SATELLITE COMMUNICATION SIMULATION AND ITS APPLICATIONS

Lily L. Wang and Paul P. Yeh
Members of the Technical Staff
The Aerospace Corporation
2350 E. El Segundo Blvd.
Los Angeles, California

ABSTRACT

The computer simulation activities which have been carried out at The Aerospace Corporation for satellite link performance studies and system analysis are reported. A brief description of the modelings of a filter, nonlinear device, modulator, detector and receiver is also given. Some results from the simulation studies, such as the basic link performance in the presence of filters and nonlinear device (hard limiter or TWT), the comparisons of various modulation techniques (OK-QPSK, MSK and PFQPSK), the study of cross talk in a FDMA system, the interference or jamming at the presence of a nearby source, and finally, the intermodulation problem of a multiple channel MFSK system using the frequency hopping, are addressed.

INTRODUCTION

The continuous advances in technology have resulted in complex communication satellites and related devices. As the theoretical analysis of a satellite communication link becomes more difficult and the complexity of the system increases, computer simulation becomes an increasingly important and useful approach for system design and performance evaluation. The Aerospace Corporation has been working jointly with companies such as Hughes Aircraft, TRW, General Electric, Rockwell International and the Computer Science Corporation, to develop a satellite link simulation capability. This report briefly discusses the basic modeling of the signal generator, filter, nonlinear device (such as the hard limiter or traveling wave tube (TWT)), and the receivers and error detectors used in the simulation. These devices are modeled in the time domain. For a given communication system, devices such as the filter and limiter are modeled and connected in cascade. In the majority of the system studies, baseband simulation has been used. To simulate the data stream, pseudorandom (PN) sequences of variable lengths are generated. The signal is detected at the receiver and the bit error rate (BER) is measured through error counting or estimation. In this paper, the latter has been used on the assumption that only downlink

zero mean Gaussian noise of power density N_o is present. The bit energy to noise ratio (E_b/N_o) is calculated at the detector and the BER is estimated.

Various activities in satellite link simulations, which have been carried out or are under study, are also addressed. The basic link with filters and a nonlinear device is described and its BER performance is discussed. Simulation has also been used to investigate and compare several modulation techniques such as off-set quadrature phase shift keying (OK-QPSK), minimum shift keying (MSK) and prefiltered quadrature phase shift keying (PFQPSK). Degradation is a concern in the design of a frequency division multiple access (FDMA) system with filters and the nonlinear device due to cross talk between channels. Also two parallel OK-QPSK channels have been simulated in the system study. The link performance in the presence of interference is also addressed. Finally, the simulation of an 8-ary frequency shift keying (FSK) system using frequency hopping with multiple simultaneous users is described. Other efforts, such as the link simulation using coding, are also under consideration.

BASIC MODELING

The basic modelings of devices such as the signal generator, filter, nonlinear devices, receiver and detector are briefly discussed as follows:

Signal Generation

PN Sequence. To simulate the digital data stream, a PN sequence is used to provide the binary sequence of ONEs and ZEROs (or minus ONEs). To generate such a sequence, one of the simplest and most effective ways is to use a shift register. With a shift register of degree n, the output sequence from each generator is always ultimately periodic with a period $P \leq 2^n$. Tables for generating sequences with specified periods using a shift register of given degree n and logic function can be found[1].

Baseband Signal. The baseband signal for each modulation technique is based on the PN sequence weighted by a specific waveform. For the OK-QPSK modulation[2, 3], two PN sequences of rectangular pulse shapes, one for the in-phase channel (I channel) and the other for the quadrature channel (Q channel), are used as the baseband data streams with a half symbol time shift between them. For MSK modulations[3, 4], each symbol of these sequences is weighted by a sinusoidal shaping waveform which has a period twice the symbol time 2T. For other modulation such as the PFQPSK[5], an overlapping signal of SINC function, $\sin(\pi t/T)/(\pi t/T)$, is used for the symbol waveform for each channel. The sign of such an overlapping signal, +1 or -1, coincides with the pulse sign of the PN sequence. The baseband waveforms of the I and Q channels for these modulation techniques generated from the use of PN sequences of length 63 are shown in Figure 1.

Here, each symbol of the SINC function for the PFQPSK modulation technique is truncated to zero for $t \geq 5T$.

Filter

Two types of filter algorithms can be used for communication link simulation. The first type was adopted from the NASA SYSTID[6] software package and is the basic recrusive digital filter[7] where the well known filter types such as Butterworth, Chebyshev, Bessel, Butterworth Thompson, etc. can be used with variable parameters such as the number of poles and power of ripple. The second type is the algorithm which was developed for simulating practical filter response with measured data points using curve fitting.

Nonlinearity

The limiter and TWT are the essential nonlinearities which are considered in system simulation. These nonlinearities are modeled as mernoryless nonlinear devices.

Limiter. The limiter generates a nonlinear input-output power effect (AM-AM conversion) and is modeled in one of three types: soft, quasi-linear and hard limiters. A soft limiter has a gradual transition from the linear region to the saturation region and is described by an error function[8]. A quasi-linear limiter has a linear region with a sharp break at the saturation point and is expressed analytically by the integral of the sine functions[8]. For given baseband signal, A(t) for the I channel and B(t) for the Q channel, a hard limiter is modeled such that the output is given by the expression $[A(t) + jB(t)]/\sqrt{(A(t)^2 + B(t))^2}$ where $j = \sqrt{-1}$

TWT. This device exhibits, in general, two nonlinear distortion effects - a nonlinear input-output power effect (AM-AM conversion) and a nonlinear input power-output phase effect (AM-PM conversion). To simulate the TWT nonlinearity, a quadrature model[9,10] shown in Figure 2 is used. For the input envelope x(t), the two envelope nonlinearities $z_p[x(t)]$ and $z_q[x(t)]$ in the in-phase and quadrature paths are modeled by the first kind zero order and first order modified Bessel functions, where the coefficients B_1, B_2, C_1 and C_2 are determined from measured TWT characteristics.

Receiver and Detector

Data Synchronization. As the data stream passes through the filters and the nonlinearities, a time delay will take place at the output of these devices. Thus, data synchronization is needed before signal detection can be carried out. The approach for data bit synchronization used in the simulation is to search for the maximum correlation between the input data pulse train originating at the transmitter and the data pulse train arriving at

the input of this receiver. (The minimum BER can be found close to the maximum correlation point).

I&D Matched Filter and Bit Error Rate. To detect the signal, an integrate and dump (I&D) matched filter is used which maximizes the output signal-to-noise ratio. This device is modeled analytically by integrating the product of the transmitted data pulse and the data pulse arriving at the detector, which is reset to zero at the end of each symbol time. The measure of signal detection can be based on two approaches. One is to use an error counter where the output of the matched filter is compared with an optimum threshold level (for balanced binary symbols for example, the level is set at zero). A "1" will be chosen if the output is greater than the threshold level, otherwise a "0" will be chosen. An error is registered whenever a wrong decision is made. The BER is then simply the number of errors divided by the total number of transmitted bits. For a bit error rate of 10^{-4}, approximately 10^5 bits would be needed in the simulation. To save computer time, the second approach, error estimation, is used where the signal bit energy is calculated at the output of the I&D matched filter. With the given Gaussian noise power density N_o assumed to be present at the input of the receiver, the bit energy-to-noise density ratio E_b/N_o is estimated and the analytical expression of the BER for the various modulation techniques is used. The average BER for a typical link is obtained by taking the average BER over the total number of bits from the PN sequences.

SIMULATION AND APPLICATIONS

Various activities in satellite link simulations, which have been carried out, or are under study for system evaluation, are discussed as follows.

Basic Link Simulation

A basic satellite link considered in the simulation for system study is depicted in Figure 3, where the effect of the filtering and nonlinearity has been investigated. By using the OK-QPSK modulation technique, two PN sequences (each with a length of 63) are used to simulate the baseband signals. The filters considered in the link are 9-pole Butterworth low pass filters, where a nonlinear device such as the hard limiter or TWT is also present. The bit error rates are estimated and plotted at various bit energy-to-noise density ratios (E_b/N_o) in Figure 4 at BT = 1 when the hard limiter or TWT is used. The TWT used in the simulation is a typical tube manufactured by Hughes Aircraft where AM-AM and AM-PM conversion curves were provided and used in the modeling. The typical phase shift in the saturation region for this tube is about 4.4°/dB. The bandlimiting of the digital waveform from the use of a filter results in rounding and widening each individual pulse. When the bandwidth time product BT is small, the adjacent symbols may be smeared into each other and cause intersymbol interference. However, at BT = 1, the major effect of filtering is the

loss of the bit energy due to the cut-off of the high frequency components of the pulse spectrum. Using the hard limiter, the restoration of a flat envelope causes the recovery of signal energy. On the other hand, the restoration provided by the TWT is not as strong as the hard limiter. In addition, the phase fluctuations introduced by the TWT produce high frequency components, which will be removed by the second filter following the nonlinear device. From Figure 4, it can be seen that the degradation using the TWT is about 3 dB more than using the hard limiter.

Comparisons of Modulation Techniques: OK-QPSK, MSK and PFQPSK

One of the most interesting and important problems in communication systems is minimizing and controlling the spectrum occupied by the modulation signal. The reports on the study[5] of PFQPSK modulation signaling through the use of cross correlation functions and the study[11] using overlapping baseband pulses for improving the spectral efficiency lead to the investigation and comparison of modulation techniques such as OK-QPSK, MSK and PFQPSK through simulation based on the basic satellite link described in Figure 3. At the receiver, the I&D matched filter is used for signal detection when OK-QPSK or MSK modulation is considered. For PFQPSK, the impulse response of the I&D filter is not perfectly matched to the baseband signaling of the form of $\sin(0[\alpha\pi t/T)/(\alpha\pi t/T)$ at $\alpha = 1$. Instead, the impulse response of the filter has the same form except with $\alpha(\alpha \leq 1)$ adjusted at the minimum BER. With the BER fixed at 10^{-4}, the degradations of E_b/N_o for a link with filters and the hard limiter for various modulation techniques are plotted n Figure 5 as a function of bandwidth time product BT. The degradations are also plotted when the hard limiter is replaced by the Hughes TWT. It can be seen that the modulation technique PFQPSK, which has an almost rectangular power spectrum, shows promising performance at $BT > 1$. However, the performance of the modulation OK-QPSK is most favorable in the region of $.75 < BT \leq 1$.

Degradation Due to Intermodulation and Cross talk in a Multiple Carrier TWT System

An alternate way to determine the effectiveness of a multiple access system when a TWT is present is by evaluating the performance degradation caused by intermodulation and cross talk from the ideal link performance. Simulation has been used to carry out this type of study for a number of satellite communication systems. A typical case shown in Figure 6 is a dual channel link using OK-QPSK modulation. The channel spacing is set at about three times that of the given symbol rate. The modulated signal is amplified by the Hughes TWT and then passed through a 3-pole Chebyshex bandpass filter before being transmitted. At the receiver, the signal disturbed by zero rnean Gaussian noise is filtered by the same type of bandpass filter and then demodulated and detected after the I&D matched filter. The bit error rate as a function of E_b/N_o for either channel is shown in

Figure 7. At the BER of 10^{-4}, a degradation of about 2.7 dB in E_b/N_o is expected for such a system. Link parameters such as data rate, bandwidth, channel spacing, type and/or operating point of TWT have also been considered.

Interference and Jamming

Interference (or jamming) from an unpredicted source may pass through a communication link and thus degrade the system. The link used in a system parametric study in such an environment is shown in Figure 8. Here, the lowpass 3-pole Chebyshev filter and 4-pole Butterworth filter are used. The same Hughes TWT is used in the link. The interference is assumed to have the same type of modulation as the signal. With zero mean Gaussian noise also present at the receiver, the link performance has been investigated. Figure 9 shows the bit error rate as a function E_b/N_o at various signal-to-interference ratios (S/I). Simulation with the interference greater than the signal (jamming) is also under investigation.

Multiple MFSK with Frequency Hopping

The performance of the multiple M-ary FSK system using frequency hopping is of interest and has been under investigation. As the theoretical analysis becomes more difficult, in particular, with the presence of a nonlinear device such as the hard limiter, simulation becomes a reasonable approach for system evaluation. Figure 10 shows the system under study where L simultaneous users are assumed and M-ary FSK modulation is used in each channel. For each one of the M symbols, the tone in each channel is hopped within the M FSK levels according to one word of a given code word set. A typical power spectrum is shown in Figure 11. Link performance based on the BER for each channel can also be evaluated through simulation, and is presently under investigation.

SUMMARY AND CONCLUSION

A brief description of the modelings of devices, such as the signal generator, filter, limiter, TWT, receiver and detector, and of various activities in satellite link evaluation using simulation has been given. It is clear that parametric studies of certain communication systems, which are often difficult to do analytically, can be reasonably carried out through the use of computer simulation. Device modelings using measured data points, such as for the filter and TWT, help to provide realistic system performance evaluations.

The basic satellite communication system with a hard limiter or TWT (shown in Figure 3) was used for link performance investigations. With channel bandwidth set equal to the data rate 1/T, the link degradation in E_b/N_o using the typical TWT is 3 dB more than the link using the hard limiter as shown in Figure 4. The higher degradation for the link using the

TWT is due to its higher bit energy loss in the link than the latter. After the signal passes through the first low pass filter, the recovery out-of-band energy is greater using the hard limiter than the TWT according to their AM-AM conversion characteristics. Furthermore, the phase shift from the AM-PM conversion characteristic of TWT generates more higher frequency components which are filtered by a second filter causing an additional energy loss in the link relative to the use of a hard limiter.

The comparison of the modulation techniques OK-QPSK, MSK and PFQPSK is also interesting and worthy to discuss. The advantage of the nearly rectangular spectrum in PFQPSK is shown by its link performance with a hard limiter in Figure 5. Thus PFQPSK seems to be a promising technique for high data rate implementation. However, the phase shift and poor energy recovery at small signal levels due to the presence of the TWT, increase system degradation for the region of $BT < 1$. On the other hand, in addition to the simplicity of hardware implementation, the link degradation using OK-QPSK within the range of $.75 \leq BT < 1.$ is the smallest among the three using either a hard limiter or TWT.

The study of cross talk between adjacent channels for a link with filters and a nonlinear device is important in making trades between frequency utilization efficiency and hardware cost. Prediction of interference or jamming from unwanted signal sources is essential for system design and operation. Link performance of a multiple access system using frequency hopping and coding is of concern for practical system evaluation. System parametric studies for these links, shown in Figure 6, 8 and 10, become possible through computer simulation.

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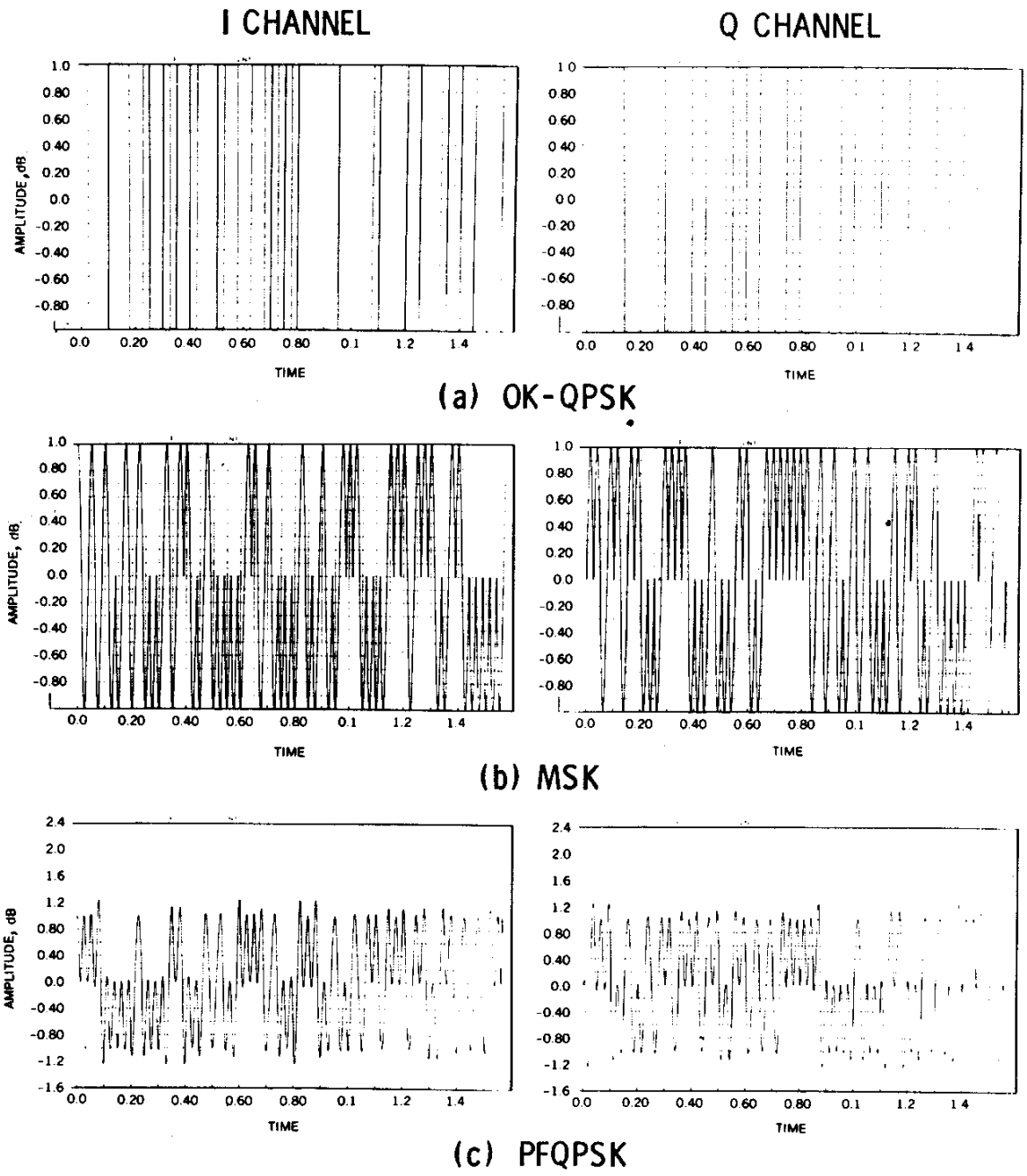

Figure 1. Baseband Waveforms for Various Modulated Data Sequences

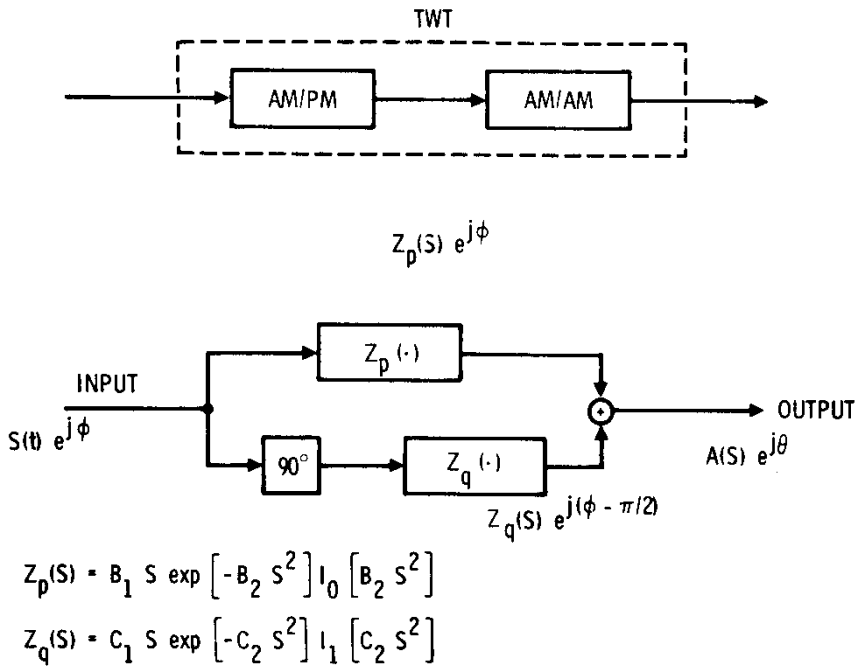

Figure 2. Quadrature Model of TWTA

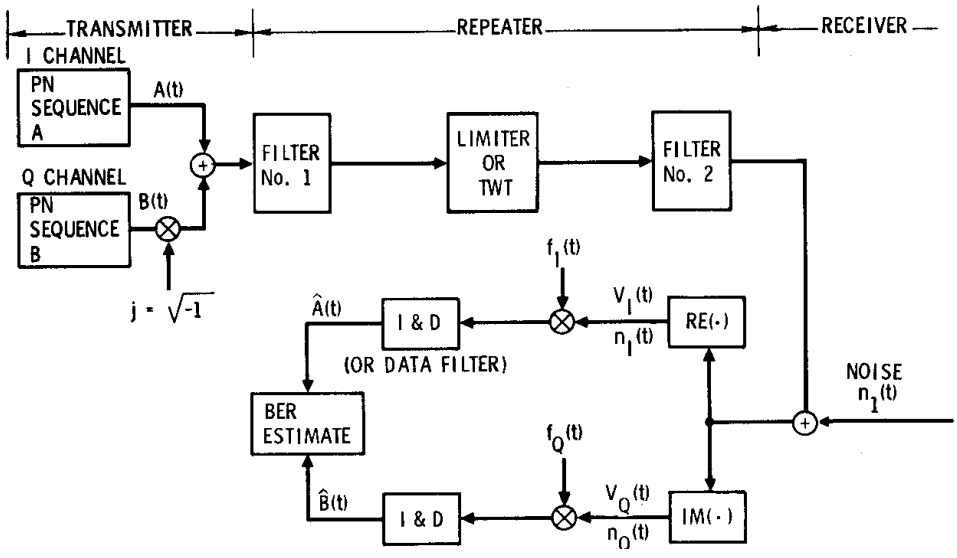

Figure 3. Two Hop Link Simulation Block Diagram

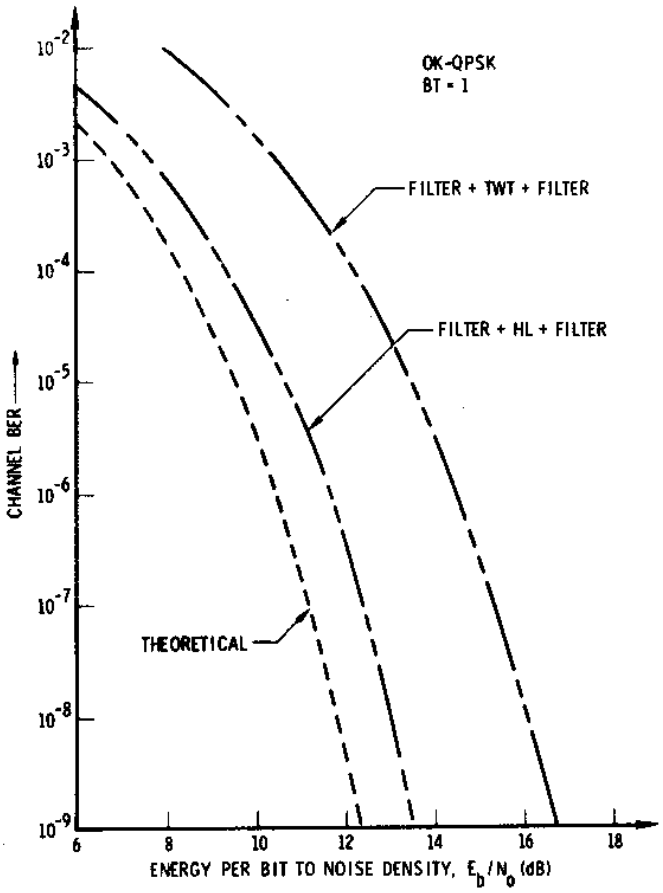

Figure 4. Link BER Using Hard Limiter or TWT (System from Figure 3)

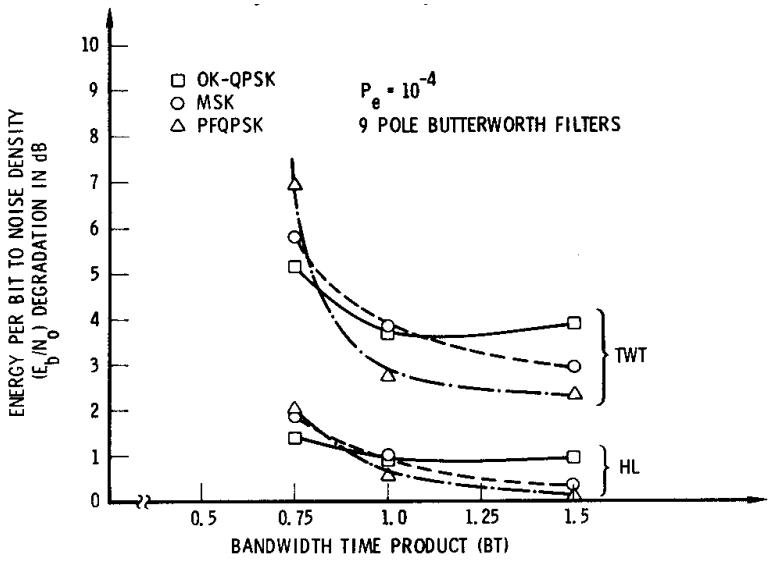

Figure 5. Energy Per Bit to Noise Density Ratio (E_b/N_o) Degradation at Various BT for OK-QPSK and PFQPSK

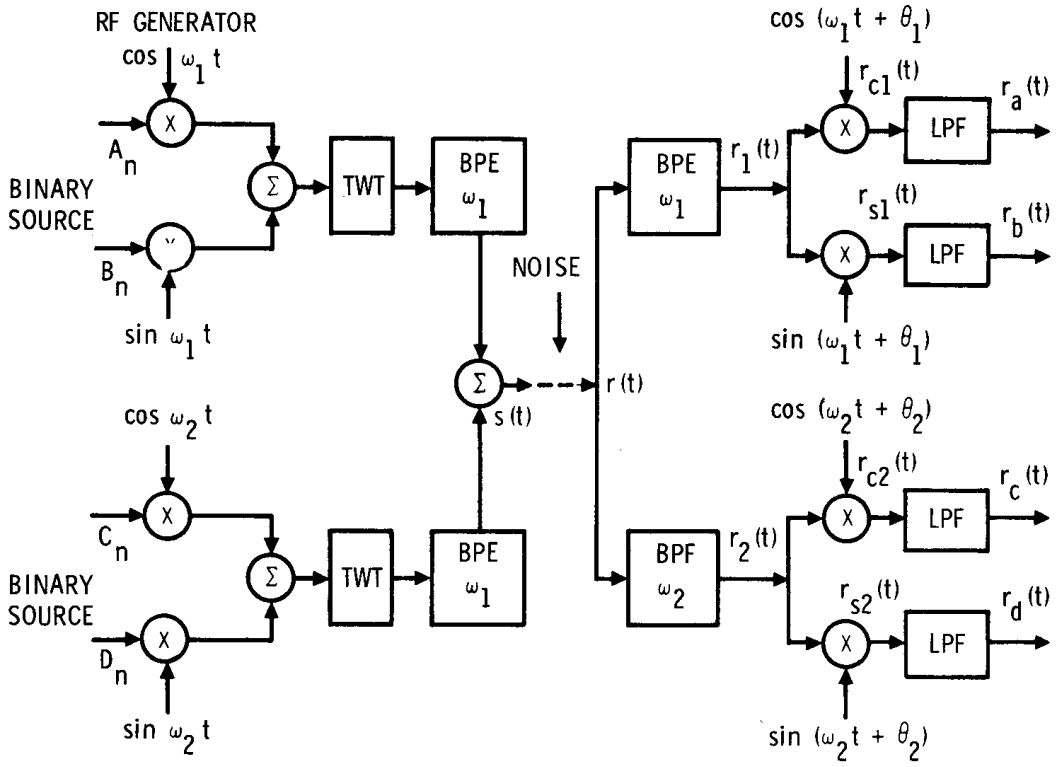

Figure 6. Communications Link Simulation Model for Double OK-QPSK Signaling

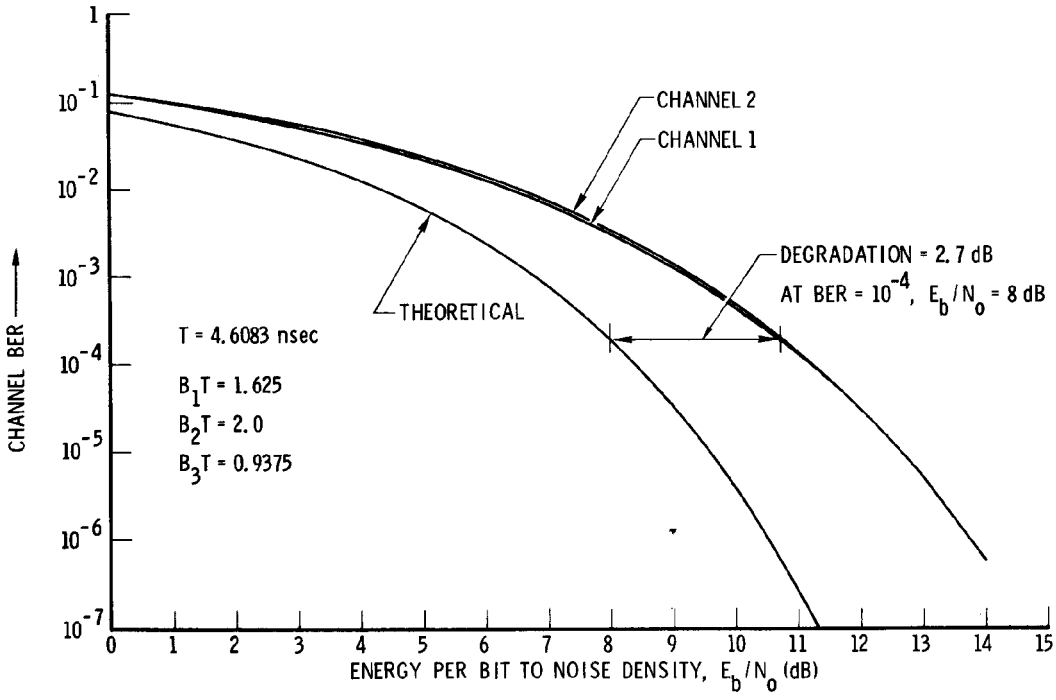

Figure 7. Link BER vs E_b/N_o in dB for A Multiple Access Communication System

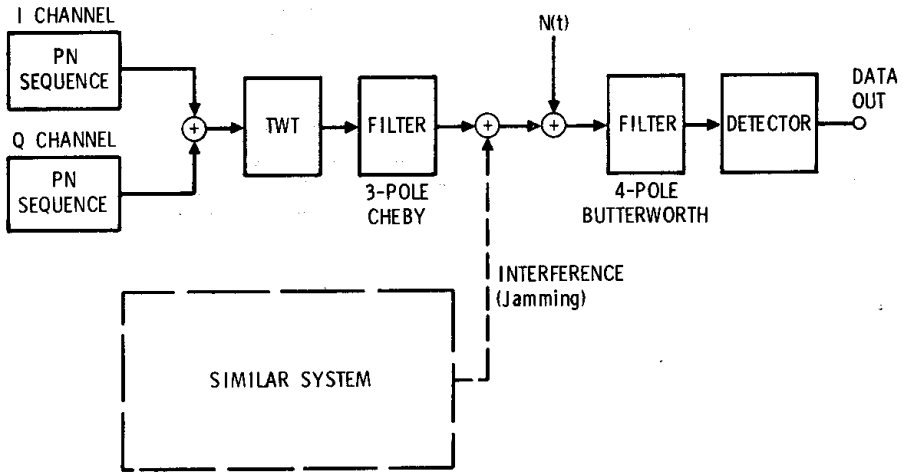

Figure 8. Link With interference (Jamming)

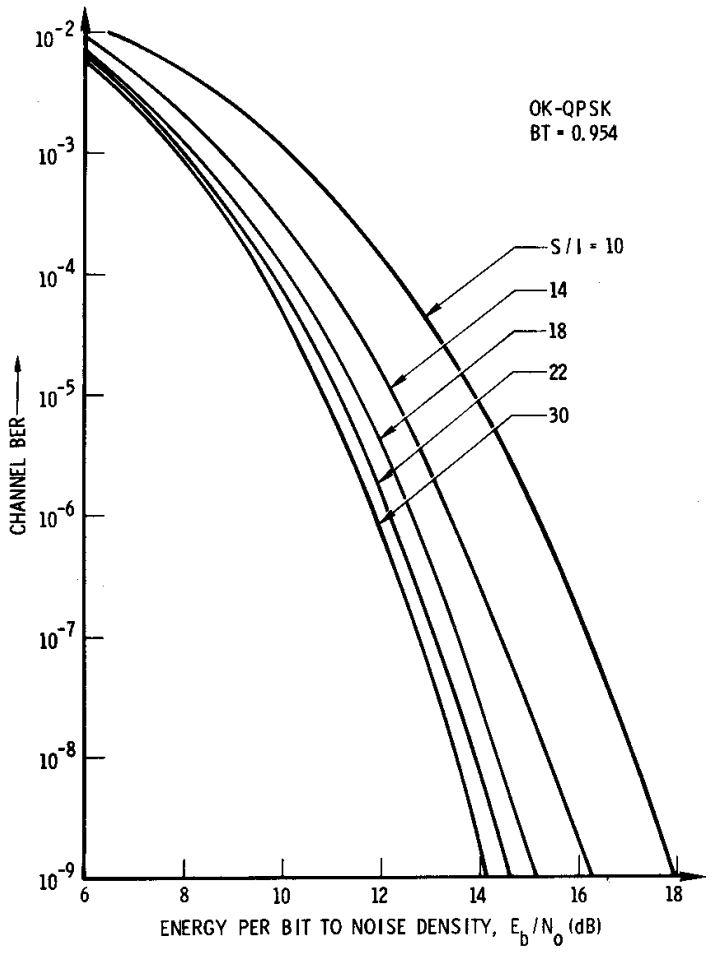

Figure 9. Link BER At The Presence of Interference (System from Figure 8)

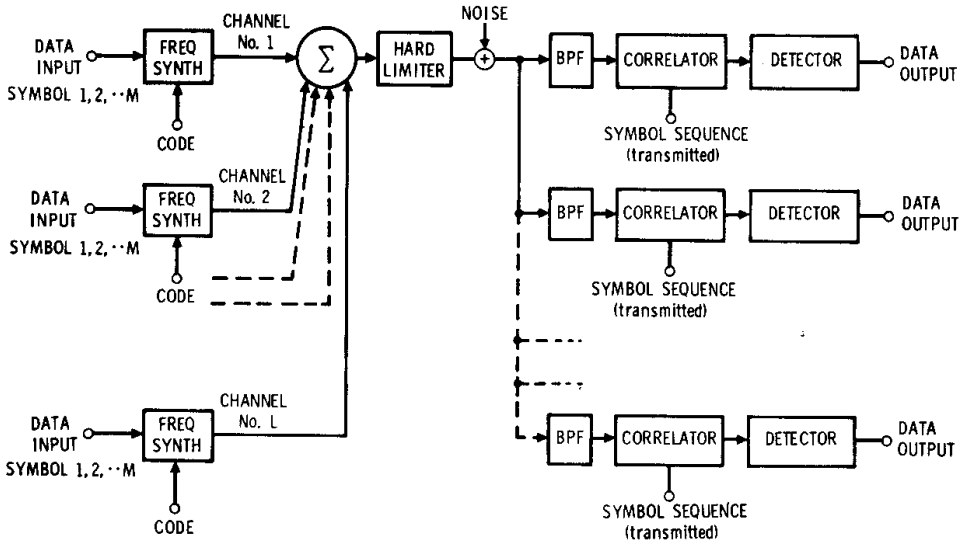

Figure 10. Baseband Simulation of a Multiple MFSK System with Frequency Hopping for Simultaneous Users

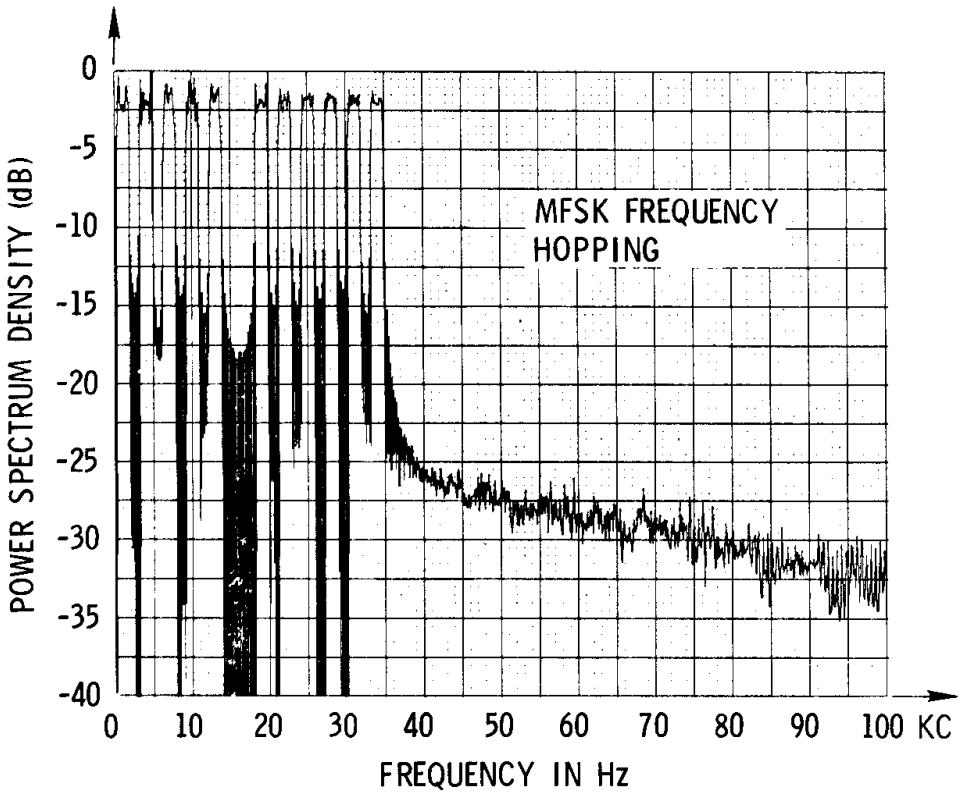

Figure 11. Power Spectrum of the Signal at the Output of the Hard Limiter for a Typical System (System from Figure 10)