Analysis of Chirp Spread Spectrum System for Multiple Access

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Abstract

This paper evaluates the performance of an efficient chirp spread spectrum multiple access technique. The technique is motivated by the inherent interference rejection capability of such spread-spectrum type system, especially in circumstances where immunity against Doppler shift and fading due to multipath propagation are important. Linear chirp of different chirp rates and phases spreads the modulated signal, that creates a pseudo-orthogonal set of spreading codes. An efficient system for spread spectrum multiple access can be made by combining linear chirp modulation with polar signaling, which reduces the multiple access interference. A simulation model has been outlined in MATLAB^{TM} and bit error rates over fading channels in different Doppler environments, have been calculated when the coherence time is of the order of bit duration. Simulation results show that under proper selection of parameters; the proposed technique performs approximately well in all flat fading channels in terms of bit error rate.

Keywords: spread spectrum multiple access, chirp spread spectrum, wireless network, MATLAB^{TM}, flat fading.

1. Introduction

Through the years, the Federal Communication Commission (FCC) managed the spectrum allocations on a request-by-request basis; the FCC has realized that it had no more spectra to allocate [5], which gave rise to spread spectrum techniques. With the rapid development in wireless communication, spread spectrum techniques and spread spectrum systems have received quite some attention. As a future communication systems a spread spectrum system has the advantage of inherent detection protection due to their noise-like spectra, interference rejection, multipath suppression, code division multiple access, and high resolution ranging. Spread spectrum is a technique whereby a modulated waveform is modulated (spread) a second time in such a way as to generate an expanded-bandwidth wideband signal by means of a code which is independent of the information message, and a synchronized reception with the code at the receiver is used for dispreading and subsequent data recovery [3]. The spread spectrum techniques are classified as direct sequence, carrier sense multiple access, chirp modulation, frequency hopping, time hopping and hybrid spread spectrum [12]. Chirp modulation or linear frequency modulation was introduced by Winkler [8] in 1962. She suggested the use of one pair of linear chirps that have opposite chirp rates, for binary signalling. Chirp spread spectrum is a spread spectrum technique that uses wideband linear frequency modulated chirp pulses to encode information. A chirp is a sinusoidal signal whose frequency increases or decreases over a certain amount of time [7]. Theoretically, chirp modulation is found to be superior in the partially coherent and frequency-selective fading cases over certain ranges of channel conditions [9]. Multi-user phased chirp spread spectrum systems was introduced by Khamy for multiple access [4]. In 1974, Cook [1] assigned pairs of linear chirps with different chirp rates to several users, thus allowing multiple access within a common frequency band. The performance of chirp spread spectrum systems can still be further improved in the case of multiple access by means of polar signalling in conjunction with a good selection of the chirp parameters.

2. System Model

The chirp spread spectrum for N users is shown in Figure 1. Let the transmitted power P_i of each user for its transmitted bit $b_i(t) \in \{-1; +1 \,|\, 0 \leq t < T_b\}$ be same $P_i = P_t \; \forall$ i; where i =1, 2, … N and T_b denotes the bit duration. On transmitter side the binary data sequence modulates a linear chirp signal centered at some given carrier frequency f_c i.e.

$$x(t) = c_i(t) b_i(t) \tag{1}$$

From the set of spreading signals each user is assigned a separate chirp signal $c_i(t)$. Spreading and up conversion to a carrier frequency f_c is achieved by multiplication with one of the chirp signals.

$$c_t(t) = \begin{cases} \sqrt{2}\cos\left[2\pi f_c t + i\pi\Delta\bar{\alpha}\left(\frac{t^2}{T_b^2} + \bar{\theta}\right)\right], & 0 \leq t < \frac{T_b}{2} \\ \sqrt{2}\cos\left[2\pi f_c t + (M-i)\pi\Delta\bar{\alpha}\left(\frac{t}{T_b} - \frac{1}{2}\right)^2 + i\pi\Delta\bar{\alpha}\left(\frac{t}{T_b} - \frac{1}{2}\right) + i\pi\Delta\bar{\alpha}\left(\frac{1}{4} + \bar{\theta}\right)\right], & \frac{T_b}{2} \leq t < T_b \end{cases} \tag{2}$$

where $\Delta\bar{\alpha}$ denotes the chirp rate and $\bar{\theta}$ denotes the phase of the spreading signals. The chirp rate parameter $\Delta\bar{\alpha}$ and the phase parameter $\bar{\theta}$ have to be selected carefully, as they heavily impact the overall system performance. In particular, the cross-correlation between two spreading chirps $C_i(t)$ and $C_j(t)$can be approximated by

$$\rho_{ij} = \frac{1}{T}\int_0^T C_i(t) \;\; C_j\;(t) \tag{3}$$

Which can be further reduced to

$$\rho_{ij} = \frac{\sin(2\pi(i-j))}{2\pi(i-j)} \quad \begin{cases} 1 \; for\; all\; interger\; i = j, \\ 0 \; for\; all\; integer\; i \neq j \end{cases} \tag{4}$$

The chirp rate parameter is given by

$$\Delta\bar{\alpha} = \frac{2BT_B}{N} \tag{5}$$

For $\Delta\bar{\alpha} \geq 1$, this will usually yield a pseudo-orthogonal set of spreading codes. For smaller values of $\Delta\bar{\alpha}$, the linear chirp would be too densely spaced in the joint time frequency domain. Thus pseudo-orthogonal codes can't be obtained and system may suffer from multiple access interference.

Chirp modulation uses the concept of OFDM, where all N user channels are parallel-sloped slices of bandwidth in joint time-frequency domain. In this way it can be easily compared with TDMA and FDMA, in which channels are parallel slices orthogonal to time and frequency axis.

Demodulation and detection can then be realized by an array of correlation receivers. Each receiver multiplies the received signal with its coherent, locally generated replica of spreading signal of unit energy and integrates this product over one symbol interval to obtain the decision variable.

$$u_i = \frac{1}{\sqrt{E_s}}\int_0^{T_s} C_i(t) x(t)\, dt \tag{6}$$

where E_s is the energy ,T_s is symbol duration and x(t) is transmitted signal. Finally a threshold detector estimates the data symbol sent, simply by detecting the sign of the decision variable u_i.

3. Fading Channels

The mobile channel places fundamental limitations on the performance of wireless communication systems.

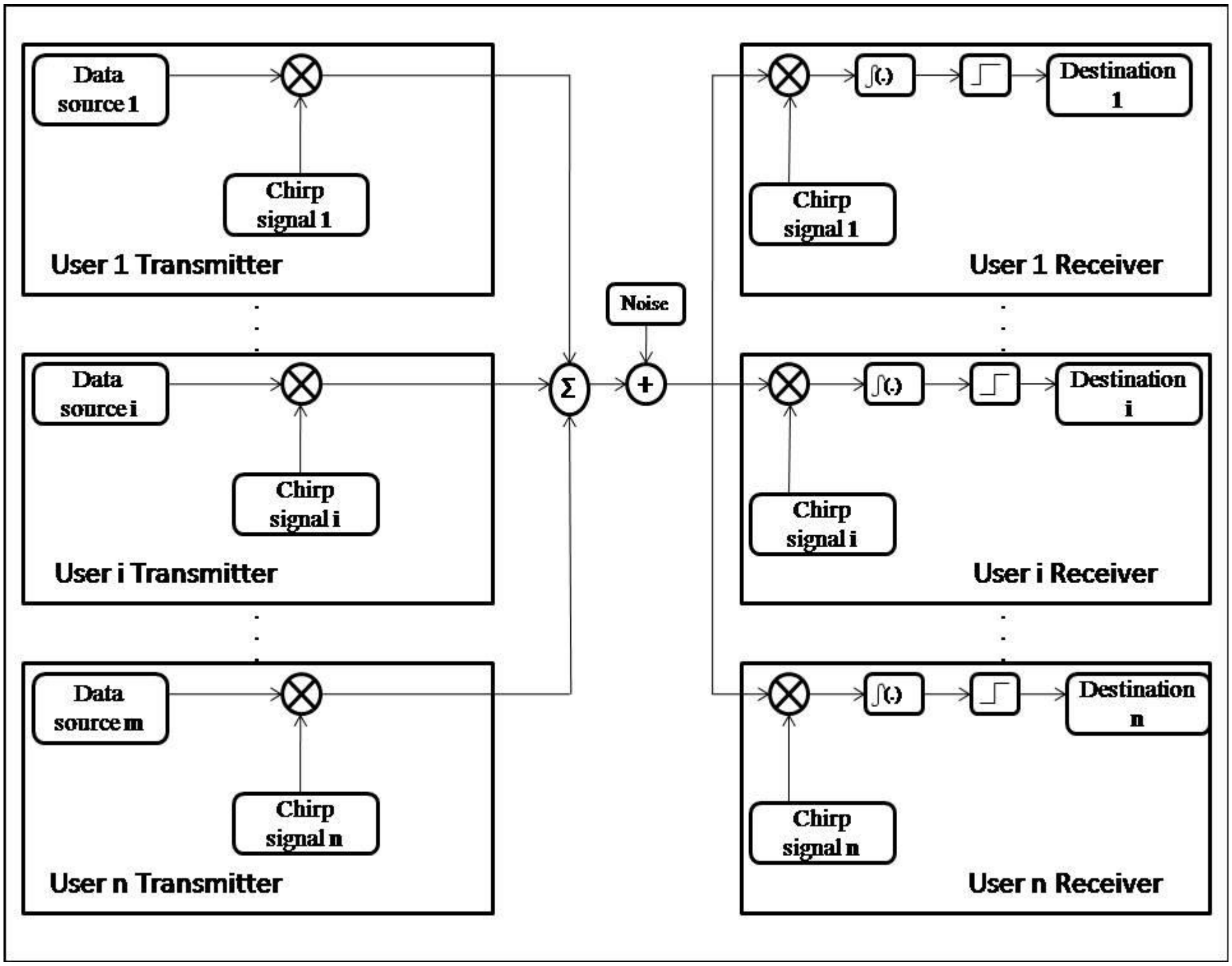

Figure 1. Chirp spread spectrum system.

Multi-path is a condition where the transmitted radio signal is reflected by physical features/structures, creating multiple signal paths between the base station and the user terminal. These multipath signals can interfere with the desired signal and make it harder for receiver to detect the original signal that was transmitted. When the waves of multi-path signals are out of phase, reduction in signal strength can occur. One such type of reduction is called a fade; the phenomenon is known as "Rayleigh fading" or "fast fading." The Rayleigh, Ricean and Nakagami are the most commonly used statistical models to represent small-scale fading phenomenon. The Rayleigh distribution is commonly used to describe the statistical time varying nature of the received envelope of a flat fading signal, or the envelope of an individual multipath component. In the Rayleigh flat fading channel model, it is assumed that the channel induces amplitude, which varies in time according to the Rayleigh distribution.

In micro-cellular environments, there usually exists a dominant line of sight (LOS) path in addition to numerous diffused multipath components between the transmitter and receiver [14]. In such a case, the other faded signal components are superimposed on the dominant component and the resultant signal amplitude follows Rician distribution with the ratio between the LOS and diffused components denoted by the Rice factor K. Rice fading is caused by Doppler-shifted echoes with a Gaussian distribution, but in addition there is always a direct path from the Tx antenna to the Rx antenna. A received signal envelop model, which allows for different degrees of fading severity for the desired as well as for interfering signal envelopes, and which is widely used to model many mobile radio environments, is the Nakagami-m distribution. The Nakagami-m distribution is a versatile statistical model, because it can model fading amplitudes that experience either less or severe fading than that of Rayleigh variants. It sometimes fits experimental data much better than a Rayleigh or Rician distribution [11], [15]. The Nakagami-m distribution of envelope of the received signal is given by [11].

If Υ_0 is the mean value of the received energy per bit to noise spectral density ratio, the BER of BPSK coherent receiver for slow Rayleigh fading channel [2] is given by

$$BER_{ral} = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_0}{1-\gamma_0}}\right) \qquad (7)$$

The BER of BPSK coherent receiver for AWGN is given by

$$BER_{AWGN} = \frac{1}{2} erfc\sqrt{\gamma_0} \qquad (8)$$

The average system BER of chirp spread spectrum was derived in [4] for AWGN channels when N users exhibit the same SNR per bit γ_b is given by

$$\overline{BER}(\gamma_b) = \frac{1}{N}\sum_{i=1}^{N} \frac{1}{2^{N-1}} \sum_{B_i} Q\left(\sqrt{2\gamma_b}\left[1 - \sum_{j=1, j\neq i}^{N} b_j(t)\rho_{ij}\right]\right) \qquad (9)$$

If the set of all possible bit variations is given by $B_i = \{b_j(t) \in \{-1; +1\} | j = 1,2,\dots,N; j \neq i\}$, where independent user bit sequences with equally likely 0s and 1s are assumed. It is easily seen that the bit error probability of user i for a fixed bit variation B_i is

$$BER(B_i;\, \gamma_b) = Q\left(\sqrt{2\gamma_b}\left[1 - \sum_{j=1, j\neq i}^{N} b_j(t)\rho_{ij}\right]\right) \qquad (10)$$

This expression allows us to apply the moment generating function technique for average error probability derived in Section 6.4.3 [6]. In our case, we find α =1 and

$$g = g_i(B_i) = \left[1 - \sum_{j=1, j\neq i}^{N} b_j(t)\rho_{ij}\right]^2 \qquad (11)$$

The parameter g depends on the other user's data bits and the cross-correlation coefficients. Hence, it captures the effects of multiple access interference. Smaller the g is, more the multiple access interference present and higher the probability of bit error. Note that this derivation for g is not strictly correct since it implies that all users experience the same instantaneous SNR γ_b. This does not hold true anymore for independent fading channels as considered here. Despite that, we will use this definition of g as an anticipated average value without further proof. Using the moment generating function (MGF) technique, the average user bit error rate for an average user SNR $\overline{\gamma_b}$ in Nakagami-m fading [13] yields

$$\overline{BER}(g_i(B_i); \bar{\gamma}_b) = \frac{1}{\pi}\int_0^{\frac{\pi}{2}} N_m\left(\frac{-g_i(B_i)}{\sin^2\emptyset}; \bar{\gamma}_b\right) d\emptyset \qquad (12)$$

Where

$$N_m\left(\frac{-g_i(B_i)}{\sin^2\emptyset}; \bar{\gamma}_b\right) = \left(1 + \frac{g\,\bar{\gamma}_b}{m\,\sin^2\emptyset}\right)^2$$

is the MGF corresponding to Nakagami-m fading. Averaging this bit error rate over all possible bit variations and users results in an exact expression for the average system BER in Nakagami-m fading, which is

$$\overline{BER}(\bar{\gamma}_b) = \frac{1}{N} \qquad (13)$$

4. Simulation Environment

To simulate bit error rate performance of chirp spread spectrum system over flat fading channels, an equivalent discrete-time baseband model in MATLAB™ has been implemented. Separating the chirp signals into in-phase and quadrature components, allows us to find their complex baseband equivalent. In our system model, the transmitter uses these equivalent baseband chirp codes to spread the binary phase shift keyed (BPSK) data sequence. A binary random number generator creates independent data bit sequences for the users, where 0s and 1s occur with equal probability. Notice that we use a rectangular pulse shape although raised cosine or other pulse shaping techniques may be applied advantageously.

For the flat fading channels, we follow the procedure proposed by Beaulieu [10] to generate independent flat fading Nakagami-m sequences. This approach first generates a Rayleigh fading sequence with Doppler spectrum at the desired Doppler frequency. This Rayleigh sequence is then transformation mapped into a Nakagami-m sequence of given parameter m. The simulation model generates an independent Nakagami-m flat fading channel for each user over the entire duration of the data bit sequence. Rayleigh and Rician (with parameter *K*) fading channels follow as special cases of the Nakagami-m channel for m=1 and $m = (K+1)^2 / 2K+1$ respectively. The Nakagami-m fading channel model accepts m parameters of range $0.65 \le m \le 10$ and $m=\infty$ for no fading. Each user's receiver simply computes the cross-correlation coefficient between the received signal and its coherent spreading code in discrete time. The transmitted data bit is estimated by deciding about the sign of the cross-correlation coefficient. Comparing the estimated data bit sequence with the transmitted sequence determines the number of bit errors. The average system BER is then obtained by averaging the number of bit errors over the number of bits sent per user and the number of users.

5. Simulation Results

The parameters for the four chirp spread spectrum systems selected for simulation are given in Table 1. The average system BER versus average user SNR for all systems was simulated over five channels in three Doppler environments. The channels considered are no fading ($m\rightarrow\infty$), Nakagami-m (m=0.65), Rayleigh (m=1), Nakagami-m (m=3), and Rician (k=10, so m=5.76).

Table 1. Parameters of simulated chirp spread spectrum systems.

System	N	R/B[bits/s/Hz]	$\Delta\bar{\alpha}$	$\bar{\theta}$
System 1	4	0.125	16	1.82
System 2	4	0.500	4	1.94
System 3	8	0.0625	32	1.86
System 4	8	0.125	16	1.97

To investigate BER performance, when the channel coherence time $T_c \approx 1/f_D$ is in the order of the bit duration, we simulated the systems for $f_D T_b=0.5$, $f_D T_b=1$ and $f_D T_b=2$, where f_D denotes the Doppler frequency.

The simulation results for system 1 are given in Figures 2 to 4. For each data point, a bit sequence of length 10^4 per user has been simulated. The figures show that BER performance is worst in the case $f_D T_b=0.5$, where the coherence time is twice the bit duration. In all three Doppler environments, the penalty over no fading is less than 1dB for the Nakagami-m (m=3) and Rician channel at a target BER of 10^{-3}. At $f_D T_b=1$ and $f_D T_b=2$, there is virtually no performance loss for these two channels.

However when going to the severely fading channels Nakagami-m (m=0.65) and Rayleigh (m=1), the simulation results indicate considerable penalties over no fading. For the worst case again at $f_D T_b=0.5$, Rayleigh fading causes about a 2 dB loss and Nakagami-m (m=0.65) even a 6 dB loss at a BER of 10^{-3}. Moreover, the latter case shows

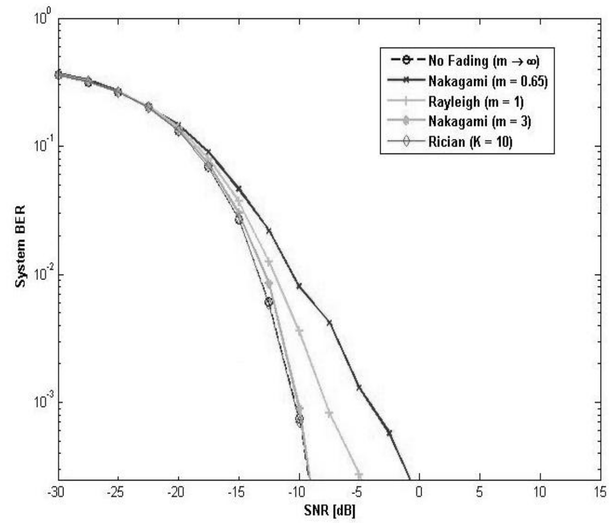

Figure 2. Performance of system 1 at f_DT_b= 0.5

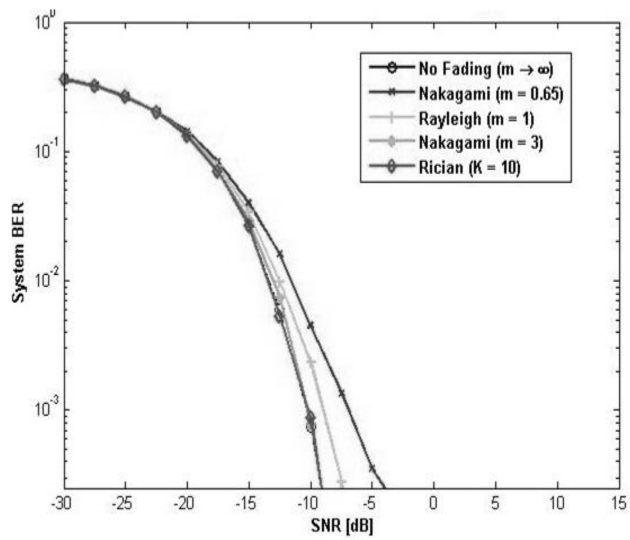

Figure 3. Performance of system 1 at f_DT_b= 1

evidence of an error floor for SNRs above 5 dB.

Let us now consider the performance of system 2. It has a spectral efficiency 0.5 bits/s/Hz, four times that of system 1. Intuitively, from its less ideal cross-correlation, we expect it to perform worse than system 1. The simulated bit error rates for chirp spread spectrum system 2 are shown in Figures 5 to 7.

At useful average system BERs, the average user SNR increases by at least 4 dB over system 1; the price to pay for higher spectral efficiency.

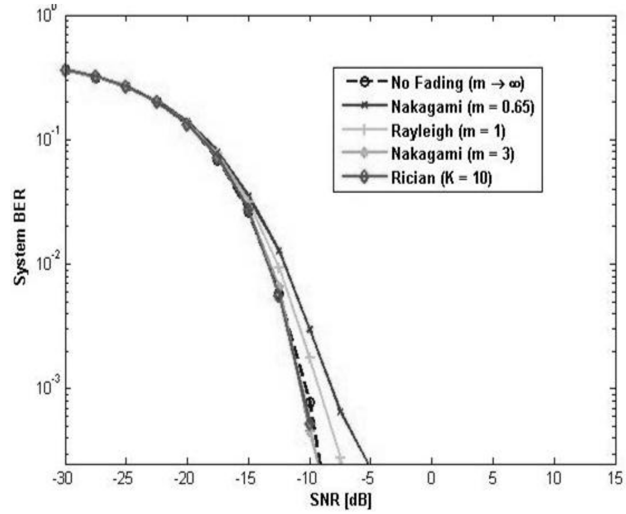

Figure 4. Performance of system 1 at f_DT_b= 2

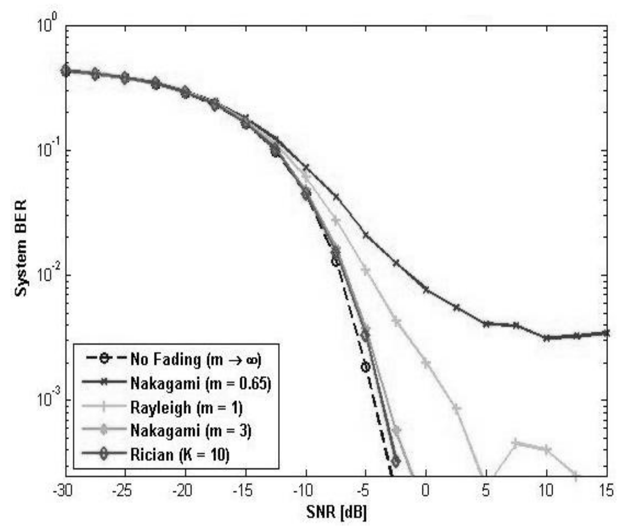

Figure 5. Performance of system 2 at f_DT_b= 0.5

Compared to no fading, the penalties for the Nakagami-m (m=3) and Rician channel are negligibly small, within about 2 dB at a BER of 10^{-3}.

However, the two severely fading channels indicate error floors in almost all Doppler environments. For the Nakagami-m (m=0.65) channel, BERs below 10^{-3} are not even attainable for coherence times at or above the bit duration. Rayleigh fading causes about a 3,2,1.5 dB loss and Nakagami-m (m=0.65) 5,4,3 dB loss at a BER of 10^{-2} at Doppler shift of 0.5, 1 and 2 .The channel fading essentially destroys the pseudo- orthogonality of the spreading chirps.

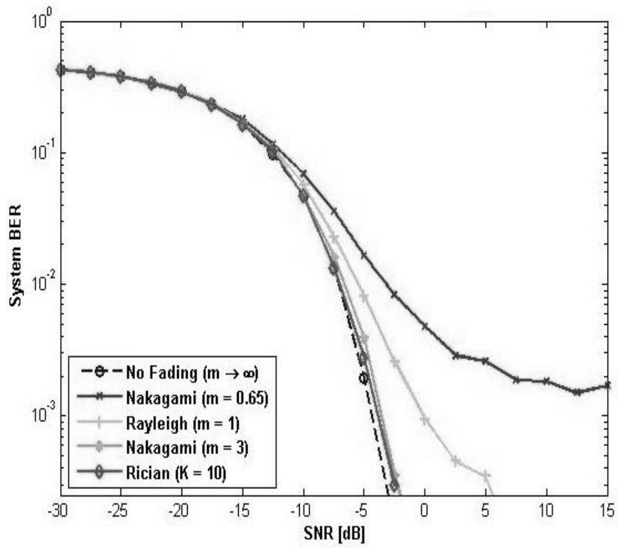

Figure 6. Performance of system 2 at $f_D T_b$= 1

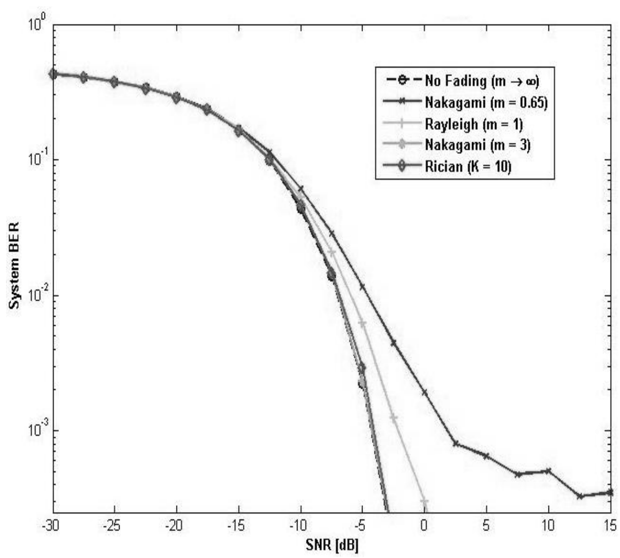

Figure 7. Performance of system 2 at $f_D T_b$= 2

Considering the performance of system 3 that has a spectral efficiency 0.0625bits/s/Hz, half that of system 1. The simulated bit error rates for chirp spread spectrum system 3 are shown in Figures 8 to 10. At an average system BER of 10^{-3}, the average user SNR decreases by at least 7 dB over system 1 but at the cost of spectral efficiency.

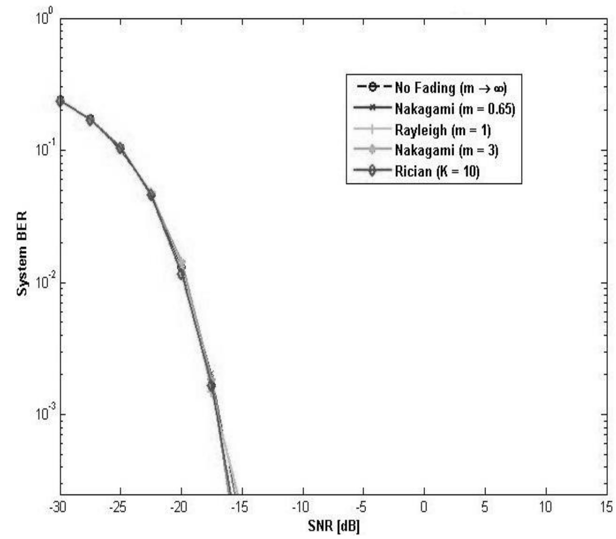

Figure 8. Performance of system 3 at $f_D T_b$= 0.5

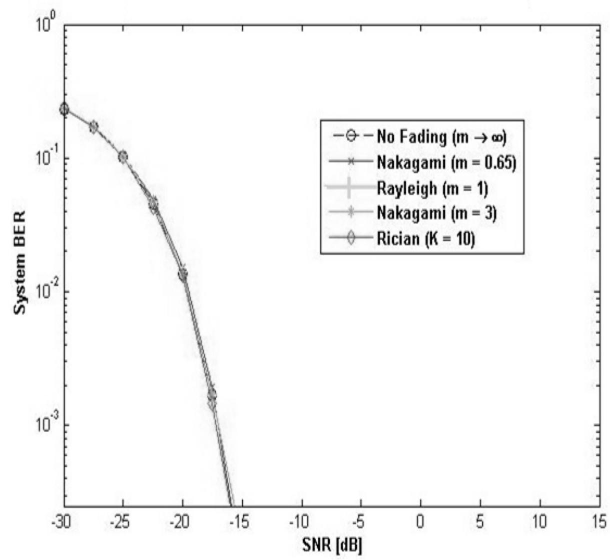

Figure 9. Performance of system 3 at $f_D T_b$= 1

Compared to other systems it performs almost same in all fading environments. Close analysis shows that the system performs best when the coherence time is same as the bit duration. The pseudo-orthogonality of the spreading chirps is maintained.

System 4 has a spectral efficiency 0.125bits/s/Hz, same as system 1 but number of users is double. The simulated bit error rates for multi-user system 4 are shown in Figures 11 to 13.

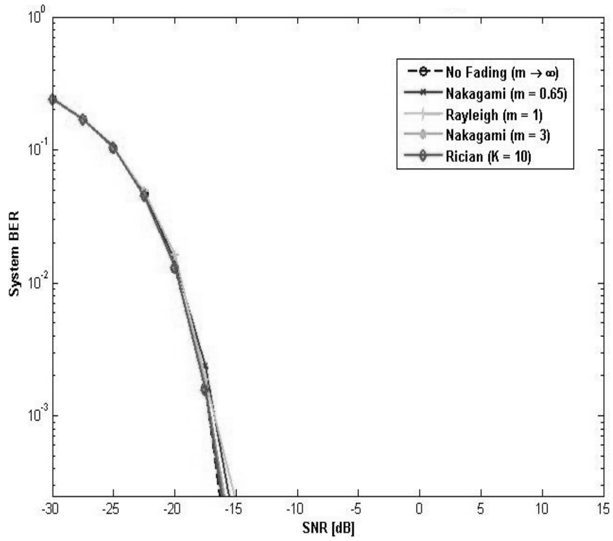

Figure 10. Performance of system 3 at $f_D T_b$= 2

At useful average system BERs, the average user SNR decreases by at least 5 dB over system 1 for no fading, Rician and Nakagami-m (m=3) at BER of 10^{-3}. Compared to no fading, the penalties for the Nakagami-m (m=3) and Rician channel are negligibly small, within about 0.5 dB at a BER of 10^{-3}.

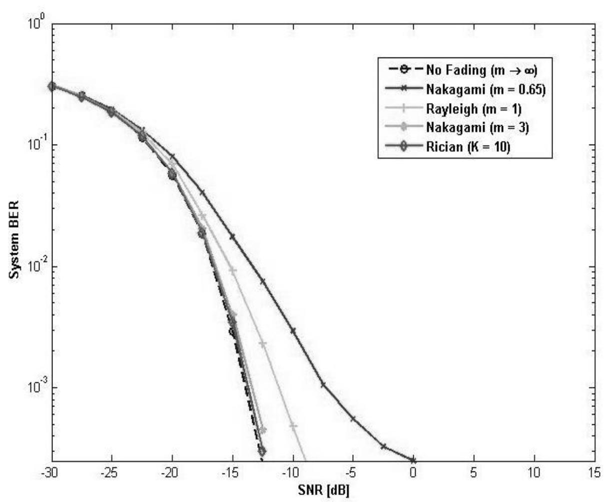

Figure 11. Performance of system 4 at $f_D T_b$= 0.5

However, the two severely fading channels indicate error floors in almost all Doppler environments. Rayleigh fading causes about a 3, 2, 1dB loss and Nakagami-m (m=0.65) even a 6,4,3 dB loss at BER of 10^{-3} at Doppler shift 0.5, 1 and 2. The system performs better at coherence time greater than the bit duration.

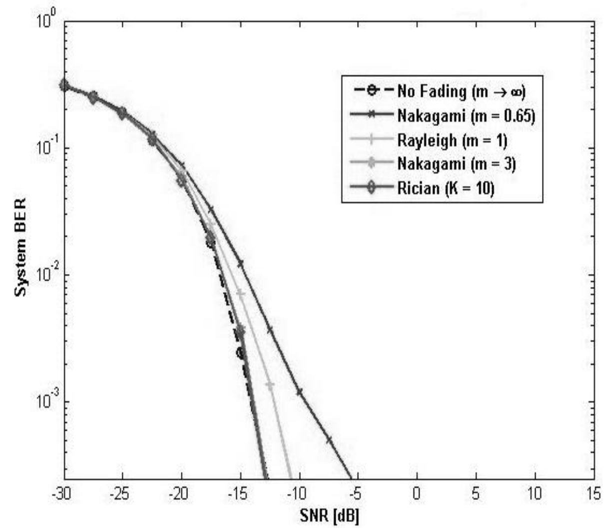

Figure 12. Performance of system 4 at $f_D T_b$= 1

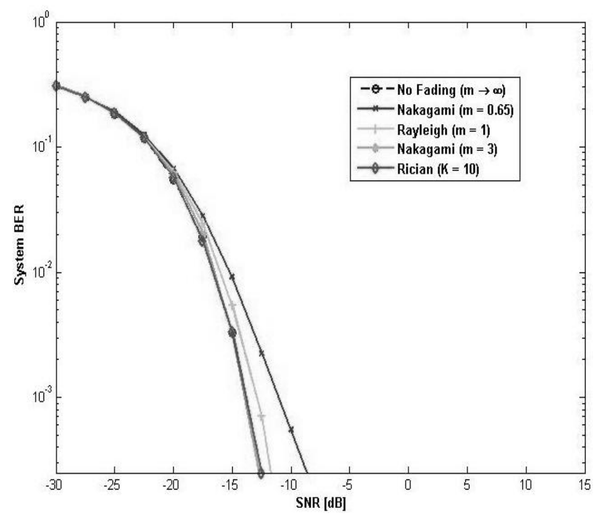

Figure 13. Performance of system 4 at $f_D T_b$= 2

6. Conclusions

In this paper, a chirp spread spectrum system model has been described for use in MAC channels experiencing flat amplitude fading. An analytical expression for the average system probability of bit error was derived using the moment generating function technique. An equivalent baseband system model for BER simulations has been outlined in MATLAB™, which included a general Nakagami-m fading generator based on transformation mapping. Simulations of system BER over user SNR were carried out over four flat fading channels in three different Doppler environments, when the channel coherence time is in the order of the bit duration. The BER results show good agreement between the theory and simulation. The results show that the penalty to no fading for moderately fading channels is small for Nakagami-m with *m* parameters greater than 3 it is within 2 dB. In severe fading like Rayleigh, the penalty increases significantly, even introduces an error floor. Furthermore, the simulation results indicate that performance degrades most for channel coherence times greater than the bit duration.

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