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ABSTRACT

This report analyzes and discusses the use of PSK subcarrier demodulators to overcome the SNR degradation and filtering errors associated with signal conditioners now being used as demodulators for low data rate PCM/PSK. It is shown that a PSK subcarrier demodulator provides very close to ideal performance.

The signal conditioners, which were not designed for the subcarrier demodulation function, are deficient in the following areas: 1) improper filtering of the signal prior to squaring for subcarrier regeneration; 2) low sensitivity of phase lock loop; and, 3) filtering matched to the subcarrier rate rather than the data rate. Because the envisioned PSK demodulator can be optimized for these functions it will provide about 10 db more sensitivity at threshold than now being achieved.

PCM/PSK SUBCARRIER DEMODULATOR FOR DATA ACQUISITION

INTRODUCTION

Subcarrier coherent phase shift keying (PCM/PSK) telemetry coding and modulation is a very efficient and easily implementable technique for transmitting low data rate digital information. Results of recent discussions with cognizant GSFC personnel indicate that spacecraft telemetry designers prefer PCM/PSK/PM and its usage is on the increase. To realize the full advantages of PCM/PSK, however, an optimum demodulator must be used in the receiving system. At present such a demodulator does not exist in the STADAN; instead, general-purpose signal conditioners are serving this function. These can demodulate PSK subcarriers but lack the performance sensitivity of a conventional demodulator.

SUBCARRIER PSK

Subcarrier PCM/PSK is a modulating scheme where the phase of a subcarrier oscillator, SCO, is alternately shifted ±90° by a modulating signal consisting of a stream of binary bits. When generated, these binary bits are synchronized by the clock that is coherently related to the SCO frequency by some factor "n" which is the ratio of SCO cycles to data cycles. The fact that the SCO is phase-shift-keyed by the digital information determines that no subcarrier component is present in the transmitted signal. In order to maintain sensitivity, however, it is necessary to perform the demodulation synchronously; thus, the subcarrier component must be generated from the received signal.

COHERENT DEMODULATION

Coherent or synchronous demodulation requires that the received signal be multiplied by a clean, noise free, regenerated subcarrier. At least two methods exist for performing this function: (1) squaring the received signal and noise to generate a spectral component at twice the frequency of the absent subcarrier—this component is then phase-locked to a voltage controlled oscillator (VCO); and (2) the quadra correlator or Costas method which synchronizes a VCO by sampling both the quadrature and the in-phase components of the received signal. In both of these demodulating systems the received signal is multiplied by a VCO which is synchronized to the suppressed subcarrier signal. It should also be noted that these two methods are mathematically equivalent.

For purpose of comparing the coherent demodulator technique to the signal conditioner method, the coherent demodulator using the squaring technique will be considered in this report. As shown in the block diagram, Figure 1, a band-pass filter is used at the input of the demodulator.

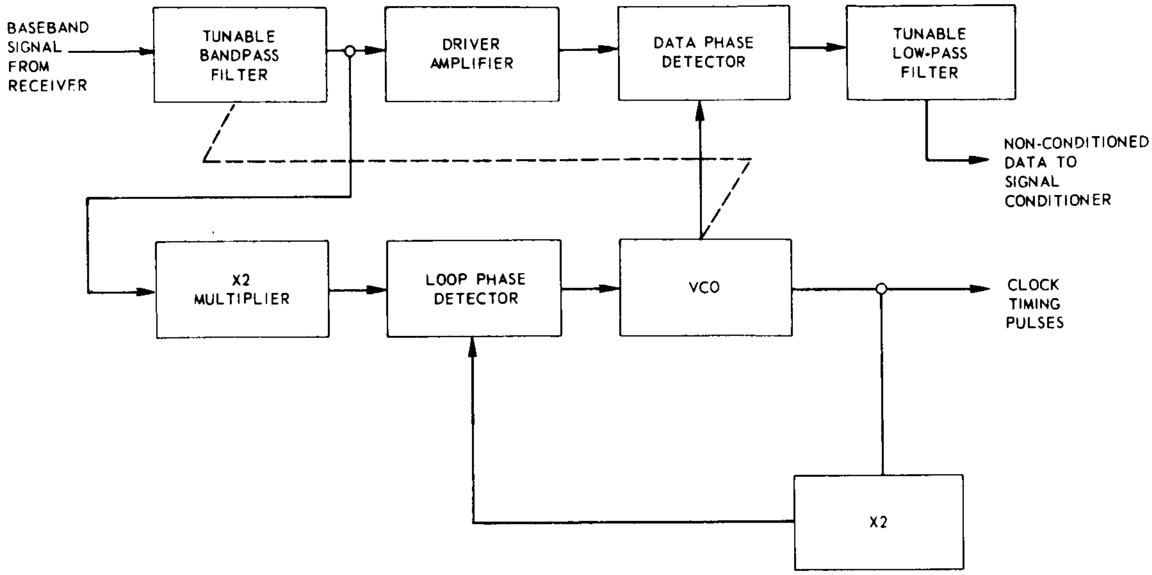

Figure 1. Functional Block Diagram Tunable PSK Demodulator

Under normal operating conditions this filter maintains the SNR above unity at the input to the squaring circuit. This results in negligible deterioration in output SNR as a result of the non-linear squaring operation. Since there is essentially no SNR deterioration with this method, it very closely approaches ideal performance and is considerably better than the signal conditioner method.

SIGNAL CONDITIONER

The signal conditioners, which operate on pulse code modulated signals, are designed to perform two functions: (1) the regeneration of the clock for bit synchronization; and, (2) providing matched filtering and ideal decision-making on the operated signal. The circuitry used for accomplishing these two functions has exactly the same configuration as that of the optimal coherent demodulator (see Figures 1 and 2); thus, a signal conditioner will perform the coherent demodulation. When this modulation technique began to be used in the NASA Space Program, it was expedient to use the existing stock of signal conditioners as demodulators, even though their performance is considerably less than ideal.

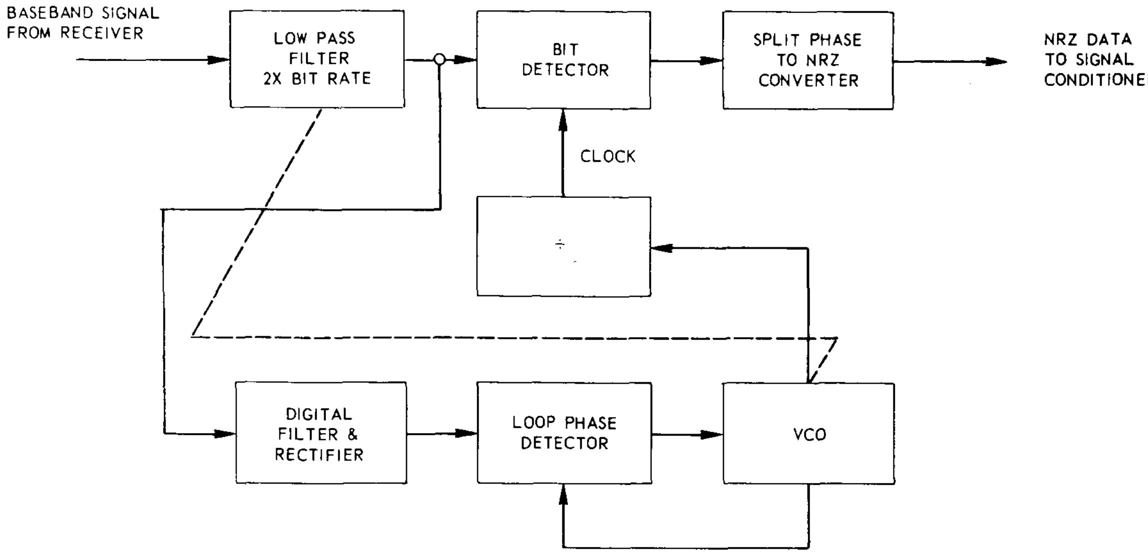

Figure 2. PSK Detection Scheme Using Two Signal Conditioners

As a matter of interest, just one signal conditioner will demodulate the data and will also provide the matched filter function; however, the averaging time is proportional to the subcarrier rate rather than the data rate. This results in less than optimum performance by an amount "n" which is the SCO rate to data rate ratio. To achieve better performance, a second signal conditioner is required which further improves the output of the first. The second signal conditioner averages "n" discrete decisions of the first; thus, two decisions are made rather than just one and some degradation is to be expected. The use of signal conditioners is analyzed in Appendix A. The results show that even with two signal conditioners the performance is 2.5 to 3.0 db less than optimum, assuming perfect synchronization.

SUBCARRIER REGENERATION

Even though the signal conditioners will provide coherent demodulation, their performance is less than ideal in the categories of filtering and synchronization. Since the signal conditioner regenerates the clock or subcarrier with an effective noise bandwidth, "n" times greater than that of a conventional demodulator, it does not take advantage of adequate filtering before frequency doubling. It is important that this SNR be improved as much as possible prior to frequency doubling since this operation involves squaring the noise as well as the signal. At negative SNR's the output SNR is equal to the square of the input SNR. For instance, if the input SNR to the frequency doubler is -8 db (see example in Appendix B) the output SNR is approximately -16 db. Although this SNR is improved 20 db by a narrow band phase-lock tracking filter, the resulting +4 db SNR will still cause deterioration in performance when this reference signal is applied to the product detector (multiplier). Starting with a 1 db SNR, however, results in the reference signal having a 21 db SNR which will provide substantially better performance.

The effect of noise on the reference signal can be converted to rms phase noise at the output of the multiplier as follows:[1]

$$\sigma_\phi = \frac{1}{\sqrt{SNR}}$$

$$= .063 \text{ radians or } 3.6^\circ$$

Phase noise is converted to percent timing error by taking the ratio of the phase noise to 360°. For the 21 db SNR reference signals, the 1% timing error will cause negligible deterioration. An SNR of 9 db is required to assure reliable phase-lock with low phase jitter;[2] a 4 db SNR is insufficient to maintain synchronization without skipping cycles; thus, without adequate filtering and when used at low SNR's the signal conditioners will not perform as well as a coherent demodulator.

TRACKING FILTER PERFORMANCE

There is one more source of performance deterioration associated with the signal conditioner method. It was assumed that the narrow band tracking filter would operate properly with SNR's of -16 db applied. In theory, such tracking filters can be fabricated; however, the tracking filters used in the present signal conditioners do not possess this capability— probably because this performance is not normally required of signal conditioners. In fact, the tracking filter in the Dynatronic unit cannot be relied upon to remain phase-locked at 0 db SNR. The Radiation Inc. units drop lock at -6 db SNR. This means that for this factor alone, a deterioration of as much as 8 db in sensitivity is suffered. Thus, at threshold, the overall deterioration using the signal conditioner method is between 5 db and 11 db depending on which signal conditioner is used.

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[1] Benn D. Martin, JPL Report No. 32-315

[2] F. J. Charles and W. C. Lindsey, Some Analytical and Experimental Phase-Lock Loop Results for Low SNR's, Proceedings of IEEE, September, 1966.

The phase lock performance of both types of signal conditioners was verified by laboratory measurements. Measurements were also made with the set up described in Figure 2 where high baseband SNR's were used to assure good synchronization. Even at these high SNR's the two signal conditioner method provides a performance which is 4 db less than ideal as shown by Figure 2, Appendix A. When a coherent demodulator is used to demodulate a PSK subcarrier, good data is obtainable at a signal level of -142 dbm as shown in the example (Appendix B). The signal conditioners, however, could not be evaluated at this level because synchronization was lost below -134 dbm.

CONCLUSIONS

The use of coherent demodulators instead of signal conditioners for demodulating PSK subcarriers will, therefore, provide an improvement in performance. The cost of a coherent demodulator is estimated to be a few thousand dollars less than the complex general purpose signal conditioner. Instead of using two complex signal conditioners for demodulation and match filtering, the coherent demodulator could be designed to include the matched filter. Thus, the functions of demodulation and filtering could be achieved within one equipment that would provide close to optimum performance at half the cost of two signal conditioners, and will have the versatility to accommodate virtually all anticipated signals of the subcarrier PSK type.

RECOMMENDATIONS FOR DATA STANDARDS

Subcarrier PSK is normally used for low data rate PCM with the SCO frequency located sufficiently away from the carrier. This, of course, prevents low frequency signal components from interfering with the carrier phase-lock. The terminology "low data rate" and "sufficiently away from the carrier" are somewhat arbitrary depending on the particular application. It is recommended that the Data Systems Requirement Committee establish standards for this type of telemetry modulation restricting users to the appropriate performance parameters; e.g., bit rate, SCO rate, etc. The following parameters are offered as a suggestion: (1) an SCO rate ranging from 200 cps to 20,000 cps; (2) a bit rate ranging from 20 cps to 1,000 cps; (3) an SCO rate to data rate ratio in binary multiples ranging from 2 to 64.

ACKNOWLEDGEMENTS

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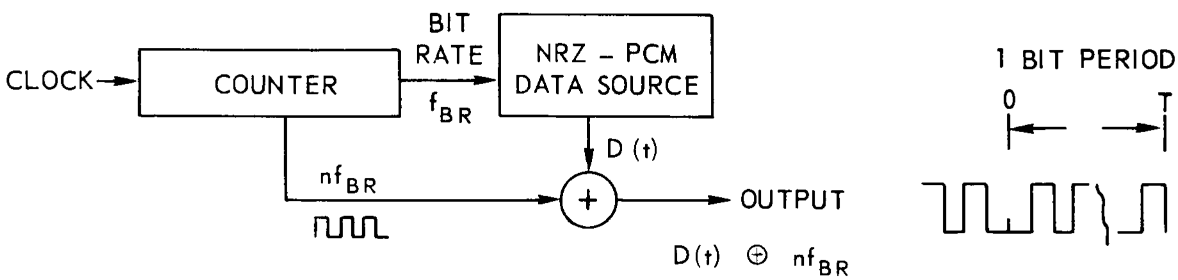
Appendix A

THEORETICAL ANALYSIS OF OPTIMUM VERSUS NON-OPTIMUM PSK SUBCARRIER DECODING

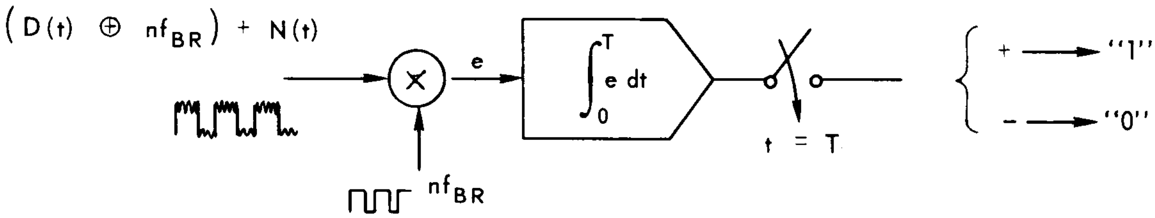
The "best possible performance" bound is calculated and derived only from data decoding considerations and assumes perfect sync.

The encoding model chosen for analysis is shown below. Note that the subcarrier is synchronous with the bit rate and that a square wave subcarrier is used. The same results will be had if a sine wave subcarrier is used.



Encoding Model of PCM on a subcarrier "n" times higher than the bit rate.

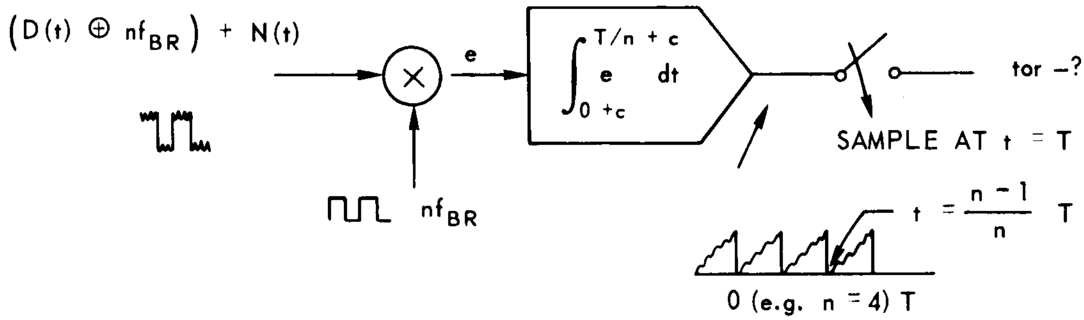
A matched filter followed by a "plus" or "minus" decision is the optimum detector and is shown below.



The PSK demodulator can perform the multiplier function and an ordinary PCM bit synchronizer can perform the integrate and decision function. Commercially available bit synchronizers generally cannot perform the demodulator function and non-optimum methods must be used. Two detection methods which have been used are analyzed below.

<u>System 1</u> — One Bit Synchronizer Operating at the Subcarrier Rate

The decoding model is shown below. Again, perfect sync is assumed.



It is well known that with white additive Gaussian noise, the matched filter output SNR is:

$$\text{voltage SNR} = \frac{\text{mean}}{\text{standard deviation}} = \sqrt{2\,\frac{ST}{N_0}} \quad \text{for ideal PCM.}$$

$$\text{and prob(bit error)} = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{ST}{N_0}}}^{\infty} \epsilon^{-u^2} du$$

For case 1:

$$\text{SNR} = \sqrt{2\,\frac{S(T/n)}{N_0}} = \frac{1}{\sqrt{n}} \sqrt{2\,\frac{ST}{N_0}}$$

where:

S = signal power (watts)

T = time per information bit (sec.)

and N_0 = noise power density (watts/cps.)

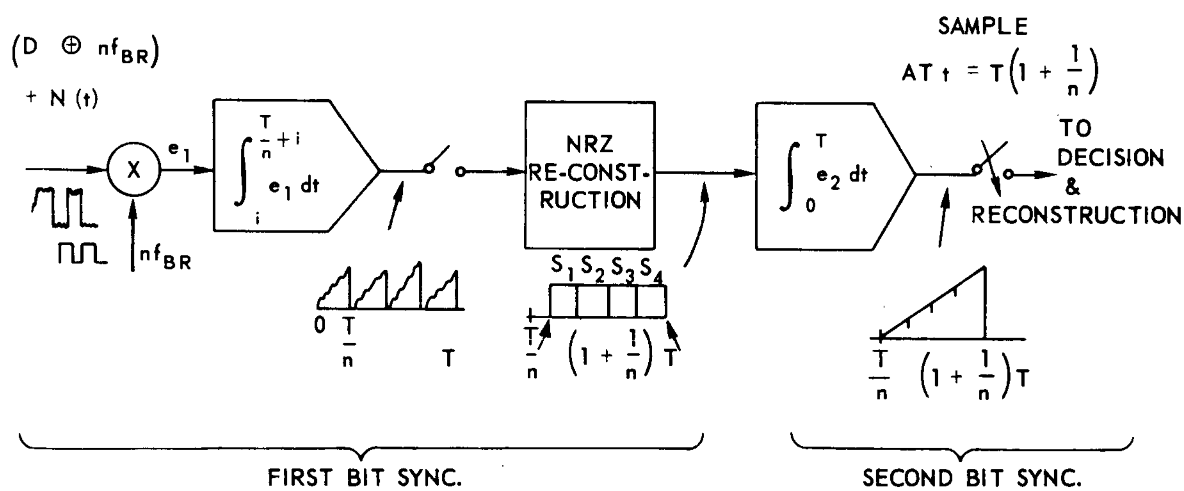
Since the statistics are identical for each case, the resulting error probability curve will be the same as for the ideal case but translated "n" times higher in power SNR.

Figure 1 is a plot of these results for even "n".

<u>System 2</u> — Two Bit Synchronizers — One Operating at the Subcarrier Rate, the Other Operating at the Information Bit Rate

This method is a clever way of obtaining reasonably good performance when "in a pinch". The first synchronizer decodes individual subcarrier cycles exactly as in the previous method. A second bit synchronizer takes this NRZ-PCM output and essentially averages over a whole bit period. Namely, over the "n" symbols comprising each information bit. A decision is then based on this resulting average.

With perfect sync assumed, the decoding model is shown below.



<u>Decoding Model 2</u>

A bit error can only occur when more than half of the "n" symbols are in error. Or more precisely, if n is even, then when n/2 symbol errors occur, only half of these will give rise to bit errors. This follows from the fact that the symbol average will be zero and yet the decision logic requires a + or -

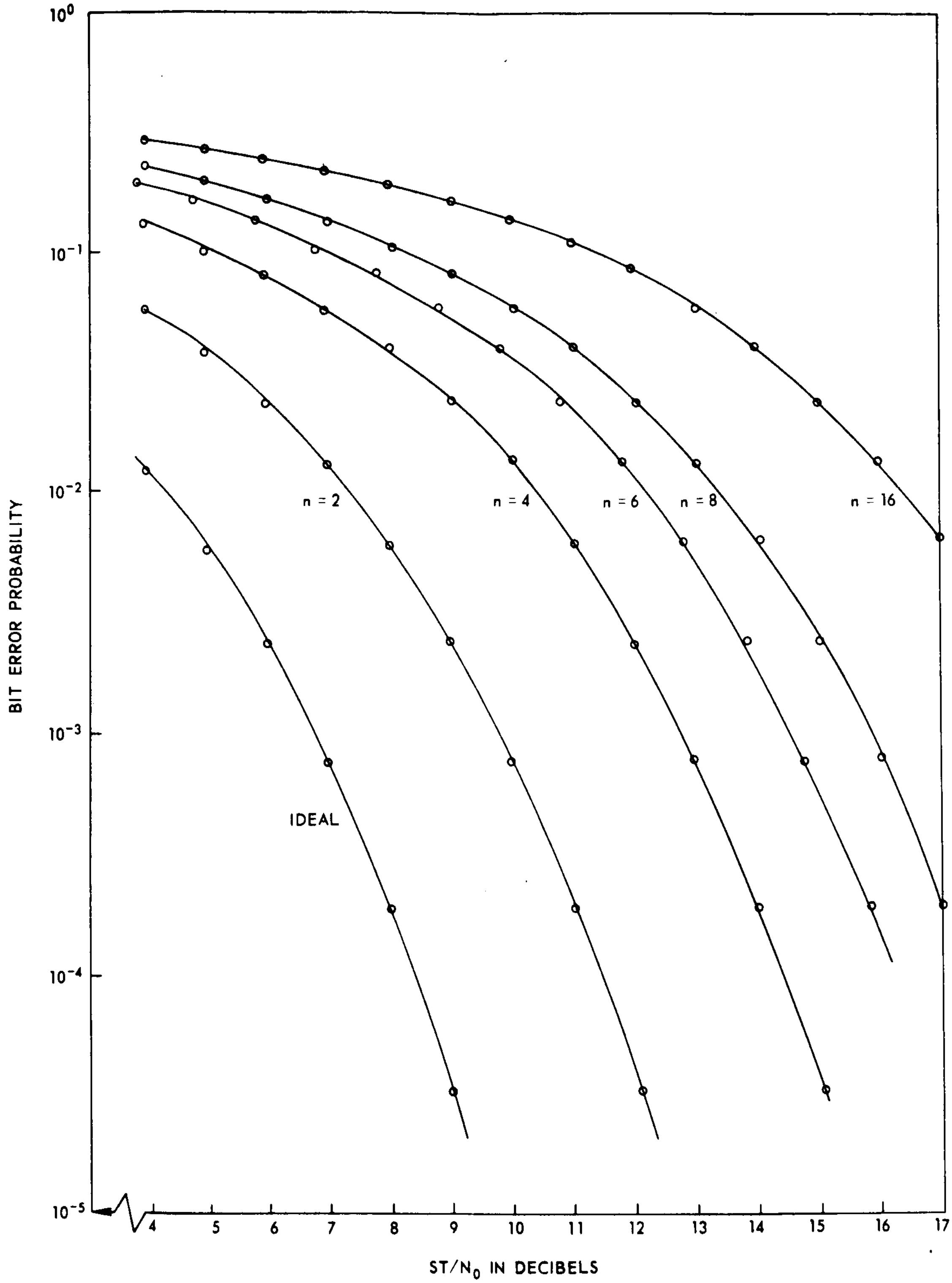


Figure 1. Error Probability vs for System 1 (n = # symbols/bit)

decision. With the finite offsets that exist in real life equipment and an equal number of ones and zeroes transmitted, then only half of these combinations will be in error. If Q is the probability of a symbol error and the statistics are stationary, then $P(\text{Bit error}) = \frac{1}{2} P\left(\frac{n}{2} \begin{array}{c}\text{symbol} \\ \text{errors}\end{array}\right) + P > \frac{N}{2} \begin{array}{c}\text{symbol} \\ \text{errors}\end{array}$

$$P_{BIT}(\epsilon) = \frac{1}{2}\binom{n}{n/2}(1 - Q)^{\frac{n}{2}}(Q)^{\frac{n}{2}} + \sum_{i=n/2+1}^{n} \binom{n}{i}(1 - Q)^{n-i} Q^{i}$$

This has been evaluated for all even n up to 16 and the results compared with ideal PCM decoding in Figure 2. It is interesting to note that the SNR degradation is a nearly constant 2.15 to 3 decibels independent of "n".

Conclusions

Decoding system 1 departs rather drastically from the ideal for large numbers of subcarrier cycles per information bit (n). However, the system using two bit synchronizers is only about 2.5 to 3 db worse than theoretical for most any practical "n". Provided synchronization is good, this second method is probably adequate for most non-critical telemetry systems. But for more critical, low bit-rate, deep space missions a near optimal PSK-subcarrier demodulator is clearly needed if uncoded PCM is employed.

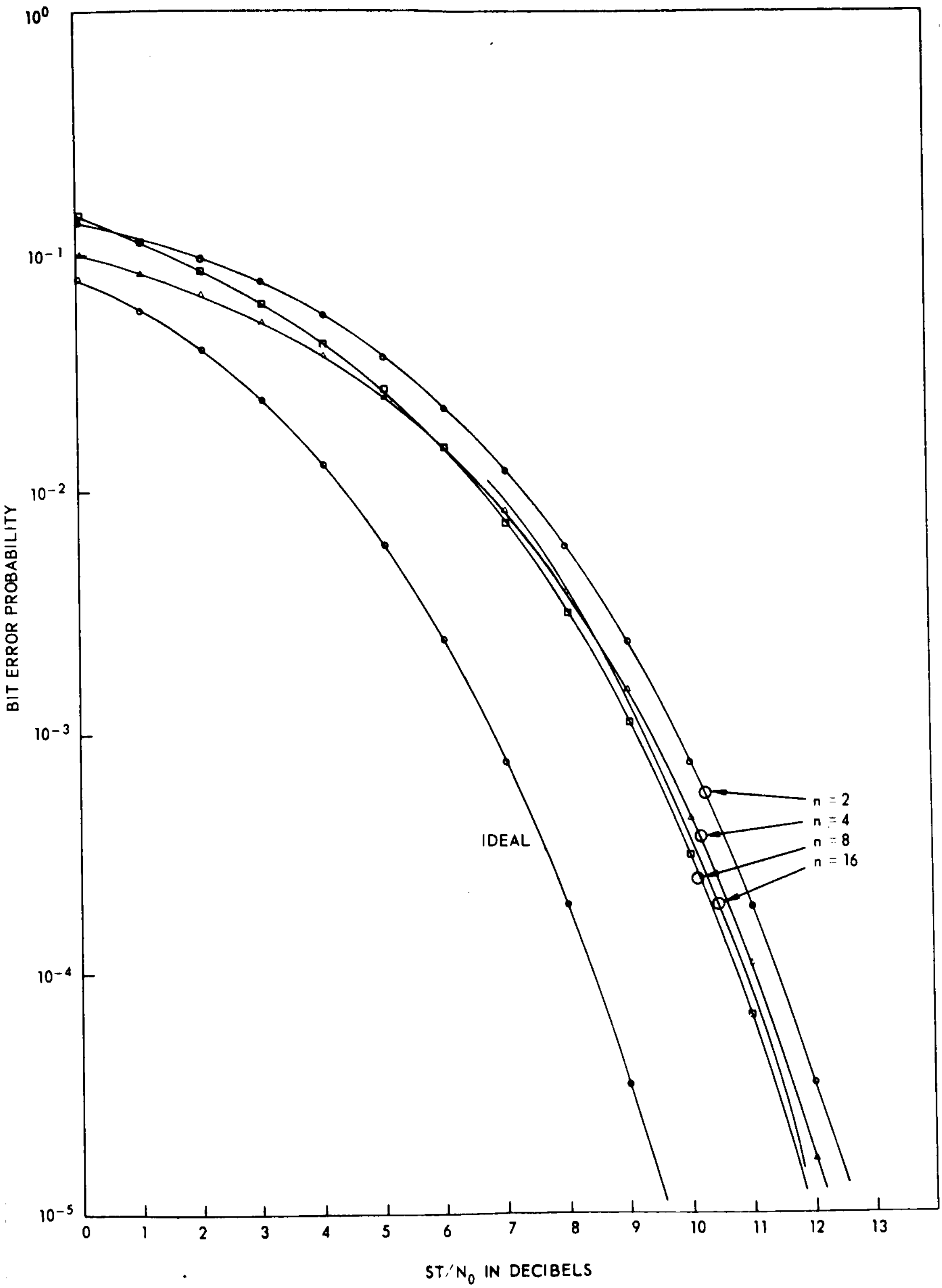


Figure 2. Error Probability vs SNR for System 2 (n = # symbols/bit)

Appendix B

SUBCARRIER REGENERATION ANALYSIS

The purpose of this example is to compare the subcarrier regeneration performance of the coherent demodulator (with bandpass filter) to that of signal conditioner (with low pass filter). For this comparison, the following parameters are assumed:

1. Data Rate (f_b) = 320 bit per second

2. SCO Rate (f_{sco}) = 2560 cycles per second

3. SCO Rate to Data Rate (n) = 8:1

The signal conditioners are implemented with a low pass filter having a cut-off frequency $2xf_{sco}$, thus, for the example cited, the equivalent noise power $N_1 = KT_0 + KTB_1 = -134$ dbm where KT_0 is the noise level at the input terminals of a receiver having, for convenience, an effective noise temperature of 290°K. The coherent demodulator is implemented with a bandpass filter, $2f_b$, centered at f_{sco}; thus, the noise power is reduced by $2f_{sco}/2f_b$ = 8:1 or 9 db.

The noise power in the coherent demodulator prior to frequency doubling is $N_2 = KT_0 + KTB_z = -143$ dbm. The signal power required for a 10^{-3} error rate, assuming an ideal matched filter, is -142 dbm. Thus, the baseband SNR prior to frequency doubling is -142 dbm-(-143 dbm) = +1 db, when using a coherent demodulator, and is -142 dbm-(134 dbm) = -8 db when using the signal conditioner. Both these signals are frequency doubled by a non-linear process which degrades the SNR from -8 db to -16 db, but does not essentially change the +1 db SNR. In both systems a narrowband phase-lock tracking filter improves the SNR of the doubler output by 20 db. Thus, the clock or subcarrier is regenerated with +21 db and +4 db SNR's respectively. In this example, the coherent demodulator regenerates a clock or subcarrier with an SNR 17 db better than that of a signal conditioner.