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MODULATION AND CODING STUDY OF DATA TRANSMISSION FROM THE GATEWAY STATION TO THE MOBILE AND VICE VERSA

EXECUTIVE SUMMARY

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MODULATION AND CODING STUDY OF DATA TRANSMISSION FROM THE GATEWAY STATION TO THE MOBILE AND VICE VERSA

EXECUTIVE SUMMARY

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Subject: Re: Old contractor report - still classified?

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John

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We have a report in the vault made by Miller Communications Systems in 1985. The title is: Modulation and Coding Study of Data Transmission from the Gateway Station to the Mobile and Vice Versa (Final Report and Executive Summary). This report was classified because it may contain information of commercial value. Is it still the case? Is it not covered by a patent now?

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Thank you.

Carole Laplante
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1.0 INTRODUCTION

The purpose of this study was to develop a software tool to evaluate several different modulation strategies which have been proposed for communication over the mobile-satellite channel.

One of the most difficult technical problems to overcome in mobile satellite communications is the multipath fading nature of the propagation channel. The fading process is due in general to attenuation (or blockage) of the direct path, plus the interference caused by a multitude of reflections from the earth's surface. The aeronautical, maritime, and land mobile channels are progressively more difficult to handle (in some respects), since:

(i) in the aeronautical channel, the fading is due entirely to multipath reflections from the earth's surface (neglecting effects of the aircraft skin, ionosphere, troposphere etc.),

(ii) in the maritime channel, the antenna is closer to the earth's surface (resulting in stronger individual reflections), and some direct path blockage will usually result from large waves and elements of the ship's superstructure, and

(iii) in the land mobile channel, the antenna is even closer to the earth (resulting in strong individual reflections), and there will frequently be severe blockage (or shadowing) of the direct path due to tall buildings, forests, etc.

A particular model of the mobile satellite communications channel is shown in Figure 1.1 [1], which has been shown to be valid for the land mobile case under certain

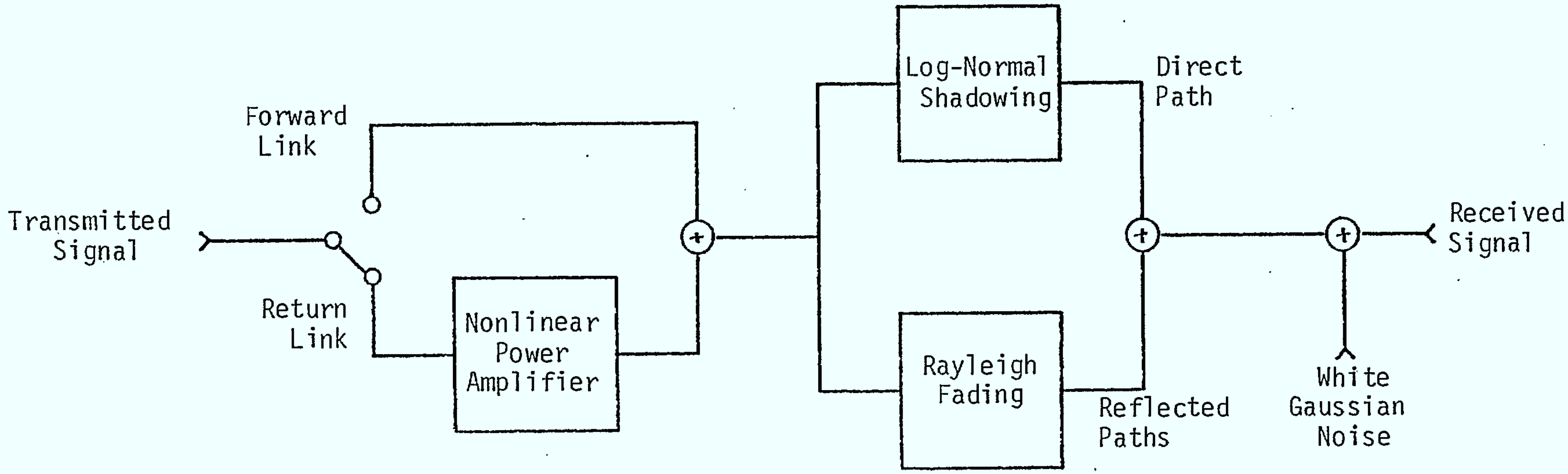


Figure 1.1 : A Model of the Satellite-Mobile Channel

circumstances [2]. The log-normal shadowing of the direct path is typical of forested terrain. Note that in the aeronautical case, the shadowing would not be present, and in the maritime case, it would not be log-normal.

In Figure 1.1, the fading rates of the Rayleigh and log-normal processes differ typically by at least an order of magnitude, with the former rate being typically 100 Hz, and the latter being perhaps a few Hz. (Both rates are proportional to the radial velocity of the vehicle.) Hence, during a few fade cycles of the Rayleigh process, the log-normal process is essentially constant, so that the short-term fading statistics will be seen as Rician, with a K-factor* determined by the direct path attenuation and the multipath power. Over a longer term, the overall process can be viewed as a Rician process with a varying K-factor.

Although strictly speaking, the individual reflections comprising the Rayleigh process will have different propagation delays, it is easy to show that this delay spread is negligible for the geometries and data rates of interest here.

The remainder of the channel is self-evident. There may (will) be a non-linear power amplifier in the (mobile) transmitter, and there will certainly be additive white Gaussian noise in the receiver.

The communications problem thus posed is to design a system that can provide reliable and satisfactory communications over the fading channel described above and specifically modelled in Figure 1.1.

*The K-factor is defined as 10 log (multipath power/direct power).

1.1 System Trade-Offs and Objectives

The degrees of freedom available to the systems designer, as reflected in the model of Figure 1.1, through which to realize a satisfactory system are:

(i) provide sufficient link margins to overcome the direct path shadowing,

(ii) minimize the multipath power through careful antenna design etc, and

(iii) adopt a modulation and coding strategy which is best suited to communicating over the resulting fading channel.

The subject study deals specifically with only the last of these, since effects of the first two will simply show up through choice of parameters in the channel model of Figure 1.1. In particular the specific objectives of the study were to evaluate, through computer simulation, and compare the performance of several candidate modulation strategies, with the channel modelled in Figure 1.1.

To be specific, the three modulation strategies evaluated were:

(i) Differential Minimum Shift Keying (DMSK)

(ii) Differential Offset Four Phase PSK (DOQPSK)

(iii) Coherent Binary Phase Shift Keying (BPSK) in conjunction with a Transparent Tone-In-Band (TTIB) Amplitude Companding Single Sideband modem (ACSSB)

All three strategies were tested at a data rate of 2.4 kbps and were restricted to a 5 kHz channel bandwidth.

1.2 Computer Simulation

The main focus of the evaluation of the three proposed modulation strategies was their computer simulation. MCS has previously developed and delivered a fading channel communications simulation under an MSAT Data Services contract. The main disadvantage of this existing simulation structure is that the instantaneous probability of error is computed for each bit from the (noise-free) demodulator output and the known (or assumed) noise distribution at that point in the system. Although efficient, this approach is rather restrictive in that exact and tractable expressions for detector noise statistics (first and second order) become unmanageable for all but relatively simple demodulators (e.g. CPSK and DPSK with no noise correlation from bit to bit). In addition, if the simulation is to be used to test coding strategies, actual (hard and soft) data sequences (rather than error probability sequences) are required for codec evaluation. In fact, for soft decision decoding, "signal" sequences are required. For these reasons, it was necessary to revert to a direct simulation approach, whereby AWGN is added at the receiver, and bit errors are counted. This of course implies large amounts of processing time to run the long sequences necessary in obtaining reasonably accurate performance estimates.

The channel simulation was developed in Fortran-77 under a VAX/VMS operating environment. In addition to the completely VAX compatible version, some time-consuming routines were also coded to make use of MCS's FPS-5100 Array Processor for evaluating performance at lower bit error rates.

In some cases the array processor provided a speed improvement of up to a factor of seventy-five over the VAX only version. This not only allowed evaluating the proposed modulation strategies at lower bit error rates but allowed faster debugging and testing of more scenarios than originally envisioned.

1.3 Scope of The Evaluation

The objective of the project was to evaluate the performance of three proposed modulation strategies over the described Rician fading channel. The performance of the different strategies was evaluated at bit error rates of 10^{-4} and worse, over Rician fading channels with K factors ranging from $-\infty$ (no fading path) to 0 dB (equal power in the direct and the fading path). The fading rate was fixed at 100 Hz. The effect of nonideal bit timing recovery, which would be common to all the proposed strategies, was not considered in the simulation or as part of the evaluation. However, excluding this the simulation fits the model of the mobile-satellite communications channel described in the preceding pages.

2.0 MODULATION STRATEGIES

2.1 DMSK

Minimum Shift Keying (MSK), which is also known as Fast Frequency Shift Keying (FFSK), is a phase coherent binary FSK modulation with modulation index h = 0.5 [3 - 12]. It has the following significant properties:

(a) 99.5% of the signal energy is contained within an IF bandwidth of 1.5 x (data rate),

(b) the signal envelope is constant and therefore MSK is suitable for use in nonlinear channels,

(c) the ideal error rate (coherent detection) is the same as that of 2- and 4-phase PSK.

As a result of these properties, MSK has received widespread interest [3, 7, 11] because of its potential in band-limited and power-limited systems.

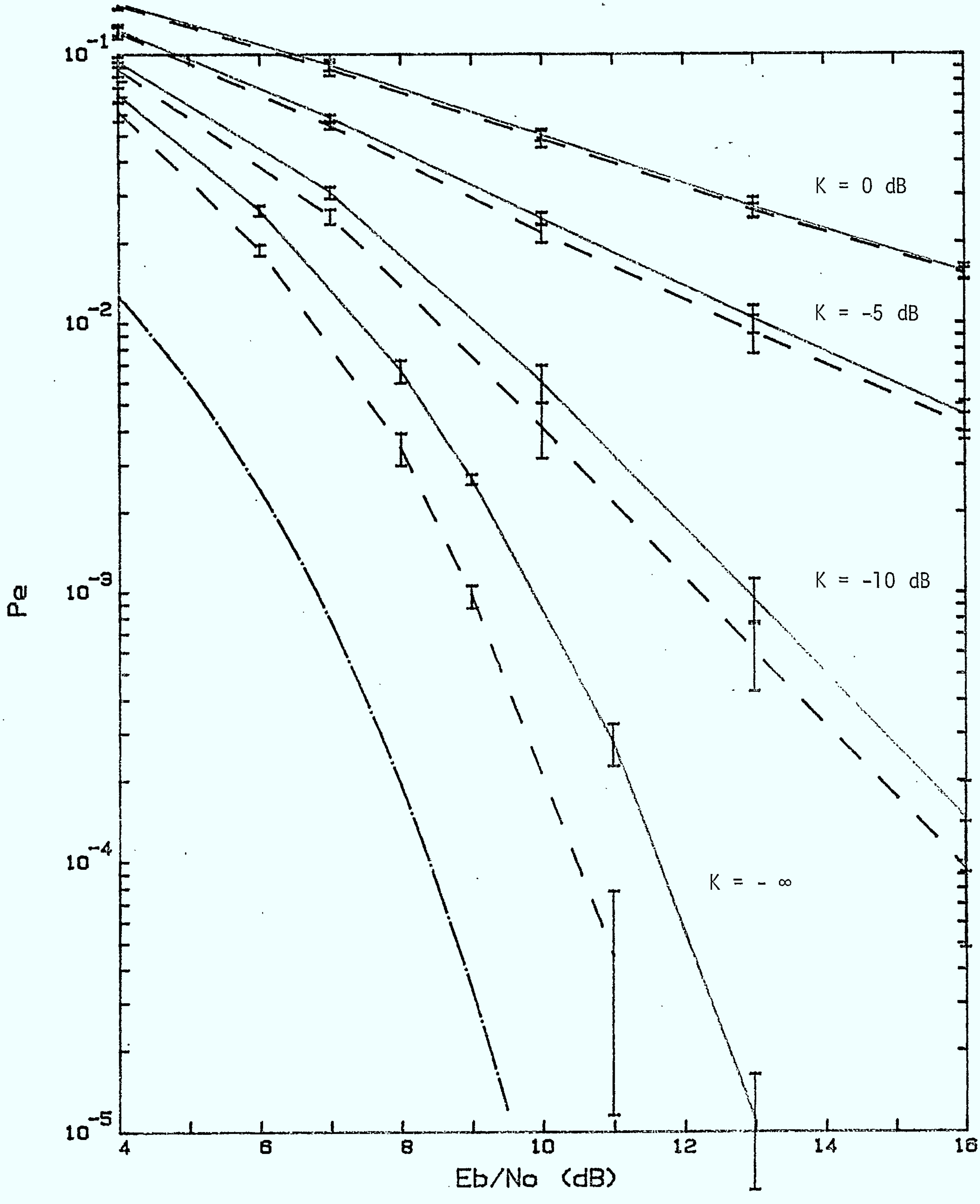
It has been shown in [4] that MSK signals can be demodulated by differential detection. While there may be implementation similarities between DMSK and DPSK, DMSK exhibits bandwidth and potentially power efficiency advantages over DPSK that make it a more attractive technique for development. A DMSK modem can use the usual FFSK/MSK modulator but recovers data by differential detection. Signal acquisition times for DMSK are primarily based upon clock recovery while joint carrier and clock recovery determine acquisition times for MSK. This is of prime concern for DAMA signalling for the MSAT mobile radio service.

The major disadvantage of differential detection is a theoretical E_b/N_o penalty arising from the use of an essentially noisier reference signal and ISI imposed by the receive filter. Filtering, as it relates ultimately to bit error rate performance, is a major concern. This penalty can be reduced, however, by observing [4] that phase comparison of alternate symbol intervals provides a parity check for successive symbols. Single errors can be corrected by a simple circuit without the need for the transmission of redundant bits. Such circuitry has been shown to be particularly useful for the correction of errors due to intersymbol interference.

2.1.1 DMSK Results

The DMSK modulation employed the standard half cosine pulse shape typical of MSK modulators, and a transmit filter to reduce the adjacent channel interference. The DMSK demodulator used a fourth-order linear-phase Butterworth receive filter with a BT product of 1.1 prior to the standard differential detector. This choice of receive filter was found in [13] to provide a near optimal tradeoff between intersymbol interference and noise for this detection scheme at a bit error rate of 5×10^{-4}.

With this combination of modem parameters the results obtained for a Rician fading channel are shown in Figure 2.1 for conventional DMSK detection and for the case where single error correction is performed. As this figure illustrates, even under no multipath conditions there is approximately a 3 dB penalty to pay relative to ideal coherent detection for using conventional DMSK detection over the range indicated. Use of the single error correction circuit regains approximately 1 dB of this penalty over the range of interest.



Comparison of conventional and SEC DMSK without nonlinearity

——————— conventional

— — — — SEC

—·—·—·— Ideal Coherent Performance

Figure 2.1

The performance of DMSK with a transmit nonlinearity is about the same as that shown without. This is because nonlinearities, which act on amplitude variations, do not distort the constant envelope MSK signal.

2.2 Differentially Detected OQPSK

The main problem with the DMSK signal format is that filters with BT products on the order of 1.0 cause quite severe ISI which results in degraded performance. Thus for the most part, optimizing the performance of the DMSK detector corresponds to trading off noise bandwidth against ISI.

This loss is often justified for DMSK because it is a modulation scheme with a constant envelope signal, and is relatively insensitive to frequency offsets. This constant envelope property is very desirable when the power amplifier is driven into saturation. The power amplifier used for ACSSB radios will not be driven into saturation, however, but must be somewhat more linear. For this reason, it may be advantageous to allow some envelope variation in exchange for tighter filtering (or even matched filtering) without the introduction of severe ISI. This more general approach can be viewed as differentially detected offset QPSK (DOQPSK). The modulator and demodulator for DOQPSK is essentially the same as that for DMSK; the major difference is in the pulse shaping and/or transmit filtering and receive filtering.

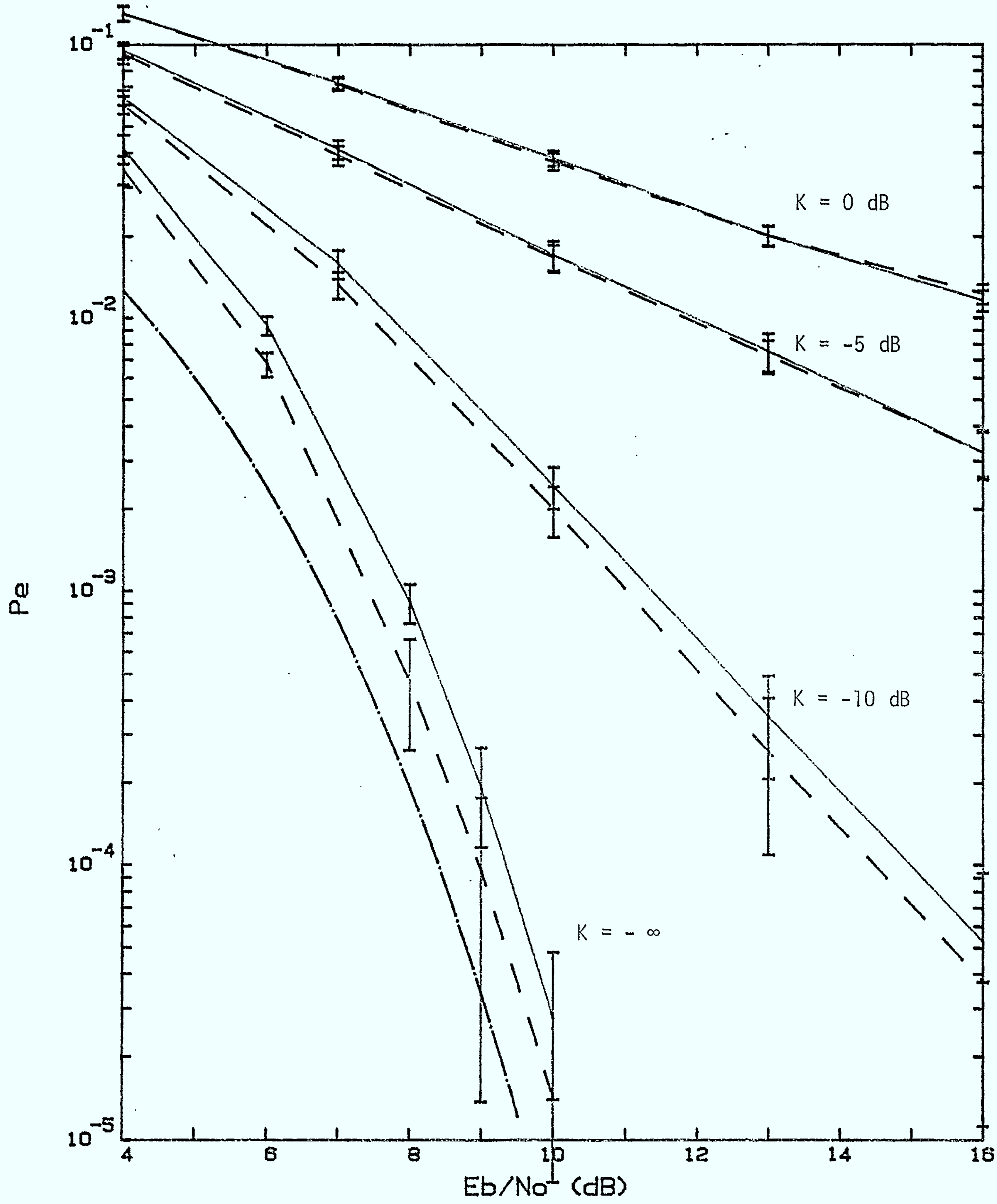
To overcome the ISI problem of DMSK, a Nyquist pulse shape can be used in the DOQPSK format and then matched filtered at the receiver. Ideally this format should suffer from no ISI, but because of the envelope variations of the transmitted signal, it is expected to suffer some degradation due to a nonlinearity.

2.2.1 DOQPSK Results

The DOQPSK modem was implemented in the simulation using a pulse with a 50% rolloff root raised cosine spectral shape. The simulated performance of this modulation strategy is shown in Figure 2.2 for the case of conventional DOQPSK and DOQPSK with single error correction. As expected with matched filtering, there is a large improvement over the performance obtained with DMSK. With no multipath, conventional DOQPSK only shows a degradation of approximately 1 dB from ideal-coherent performance over the bit error rate range of 10^{-2} to 10^{-4}, nearly identical to ideal theoretical performance for differential detection. The single error correction circuit provides a smaller but still significant improvement in this case. Under multipath conditions, DOQPSK shows a similar advantage over DMSK.

The above results refer to DOQPSK modulation without the presence of a transmit nonlinearity. One of the unexpected results of this study was that with the specified nonlinearity, this modulation scheme suffers virtually no degradation with respect to the case without the nonlinearity. An investigation into this result determined that the 50% rolloff selected was near optimal among the raised cosine pulse shapes, and resulted in an rms amplitude deviation of only 12% and a peak deviation of about 30%. In fact, using this modulation strategy with a hard limiting nonlinearity only caused approximately 0.2 dB degradation from the illustrated results.

The only potential drawback of this modulation strategy is the increased sidelobe energy levels with a nonlinear transmit amplifier and thus the possibility of unacceptable adjacent channel interference. However this may be remedied by passing the signal through a hard limiter and an appropriate transmit filter prior to the transmit amplifier.



Comparison of DOQPSK BER Performance with and without SEC

———————— conventional

— — — — SEC

—·—·—·— Ideal Coherent Performance

Figure 2.2

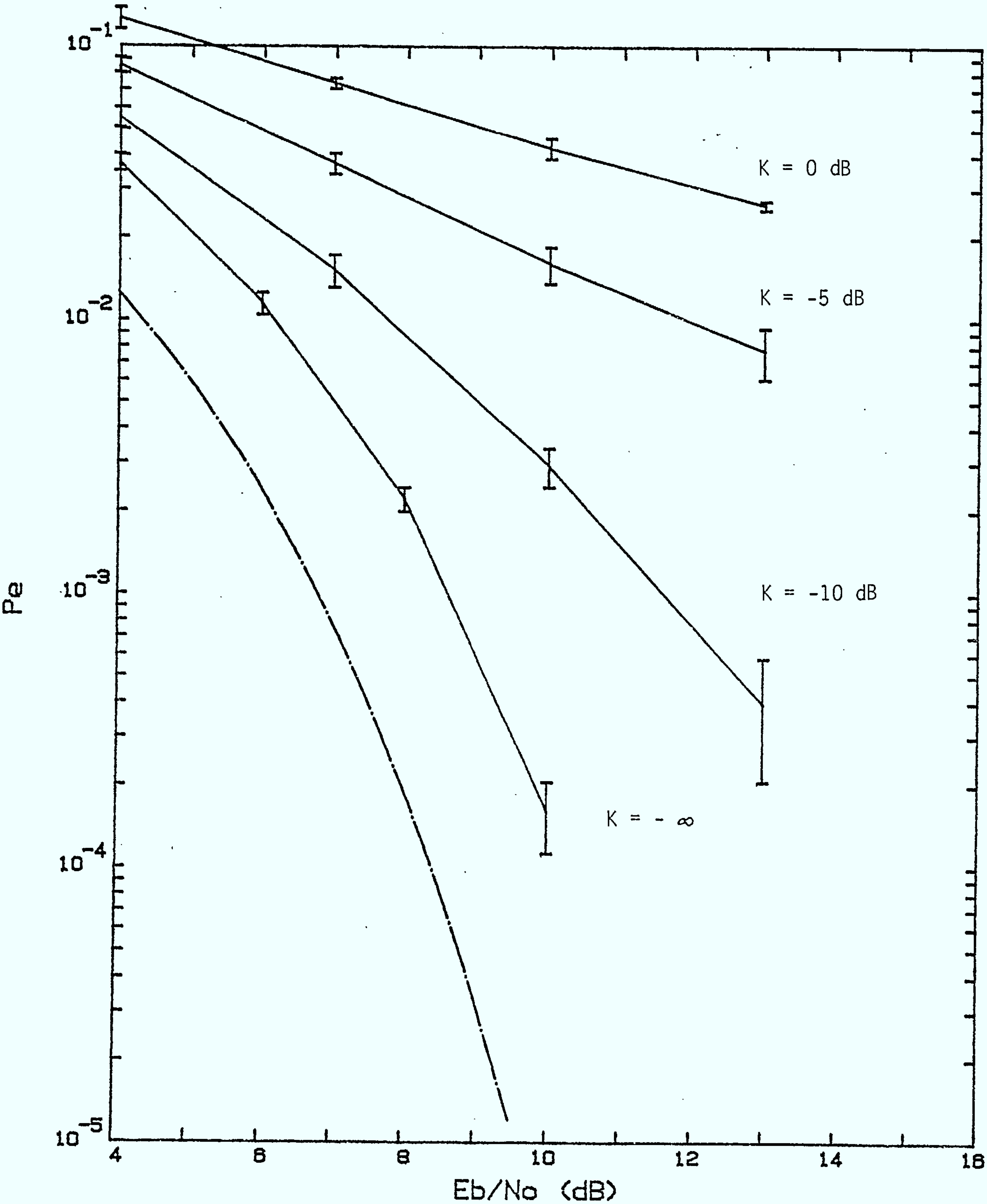
2.3 BPSK with TTIB ACSSB Modem

The third modulation strategy to be studied was to place the data modem in series with the ACSSB modem, thereby taking advantage of the ACSSB processing. Transparent tone-in-band (TTIB) ACSSB was the approach under consideration. Since an ACSSB modem with TTIB can be used to perform unambiguous carrier recovery [14], coherent modulation strategies were thought to be the most appropriate.

2.3.1 TTIB Results

In this simulation scenario, a pulse with a 20% rolloff root raised cosine spectral shape was used and the pilot levels were chosen as follows: the d.c. pilot was chosen to be 5 or 10 dB below the data signal power level and the plus and minus 300 Hz tones were each chosen to be 6 dB below the d.c. pilot.

Two different scenarios were simulated. In the first case ideal coherent subband recombining was performed. The performance results for this case, with the d.c. pilot at -5 dB, are shown in Figure 2.3. Under no multipath conditions ($K=-\infty$) this figure indicates a degradation of approximately 2 dB from ideal coherent detection. The majority of this degradation (1.7 dB) is due to the extra power required to transmit the pilots, which is included in calculating the energy per bit. Thus even under ideal conditions the TTIB ACSSB modem demonstrates poorer performance than the DOQPSK scheme. This might raise the question as to whether the pilot energy could be lowered, but the results of testing the second scenario of nonideal subband recombining, as shown in Figure 2.4, suggest not. These results show a large additional degradation (about 4 dB) with the introduction of nonideal subband recombining,

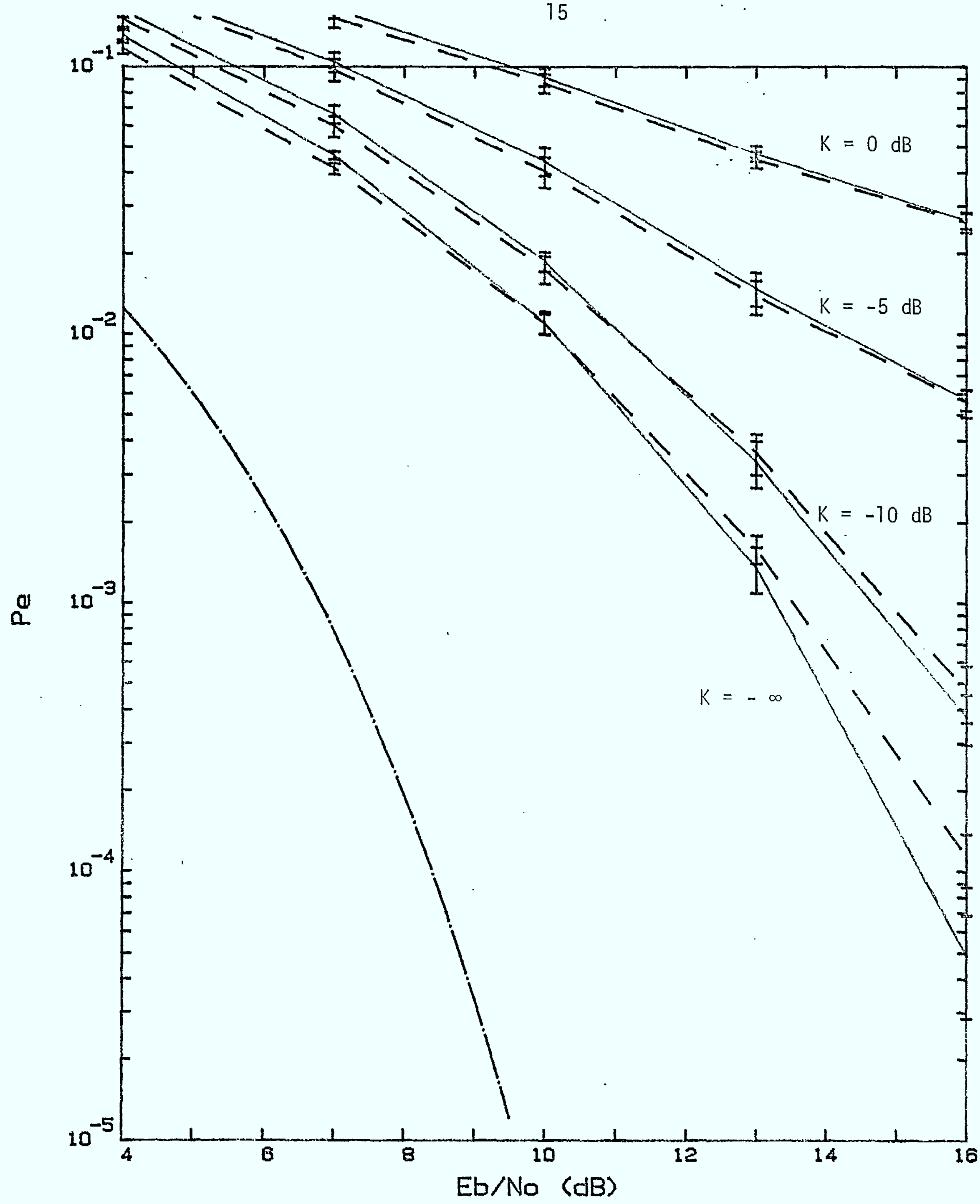


BPSK BER Performance of ACSSB Modem with Ideal Carrier Recovery

——————— K = - ∞, -10, - 5 and 0 dB

—·—·—·— Ideal Coherent Performance

Figure 2.3



BER Performance of BPSK with ACSSB (nonideal pilot recovery)

———————— without nonlinearity (-5dB pilot)

— — — — with nonlinearity (-5dB pilot)

—·—·—·— Ideal Coherent Performance

Figure 2.4

indicating that this modulation scheme is very sensitive to noise on the recovered subcarriers. This would indicate that the pilot levels should be increased rather than decreased, making this scheme even less attractive relative to DOQPSK. Further testing with lower pilot levels only provided poorer results as was anticipated.

3.0 CONCLUSIONS AND RECOMMENDATIONS

In this study we have evaluated three modulation strategies with respect to a simulated mobile-satellite communications channel.

The three modulation strategies evaluated were differentially detected MSK (DMSK), differentially detected offset QPSK (DOQPSK), and coherent BPSK in conjunction with an ACSSB modem with transparent tone-in-band (TTIB) signalling.

The main advantages of DMSK are that

(i) 99.5% of the energy is contained within an IF bandwidth of 1.5 times the data rate, and

(ii) the signal envelope is essentially constant, and as a result DMSK was demonstrated to have negligible degradation when used over a nonlinear channel.

The main disadvantages of differentially detected MSK are that

(i) there is a theoretical E_b/N_o penalty arising from the use of an essentially noisier reference signal in differential detection, and

(ii) receive filtering of the MSK signal, when using differential detection, introduces intersymbol interference (ISI).

The first results in a penalty of approximately 1 dB in SNR for bit error rates in the range 10^{-3} to 10^{-4}, when compared to ideal coherent detection. And for the near optimum receive filter tested, the second disadvantage was shown to result in an additional penalty of 2 dB in SNR. However, this penalty can be reduced by approximately 1 dB by employing a parity detector with a single error correction (SEC) circuit in the demodulator. (No additional coding is required in the modulator.)

In this study differential offset QPSK (DOQPSK) signalling with 50% rolloff root raised cosine spectrum shaping surfaced as a very attractive modulation scheme. The reasons are as follows:

(i) The main lobe bandwidth is 1.5 times the data rate, which is the same as for DMSK.

(ii) Under ideal conditions (AWGN channel) matched filtering at the receiver introduces no intersymbol interference (ISI). Thus the attainable bit error rate (BER) is essentially that of ideal differential detection, which is given by [12]

$$BER = \frac{1}{2} \exp(-E_b/N_o)$$

This performance is typically 2 dB better than that for DMSK for bit error rates in the range 10^{-3} to 10^{-4}.

(iii) BER performance does not degrade significantly when the signal is passed through a non-linear amplifier at the transmitter (less than 0.1 dB with the nominal nonlinearity, and 0.2 dB with a hard limiter).

The only disadvantages of DOQPSK are:

(i) approximately a 1 dB penalty associated with differential detection, relative to ideal coherent detection for bit error rates in the range 10^{-3} to 10^{-4}, and

(ii) the amount of sidelobe energy introduced by the nonlinearity, as adjacent channel interference must be kept to a minimum.

These disadvantages are not major however, as some of the differential detection loss can again be recovered using a single error correction circuit, and the adjacent channel interference can still be quite low when a nonlinearity is employed. Simulation results show that for the nominal nonlinearity given, the sidelobes are down 30 dB at the band edge and down 50 dB at the centre of the adjacent channel. One of the reasons for selecting a rolloff of 50% is because it results in close to the minimum RMS amplitude fluctuation attainable (only 12%) for this modulation scheme.

The third modulation strategy studied was coherent BPSK in conjunction with a TTIB ACSSB modem. The main advantages of this approach are:

(i) the ability to employ a coherent detection scheme, namely BPSK, and thus the potential to achieve ideal coherent bit error rate performance (neglecting the additional power required for the pilot tones), and

(ii) the AGC which compensates for the amplitude and phase perturbations introduced by the fading channel.

The major drawbacks of this approach are:

(i) the wider bandwidth required to transmit both data and pilot tones,

(ii) the degradation in performance due to nonideal subband recombining, and

(iii) the additional E_b/N_o penalty due to the transmitted power which must be devoted to the pilot tones.

There is little that can be done to mitigate these disadvantages. As a result, this modulation scheme faces some large penalties in performance. In fact under otherwise ideal conditions, the third disadvantage alone results in poorer performance than the DOQPSK scheme.

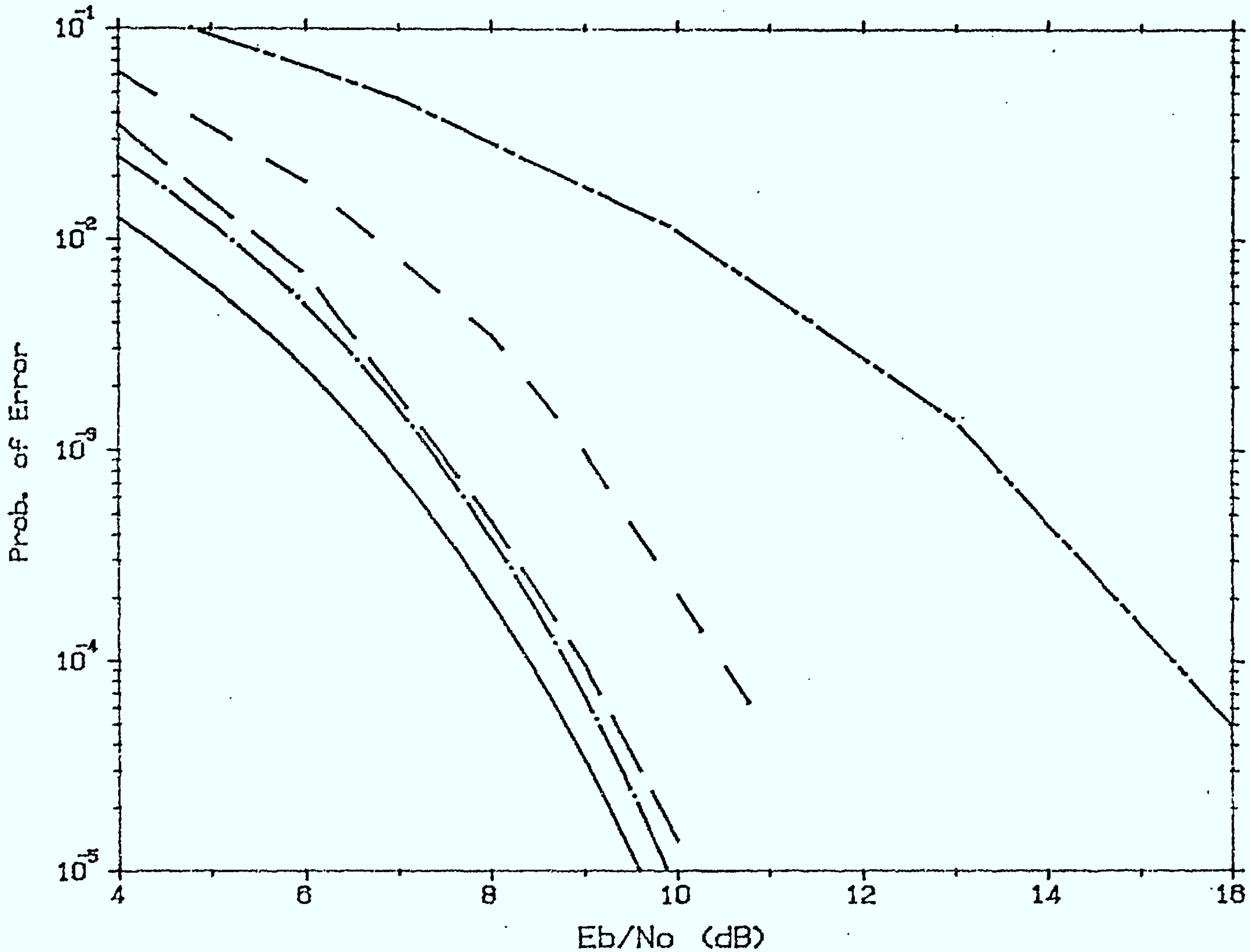
As the previous observations would tend to indicate, DOQPSK is the recommended modulation strategy, at least for low K factor fading channels. Figure 3.1 shows the performance of the best of the three modulation strategies examined under no multipath conditions. These strategies are:

(i) DMSK with single error correction (SEC)

(ii) DOQPSK with SEC

(iii) BPSK in conjunction with a TTIB ACSSB modem (the d.c. pilot is 5 dB below the data, and each subpilot is 6 dB below the d.c. pilot)

As quantitatively indicated by this figure, DOQPSK is clearly the superior modulation strategy. The curves shown do not include a nonlinearity in the channel; with the nominal nonlinearity present, the only curve which shows a



Comparison of DMSK (SEC), DOQPSK (SEC) and BPSK with ACSSB

DMSK (SEC)   DOQPSK (SEC)

BPSK with ACSSB (-5 dB pilot)

Ideal Coherent   Ideal D.E. Coherent

Figure 3.1

significant degradation is that for the TTIB ACSSB modem. The performance indicated for the TTIB ACSSB modem is for nonideal subband recombining. With ideal subband recombining the performance is still only about the same as that for DMSK with SEC. Also shown in this figure is ideal coherent bit error rate performance with differential encoding. Differential encoding is often used with coherent modulation techniques to resolve the 180° phase ambiguity problem associated with carrier recovery at the receiver*. Note that DOQPSK with SEC is very near this theoretical lower bound.

To this point, we have mainly compared the modulation strategies in terms of their performance in a nonmultipath channel. However, the relationship of the three approaches remains the same under fading conditions. These results clearly indicate that DOQPSK is superior under fading conditions as well. In all three cases, performance degrades considerably with increased fading (channel K-factor). Similar performance is obtained when the nonlinearity is introduced, although the TTIB ACSSB case degrades somewhat more than the other two cases. Thus, while pilot-oriented techniques may have an advantage over differential techniques at high SNR's (e.g. land mobile), they do not at the low to moderate SNR's typical of mobile-satellite channels.

In summary, a very useful software tool has been developed which can be used to analyze a wide range of modulation schemes for numerous time varying multipath channel scenarios. Of the three modulation strategies considered, differentially detected offset QPSK, with 50% rolloff root raised cosine spectral shaping, is clearly superior for

*A preamble could also be used to resolve the phase ambiguity at the receiver, but is not very practical for a fading channel.

both the forward and return link of a mobile-satellite communications channel. This scheme performs very close to ideal and has a significant advantage over both DMSK and BPSK in conjunction with a TTIB ACSSB modem. The former suffers from degraded performance due to significant intersymbol interference caused by receive filtering. The latter is degraded because of the poor performance of the coherent subband recombining over the range of signal-to-noise ratios of interest.

The simple structure of the DOQPSK scheme considered suggests that a fairly inexpensive digital/software modem could be easily developed. With the superior performance indicated above, such a modem should have good market potential, especially for low power, mobile-satellite applications.

3.1 Recommendations For Further Work

A number of areas merit further investigation. These include:

(i) DOQPSK signalling with filtering after a hard limiter. This scheme should yield a close to constant signal envelope with reduced adjacent channel interference.

(ii) Multiple parity branches to improve the performance with non-redundant error correction.

(iii) Forward error correction coding with interleaving (time diversity) to combat fading. Both soft and hard decision coding should be considered.

Interleaving is very important to obtain the time diversity required to improve performance with fading channels.

(iv) Channel estimation. With multilevel signalling and/or soft decision decoding it is important to have an estimate of the channel state or quality, especially for time-varying channels.

(v) Non-linearity estimation from either the transmit or receive end. This may be required if multilevel signalling schemes are employed.

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