows the RF signals and envelopes for the case of a stationary mobile unit ($N = 10$). The Rayleigh faded RF signal [Fig. 2(a)] and envelope [Fig. 2(c)] show that the signal strengths can fall below the average value, shown by the horizontal line in Fig. 2(c).

B. Rician Fading

The Rician distribution is observed when, in addition to the multipath components, there exists a direct path between the transmitter and the receiver. Such a direct path or LOS com-

ponent is shown in Fig. 1. In the presence of such a path, the transmitted signal given in (3) can be written as

$$s(t) = \sum_{i=1}^{N-1} a_i \cos(\omega_c t + \omega_{di} t + \phi_i) + k_d \cos(\omega_c t + \omega_d t) \quad (9)$$

where the constant k_d is the strength of the direct component, ω_d is the Doppler shift along the LOS path, and ω_{di} are the Doppler shifts along the indirect paths given by (2). The envelope, in this case, has a Rician density function given by [5]

$$f(r) = \frac{r}{\sigma^2} \exp\left\{ -\frac{r^2 + k_d^2}{2\sigma^2} \right\} I_o \left(\frac{rk_d}{\sigma^2} \right), \qquad r \geq 0 \quad (10)$$

where $I_0()$ is the zeroth-order modified Bessel function of the first kind. The cumulative distribution of the Rician random variable is given as

$$F(r) = 1 - Q\left(\frac{k_d}{\sigma}, \frac{r}{\sigma} \right), \qquad r \geq 0 \quad (11)$$

where $Q(,)$ is the Marcum's Q function [4], [6]. The Rician distribution is often described in terms of the Rician factor K, defined as the ratio between the deterministic signal power (from the direct path) and the diffuse signal power (from the indirect paths). K is usually expressed in decibels as

$$K(\text{dB}) = 10 \log_{10} \left(\frac{k_d^2}{2\sigma^2} \right). \quad (12)$$

In (12), if k_d goes to zero (or if $k_d^2/2\sigma^2 \ll r^2/2\sigma^2$), the direct path is eliminated and the envelope distribution becomes Rayleigh, with $K(\text{dB}) = -\infty$.

To simulate the presence of a direct component, the received signal was modeled by (9). A term without any random phase must be added to the signal generated in the case of Rayleigh fading. The rest of the simulation was carried out as in the case of Rayleigh fading.
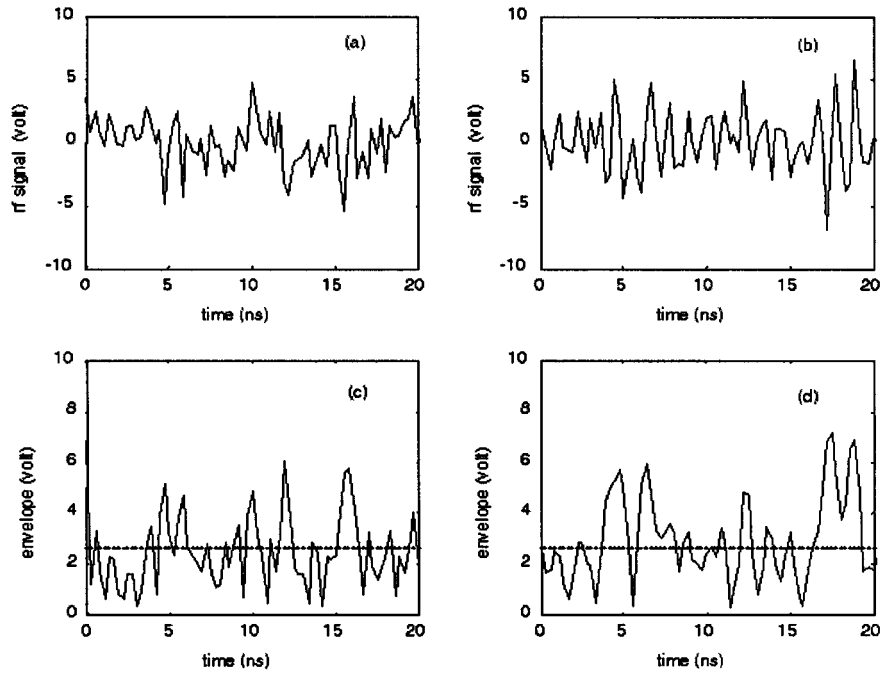
Fig. 3.   RF signals and envelopes for mobile moving at a velocity 25 m/s in (a) Rayleigh-faded signal, (b) Rician faded signal, (c) Rayleigh envelope, and (d) Rician envelope.

The RF signal and the envelope corresponding to $N = 10$ are shown in Fig. 2(b) and (d). The fluctuation in the envelope for Rician is much smaller than for the Rayleigh case [Fig. 2(c)]. The horizontal lines in Fig. 2(c) and (d) correspond to the mean value of the Rayleigh envelope.

The RF signals and demodulated envelopes for both Rayleigh and Rician cases for a mobile velocity of 25 m/s are compared in Fig. 3. The signal envelope goes below the threshold (indicated by the horizontal line) in Fig. 3(c) and (d) more often than in Fig. 2(c) and (d). Such a drop in the envelope increases the chances of loss of signal determined by the appearance of the envelope below the threshold when the mobile unit is in motion. The MATLAB program can be run with different velocities, and the effect of motion can be studied easily.

The envelope histogram and the Rayleigh fit to the envelope are shown in Fig. 4. The histogram was obtained using the *hist* function in MATLAB. The Rayleigh density function was created by calculating the Rayleigh parameter from the moments of the envelope data corresponding to (9). The fit of the histogram of the data to Rician can be undertaken similarly.
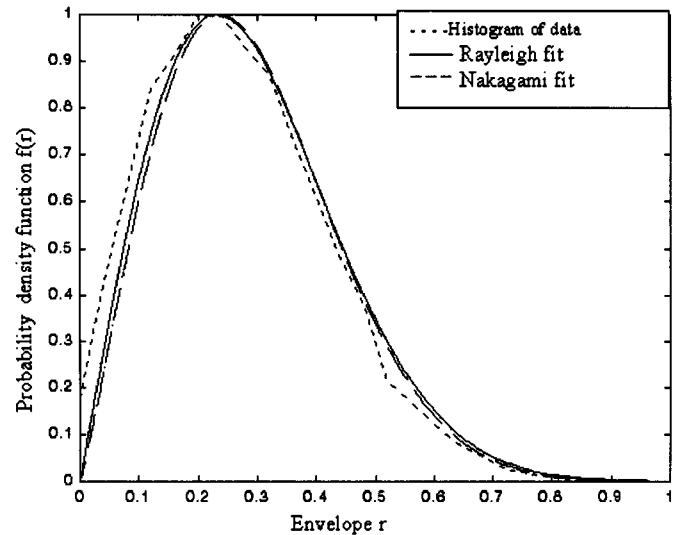

Fig. 4.   The histogram of the simulated data and the correspondingly matched density functions are shown along with the chi-square test for Rayleigh. The Nakagami test value is also shown. $N = 10$; mobile velocity 25 m/s. $\chi^2_{0.95}(19) = 30.1$ (value from the tables), $\chi^2_{0.95}(19) = 15 \pm 4$ (Rayleigh), $\chi^2_{0.95}(17) = 16 \pm 5$ (Nakagami).

C. Nakagami-m Distribution

It is possible to describe both Rayleigh and Rician fading with the help of a single model using the Nakagami distribution [6]. The fading model for the received signal envelope, proposed by Nakagami, has the pdf given by

$$f(r) = \frac{2m^m r^{2m-1}}{\Gamma(m)\Omega^m} \exp\left\{-\frac{mr^2}{\Omega}\right\}, \qquad r \geq 0 \qquad (13)$$

where $\Gamma(m)$ is the Gamma function and m is the shape factor (with the constraint that $m \geq 1/2$) given by

$$m = \frac{E^2\{r^2\}}{E\left\{[r^2 - E(r^2)]^2\right\}}. \qquad (14)$$

The parameter Ω controls the spread of the distribution and is given by

$$\Omega = E\{r^2\}. \qquad (15)$$

The corresponding cumulative distribution function can be expressed as

$$F(r) = \mathrm{P}\left(\frac{mr^2}{\Omega}, m\right) \tag{16}$$

where $P(\,,\,)$ is the incomplete Gamma function. In the special case $m = 1$, Nakagami reduces to Rayleigh distribution. For $m > 1$, the fluctuations of the signal strength reduce compared to Rayleigh fading, and Nakagami tends to Rician.

No special simulation was necessary to test for the validity of Nakagami fading. Because Nakagami distribution encompasses both Rayleigh and Rician, the signal envelopes were tested against the Nakagami distribution using the chi-square test. The program for the chi-square testing for the Nakagami distribution requires the use of *gammacdf* from the Statistics Toolbox. The Nakagami distribution seems to be a good fit for Rayleigh fading with an average value of the parameter $m = 1$, as stated in [6]. It also seems to fit the Rician distribution between $1 < m < 2$. Results for the Rayleigh and Nakagami fits are shown in Fig. 4.

D. Lognormal Distribution

Fading over large distances causes random fluctuations in the mean signal power. Evidence suggests that these fluctuations are lognormally distributed. A heuristic explanation for encountering this distribution follows. The transmitted signal undergoes multiple reflections at the various objects in its path before reaching the receiver. Then, it splits up into a number of paths that finally combine at the receiver. The expression for the transmitted signal is the same as that given in (3), except that the path amplitudes a_i are themselves the products of the amplitudes due to the multiple reflections [7], as

$$a_i = \prod_{j=1}^{M_i} a_{ji} \tag{17}$$

where M_i is the number of multiple reflections per path. Multiplication of the signal amplitude leads to a lognormal distribution [7] in the same manner that an addition results in a normal distribution by virtue of the central limit theorem [5]. A study of mobile radio propagation modeling reveals that there is no direct reference to the global statistics of path amplitudes. However, the fact that the mean of the envelope is lognormal seems to be well established in the literature. The lognormal pdf is given by

$$f(r) = \frac{1}{r\sigma\sqrt{2\pi}} \exp\left\{-\frac{(\ln r - \mu)^2}{2\sigma^2}\right\}, \qquad r \geq 0 \tag{18}$$

where μ is the mean of $\ln(r)$, and σ^2 is the variance of $\ln(r)$. With this distribution, $\ln r$ has a normal distribution.

Estimating the long-term fading from a received mobile radio signal is the same as obtaining its local average power [9]. The local average power of the mobile radio signal is obtained by smoothing out (averaging) the fast fading part and retaining the slow fading part. The received signal was generated, as in (1), with the amplitudes a_is as in (17). M_i was taken as 5, and a_js were taken to be Rayleigh random variables, using the function *raylrnd* from the Statistics Toolbox. The received power was

calculated in terms of the inphase and quadrature components as

$$p(t) = I^2(t) + Q^2(t). \tag{19}$$

The local average received power was calculated as the mean $p(t)$. This procedure was carried out 50 times in order to obtain 50 values of the average power. The path of the mobile signal used to obtain the local average power was taken to be 1250 wavelengths, which is more than sufficient for such a procedure [9]. The histogram of the local average received power was tested against the lognormal distribution and was found to be a good fit. It is possible to repeat the simulation to study the effect of the multiple reflections on the statistics of the mean power.

E. Suzuki Distribution

Another approach used to describe the statistical fluctuations in the received signal combines the Rayleigh and lognormal in a single model. Suzuki [8] suggested that the envelope statistics of the received signal envelope could be represented by a mixture of Rayleigh and lognormal distributions in the form of a Rayleigh distribution with a lognormally varying mean [8]. He suggested the formulation

$$f(r) = \int_0^\infty \frac{r}{\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) \frac{1}{\sigma\lambda\sqrt{2\pi}}$$
$$\cdot \exp\left\{-\frac{(\ln\sigma - \mu)^2}{2\lambda^2}\right\} d\sigma \tag{20}$$

where σ is the mode or the most probable value of the Rayleigh distribution, and λ is the shape parameter of the lognormal distribution. Equation (20) is the integral of the Rayleigh distribution over all possible values of σ, weighted by the pdf of σ; this attempts to provide a transition from local to global statistics. The simulation carried out in Section III-D also demonstrates that the marginal density function of the envelope will be Suzuki. This is an indirect but easier way to test the Suzuki distribution as opposed to the cumbersome integration in (20).

IV. OUTAGE PROBABILITY

In a fading radio channel, it is likely that a transmitted signal will suffer deep fades that can lead to a complete loss of the signal or outage of the signal. The outage probability is a measure of the quality of the transmission in a mobile radio channel. Outage is said to occur when the received signal power goes below a certain threshold level [3], [4]. It can be calculated as the integral of the received signal power $p(t)$ as

$$\mathrm{P}_{out} = \int_0^{P_{th}} p(t)\, dt \tag{21}$$

where P_{th} is the threshold power.

The concept of outage can be demonstrated with MATLAB using the results from the previous Section. The procedure to find the outage probability is as follows.

1) Calculate the received signal power as given in (19).
2) Set a threshold power level for the received signal relative to the average signal power.

TABLE I
COMPARISON OF OUTAGE PROBABILITIES FOR RAYLEIGH AND RICIAN FADING FOR A NUMBER OF VALUES OF MOBILE VELOCITIES

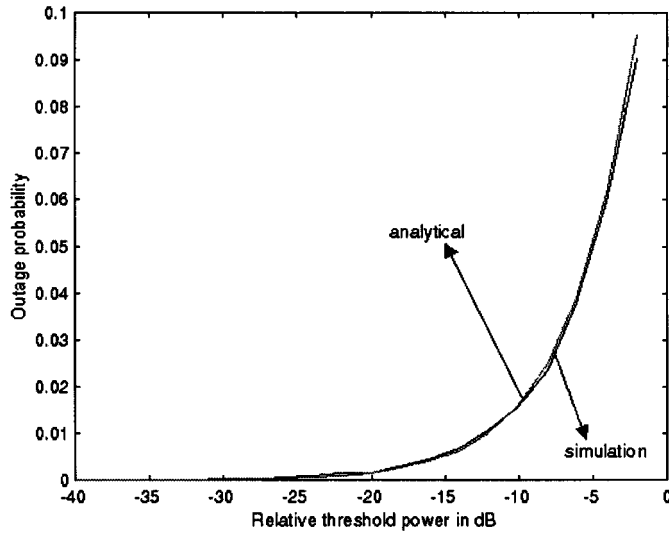| Mobile velocity in m/s	Outage Probability (Rayleigh)	Outage Probability (Rician)
0	0.19149	0.09311
2	0.19193	0.09312
4	0.19246	0.09314
6	0.19303	0.09346
8	0.19339	0.09350

Fig. 5. Outage probabilities for Rayleigh fading and stationary mobile. Simulated values are compared against theoretically computed outage values.

3) Count the number of times in the sample interval that the received signal power goes below this threshold.
4) Calculate the outage using the basic concept of probability by taking the ratio of the count in step 3) to the total number of samples.

For one received signal, the outage probabilities were calculated for various thresholds, and compared to those calculated analytically. The outage probabilities calculated analytically and through simulations were found to tally quite well. Fig. 5 shows the curves for the outage probability, calculated analytically and through simulations, for the Rayleigh-fading case. As observed from Table I, the outage probability (averaged over 50 simulations) in a Rician channel is lower than that in a Rayleigh channel, a fact attributed to the presence of an LOS path. Moreover, the probability of outage increases as the mobile velocity, or the resulting Doppler shift, increases.

V. CONCLUSION

MATLAB appears to be a simple and straightforward tool to demonstrate the concept of fading. The students can undertake these projects as a part of their homework assignments, making it easy to visualize the intricacies and understand the relationship between the different parameters involved in fading. Some of these ideas have been implemented in a course on Wireless Communications being offered at the undergraduate level at Drexel University, Philadelphia, PA [10].

APPENDIX I
MATLAB FUNCTIONS USED ALONG WITH INFORMATION ON SIMULATION

demod (Signal Processing Toolbox) *unifrnd, weibrnd, raylrnd, logncdf, raylcdf* (Statistics Toolbox) *marcumq* (Communications Toolbox), *gammainc, besseli, trapz, mean, var, std* (General MATLAB). The *trapz* function may be used in place of *marcumq* to get the Marcum Q function. Similarly, *gammacdf* may be used in place of *gammainc*.

Carrier frequency $f_c = 900$ MHz; sampling frequency $= 4f_c$; number of samples–simulation $= 5000$; number of bins used for chi-square test $= 20$.

The programs written are available at http://www.ece.drexel. edu/shankar_manuscripts/.

These programs allow the user to input the carrier frequency (900 or 1800 MHz). The velocities can be varied.

APPENDIX II
CHI-SQUARE TEST [5]

Test the hypothesis that $F(x) = F_o(x)$ for a set of $(m-1)$ points a_i as follows:

$$H_0: F(a_i) = F_0(a_i), \qquad 1 \le i \le m-1$$
$$H_1: F(a_i) \ne F_0(a_i), \qquad \text{some } i.$$

Introduce the m events

$$A_i = \{a_{i-1} < x \le a_i\}, \qquad i = 1, \dots, m$$

where $a_0 = -\infty$, and $a_m = \infty$. These events form the partition of S, the set of outcomes. The number k_i, of successes of A_I equals the number of samples x_j in the interval (a_{i-1}, a_i). Under hypothesis H_0

$$P(A_i) = F(a_i) = F_0(a_{i-1}) = p_{0i}.$$

Thus, to test the hypothesis, form the sum q (known as Pearson's test statistic) as follows:

$$q = \sum_{i=1}^{m} \frac{(k_i - np_{0i})^2}{np_{0i}}$$

where n is the total number of samples observed. Now, find $\chi_{1-\alpha}(m-1)$ from the standard chi-square value tables. Accept H_0 iff $q < \chi_{1-\alpha}(m-1)$. Note that if the parameters of the distribution function are estimated from the data, the order of the test is reduced by the number of parameters estimated. Detailed m-files (programs) for the chi-square testing for various probability density functions mentioned in this manuscript are available at the website listed in Appendix I.

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Gayatri S. Prabhu received the B.S. degree in electrical engineering from the University of Pune, Pune, India, in 1997 and the M.S. degree in electrical engineering from Drexel University, Philadelphia, PA, in 2000.

She is currently working at Lockheed Martin Global Telecommunications, Clarksburg, MD. Her research interests include wireless and mobile communication systems.

P. Mohana Shankar (SM'89) received the M.Sc. degree in physics from Kerala University, Trivandrum, India, in 1972, and the M.Tech degree in applied optics and Ph.D. degree in electrical engineering from Indian Institute of Technology, Delhi, India, in 1975 and 1980, respectively.

From 1981 to 1982, he was a Visiting Scholar at the School of Electrical Engineering, University of Sydney, Australia. In 1982, he joined Drexel University, Philadelphia, PA, where he is currently the Allen Rothwarf Professor of Electrical and Computer Engineering. He is also an Adjunct Professor of Radiology at Jefferson Medical College, Thomas Jefferson University, Philadelphia. He is the author of the textbook *Introduction to Wireless Systems*. His research interests include fading channels, wireless communications, statistical signal processing for medical applications, and medical ultrasound.