PERFORMANCE EVALUATION OF COMMUNICATION CHANNELS BY COMPUTER SIMULATION

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ABSTRACT

A computer simulation model capable of aiding in the design and predicting the performance of complex end-to-end communication systems is described in this paper. The model is used to choose the optimal modulation scheme under certain communication channel constraints, define the signal distortion characteristics introduced by realizable channel components and select the demodulator/bit synchronizer designs for minimization of bit error rate. A parameter sensitivity analysis is conducted to demonstrate the usefulness of the model in evaluating the effect of different signal distortion phenomena on overall link performance.

1. Introduction

Continuous advances in technology have resulted in increasing complex communication satellites. Until recently, the necessary supporting computer programs were developed for each satellite project after need for such software became essential. This resulted in increased costs because the software capabilities were not available when needed, and the consequent software was not sufficiently general to be used for future projects. Fast response to customer demands also dictated the development of a generalized computer program capable of characterizing the signal distortion introduced by the individual channel elements and of evaluating the effects of such distortion on system performance. The computer simulation described in this paper allows cost-effective analysis and fast response, as well as providing an accurate means of defining optimal communication payload designs. This latter capability has been already demonstrated in the transponder design for the Tracking and Data Relay Satellite (TDRS)[1].

Allowing the evaluation of system performance degradations, the model accounts for distortion-causing effects such as modulator phase/amplitude unbalances, data asymmetry, data skew, pulse fall/rise times, and nonlinear AM/PM and AM/AM characteristics.

Moreover, the simulation is capable of accepting laboratory measurement data for the purpose of characterizing link component behavior.

Other salient features of the wideband link computer simulator are:

a) Allows performance evaluation of complex, flexible models.

b) Permits cost effective optimization of designs by virture of its accuracy, speed, and low cost. This feature is particularly attractive when considering high data rate systems where bandwidth and power conservation is demanded.

c) Is unconstrained by the number of devices and, in fact, can handle a large number of nonlinear amplifiers and filters in any order.

d) Is particularly well-suited for evaluating the effects of each link component on the overall transponder performance; an important characteristic for isolating major degradation contributors.

e) Has the capability to evaluate the transient response of the link at any point desired.

f) Has been shown to predict actual hardware performance to within a few tenths of a dB[2].

This paper illustrates the simulation procedure as applied to the three vital stages in the design of a communication channel:

1) Selection of optimal modulation scheme.

2) Characterization of signal distortion introduced by channel components.

3) Definition of receiver/demodulator design for minimization of bit error rate.

2. Computer Program Description

The digital link simulation program, LINK, is capable of evaluating the performance of complex digital channels containing an arbitrary large number of filters and nonlinearities in any order. The LINK simulator permits user specification of such parameters as modulator gain/phase imbalances, filter* variables, amplifier parameters, and input sequence parameters. Filter modeling can be accomplished by choosing either ideal filters

* The term "filter" is used here to represent a frequency response which can be attributed to any device or propagation effect, and it need not represent an actual realizable filter.

(Chebyshev, Butterworth, Gaussian, or any pole pattern) or by specifying phase and magnitude at any set of frequencies. Amplifier nonlinearity modeling provides the capability of simulating linear amplifiers, hard and soft limiters, and TWTA-type amplifiers. For the latter, the program offers the capability of using actual (measured) swept amplitude and phase data following the procedures described in Reference 2.

The input sequence or data source can be chosen from several PN (i.e., maximal length shift register) sequences of length 15, 31, or 63 bits. An infinite length digital sequence is effectively obtained by assuming that the input sequence is periodic. These sequences optimally account for intersymbol interference within their prescribed length constraint, and larger sequence lengths more accurately predict intersymbol interference effects as filter bandwidths become narrow compared to the baud rate. The selected PN sequences are sampled at equidistant points, with the total number of samples being specified by the user. A nominal choice of a 31 bit PN sequence with a sample rate of 512 samples per 31 bits, for example, allows the consideration of spectral components past the eighth null.

The user also has the choice of selecting MSK or biphase/quadriphase CPSK, with the ability to specify the phase and amplitude imbalance of each biphase modulator. For the quadriphase case, the program offers the capability of delaying one channel with respect to the other in order to simulate data skew or differential time delay observed in actual systems.[**] In either case, the simulation outputs will be either in terms of bit error rate as a function of signal-to-noise ratio or as plots of signal waveforms at any point in the system. Bit error rate is determined for each bit in the sequence and subsequently averaged over all bits in each channel, while bit synchronization and phase rotation are accomplished by correlating the actual incoming signal with a distortionless signal.

In addition to the above features, the simulator incorporates a digital adaptive equalization algorithm, with the user selecting parameters such as the desired type of equalizer (linear or nonlinear) and the number of taps. A summary of simulation parameters is presented in Table 1. A more detailed description of these parameters is included in Reference 2.

3. Channel Design and Performance Evaluation

The simulation program described in Section 2.0 was utilized in the design of the high data rate (300 Mbps) TDRSS channel. Performance optimization of this channel was accomplished by selecting a realizable modulation scheme to minimize the adverse effects of bandlimiting and nonlinear amplification, evaluating the level of signal distortion introduced by the spacecraft communication payload components, and defining the

[**] With the delay, intersymbol interference patterns generated at the end of the block loop back to the beginning so that all data bit patterns in the delayed channel still have equal weight.

demodulator/bit synchronizer design to reduce the effect of this distortion on bit error rate. The results of the design optimization procedure using LINK are now described for each of the above three stages.

3.1 Modulation Selection

Staggered QPSK, with 0.5 bit shew between the I and Q channels, was chosen as the preferred modulation scheme for the 300 Mbps TDRSS channel. Data collected using the LINK program established conclusively its superiority over aligned (unstaggered) QPSK. This section presents data to support this claim and some of the reasons for the superiority of staggered QPSK.

Using the LINK simulation a PRN data sequence was filtered, limited (with a saturating amplifier) and then filtered again. At each point in the system, time waveforms (as both I/Q channels and Magnitude/Phase) and signal spectra were plotted for staggered and unstaggered quadriphase. These plots are shown in Figure 1.

Several interesting differences between staggered and unstaggered QPSK are shown in this figure. Comparison of the magnitude waveforms at the input to the TWTA (Figures 1-A and 1-B) shows much more AM for the aligned case than for the staggered case. In fact, the magnitude for the aligned data drops to zero each time a transition occurs simultaneously in both the I and Q channels. When a signal passes through a TWTA-type device it is distorted by AM-to PM conversion. Thus more PM will be generated by the unstaggered signal, resulting in poorer performance.

Another interesting feature of Figure 1 is the spectral regeneration caused by the TWTA. Comparison of the spectra after filtering (Figures 1-D and 1-E) with those after limiting (Figures 1-F and I-G) show that for unstaggered QPSK the sidelobes are regenerated (compared to Figure 1-C). This is undesirable when one is trying to keep out of band and adjacent channel interference to a minimum. When applied to the channel illustrated in Section 3.2, the BER performance of aligned QPSK is shown to be 1.5 dB worse than staggered QPSK at a bit error rate of 10^{-5}.

3.2 Payload Distortion Characterization

The LINK computer program was exercised to characterize the signal distortion environment for the 300 Mbps TDRSS channel shown in Figure 2, and to evaluate the sensitivity of this channel to transponder parameter variations.

Amplitude and phase response characteristics, as well as group delay, for the 300 Mbps channel (prior to the spacecraft TWTA) are presented in Figure 3. I/Q channel waveforms are included in Figure 4 for the purpose of illustrating the effects of hardware-generated distortion on the transmitted user data at different points in the link. The waveform at the input to the TWTA (point B) shows the effects of gain and phase distortion, as well as bandlimiting, introduced by the channel elements following the modulator. Comparison of the waveforms at points B and C highlights the distortion introduced by a nonlinearity (TWTA) with nominal AM-to-PM compression of 0.7 dB/dB and nominal AM-to-PM conversion of 4.7 deg/dB. The bandlimiting feature of the receive filter provides a reduction in the high frequency distortion components resulting from the AM-to-PM conversion process (see waveform at point D). The data distortion characteristics observed in Figure 4 correspond to a total performance degradation of 6.2 dB (at 10^{-5} BER), as shown in Figure 5[*]. Figure 6 provides a clear visualization of the level of crosstalk generated by an active I-channel on a static Q-channel at the output of the saturated spacecraft TWTA.

Additional data was collected using the computer model to establish the link's sensitivity to certain transponder parameter variations (see Figure 7). The ability to execute a computational parameter sensitivity analysis allows evaluation of the effect of each link component on the overall link performance and isolation of the major degradation contributors. Determining the effect on system performance of small increases in expected distortion parameters also provides an assessment of the risk associated with any established transponder operating condition.

3.3 Optimal Demod/Bit Sync Design

The performance degradation of 6.2 dB at a BER of 10^{-5} for the channel shown in Figure 2 was deemed excessive and certainly larger than could be tolerated by system operational requirements. This dictated a study oriented towards selecting the optimal type of detection filtering and adaptive equalization required to minimize the effect of payload hardware-generated signal distortion on channel bit error rate.

The generic adaptive equalizer for a quadriphase system is shown in Figure 8. The adaptation algorithm is the method of steepest descent widely descrived in the literature. The tap weight increments are obtained by correlating the particular tap input with the equalized error defined as the difference between the decision circuit input and output.

The Ws and Zs shown in Figure 8 represent filters which are nominally transversal filters with settable tap weights. For a linear adaptive equalizer[4], the Zs are omitted, and for a nonlinear (i.e., decision-feedback) adaptive equalizer[5] the Zs are present. The "limiters" in the figure represent decision circuits. Although not shown in the block

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[*] This performance degradation was established utilizing a Butterworth detection filter (see Section 3.3).

diagram, the decision circuit is imbedded in the bit synchronizer which informs the decision circuit when to make a decision.

The LINK computer program was exercised incorporating the channel of Figure 2 and the adaptive equalization algorithm illustrated in Figure 8. The required E_b/N_o to achieve a BER = 10^{-5} is given in Table 2 for integrate and dump and Butterworth detection filters, both with and without phase noise. In addition, 1, 3, 5, and 7 tap equalizers are considered. Note that for 1-tap equalizers either there is no improvement or increased degradation in performance occurs. Such degradation can result when equalization increases the noise more than it decreases intersymbol interference.

Three important conclusions can be drawn from the results shown in Table 2. First, adaptive equalization can indirectly mitigate the effects of phase noise. Equalization, of course, cannot reduce phase noise; however, by reducing intersymbol and more importantly interchannel interference, the effects of phase noise are greatly reduced. Without equalization phase noise causes an increase in degradation of more than 1.5 dB. With at least 3-tap equalizer, the increase in degradation is between 0.5 and 1.0 dB. Moreover, the effects of adaptive equalization on AM/PM-induced distortion parallels the effect described above for phase noise. Equalization is capable of minimizing the effect of AM/PM on other distortion parameters, and therefore, it will minimize its degrading effect on channel BER performance (see Figure 9).

Secondly, Table 2 highlights the performance differences to be expected when a 2-pole Butterworth detection filter is used in place of an integrate and dump filter. In the case of no phase noise, there is almost negligible difference between an integrate and dump and a Butterworth detection filter. With phase noise, there is 0.5 dB difference between the integrate and dump and the Butterworth filters in the unequalized case. However, equalization reduces this difference significantly indicating that equalization mitigates the effects of an improperly-matched detection filter. Although the 2-pole Butterworth detection filter does not offer a significant improvement over an integrate and dump detection filter, it is noteworthy that their performances in most cases are approximately equal. This is important since in high data rate systems, it is difficult and expensive to fabricate and align an integrate and dump filter. On the other hand, it is relatively simple and inexpensive to fabricate a 2-pole Butterworth filter, and in fact, optimal performance could be attained by fabricating several of these filters, each of different bandwidth, and choosing one that performs best.

The above conclusions on the merits of a 2-pole Butterworth detection filter for bandlimited channel operation are corroborated by the performance comparison illustrated in Figure 10. The data of Figure 10 was obtained using the LINK simulator for the TDRSS high data rate channel and varying the transmitted data rate, while maintaining the detection bandwidth of the filters constant. Although the performance difference at the data rate of optimization is minimal, note the extreme sensitivity of the integrate and dump filter to deviations form the optimized data rate, as compared to the 2-pole Butterworth. This feature of the 2-pole Butterworth filter is of particular importance for operating conditions such as those encountered in the TDRSS wideband channel, where the demodulation and detection equipment must handle up to 3:1 data rate range (100 to 300 Mbps).

Finally, the results of Table 2 clearly indicate that for a desired bit error rate of 10^{-5}, an improvement in system performance of $\geq$3.3 dB is attainable with linear equalization (number of taps $\geq$5), while a $\geq$3.8 dB savings can be realized with decision feedback equalization.

4. Conclusion

This paper has demonstrated the versatility and efficiency of the LINK computer simulator in establishing a high data rate communications channel which minimizes bit error rate degradation, while preserving cost-effective hardware design. LINK allowed selection of an effective modulation scheme, characterization of the link’s distortion mechanism and definition of an adaptive equalization algorithm to enhance overall performance.

The simulation model also facilitated the selection of proper component specifications in order to achieve the desired performance objectives. This exercise was accomplished by means of a parameter sensitivity analysis.

REFERENCES

1. H.B. Poza, “TDRSS Telecommunications Payload: An Overview,” NTC 1977 Conference Proceedings, December 1977.
2. H.B. Poza, H.L. Berger and D.M. Berstein, “A Wideband Data Link Computer Simulation Model,” Int. Journal of Computers and Elect. Engr., July 1978.
3. J.G. Proakis and J.H. Miller, “Adaptive Receiver for Digital Signalling Through Channels with Intersymbol Interference,” IEEE Trans. Information Theory, July 1969.
4. J. Stilwell and C. Ryan, “Performance of a High Data Rate Adaptive Equalized QPSK Modem Under Media Distortion,” International Conference on Communications, San Francisco, California, June 1975.
5. P. Monsen, “Feedback Equalization of Fading Dispersive Channels,” IEEE Transactions on Information Theory, January 1971.

Table 1. Simulation Parameters

- Input (PRN) Sequence, Modulator, Modulation variables
  - Length of PRN sequence
  - Skew between I and Q channels
  - Data asymmetry, pulse fall/rise times
  - Modulator gain/phase imbalances
  - Biphase/quadriphase/octaphase
  - NRZ/MSK/Manchester

- Filter Parameters (RF and baseband)
  - Ideal filters
    Chebyshev, Butterworth, Arbitrary pole pattern

or

  - Arbitrary magnitude/phase at a set of frequencies (linearly interpolated)

- Amplifier Parameters
  - AM/AM
    TWT type power transfer (analytic or measured data)
    Hard/soft limiter
    Linear
  - AM/PM
    Truncated series expansion
    Berman-Mahle model

- Demodulator Parameters
  - Phase offset and nonorthogonality
  - Phase noise
  - Synchronization jitter
  - Arbitrarily specifiable detection filters

- Adaptive Equalization
  - Number of taps
  - Alignment of cross-channel
  - Number of iterations

  - Linear or decision-feedback

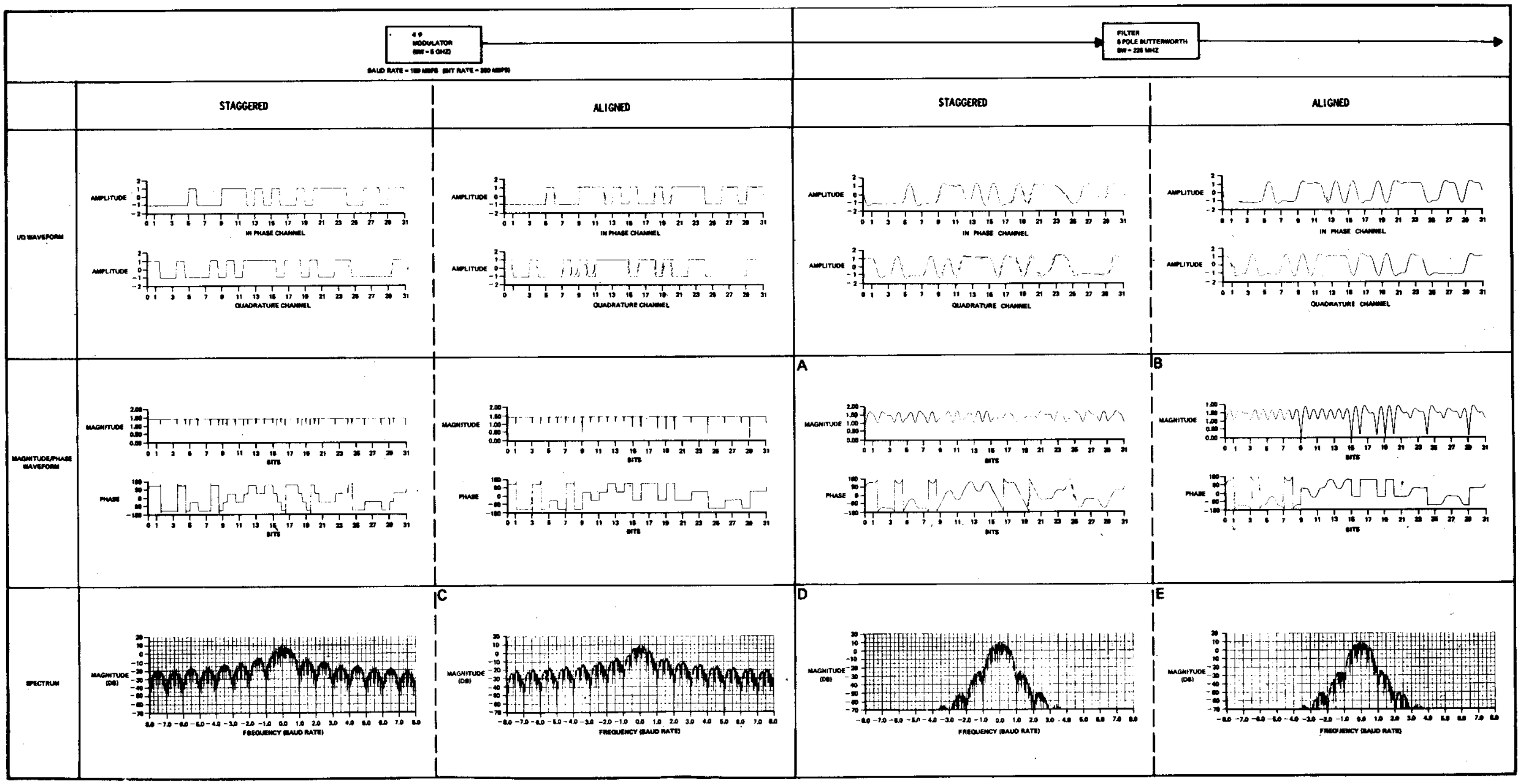

Figure 1. Comparison of Staggered and Unstaggered QPSK

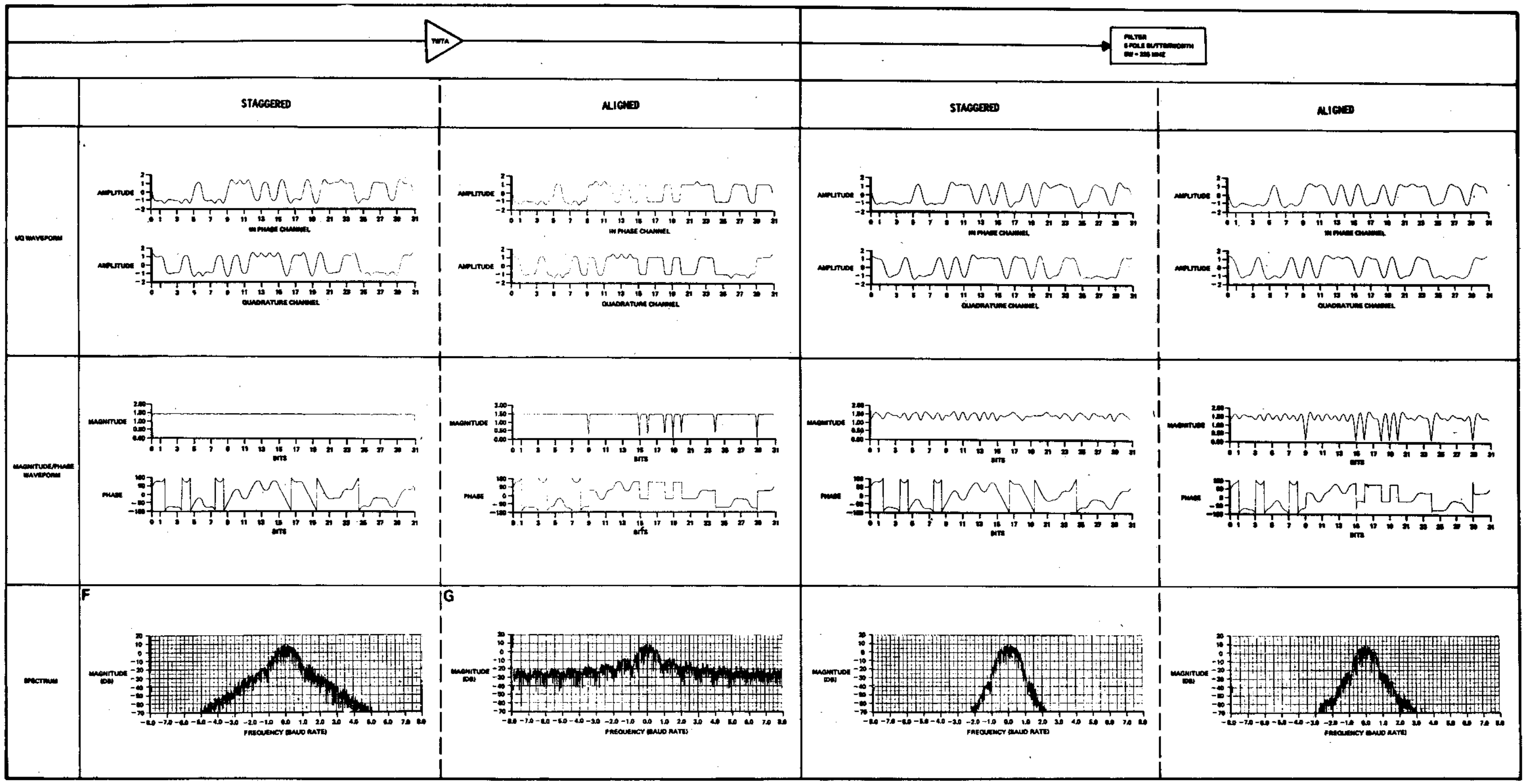

Figure 1 . Comparison of Staggered and Unstaggered QPSK (Continued)

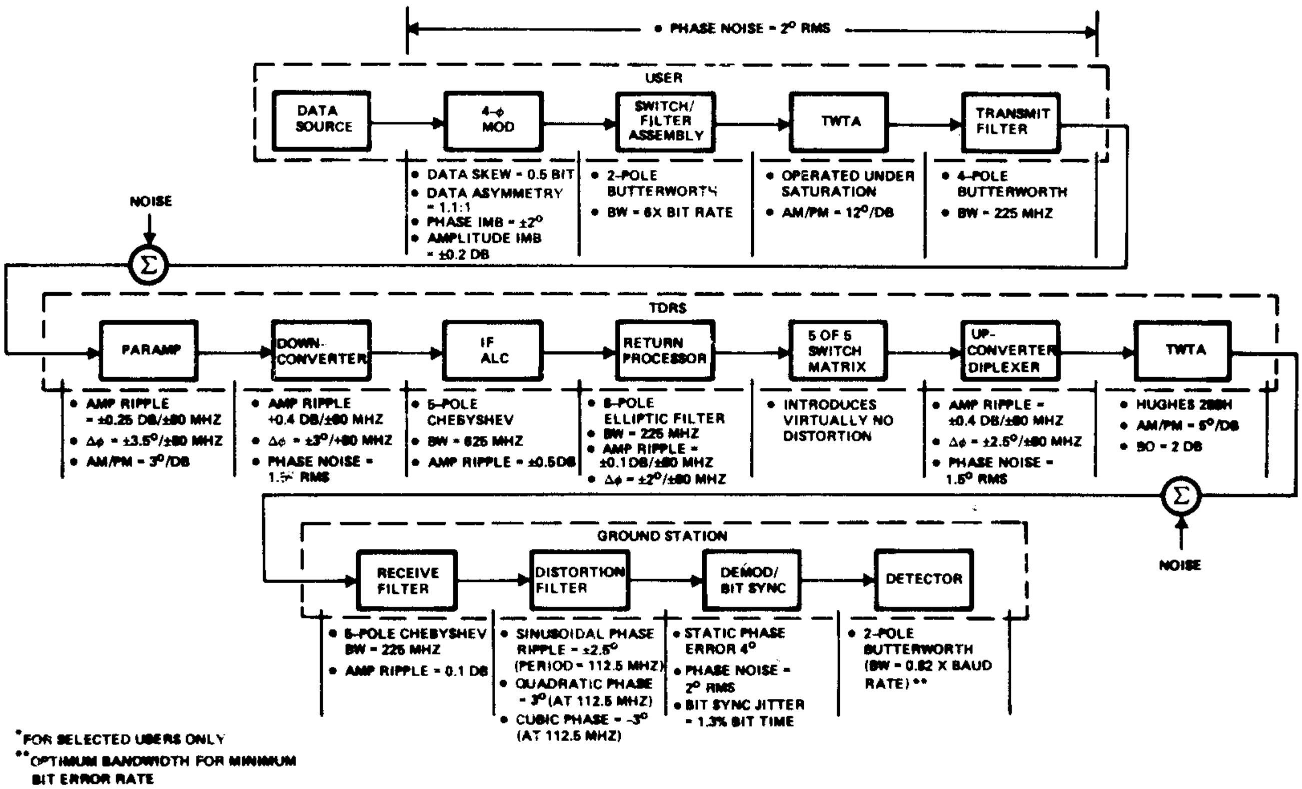

Figure 2. TDRSS Wideband Data Channel: Block Diagram

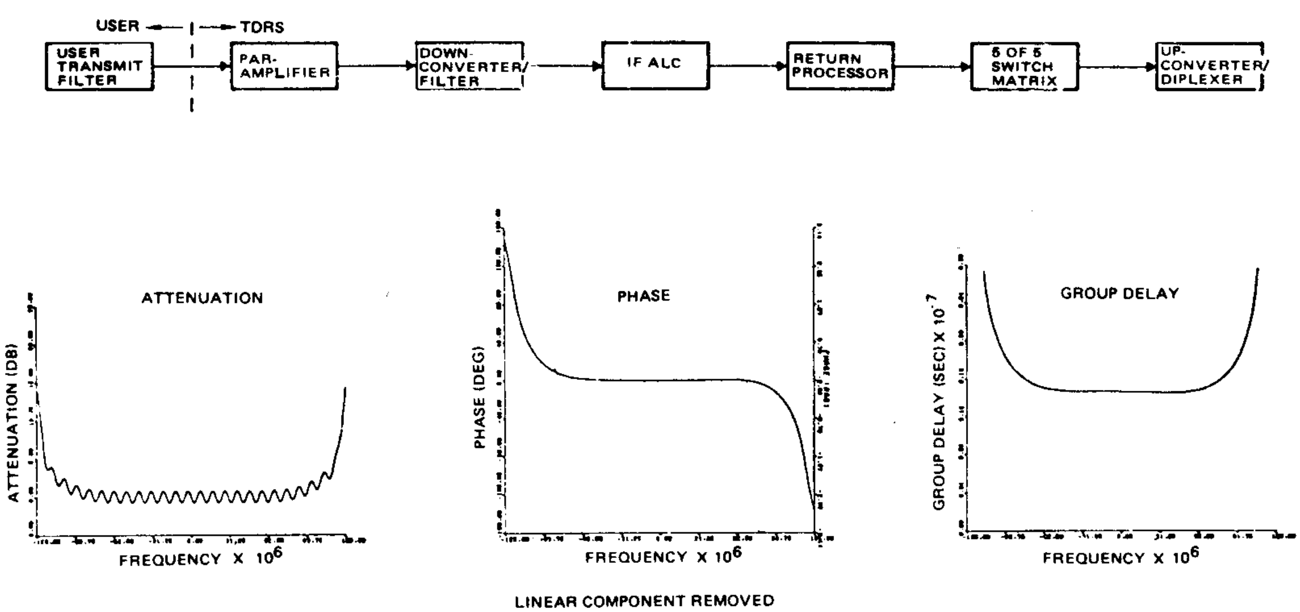

Figure 3. Wideband Channel Frequency Response (Prior to Spacecraft TWTA)

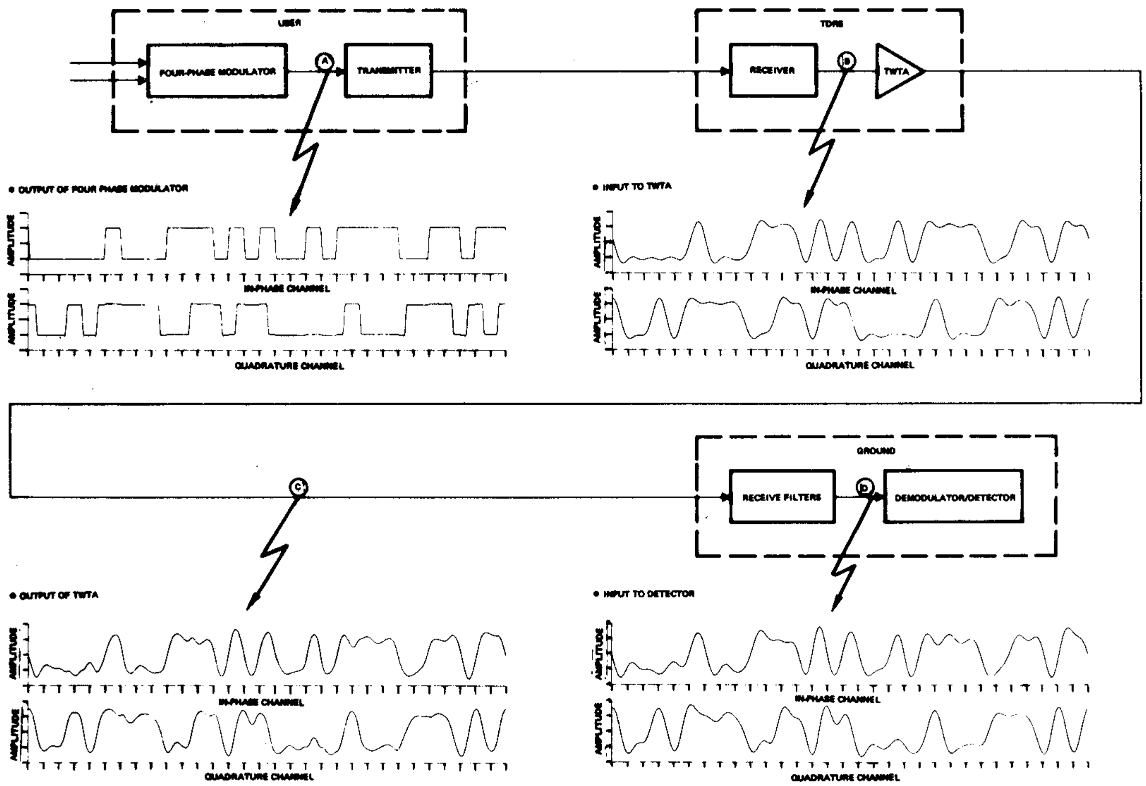

Figure 4. Channel Waveforms

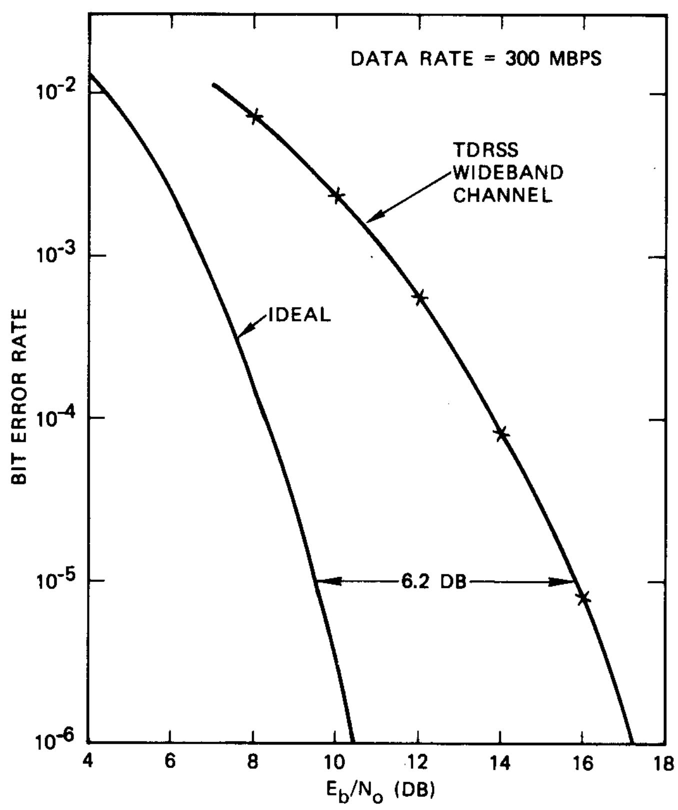

Figure 5. Bit Error Rate Versus E_b/N_o : TDRSS Wideband Channel

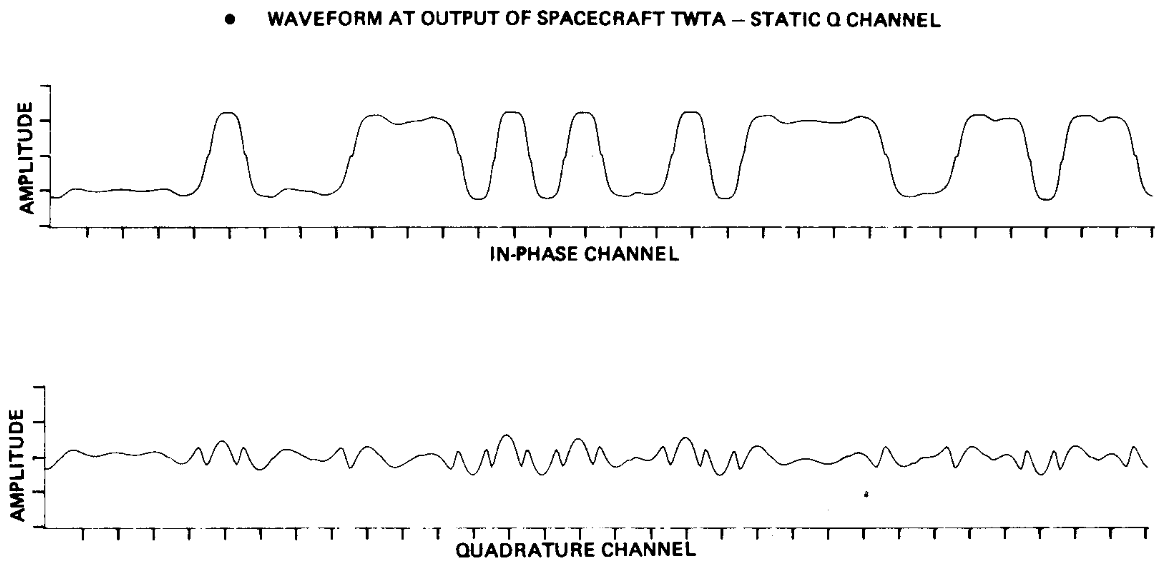

Figure 6. Generated Crosstalk at Output of Spacecraft TWTA - Static Q-Channel

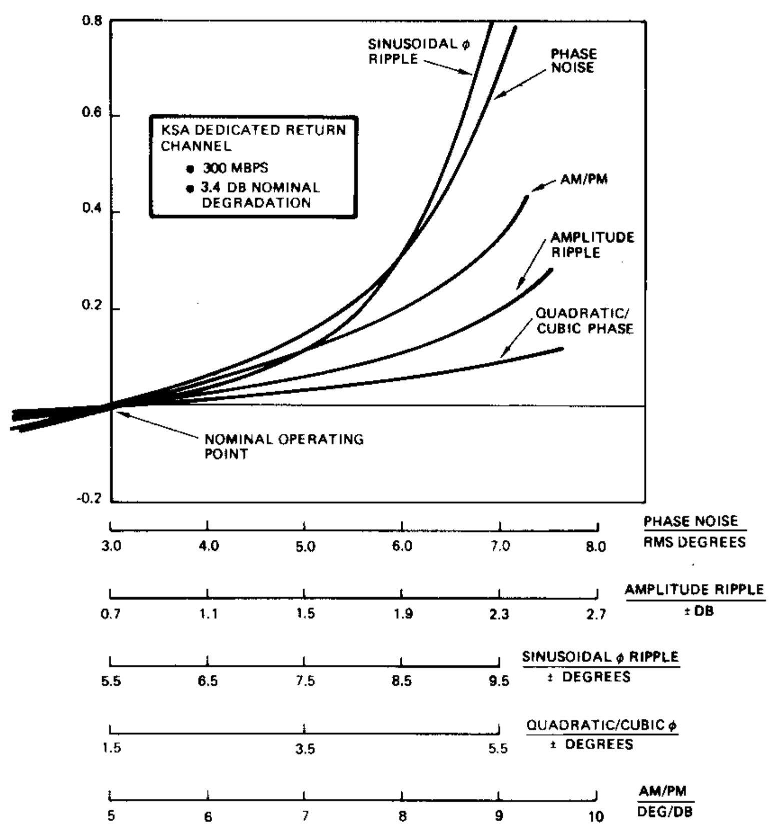

Figure 7. Transponder Parameter Sensitivity Analysis

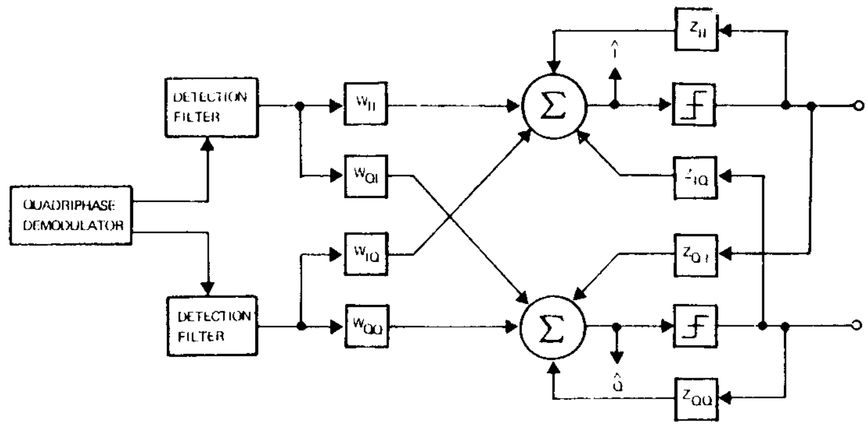

Figure 8. Generic Adaptive Equalizer

Table 2. Performance of 300 Mbps TDRSS Channel With Adaptive Equalization

EQUALIZER TYPE	REQUIRED E_b/N_o FOR BER = 10^{-5} (DB)			
NO PHASE NOISE				
NUMBER TAPS =	1	3	5	7
LINEAR	14.6 (14.3)	12.5 (12.5)	12.3 (12.2)	12.2 (12.1)
NONLINEAR	14.8 (14.4)	12.6 (12.6)	11.8 (11.7)	11.6 (11.6)
		UNEQUALIZED = 14.6 DB (14.5)		
PHASE NOISE = 4 DEG RMS				
LINEAR	16.8 (16.0)	13.3 (13.3)	13.0 (13.0)	12.9 (12.8)
NONLINEAR	17.2 (16.3)	13.4 (13.4)	12.5 (12.5)	12.2 (12.2)
		UNEQUALIZED = 16.3 DB (15.8)		

--- INTEGRATE AND DUMP

(---) 2-POLE BUTTERWORTH BW = 140 MHZ

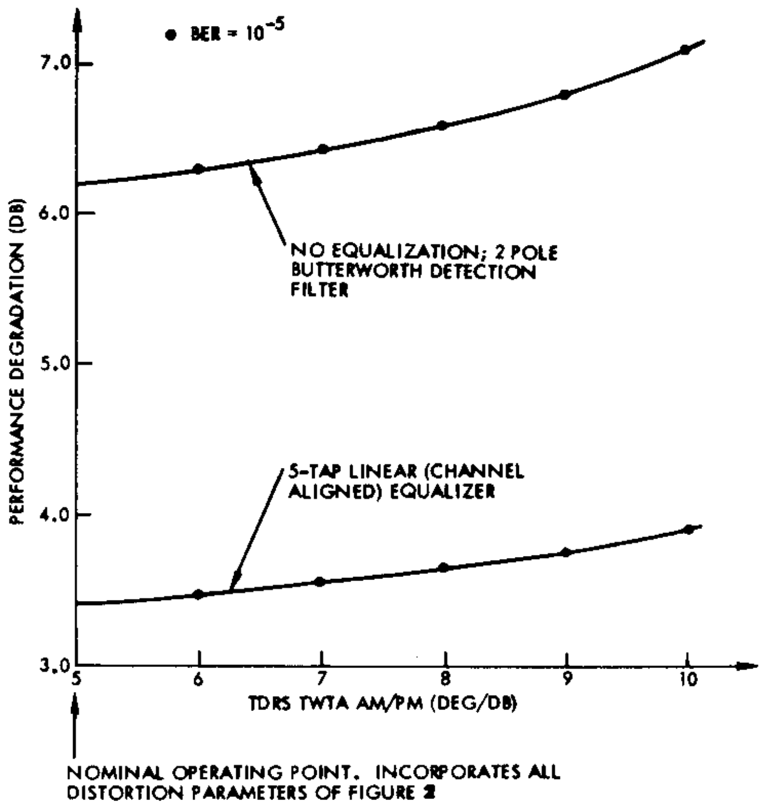

Figure 9. Effect of Adaptive Equalization on AM/PM-Induced Performance Degradation

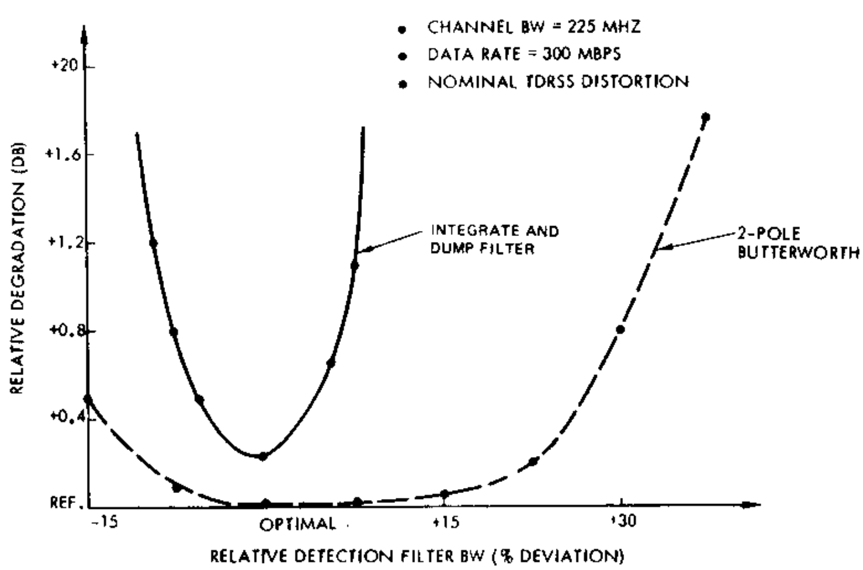

Figure 10. Performance Comparison: 2-Pole Butterworth Versus Integrate and Dump Detection