APPENDIX A: LINK BUDGET

This appendix contains data from link calculations for both the low-end and high-end receiving systems. The receiving systems are defined by the receiver noise figures and antennas described in Section 2 of this report. The transmitter and receiver losses are assumed to include antenna circuit losses, polarization mismatch, and transmission line losses. Modulator/demodulator losses are given in Section 5 and are included in the required CNR.

Tables A-1 through A-4 give the link budget data for various noise environments and receiving systems. The first column of numbers in the link budget corresponds to a 5-W spacecraft (S/C) transmitter and the second column corresponds to a 15-W S/C transmitter. The antenna temperature and system temperature correspond to the definitions given in Section 2 of this report.

Figures A-1 through A-8 give the cumulative distributions (with respect to time) of the received CNR for high-end and low-end systems in various noise environments. The threshold levels required for both DEBPSK and DEQPSK modulation are included in the figures. In each figure, there are four curves corresponding to two elevation angles and two transmitter powers P_t. The upper two curves are for an elevation of 90° (15-W and 5-W transmitter power) and the lower two curves are for an elevation of 5° and the same two transmitter power levels.

Table A-1. Link Budget for the Low-end System and 90^{0} Satellite Elevation

S/C Transmitting RF Channel Performance			
Transmitter power	(dBW)	7.0	11.8
Antenna gain	(dB)	3.7	3.7
Antenna circuit loss	(dB)	2.2	2.2
EIRP	(dBW)	8.5	13.3
Space-to-Earth Path Performance			
Path length	(km)	824.0	824.0
Free space loss	(dB)	133.5	133.5
Atmospheric Attenuation	(dB)	.0	.0
Ionospheric Attenuation	(dB)	.0	.0
E/S Receiving RF Channel Performance			
Antenna gain	(dB)	3.2	3.2
Antenna circuit loss	(dB)	2.0	2.0
Receiver noise figure	(dB)	6.0	6.0
Receiver temperature	(K)	8.6E+02	8.6E+02
Received carrier power	(dBW)	-121.8	-117.0
Receiver bandwidth	(dB-Hz)	48.6	48.6
Boltzmann const	(dB W/K/Hz)	-228.6	-228.6
Required CNR			
DEBPSK	(dB)	8.5	8.5
DEQPSK	(dB)	5.8	5.8
Man-made noise environments for 99.8% time availability			
Business			
Antenna temperature	(K)	2.5E+06	2.5E+06
System temperature	(K)	2.5E+06	2.5E+06
System noise power	(dBW)	-116.0	-116.0
Received CNR	(dB)	-5.8	-1.0
DEBPSK margin	(dB)	-14.3	-9.5
DEQPSK margin	(dB)	-11.6	-6.8
Residential			
Antenna temperature	(K)	9.4E+05	9.4E+05
System temperature	(K)	9.4E+05	9.4E+05
System noise power	(dBW)	-120.3	-120.3
Received CNR	(dB)	-1.5	3.3
DEBPSK margin	(dB)	-10.0	-5.2
DEQPSK margin	(dB)	-7.3	-2.5
Rural			
Antenna temperature	(K)	2.8E+05	2.8E+05
System temperature	(K)	2.8E+05	2.8E+05
System noise power	(dBW)	-125.6	-125.6
Received CNR	(dB)	3.8	8.6
DEBPSK margin	(dB)	-4.7	.1
DEQPSK margin	(dB)	-2.0	2.8
Quiet Rural			
Antenna temperature	(K)	7.8E+03	7.8E+03
System temperature	(K)	9.3E+03	9.3E+03
System noise power	(dBW)	-140.3	-140.3
Received CNR	(dB)	18.6	23.3

Table A-1. Continued

DEBPSK margin	(dB)	10.1	14.8
DEQPSK margin	(dB)	12.8	17.5
Man-made noise environments for 90.0% time availability			
Business			
Antenna temperature	(K)	1.6E+05	1.6E+05
System temperature	(K)	1.6E+05	1.6E+05
System noise power	(dBW)	-128.0	-128.0
Received CNR	(dB)	6.3	11.1
DEBPSK margin	(dB)	-2.2	2.6
DEQPSK margin	(dB)	.5	5.3
Residential			
Antenna temperature	(K)	5.8E+04	5.8E+04
System temperature	(K)	5.9E+04	5.9E+04
System noise power	(dBW)	-132.3	-132.3
Received CNR	(dB)	10.5	15.3
DEBPSK margin	(dB)	2.0	6.8
DEQPSK margin	(dB)	4.7	9.5
Rural			
Antenna temperature	(K)	1.7E+04	1.7E+04
System temperature	(K)	1.9E+04	1.9E+04
System noise power	(dBW)	-137.2	-137.2
Received CNR	(dB)	15.5	20.3
DEBPSK margin	(dB)	7.0	11.8
DEQPSK margin	(dB)	9.7	14.5
Quiet Rural			
Antenna temperature	(K)	1.0E+03	1.0E+03
System temperature	(K)	2.6E+03	2.6E+03
System noise power	(dBW)	-145.9	-145.9
Received CNR	(dB)	24.2	28.9
DEBPSK margin	(dB)	15.7	20.4
DEQPSK margin	(dB)	18.4	23.1

Table A-2. Link Budget for the Low-end System and 13^0 Satellite Elevation

S/C Transmitting RF Channel Performance			
Transmitter power	(dBW)	7.0	11.8
Antenna gain	(dB)	.0	.0
Antenna circuit loss	(dB)	2.2	2.2
EIRP	(dBW)	4.8	9.6
Space-to-Earth Path Performance			
Path length	(km)	2207.5	2207.5
Free space loss	(dB)	142.1	142.1
Atmospheric Attenuation	(dB)	.0	.0
Ionospheric Attenuation	(dB)	.0	.0
E/S Receiving RF Channel Performance			
Antenna gain	(dB)	.4	.4
Antenna circuit loss	(dB)	2.0	2.0
Receiver noise figure	(dB)	6.0	6.0
Receiver temperature	(K)	8.6E+02	8.6E+02
Received carrier power	(dBW)	-136.8	-132.1
Receiver bandwidth	(dB-Hz)	48.6	48.6
Boltzmann const	(dB W/K/Hz)	-228.6	-228.6
Required CNR			
DEBPSK	(dB)	8.5	8.5
DEQPSK	(dB)	5.8	5.8
Man-made noise environments for 99.8% time availability			
Business			
Antenna temperature	(K)	2.5E+06	2.5E+06
System temperature	(K)	2.5E+06	2.5E+06
System noise power	(dBW)	-116.0	-116.0
Received CNR	(dB)	-20.8	-16.1
DEBPSK margin	(dB)	-29.3	-24.6
DEQPSK margin	(dB)	-26.6	-21.9
Residential			
Antenna temperature	(K)	9.4E+05	9.4E+05
System temperature	(K)	9.4E+05	9.4E+05
System noise power	(dBW)	-120.3	-120.3
Received CNR	(dB)	-16.5	-11.8
DEBPSK margin	(dB)	-25.0	-20.3
DEQPSK margin	(dB)	-22.3	-17.6
Rural			
Antenna temperature	(K)	2.8E+05	2.8E+05
System temperature	(K)	2.8E+05	2.8E+05
System noise power	(dBW)	-125.6	-125.6
Received CNR	(dB)	-11.2	-6.5
DEBPSK margin	(dB)	-19.7	-15.0
DEQPSK margin	(dB)	-17.0	-12.3
Quiet Rural			
Antenna temperature	(K)	7.8E+03	7.8E+03
System temperature	(K)	9.3E+03	9.3E+03
System noise power	(dBW)	-140.3	-140.3
Received CNR	(dB)	3.5	8.3

Table A-2. Continued

DEBPSK margin	(dB)	-5.0	-.2
DEQPSK margin	(dB)	-2.3	2.5
Man-made noise environments for 90.0% time availability			
Business			
Antenna temperature	(K)	1.6E+05	1.6E+05
System temperature	(K)	1.6E+05	1.6E+05
System noise power	(dBW)	-128.0	-128.0
Received CNR	(dB)	-8.8	-4.0
DEBPSK margin	(dB)	-17.3	-12.5
DEQPSK margin	(dB)	-14.6	-9.8
Residential			
Antenna temperature	(K)	5.8E+04	5.8E+04
System temperature	(K)	5.9E+04	5.9E+04
System noise power	(dBW)	-132.3	-132.3
Received CNR	(dB)	-4.5	.2
DEBPSK margin	(dB)	-13.0	-8.3
DEQPSK margin	(dB)	-10.3	-5.6
Rural			
Antenna temperature	(K)	1.7E+04	1.7E+04
System temperature	(K)	1.9E+04	1.9E+04
System noise power	(dBW)	-137.2	-137.2
Received CNR	(dB)	.4	5.2
DEBPSK margin	(dB)	-8.1	-3.3
DEQPSK margin	(dB)	-5.4	-.6
Quiet Rural			
Antenna temperature	(K)	1.0E+03	1.0E+03
System temperature	(K)	2.6E+03	2.6E+03
System noise power	(dBW)	-145.9	-145.9
Received CNR	(dB)	9.1	13.9
DEBPSK margin	(dB)	.6	5.4
DEQPSK margin	(dB)	3.3	8.1

Table A-3. Link Budget for the High-end System and 90^0 Satellite Elevation

S/C Transmitting RF Channel Performance			
Transmitter power	(dBW)	7.0	11.8
Antenna gain	(dB)	3.7	3.7
Antenna circuit loss	(dB)	2.2	2.2
EIRP	(dBW)	8.5	13.3
Space-to-Earth Path Performance			
Path length	(km)	824.0	824.0
Free space loss	(dB)	133.5	133.5
Atmospheric attenuation	(dB)	.0	.0
Ionospheric attenuation	(dB)	.0	.0
E/S Receiving RF Channel Performance			
Antenna gain	(dB)	10.0	10.0
Antenna circuit loss	(dB)	2.0	2.0
Receiver noise figure	(dB)	1.0	1.0
Receiver temperature	(K)	7.5E+01	7.5E+01
Received carrier power	(dBW)	-115.0	-110.2
Receiver bandwidth	(dB-Hz)	48.6	48.6
Boltzmann const	(dB W/K/Hz)	-228.6	-228.6
Required CNR			
DEBPSK	(dB)	8.5	8.5
DEQPSK	(dB)	5.8	5.8
Man-made noise environments	**99.8% time availability**		
Business			
Antenna temperature	(K)	8.6E+05	8.6E+05
System temperature	(K)	8.6E+05	8.6E+05
System noise power	(dBW)	-120.7	-120.7
Received CNR	(dB)	5.7	10.5
DEBPSK margin	(dB)	-2.8	2.0
DEQPSK margin	(dB)	-.1	4.7
Residential Noise			
Antenna temperature	(K)	3.2E+05	3.2E+05
System temperature	(K)	3.2E+05	3.2E+05
System noise power	(dBW)	-125.0	-125.0
Received CNR	(dB)	10.0	14.8
DEBPSK margin	(dB)	1.5	6.3
DEQPSK margin	(dB)	4.2	9.0
Rural			
Antenna temperature	(K)	9.4E+04	9.4E+04
System temperature	(K)	9.4E+04	9.4E+04
System noise power	(dBW)	-130.2	-130.2
Received CNR	(dB)	15.3	20.0
DEBPSK margin	(dB)	6.8	11.5
DEQPSK margin	(dB)	9.5	14.2
Quiet Rural			
Antenna temperature	(K)	2.7E+03	2.7E+03
System temperature	(K)	2.9E+03	2.9E+03
System noise power	(dBW)	-145.3	-145.3
Received CNR	(dB)	30.3	35.1

Table A-3. Continued

DEBPSK margin	(dB)	21.8	26.6
DEQPSK margin	(dB)	24.5	29.3
Man-made noise environments	**90.0% time availability**		
Business			
Antenna temperature	(K)	5.3E+04	5.3E+04
System temperature	(K)	5.3E+04	5.3E+04
System noise power	(dBW)	-132.7	-132.7
Received CNR	(dB)	17.8	22.5
DEBPSK margin	(dB)	9.3	14.0
DEQPSK margin	(dB)	12.0	16.7
Residential			
Antenna temperature	(K)	2.0E+04	2.0E+04
System temperature	(K)	2.0E+04	2.0E+04
System noise power	(dBW)	-137.0	-137.0
Received CNR	(dB)	22.0	26.8
DEBPSK margin	(dB)	13.5	18.3
DEQPSK margin	(dB)	16.2	21.0
Rural			
Antenna temperature	(K)	5.9E+03	5.9E+03
System temperature	(K)	6.2E+03	6.2E+03
System noise power	(dBW)	-142.1	-142.1
Received CNR	(dB)	27.1	31.9
DEBPSK margin	(dB)	18.6	23.4
DEQPSK margin	(dB)	21.3	26.1
Quiet Rural			
Antenna temperature	(K)	3.5E+02	3.5E+02
System temperature	(K)	6.4E+02	6.4E+02
System noise power	(dBW)	-152.0	-152.0
Received CNR	(dB)	37.0	41.7
DEBPSK margin	(dB)	28.5	32.5
DEQPSK margin	(dB)	31.2	35.9

Table A-4. Link Budget for the High-end System and 5^0 Satellite Elevation

S/C Transmitting RF Channel Performance			
Transmitter power	(dBW)	7.0	11.8
Antenna gain	(dB)	-.3	-.3
Antenna circuit loss	(dB)	2.2	2.2
EIRP	(dBW)	4.5	9.3
Space-to-Earth Path Performance			
Path length	(km)	2833.3	2833.3
Free Space Loss	(dB)	144.2	144.2
Atmospheric attenuation	(dB)	.0	.0
Ionospheric attenuation	(dB)	.0	.0
E/S Receiving RF Channel Performance			
Antenna gain	(dB)	10.0	10.0
Antenna circuit loss	(dB)	2.0	2.0
Receiver noise figure	(dB)	1.0	1.0
Receiver temperature	(K)	7.5E+01	7.5E+01
Received carrier power	(dBW)	-129.7	-125.0
Receiver bandwidth	(dB-Hz)	48.6	48.6
Boltzmann const	(dB W/K/Hz)	-228.6	-228.6
Required CNR			
DEBPSK	(dB)	8.5	8.5
DEQPSK	(dB)	5.8	5.8
Man-made noise environments	**99.8% time availability**		
Business			
Antenna temperature	(K)	8.0E+06	8.0E+06
System temperature	(K)	8.0E+06	8.0E+06
System noise power	(dBW)	-111.0	-111.0
Received CNR	(dB)	-18.7	-14.0
DEBPSK margin	(dB)	-27.2	-22.5
DEQPSK margin	(dB)	-24.5	-19.8
Residential Noise			
Antenna temperature	(K)	3.0E+06	3.0E+06
System temperature	(K)	3.0E+06	3.0E+06
System noise power	(dBW)	-115.3	-115.3
Received CNR	(dB)	-14.4	-9.7
DEBPSK margin	(dB)	-22.9	-18.2
DEQPSK margin	(dB)	-20.2	-15.5
Rural			
Antenna temperature	(K)	8.8E+05	8.8E+05
System temperature	(K)	8.8E+05	8.8E+05
System noise power	(dBW)	-120.6	-120.6
Received CNR	(dB)	-9.1	-4.4
DEBPSK margin	(dB)	-17.6	-12.9
DEQPSK margin	(dB)	-14.9	-10.2
Quiet Rural			
Antenna temperature	(K)	2.5E+04	2.5E+04
System temperature	(K)	2.5E+04	2.5E+04
System noise power	(dBW)	-136.0	-136.0
Received CNR	(dB)	6.3	11.1

Table A-4. Continued

DEBPSK margin	(dB)	-2.2	2.6
DEQPSK margin	(dB)	.5	5.3
Man-made noise environments	**90.0% time availability**		
Business			
Antenna temperature	(K)	4.9E+05	4.9E+05
System temperature	(K)	4.9E+05	4.9E+05
System noise power	(dBW)	-123.1	-123.1
Received CNR	(dB)	-6.6	-1.9
DEBPSK margin	(dB)	-15.1	-10.4
DEQPSK margin	(dB)	-12.4	-7.7
Residential			
Antenna temperature	(K)	1.8E+05	1.8E+05
System temperature	(K)	1.8E+05	1.8E+05
System noise power	(dBW)	-127.4	-127.4
Received CNR	(dB)	-2.3	2.4
DEBPSK margin	(dB)	-10.8	-6.1
DEQPSK margin	(dB)	-8.1	-3.4
Rural			
Antenna temperature	(K)	5.5E+04	5.5E+04
System temperature	(K)	5.5E+04	5.5E+04
System noise power	(dBW)	-132.6	-132.6
Received CNR	(dB)	2.9	7.6
DEBPSK margin	(dB)	-5.6	-.9
DEQPSK margin	(dB)	-2.9	1.8
Quiet Rural			
Antenna temperature	(K)	3.3E+03	3.3E+03
System temperature	(K)	3.6E+03	3.6E+03
System noise power	(dBW)	-144.5	-144.5
Received CNR	(dB)	14.8	19.6
DEBPSK margin	(dB)	6.3	11.1
DEQPSK margin	(dB)	9.0	13.8

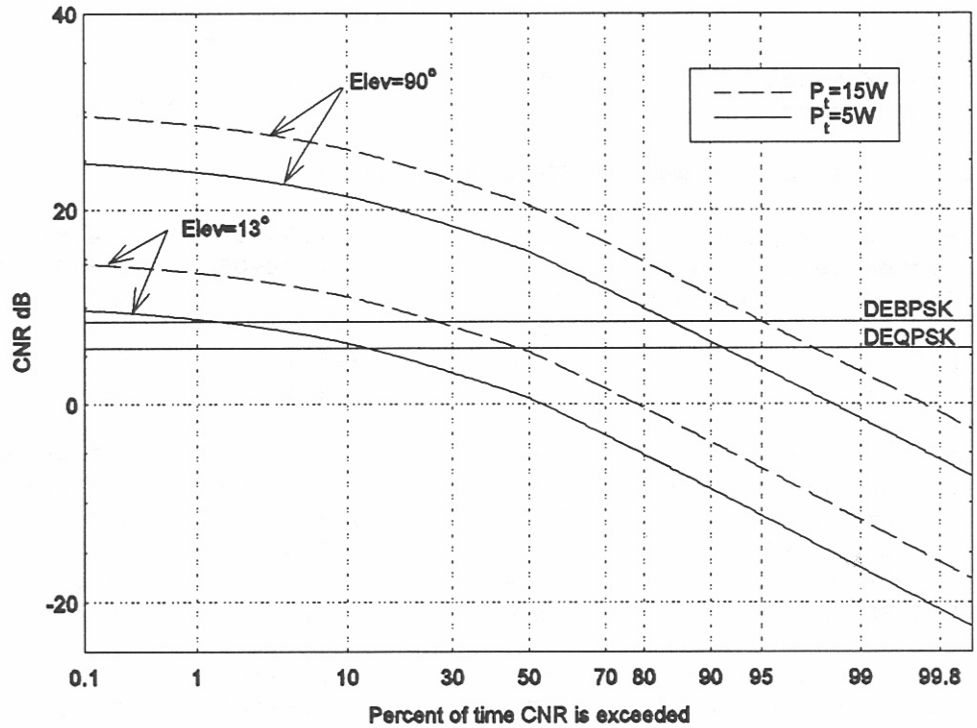

Figure A-1. Cumulative distribution of CNR for a business noise environment with the low-end receiving system.

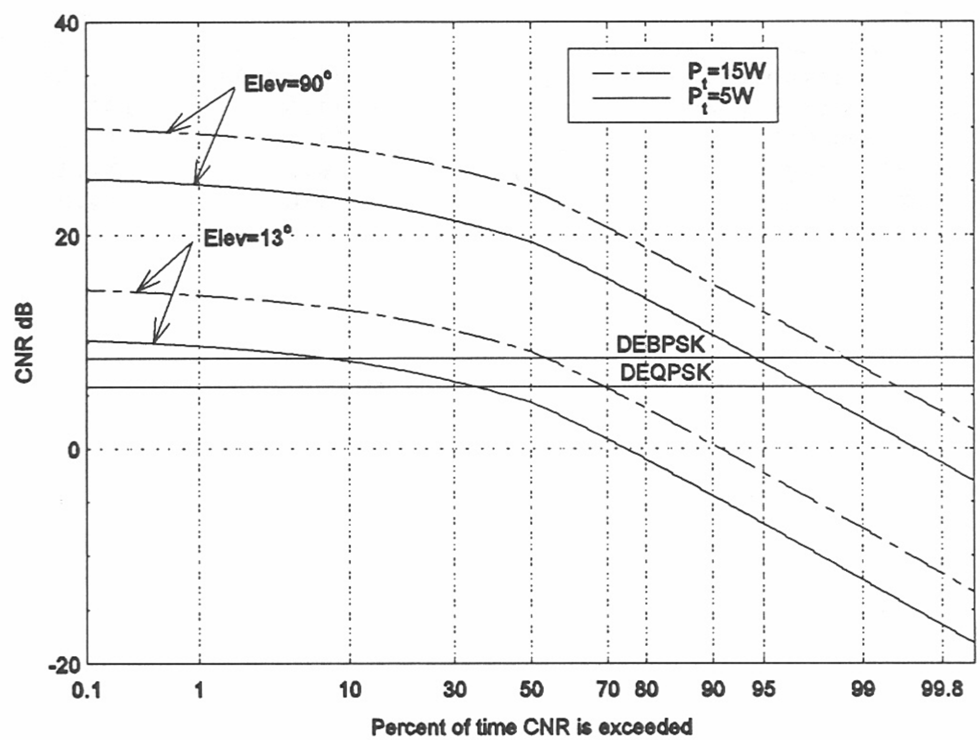

Figure A-2. Cumulative distribution of CNR in a residential noise environment with the low-end receiving system.

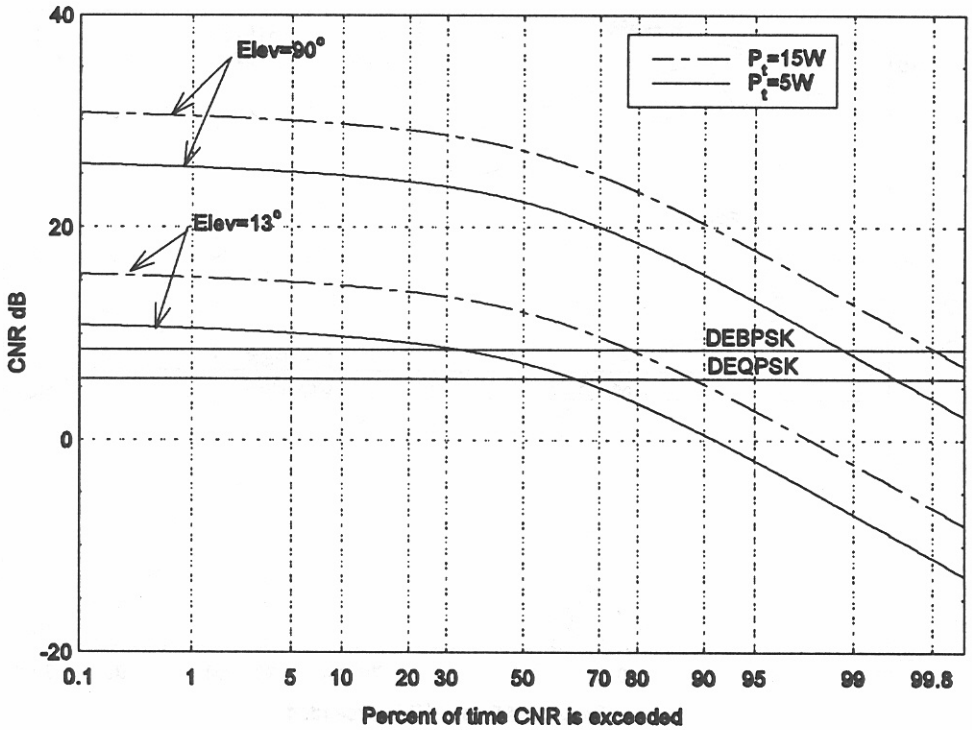

Figure A-3. Cumulative distribution of CNR in a rural noise environment with the low-end receiving system.

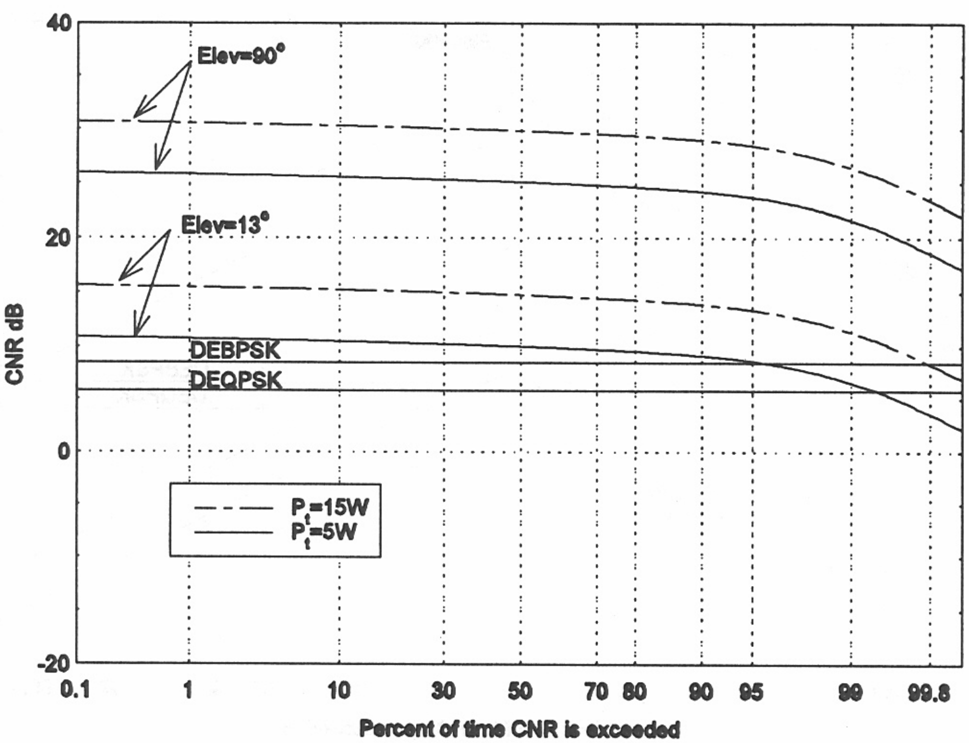

Figure A-4. Cumulative distribution of CNR in a quiet rural noise environment with the low end receiving system.

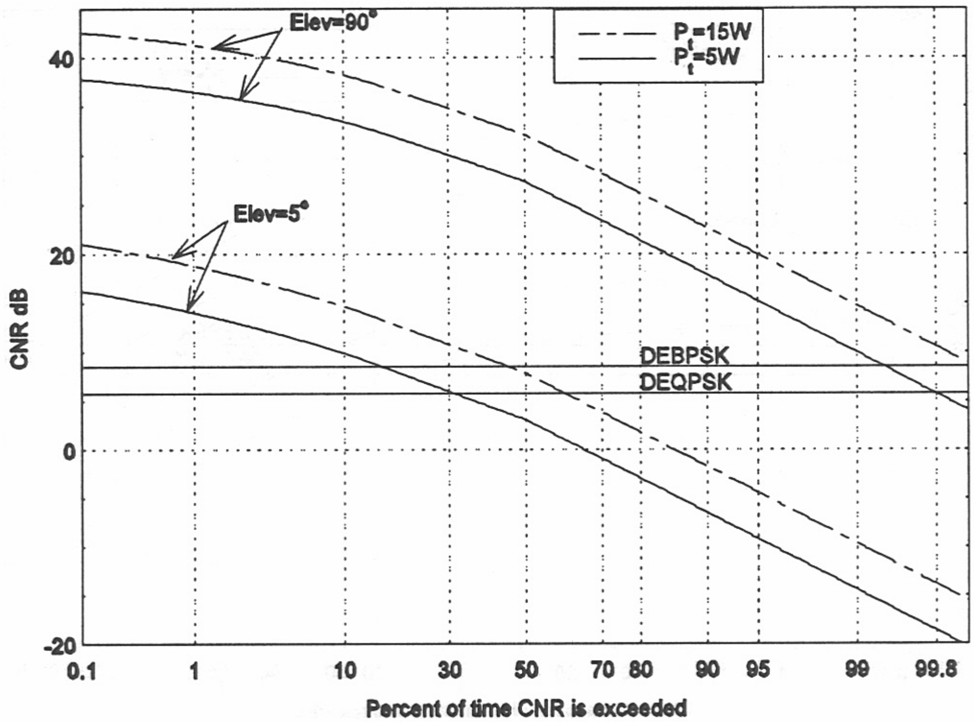

Figure A-5. Cumulative distribution of CNR in a business noise environment with the high-end system.

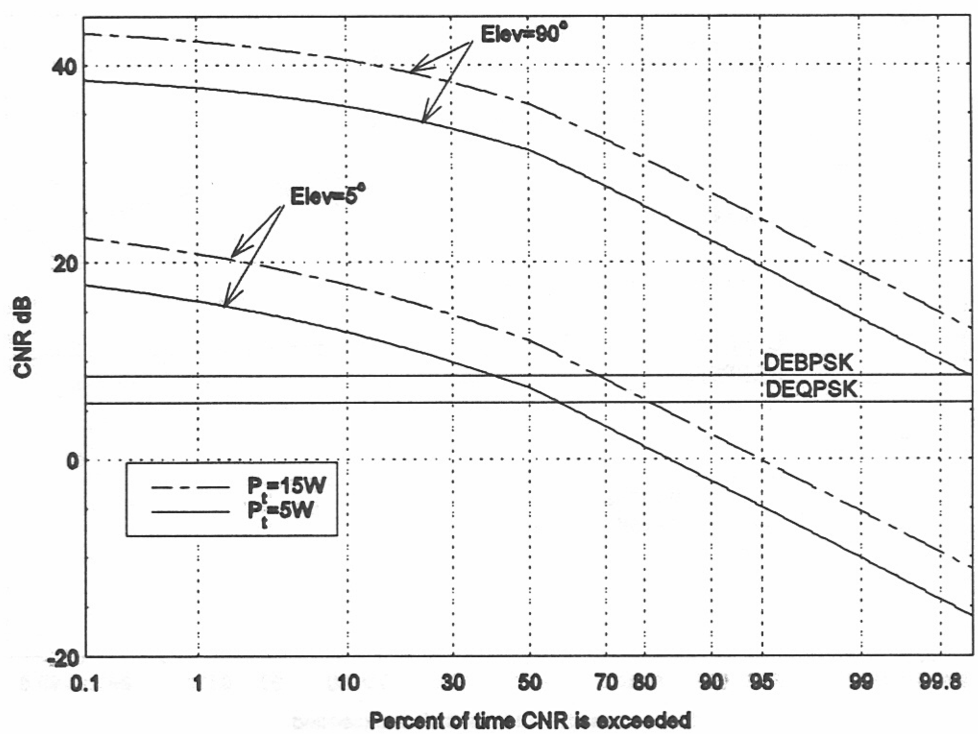

Figure A-6. Cumulative distribution of CNR in a residential noise environment with the high-end receiving system.

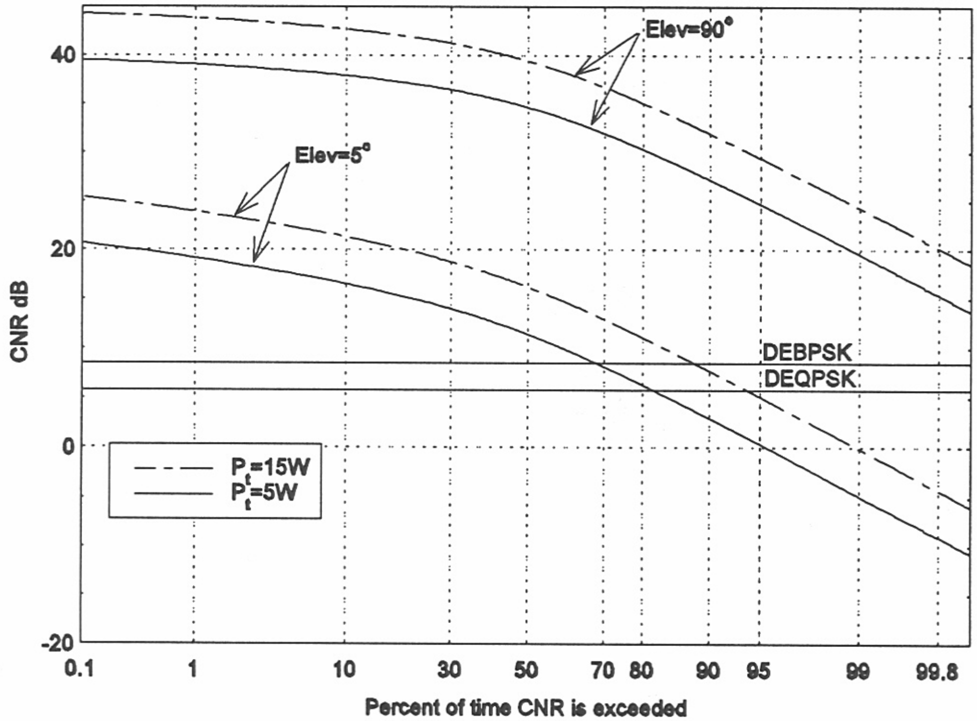

Figure A-7. Cumulative distribution of CNR in a rural noise environment with the high-end receiving system.

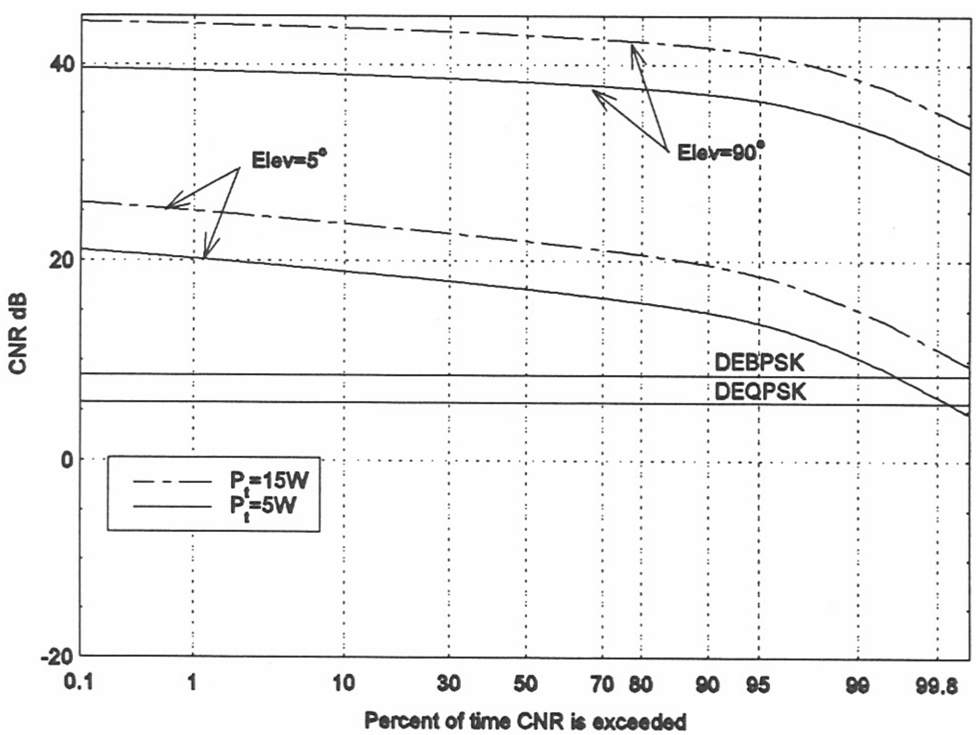

Figure A-8. Cumulative distribution of CNR in a quiet rural noise environment with the high-end receiving system.

APPENDIX B: REFERENCE EQUATIONS USED IN SECTION 5

B.1 BPSK Probability of Error

The following equations are from [1] and are used for calculating bit error probabilities P_b, where R_d is the symbol energy-to-noise ratio.

● BPSK [eq. 5-47, ref. 1]

$$P_b = \frac{1}{2} erfc(\sqrt{R_d})$$

● DEBPSK [eq. 5-114, ref. 1]

$$P_b = erfc(\sqrt{R_d}) - \frac{1}{2} erfc^2(\sqrt{R_d})$$

● DBPSK [eq. 5-125, ref. 1]

$$P_b = \frac{1}{2}\exp(-R_d)$$

B.2 QPSK Probability of Error

The following CV code equation is from [2]. For the (1, 2, 7) CV code, $N = 20$, $d_{free} = 10$, and β is an array having values 36, 211, 1,404, 11,633, 76,628, and 469,991 for elements 10, 12, 14, 16, 18, and 20 respectively.

$$P_b < \sum_{d=d\ free}^{N} \beta_d P_2(d)$$

● P_2(d) for QPSK and DEQPSK

$$P_2(d) = \frac{1}{2} erfc\left(\sqrt{\frac{R_d d}{2}}\right) = Q(\sqrt{R_d d})$$

● P_2(d) for DQPSK

$$P_2(d) = \frac{2}{3}[erfc(\sqrt{R_d d}\ \sin(\frac{\pi}{4\sqrt{2}}))] = \frac{4}{3}[Q(\sqrt{2R_d d}\ \sin(\frac{\pi}{4\sqrt{2}}))]$$

B.3 Carrier Recovery

The carrier recovery equations are from [3]. In the following equations, R is the input signal-to-noise ratio, B_N is the narrowband filter bandwidth, T is the symbol period, σ_φ is the rms phase jitter in radians, φ is the instantaneous phase, $\hat{\varphi}$ is the average phase, and $E\{\bullet\}$ is the expectation operator.

$$\sigma_\varphi^2 = E\{\varphi - \hat{\varphi}\}^2$$

- BPSK

$$\sigma_\varphi^2 = B_N T [\frac{1}{2R} + \frac{1}{4R^2}]$$

- QPSK

$$\sigma_\varphi^2 = B_N T [0.1125 + 1.4625\frac{1}{R} + 24.469\frac{1}{R^2} + 21.094\frac{1}{R^3} + 2.531\frac{1}{R^4}]$$

B.4 Symbol Timing Recovery

The symbol timing recovery equations are from [4]. In the following equations, T is the symbol period, τ is the instantaneous delay, $\hat{\tau}$ is the average delay, ξ is the relative delay error, $\pi\sigma_\xi$ is the rms timing jitter in radians, R_s is the symbol rate, and B_N is the narrowband filter bandwidth. The relative delay error is expressed as:

$$\xi = \frac{(\tau - \hat{\tau})}{T}$$

and the variance can be expressed as

$$(\pi\sigma_\xi)^2 = \frac{\pi^2 B_N N_0 (1 + \frac{N_0}{2E_s})}{4E_s R_s}$$

B.5 Reed Solomon Code

The RS code equations were derived from results in [2]. N is the number of symbols in the codeword, p is the probability of input bit error, m is the number of bits per symbol, t is the number of correctable symbol errors, and P_b is the output bit error rate.

$$P_b = \sum_{i=t+1}^{N} \binom{N}{i} \frac{i}{2N} (mp)^i (1 - mp)^{N-i}$$

B.6 References

[1] W.C. Lindsey and M.K. Simon, *Telecommunication System Engineering,* Englewood Cliffs, NJ: Prentice Hall, 1973.

[2] J.G. Proakis, *Digital Communications 3rd Edition,* New York, NY: McGraw Hill, pp. 464-466 and 470-511.

[3] L.E. Franks, "Carrier and bit synchronization in data communications - A tutorial review," *IEEE Transactions on Communications,* vol. COM-28, no. 8, pp. 1107-21, 1980.

[4] L.C. Palmer, S.A Rhodes, and S.H. Lebowitz, "Synchronization for QPSK transmission via communication satellites," *IEEE Trans. Comm.,* vol. COM-28, no. 10, pp. 1302-1314, 1980.