

Transmission Over EHF Mobile Satellite Channels *

W. Zhuang[†], J.-Y. Chouinard, A. Yongaçoğlu
 Department of Electrical Engineering, University of Ottawa
 161 Louis-Pasteur, Ontario, Canada K1N 6N5
 Tel.: +1 613 564-8159, Fax: +1 613 564-6882

Abstract

Land mobile satellite communications at Ka-band (30/20 GHz) are attracting an increasing interest among the researchers because of the frequency band availability and the possibility of small earth station designs. However, communications at the Ka-band pose significant challenges in the system designs due to severe channel impairments. Because only very limited experimental data for mobile applications at Ka-band is available, this paper study the channel characteristics based on experimental data at L-band (1.6/1.5 GHz) [1]-[3] and the use of frequency scaling [4]. The land mobile satellite communication channel at Ka-band is modelled as lognormal-Rayleigh fading channel. The first and second-order statistics of the fading channel are studied. The performance of a coherent BPSK system over the fading channel at L-band and Ka-band is evaluated theoretically and validated by computer simulations. Conclusions on the communication channel characteristics and system performance at L-band and Ka-band are presented.

1. Introduction

Land mobile satellite (LMS) services at L-band frequencies have been investigated and developed throughout 1980s; system concepts and corresponding technologies are being transferred to the land mobile satellite communication industry [5]. In order to be viable, future LMS telecommunication systems, such as personal communication systems, will have to provide a large number of users with diversified services, while being

cost-effective. However, increased use of L-band frequencies leads to the important problem of radio spectrum congestion: because of the availability of large bandwidths, Ka-band is attracting more and more attention in the land mobile satellite research field. Furthermore, at Ka-band, the user equipment (e.g. portable transceivers) can be significantly smaller and eventually less expensive than the equipment used at L-band. It is therefore expected that LMS systems operating in the Ka-band will provide the service users with larger information capacities, a wider variety of services, and this at a low cost. Unfortunately, the Ka-band LMS channel is subjected to severe propagation impairments such as rain attenuation, scintillation, as well as large Doppler frequency shifts, all of which must be taken into account while designing personal satellite communication systems.

The objective of this paper is to model and analyze the EHF land mobile satellite channel, and to evaluate the performance of a coherent BPSK system in the channel. Here, we consider the 30/20 GHz Ka-band channel with up links at 30 GHz and down links at 20 GHz. Being the critical link, only the down link propagation channel is discussed. The remainder of this paper is organized as follows. The first-order statistical description of the LMS channel is discussed in Section 2. Section 3 presents the second-order statistics of the fading channel at Ka-band, which are compared with those at L-band. An upper bound of the bit error rate of a coherent BPSK system over the fading channel is derived theoretically in Section 4, and is validated by computer simulations for the cases of light, average and heavy shadowings. Finally, Section 5 concludes the present work.

*This work is supported by a strategic grant (STR-0100720) from the Natural Sciences and Engineering Research Council (NSERC) of Canada

[†]Currently with TR Labs, Edmonton, Canada.

2. First-Order Statistics of the LMS Channel

It is well known [1], [6] that a land mobile radio channel can be modelled as a Rayleigh fading channel with its local mean, the line-of-sight (LOS) component, following a lognormal statistical distribution. The channel corrupts the transmitted signaling waveform by introducing a multiplicative gain $r(t)$ and phase shift $\theta(t)$, which can be expressed as

$$R(t) = r(t) \cdot \exp[j\theta(t)] = \quad (1)$$

$$z(t) \cdot \exp[j\phi_L(t)] + g(t) \cdot \exp[j\phi_M(t)] \quad (2)$$

where the LOS and multipath phases ($\phi_L(t)$ and $\phi_M(t)$) are uniformly distributed between 0 and 2π . $z(t)$ is a lognormally distributed random process representing the amplitude of the LOS signal, $g(t)$ is the envelope of the multipath component and is Rayleigh distributed. The probability density function (PDF) of the lognormally distributed LOS component is [7]

$$p(z) = \frac{1}{\sqrt{2\pi d_0} z} \exp\left[-\frac{(\ln z - \mu)^2}{2d_0}\right] \quad (3)$$

where μ and $\sqrt{d_0}$ are the mean value and standard deviation of the normally distributed random process $\ln[z(t)]$. The PDF of the received signal envelope $r(t)$ is [1]

$$p(r) = \frac{r}{b_0 \sqrt{2\pi d_0}} \int_0^\infty \frac{1}{z} \exp\left[-\frac{(\ln z - \mu)^2}{2d_0} - \frac{r^2 + z^2}{2b_0}\right] I_0\left(\frac{rz}{b_0}\right) dz \quad (4)$$

where b_0 is the power of the multipath signal.

In Table 1, the parameters of the L-band (1.5 GHz) mobile satellite channel are displayed [1]-[3]. The calculations are based on measurement carried on in Ottawa, Canada. For the experiment, the INMARSAT's MARECS A satellite was used. The elevation angle from Ottawa to the satellite was about 20°. So far, the assessment of the LMS model has been carried out only at UHF and L-band. Due to lack of sufficient experimental LMS data at Ka-band, a comprehensive prediction of the relevant fading parameters cannot be done. However, from the mechanism of the LMS modelling at L-band, it is reasonable to assume that the LMS model is suitable

to be used for the channel at Ka-band with the model parameters being appropriately scaled. In this paper, we concentrate our analysis on the frequency non-selective fading channel.

Table 1: L-band channel model parameters.

L-band (1.5 GHz) channel	b_0	μ	$\sqrt{d_0}$
light shadowing	0.158	0.115	0.115
average shadowing	0.126	-0.115	0.161
heavy shadowing	0.0631	-3.91	0.806

The effect of multipath fading and shadowing on the LMS system performance depends on the system operation environments. In open and tree-shadowed areas, multipath fading results from both specular reflection and diffuse scattering from the terrain surrounding the mobile earth station. With the increase of the RF frequency, the amplitude of the reflection coefficient and the ground conductivity also increase; therefore, more scattering at Ka-band may come from small obstacles or terrain irregularities than those at L-band [8]. On the other hand, the mobile antenna radiation patterns at Ka-band are expected to be narrow enough to eliminate the problem to a great extent. As a result, in first approximation, it may be considered that multipath fading does not impair system performance at Ka-band more than that at L-band [4]. In the following discussion, the power of multipath component at Ka-band is taken to be the same as that at L-band.

With the RF frequency 30/20 GHz of Ka-band, the shadowing on the LOS component may come even from the leaves and the small branches of the trees whose dimensions are comparable with the wavelength (1.0-1.5 cm). Therefore, the LMS systems at Ka-band are expected to suffer more attenuation and diffusion due to shadowing in comparison with those at L-band. To the authors knowledge, very limited experimental data at Ka-band for mobile applications is available at the present time in the open literature and existing frequency scaling methods are not of straightforward applicability. An attempt has been made to estimate such a scaling factor using the *Modified Exponential Decay (MED) model* [9], developed from static propagation measurements through deciduous trees in Colorado, US. The attenuation coefficient (dB/m) can be computed by the

following equation [4]:

$$\alpha \approx 0.45f^{0.284} \quad \text{for } 0 \leq d_t \leq 14$$

$$\alpha \approx 1.33f^{0.284}d_t^{-0.412} \quad \text{for } 14 \leq d_t \leq 400 \quad (5)$$

where f is the frequency (in GHz) and d_t is the depth of trees (in m) intercepted by the LOS signal. The scaling factor is therefore:

$$\alpha_{20GHz} \approx 2.1\alpha_{1.5GHz} \text{ (dB/m)}. \quad (6)$$

It should be pointed out that such an estimate model is based on particular channel conditions, and that further modifications may be necessary when experimental data at Ka-band becomes available.

In the following channel modelling and LMS performance analysis at Ka-band, we use the L-band parameters with the frequency scaling technique discussed above to calculate the Ka-band channel parameters. The amplitude attenuation of the lognormally distributed LOS component at L-band equals [4]

$$A_{1.5GHz} = e^{X_{1.5}} \quad (7)$$

where $X_{1.5}$ has a Gaussian distribution with mean $\mu = \mu_{1.5}$ and variance $d_0 = \sigma_{1.5}^2$. At Ka-band with RF equal to $20 GHz$, the attenuation of the received LOS signal power in dBW is 2.1 times of that at L-band (see Eq. 6), that is,

$$\begin{aligned} A_{20GHz}^2(\text{dBW}) &= 2.1 A_{1.5GHz}^2(\text{dBW}) \\ \Rightarrow A_{20GHz} &= A_{1.5GHz}^{2.1} \\ \Rightarrow e^{X_{20}} &= e^{2.1 X_{1.5}} \\ \Rightarrow X_{20} &= 2.1 X_{1.5} \\ \Rightarrow \mu_{20} &= 2.1 \mu_{1.5} \\ \Rightarrow \sigma_{20} &= 2.1 \sigma_{1.5}. \end{aligned} \quad (8)$$

Figure 1 is a software simulation model of the LMS channel. In our simulations, the Gaussian noise after the low-pass (LP) filter is generated by summing a large number of sine waves [6]. The bandwidth of the LP filters is B_1 for the shadowing component and B_2 for the multipath component.

Figure 2 shows the cumulative distribution of the received L-band and Ka-band signal envelopes over the fading channel with average shadowing. The analytical results are obtained from Eq. (4). In these figures, the signal amplitude level is relative to the LOS signal component without shadowing ($0 dB$). The Ka-band

signal loses approximately an additional $1.5 dB$, $1.0 dB$ and $0.5 dB$ at the signal amplitude levels of $-10 dB$, $-5 dB$ and $0 dB$ respectively. Figure 3 shows the cumulative distribution of the received L-band and Ka-band signal envelopes without multipath signal in the case of average shadowing. The analytic values are obtained according to Eq. (3). From this figure, one observes that the signal at Ka-band loses an additional 0 to $3.5 dB$ in comparison to the L-band in the weak signal range (which is the most important for fade margin calculation). Table 2 shows the amplitude level of the shadowed LOS components at the cumulative probabilities of 70% , 80% and 90% .

Table 2: Amplitude level (in dB) of shadowed LOS components at different cumulative probabilities.

Shadowing	RF	Pr. 70%	Pr. 80%	Pr. 90%
light	1.5 GHz	0.49	0.23	-0.10
	20 GHz	1.02	0.27	-0.63
average	1.5 GHz	-1.66	-2.07	-2.55
	20 GHz	-3.65	-4.53	-5.85
heavy	1.5 GHz	-37.4	-39.4	-41.9
	20 GHz	-77.5	-81.8	-88.3

3. Second-Order Statistics of the LMS Channel

Second-order statistics are used to describe the time-dependent fading channel performance, which include level-crossing rate (LCR) and average fading duration (AFD). In the case of Rayleigh multipath fading with lognormal shadowing, the LCR normalized with respect to the maximum Doppler frequency shift is [1]

$$\begin{aligned} LCR_n(r = R) &= LCR(r = R)/F_{dm} \\ &= \sqrt{2\pi(1-\rho^2)} \frac{b_0(b_0+2\rho\sqrt{b_0d_0+d_0})^{\frac{1}{2}}}{b_0(1-\rho^2)+4\rho\sqrt{b_0d_0}} p(r) \end{aligned} \quad (9)$$

where ρ is the correlation coefficient between the envelope $r(t)$ and the envelope change rate $\dot{r}(t)$. The corresponding normalized AFD is

$$\begin{aligned} AFD_n(r = R) &= AFD(r = R) \cdot F_{dm} \\ &= \frac{1}{LCR_n} \int_0^R p(r) dr. \end{aligned} \quad (10)$$

The analytic values and simulation results of the second order characteristics (LCR and AFD)

for the average shadowing channel are shown in Figures 4-5, where the amplitude level of the received signal is relative to the amplitude of the LOS signal component without shadowing (0 dB). In the computer simulations, assuming a vehicle speed of 43.2 km/h as an example, the maximum Doppler frequency shifts (which is the bandwidth of the complex Gaussian noise filters used to filter the process generating the multipath fading, i.e., B_2 in Figure 1) are 60 Hz for the L-band signal and 800 Hz for the Ka-band signal. The bandwidth of the filter for the shadowing components (i.e., the B_1 of Figure 1) is taken as 1/20 of B_2 , which is 3 Hz for L-band and 40 Hz for Ka-band. The signal sampling rate is 2400 Hz. Each simulation is performed over 72,000 sampled data. The results show that the maximum values of the normalized LCRs of both L-band and Ka-band are very close to 1.0, which means that the LCRs increase almost linearly with the increase of the speed of vehicle or the increase of the RF frequency. The analytic values are obtained with $\rho = 0$, i.e., no correlation between $r(t)$ and $\dot{r}(t)$. In reality, there exists some correlation between $r(t)$ and $\dot{r}(t)$ and ρ may not be a constant, which may be further confirmed by the experimental data (see Figures 2-7 of [1]). That explains the slight differences between the simulation results and the analytical results in Figures 4-5. With the channel parameters and the use of frequency scaling technique, one finds that, in the case of average shadowing, the signal level at Ka-band is slightly more attenuated than at L-band.

4. Performance Evaluation of a Coherent BPSK System

It is assumed that a carrier recovery loop can track the carrier phase jitter due to the fading channel. Therefore, only amplitude fading due to the channel is taken into account. The upper bound of the average bit error rate is [10]

$$P_e^{av} \leq \frac{1}{2} \frac{1}{\sqrt{2\pi b_0}} \cdot \frac{\sigma_N^2}{b_0 + \sigma_N^2} \cdot \int_0^\infty \frac{1}{z} \cdot \exp\left[-\frac{(\ln z - \mu)^2}{2d_0}\right] \cdot \exp\left[-\frac{z^2}{2(b_0 + \sigma_N^2)}\right] dz \quad (11)$$

and if only the LOS component is considered, then

$$P_e^{av} \leq \frac{1}{2} \frac{1}{\sqrt{2\pi d_0}} \int_0^\infty \exp\left[-\frac{z^2}{2\sigma_N^2} - \frac{(\ln z - \mu)^2}{2d_0}\right] dz \quad (12)$$

The upper bounds (analytical values) and simulation results of bit error rate for a coherent BPSK system at L-band and Ka-band are presented in Figures 6-8. Figures 6-7 show the bit error rate due to amplitude fading of the LMS channel at L-band and Ka-band in the cases of light, average and heavy shadowing. With multipath fading and at a bit error rate of 10^{-3} , the system operating at Ka-band loses 0.75 dB, 3.5 dB and 0.6 dB as compared to L-band in the cases of light, average and heavy shadowing respectively. The LOS signal component at Ka-band suffers more additional attenuation (when compared to L-band) in average shadowing than in light shadowing, which results in more system loss at Ka-band in average shadowing (3.5 dB) than in light shadowing (0.75 dB).

In the case of heavy shadowing, the LOS component is attenuated significantly, so that the channel can be represented as a Rayleigh fading channel (with only multipath components in the received signal) at both L-band and Ka-band. The weight of the LOS component is dramatically reduced compared to the cases of both light and average shadowings. The system performance depends on the dominant multipath signal component. With the assumption that the first-order statistics are the same for the multipath fading at L and Ka bands, the additional system loss at Ka-band in the heavy shadowing condition (0.6 dB) is less than that in the average shadowing (3.5 dB), which is not the case when only the LOS component is considered. Figure 8 shows the bit error rate of the system due to average shadowing only (no multipath signal is taken into account) at L-band and Ka-band. It is shown that at a bit error rate of 10^{-3} , the Ka-band system suffers an additional loss of 3.33 dB compared to L-band system.

5. Concluding remarks

A comparison study for the land mobile satellite communication system operating at Ka-band and L-band has been performed. The modelling of LMS channel at Ka-band is based on channel experimental data at L-band and a frequency

scaling technique, because of lack of sufficient experimental data of the channel at Ka-band. Both first-order and second-order statistics of the LMS channel are analyzed. The results show that: the LOS signal component at Ka-band has 0.0 dB to 3.5 dB more attenuation in the presence of average shadowing; the channel fades have a much faster rate at Ka-band compared with that at L-band because the fading rate is approximately proportional to the RF frequency, and the normalized average fading duration (AFD) increases correspondingly at Ka-band. An upper-bound bit error rate of a coherent BPSK system in the LMS channel is derived, which is further validated by computer simulations. With multipath fading and shadowing, at a bit error rate of 10^{-3} , the system performance at Ka-band loses approximately 0.75 dB, 3.5 dB and 0.6 dB more than that at L-band; in the absence of multipath fading, the system performance at Ka-band loses approximately 3.33 dB more than that at L-band in the case of average shadowing.

References

- [1] C. Loo, "A Statistical Model for a Land Mobile Satellite Link", IEEE Trans. on Vehicular Technology, vol. VT-34, pp.122-127, August 1985.
- [2] J. S. Butterworth, "Propagation Measurements for Land Mobile Satellite System at 1542 MHz," Communication Research Center, Department of Communications, CRC Technical Note 723, August 1984.
- [3] C. Loo, "Digital Transmission Through a Land Mobile Satellite Channel", IEEE Trans. on Communications, vol. COM-38, no.5, pp.693-697, May 1990.
- [4] J. Fortuny, J. Benedicto, and M. Sforza, "Mobile Satellite Systems At Ku and Ka-Band", Proc. Second European Conference on Satellite Communications, pp.55-62, Liege, October 1991.

- [5] K. Dessouky, P. Estabrook, and T.C. Jedrey, "The ACTS Mobile Terminal", JPL SATCOM Quarterly, no.2, pp.1-9, July 1991.
- [6] W.C. Jakes, *Microwave Mobile Communication*. New York: Wiley 1974.
- [7] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*. Second Edition, McGraw-Hill International Book Company, 1984.
- [8] P. Beckmann and A. Spizzichino, *The Scattering of Electromagnetic Waves From Rough Surface*. Artech House, 1987.
- [9] M.A. Weissberger, *An Initial Summary of Models for Predicting the Attenuation of Radio Waves by Trees*. U.S. Dept. of Defense, Report no. ESD-TR-81-101.
- [10] W. Zhuang, A. Yongaçoğlu, J.-Y. Chouinard, D. Makrakis, "Performance Analysis of EHF Land Mobile Satellite Systems," Technical Report No.1, Department of Electrical Engineering, University of Ottawa, September 1992.

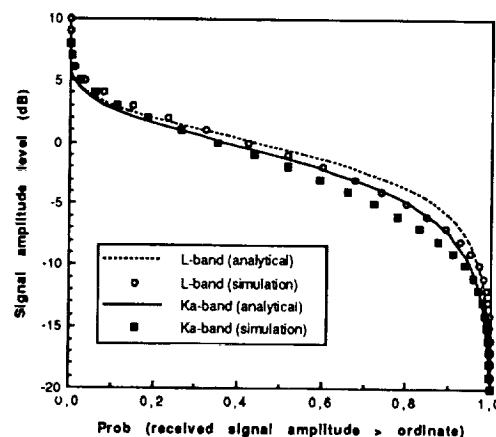


Figure 2: Received signal envelope probability distribution for average shadowing (with multipath).

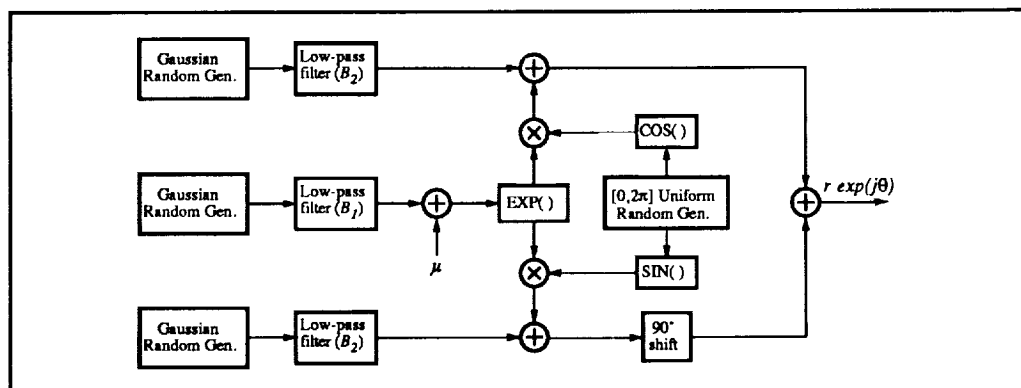


Figure 1: Land mobile satellite channel model.

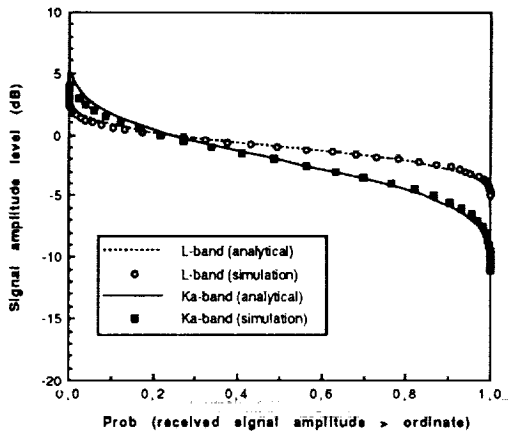


Figure 3: Received signal envelope probability distribution for average shadowing (without multipath).

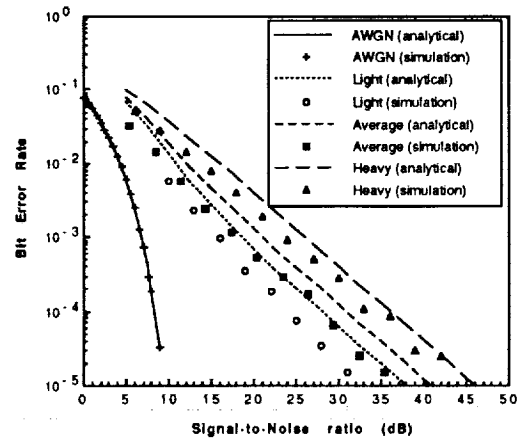


Figure 6: BER of a coherent BPSK system in a LMS channel at L-band.

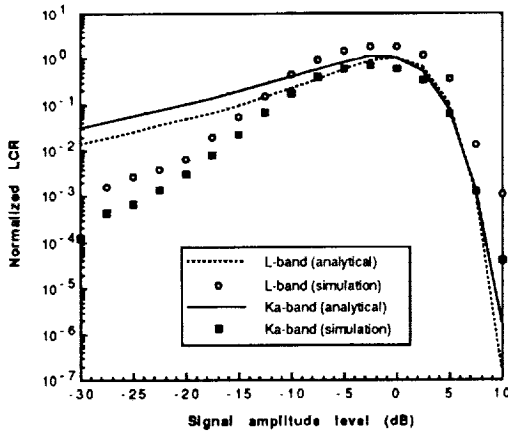


Figure 4: Normalized LCR in LMS channel at L-band and Ka-band (average shadowing).

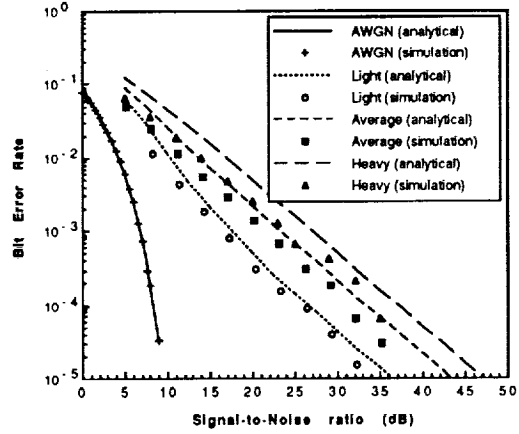


Figure 7: BER of a coherent BPSK system in a LMS channel at Ka-band.

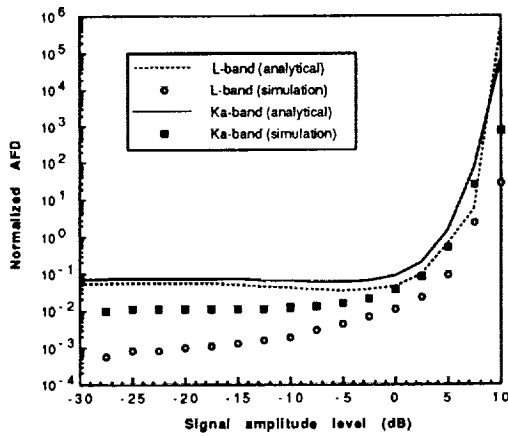


Figure 5: Normalized AFD in LMS channel at L-band and Ka-band (average shadowing).

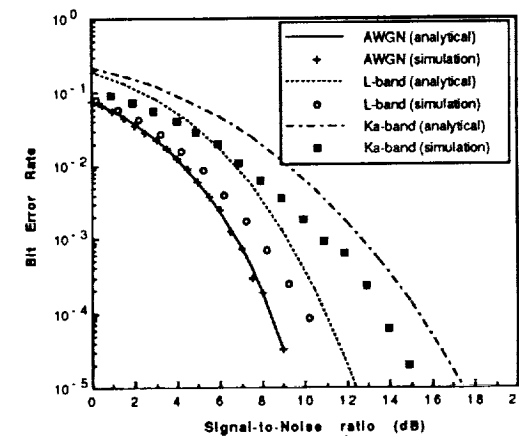


Figure 8: Performance of a coherent BPSK system over average shadowed LMS channel.