MUTUAL INTERFERENCE WITH DUAL CHANNEL OPERATION

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ABSTRACT

The Communications Interface Equipment is a multi-link communication subsystem designed to augment the command and telemetry capabilities of the Space Shuttle and its payloads. One link consists of two PSK channels which are frequency division multiplexed. In each channel the data can be at one of several possible data rates and either NRZ or Bi∅ encoded. Simultaneous operation of the two channels causes a performance degradation to each due to mutual interference. The amount of degradation is a function of modulation formats, data rates, relative channel powers, probability of error and bandpass filter characteristics. Approximations for the degradation are derived, and the performance sensitivity to the various parameters is demonstrated.

INTRODUCTION

When installed in the Space Shuttle, the Communications Interface Equipment (CIE) will increase the flexibility and capability of the Orbiter communication system. One of the CIE links connecting detached payloads to the Orbiter consists of two PSK modulated frequency division multiplexed (FDM) channels. The purpose of this study is the evaluation of performance degradation due to cross-channel interference as a function of modulation format, data rates, relative channel powers and receiver bandpass filter characteristics. The effect of filtering the signal at the transmitter is excluded, although the extension of the presented results is straightforward.

The two FDM channels are centered at subcarrier frequencies of 1.024 MHz and 1.7 MHz. Each channel has a dedicated demodulator that includes a bandpass filter and coherent tracking and detection circuitry. The modulation format in each channel can be either Non-Return-to-Zero (NRZ) or Biphase (Bi∅). The 1.024 MHz demodulator can detect any of seven data rates (1, 2, 4, 8, 16, 32 and 64 Kbps), while three data rates (64, 128 and 256 Kbps) are possible for the 1.7 MHz demodulator. The nominal design value for the ratio of carrier power-to-noise spectral density (C/N_o) maintains a probability of error (Pe) equal to 10^{-3} using coherent PSK demodulation (E_b/N_o = 6.8 dB for all data rates).

The demodulator model is shown in Figure 1. The input u(t) consists of the desired signal, the adjacent channel interference signal and white Gaussian noise.

$$u(t) \qquad = A_s \, d_s(t) + \sqrt{\ } \, A_s \, d_I(t) \cos 2\pi f_I t + n(t) \tag{1}$$

where:

A_s = desired signal amplitude

$d_s(t)$ = desired baseband signal

$d_I(t)$ = interference baseband signal

α = ratio of interference power to desired signal power

f_I = separation in center frequencies of the two channels

$n(t)$ = white Gaussian noise

The bandpass filter for each channel remains fixed for all data rates and data formats. Perfect timing and phase synchronization are assumed in the model.

SINGLE CHANNEL BANDPASS FILTER DEGRADATION

The bandpass filter causes a performance degradation due to signal attenuation and distortion as well as intersymbol interference. Accordingly, the filter bandwidth cannot be made arbitrarily small without imposing excessive degradation even during single channel operation. Following the work of Jones[1], the single channel performance degradation for Bi∅ data is shown (Figure 2) for Butterworth filters of different orders as a function of the time-bandwidth product, BT, defined as the product of the filter RF bandwidth and the symbol duration. Similar curves can be obtained for NRZ encoded data [2]; for equal BT values, the degradation with NRZ data is always less than that incurred by Bi∅ data. The curves suggest selection of $1/BT \leq 0.25$, which constrains the single channel degradation to less than 0.7 dB using the second or third order filters. The curves also indicate minimal performance difference between the second and third order filters in the region of interest ($1/BT \leq 0.25$).

DUAL CHANNEL DEGRADATION

The frequency spectra at the input of the channel demodulator are depicted in Figure 3 for a 64 Kbps signal in the 1.024 MHz channel and a 256 Kbps signal in the 1.7 MHz channel. Both signals are Bi∅ encoded and have equal power. The plot is normalized such that $A_s^2 T_s = 1$ for the 256 Kbps signal. The figure illustrates the amount of adjacent channel interference in the frequency band of each channel. This in-band interference cannot be filtered out and causes an inevitable degradation. While the figure applies to the case of equal channel powers ($\alpha = 1$), simple resealing extends the results to cases of unequal channel powers.

Figure 4 demonstrates the effect of data rate variation: all parameters are identical to those in Figure 3 except the data rate in the 1.024 MHz channel, which is reduced to 16 Kbps. The mutual interference diminishes considerably with data rate reduction.

Figure 5 demonstrates the effect of replacing the Bi∅ format with NRZ. Since NRZ involves narrower spectra, the mutual interference is less severe relative to the Bi∅ case.

During dual channel operation each signal is primarily outside the passband of the other. Thus, the interfering effect is termed adjacent channel interference, as opposed to the co-channel interference scenario more commonly modeled in existing literature. The Rosenbaum and Glave[3] and other (e.g.[4]) approaches to the analysis of adjacent channel interference provide insight into the degradation incurred but become computationally impractical for the situation of current interest. Two different computationally convenient approximations are used in this study: a constant interference approximation that yields optimistic degradation estimates and an equivalent noise approximation that yields pessimistic estimates.

Constant Interference Approximation

During dual channel operation the interference signal contributes a voltage V_I at the output of the integrate-and-dump filter. The voltage either adds or subtracts from the desired signal voltage depending on the polarity of the transmitted bit. The conditional probability of error, given the interference voltage, is:

$$\begin{aligned} P_e(\gamma_1 \mid V_I) &= 1/2 \left\{ Q\left[\frac{\sqrt{K_s}A_s - V_I}{\sqrt{K_N}\,\sigma_{no}}\right] + Q\left[\frac{\sqrt{K_s}A_s + V_I}{\sqrt{K_N}\,\sigma_{no}}\right]\right\} \\ &= 1/2 \left\{ Q\left[\sqrt{\gamma_1}\,(1 - V_I/\sqrt{K_s}A_s)\right] + Q\left[\sqrt{\gamma_1}\,(1 + V_I/\sqrt{K_s}A_s)\right]\right\} \end{aligned} \qquad (2)$$

where:

$$Q(X) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-y^2/2}\,dy$$

A_s^2 = data filter output signal power without bandpass filter

σ_{no}^2 = data filter output noise power without bandpass filter

K_s = signal power attenuation due to bandpass filter

K_N = noise power attenuatiorf due to bandpass filter

γ_1 = data filter output signal-to-noise ratio at the sampling instant

$$= K_s A_s^2 \,/\, K_n \sigma_{no}^2 = \frac{K_s}{K_N}\,\gamma_o$$

γ_o = data filter output signal-to-noise ratio without bandpass filter

The probability of error averaged over all possible inteference voltages is then

$$P_e = \int P_e(\gamma_1 | V_I)\, dV_I \tag{3}$$

The value of V_I at any particular sampling instant depends on the relative symbol durations, bit timing and phasing between the desired and interference signals as well as the particular interference data sequence. Since the exact distribution of V_I is not available, an approximation of P_e based only on the second moment of V_I shall be obtained.

The interference power at the output of the integrate-and-dump filter is:

$$P_I = \frac{1}{T_s^2} \int_{-\infty}^{\infty} |H(f)D(F)|^2\, S_I(f)\,df = \alpha A_s^2 K \tag{4}$$

where:

T_s = desired signal symbol duration

$S_I(f)$ = power spectral density of the interference signal

$H(f)$ = bandpass filter transfer function

$D(f)$ = equivalent integrate-and-dump transfer function

K_I = attenuation of interference power due to bandpass and integrate-and-dump filters

Since the power P_I represents the average squared value of V_I, (3) is subject to the constraint:

$$\int V_I^2 P(V_I) dV_I = P_I \tag{5}$$

Unfortunately, the parameter P_I alone does not specify the distribution of the amplitude V_I. However, consider the special case where the magnitude of V_I always equals $\sqrt{P_I}$. Then, (3) becomes

$$P_e = 1/2 \left\{ Q\left[\sqrt{\gamma_1}\left(1 - \sqrt{\alpha K_I / K_s}\right)\right] + Q\left[\sqrt{\gamma_1}\left(1 + \sqrt{\alpha K_I / K_s}\right)\right] \right\} \tag{6}$$

The error probability given by (6) is valid only if V_I is constant at all sampling instants. The equation yields an optimistic approximation of the degradation because most variations in V_I, subject to the average power constraint of (5), result in larger values of average P_e. The estimate is not a strict lower bound, because it is easy to conceptualize pathological amplitude distributions that give smaller average P_e.

Using (6), the degradation from ideal PSK was evaluated for the worst case combination of data rates and modulation formats: 64 Kbps at 1.024 MHz and 256 Kbps at 1.7 MHz, both BiØ encoded. The degradation is determined for various interference-to-signal-power ratios (α) by plotting the bit error rates for both ideal and degraded cases as in Figure 6. The example in Figure 6 illustrates the effect of the interference from the 1.7 MHz channel on the 1.024 MHz channel under the assumption of a 256 KHz second order Butterworth bandpass filter (i.e., BT = 4).

Figures 7 and 8 show degradation curves when the desired signal is in the 1 .7 MHz channel. The effect of varying the filter order is depicted in Figure 7 as a function of α. Figure 8 depicts the effect of varying BT. For reasonable degradations (e.g., less than 3 dB), the results demonstrate the relative degradation insensitivity to the designated filter parameters. Thus, the remainder of the paper will be restricted to the second order. Butterworth filter with a value of BT = 4 at the maximum data rate for each channel.

Equivalent Noise Approximation

A pessimistic approximation of the performance degradation can be obtained by treating the interference as zero mean additive Gaussian noise with power $P_I = \alpha K_I^2 A_s$. The new signal-to-noise ratio at the output of the integrate-and-dump filter becomes

$$\gamma = \frac{K_s A_s^2}{K_N \sigma_{no}^2 + \alpha K_I A_s^2} \doteq \frac{K_s \gamma_o / K_N}{1 + \alpha K_I \gamma_o / K_N} \tag{7}$$

To achieve a probability of bit error of 10^{-3} in the ideal case requires a γ_o of 9.8 dB. Degradation in the present case is defined as the increase in γ_o required to maintain a constant value of 9.8 dB for γ. It is straightforward to obtain

$$\text{Degradation} = D_I + 10 \log [1 - 9.55\ \alpha K_I / K_s] \tag{8}$$

where:

$D_1 = 10 \log K_s/K_N$

$=$ degradation due to bandpass filter during single channel operation

All curves in this section exclude the term D_1 and show only the additional degradation directly attributable to the adjacent channel interference.

If the interference always resulted in the same output power, (8) would represent an upper bound to the performance degradation. For "mild" variations of V_I the degradation implied by (8) is pessimistic; however, V_I distributions exist which yield degradations exceeding that predicted by (8). In general, these distributions require large deviations of V_I from its average value. A brief investigation of several interference sequences with various relative phases and bit timing revealed no significant deviations. Thus, the degradation from (8) is regarded as pessimistic.

Figures 9 and 10 present a comparison between the degradation approximation derived in this section and the constant interference approximation derived previously. In both figures, the 1.024 MHz channel has 64 Kbps BiØ data, while the 1.7 MHz channel has 256 Kbps BiØ data. In Figure 9, the 1.7 MHz channel is the interference, while in Figure 10 the 1.024 MHz channel is the interference. As shown, the "bounds" are reasonably tight for degradations less than approximately 2 dB.

The values of α that give constant degradation are plotted in Figures 11 and 12 as a function of the desired signal data rate. The 1.024 MHz channel contains the desired signal in Figure 11, and the interfering signal in Figure 12. Lowering the data rate of either the desired or interfering signal allows a larger interference value to be tolerated. As an example, for a fixed degradation of 1 dB with 256 Kbps interference (Figure 11), the value of allowable α varies between 25 dB and 7 dB as the desired signal data rate varies between 1 and 64 Kbps, respectively. When the interference data rate is reduced to

128 Kbps, the value of α varies between 27 dB and 9 dB for the same 1 dB degradation[2] . Further reduction of the interference data rate to 64 Kbps yields allowable α values between 32 dB and 14 dB.

When NRZ encoding is utilized in either the desired or interfering signal, the tolerable interference values are larger than in the Bi∅ encoding case. For example, with 256 Kbps NRZ interference from the 1.7 MHz channel, the value of α that gives 1 dB degradation in the 1.024 MHz channel varies between 29 dB and 11 dB as the desired NRZ signal varies between 1 and 64 Kbps, respectively[2].

If the performance criteria for both subcarriers are identical, a logical assignment of channel powers is in proportion to the respective data rates, since the required C/N_o for fixed P_e is itself proportional to data rate. In this case, α varies between 6 dB and 24 dB as the 1.024 MHz channel data rate varies between 64 Kbps and 1 Kbps. For such an assignment of channel powers, the worst case degradation impacts the 1.024 MHz channel when the 1.7 MHz interfering channel operates at 256 Kbps and both channels are Bi∅ encoded. The degradation remains at approximately 0.7 dB for all 1.024 MHz channel data rates and concomitant values of α[2]. For comparison, two additional 1.7 MHz interfering channel configurations are: 256 Kbps NRZ, which yields 0.4 dB degradation, and 128 Kbps Bi∅, which yields approximately 0.2 dB degradation.

All of the degradation data presented herein has presupposed a probability of bit error equal to 10^{-3}. If the required probability of error is varied while the level of degradation is held constant, the acceptable values of α are modified, as shown in Figure 13. The data is plotted for degradation values of 0.2 dB and 1 dB. As the error rate diminishes from 10^{-3} to 10^{-6} the interference-to-desired-signal-power ratio must be reduced by approximately 3.5 dB to maintain the constant degradation values specified.

CONCLUSION

Approximations of the PSK demodulator performance degradation due to adjacent channel interference have been derived. The sensitivity of the degradation to desired signal and interference data rates, relative channel powers, modulation format, probability of error and bandpass filter characteristics were shown. The worst case degradation due to adjacent channel interference over all scenarios of interest to the CIE can be bounded by approximately 0.7 dB by assigning channel powers in proportion to data rate.

REFERENCES

[1] J. J. Jones, “Filter Distortion and Intersymbol Interference Effects on PSK Signals,” IEEE Trans. Comm., Vol. COM-19, No. 2, pp 120-132, April 1971

[2] "Communications Interface Equipment Dual Subcarrier Adjacent Channel Interference Study," Rockwell International Corp., Rept. No. STS 0352, April 27, 1983

[3] A. S. Rosenbaum and F. E. Glave, "An Error-Probability Upper Bound for Coherent Phase-Shift Keying with Peak-Limited Interference," IEEE Trans. Comm., Vol. COM-22, pp. 6-16, January 1974.

[4] L. B. Milstein, R. L. Pickholtz and D. L. Schilling, "Comparison of Performance of Digital Modulation Techniques in the Presence of Adjacent Channel Interference," IEEE Trans. Comm., Vol. COM-30, pp 1984-1993, August 1982.

Figure 1. System Model for Data Detection

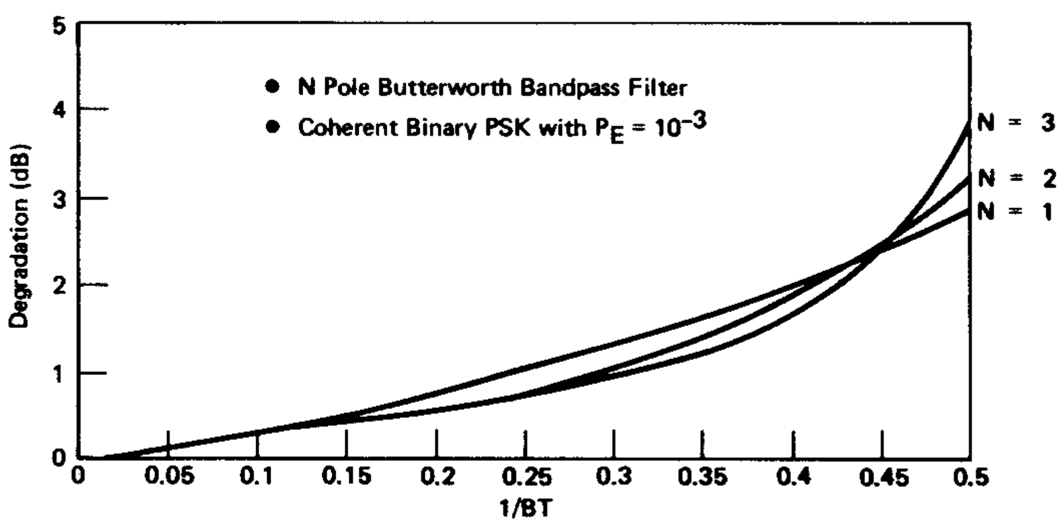


Figure 2. Single Channel Bandpass Filter Degradation with Bi∅ Data

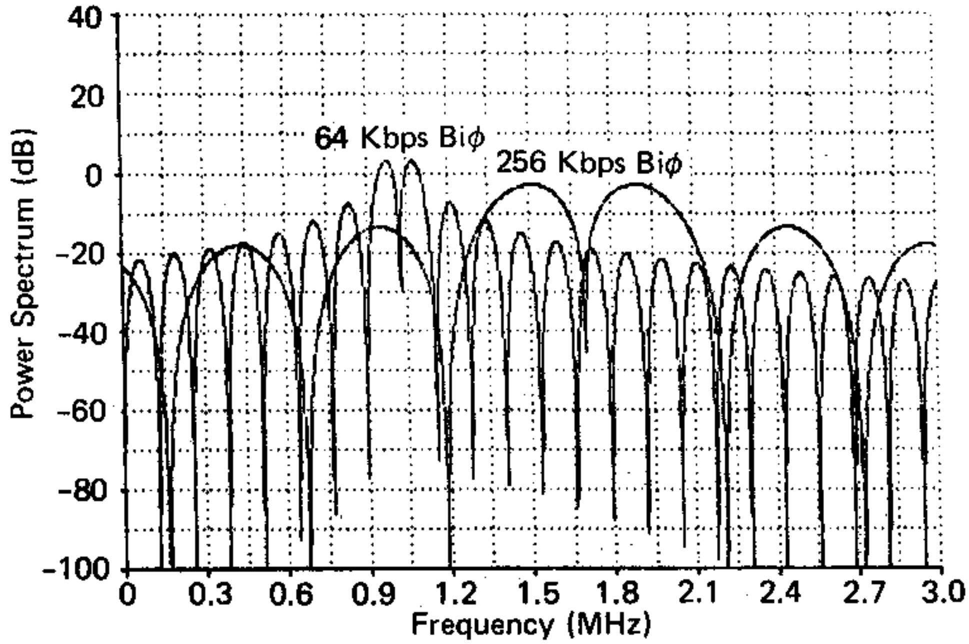


Figure 3. Power Spectrum with Bi∅ Data in Both Channels

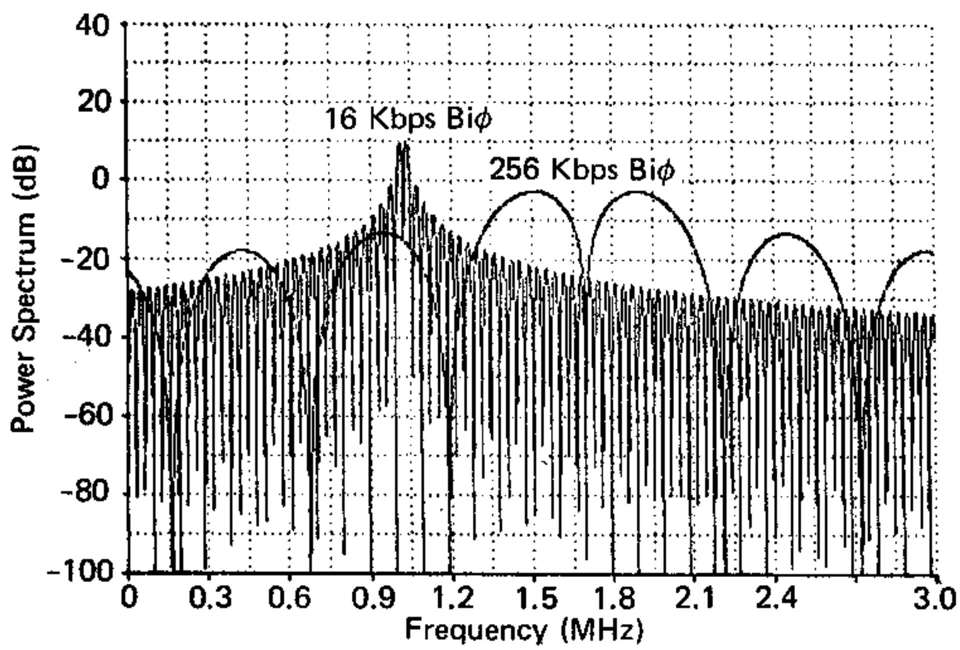


Figure 4. Power Spectrum with Bi∅ Data and Reduced Data Rate

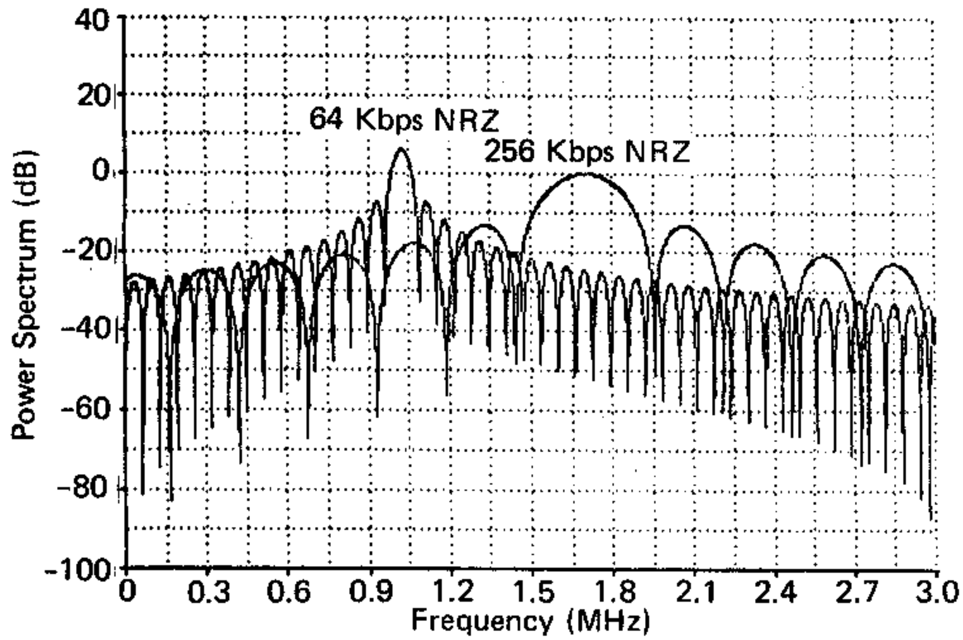


Figure 5. Power Spectrum with NRZ Data in Both Channels

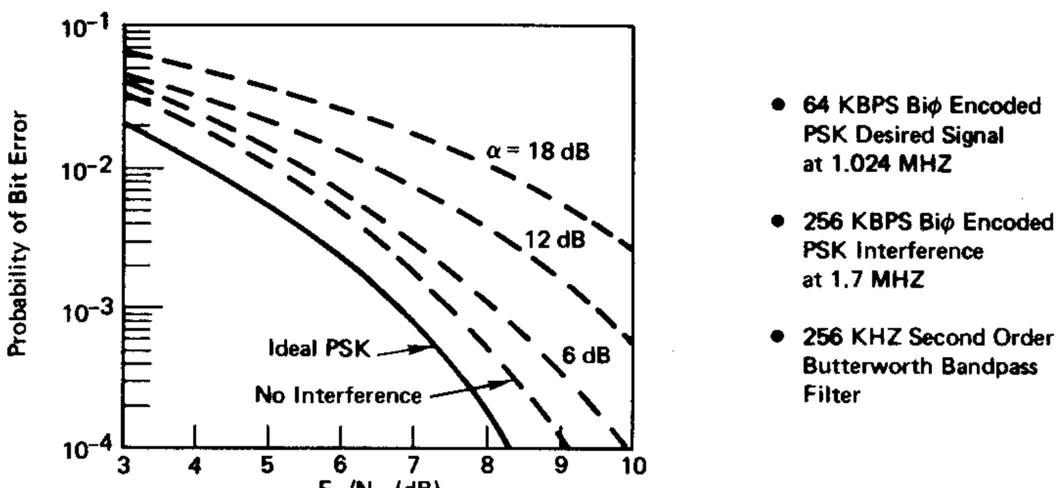


Figure 6. Constant Interference Approximation – Probability of Error

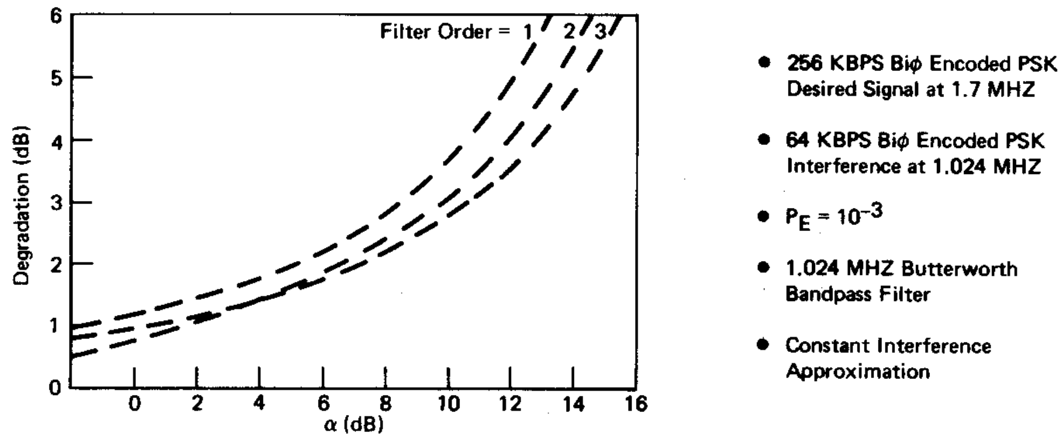


Figure 7. Effect on Degradation of Varying Filter Order

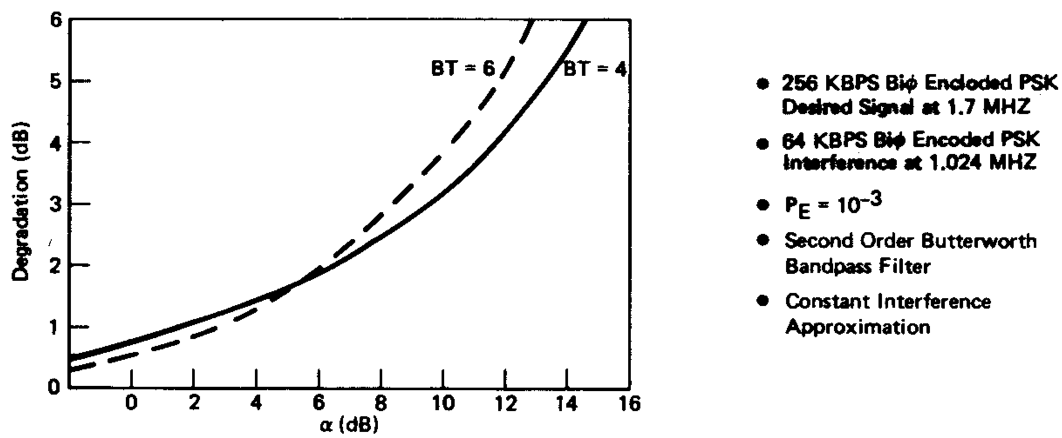


Figure 8. Effect on Degradation of Varying BT

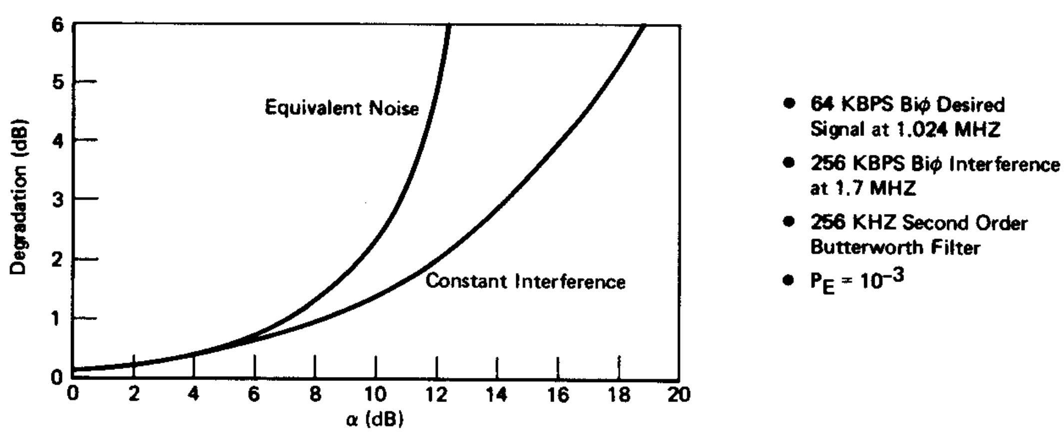


Figure 9. Comparison of Both Approximations with Desired Signal in 1.024 MHZ Channel

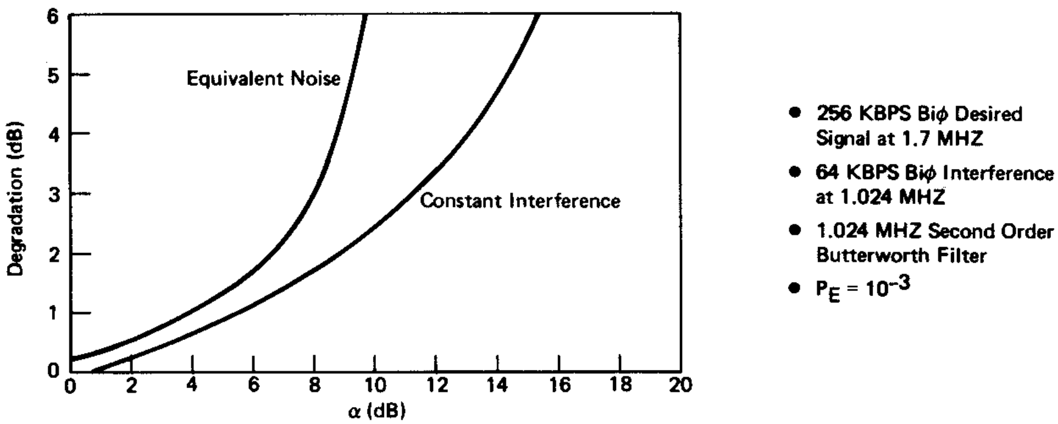


Figure 10. Comparison of Both Approximations with Desired Signal in 1.7 M HZ Channel

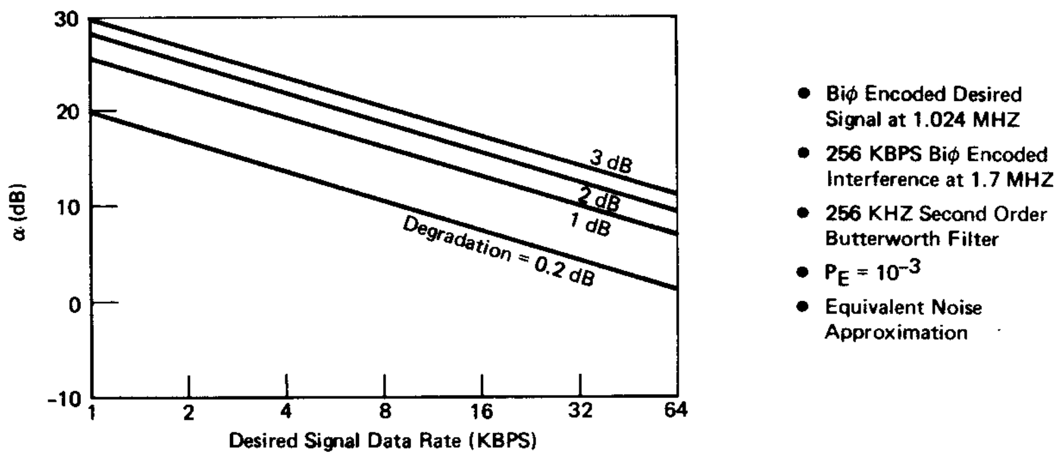


Figure 11. Degradation Due to 1.7 MHZ Adjacent Channel Interference

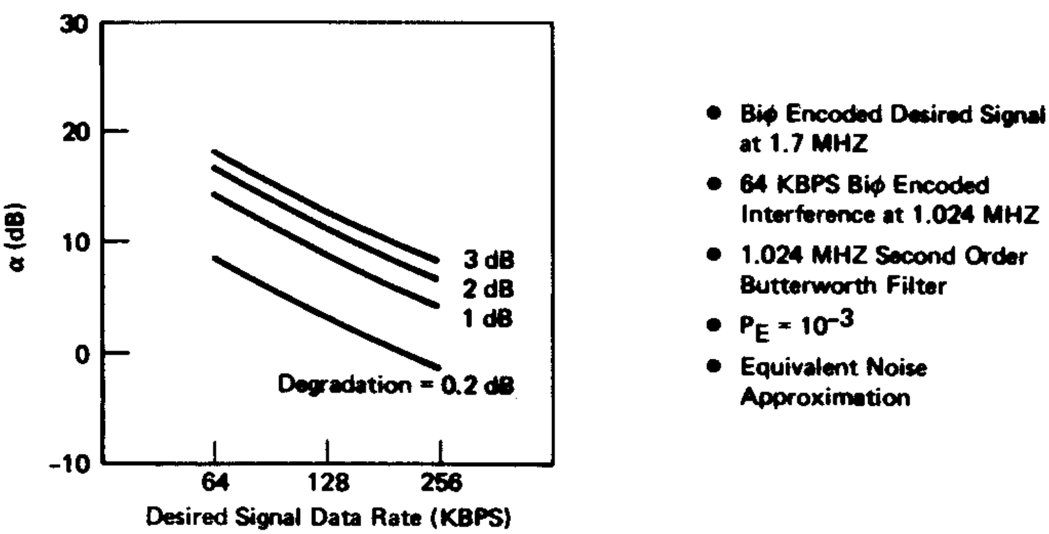
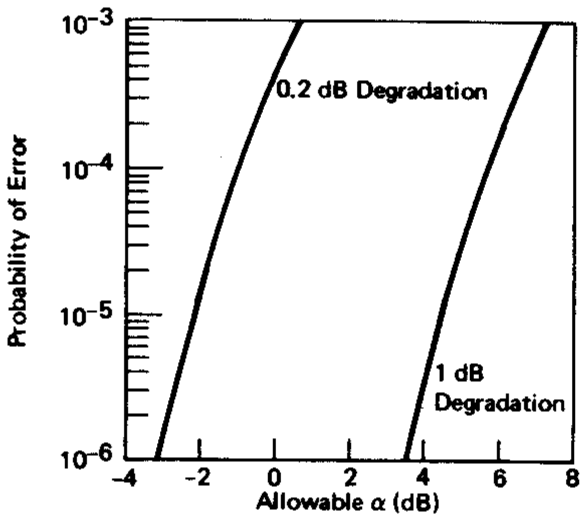


Figure 12. Degradation Due to 1.024 MHZ Adjacent Channel Interference



- 64 KBPS Biϕ Encoded Desired Signal at 1.024 MHZ
- 256 KBPS Biϕ Encoded Interference Signal at 1.7 MHZ
- 256 KHZ Second Order Butterworth Filter
- Equivalent Noise Approximation

Figure 13. Effect of Changing Probability of Error Requirement