SIMULATION OF TWO BANDWIDTH EFFICIENT MODULATION EFFORTS IN SATELLITE COMMUNICATIONS*

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SUMMARY

A bandpass limited satellite channel with uplink and downlink noise was simulated for several constant envelope modulation schemes. Minimum shift keying (MSK) significantly outperformed quadriphase shift keying (QPSK) in achieving bit error rates of 0.005 with less than 1 dB degradation for a channel bandwidth to data rate ratio B/R = 0.78, for example.

Frequency division multiple access (FDMA) scenarios with unsynchronized satellite signals were also simulated. A processing satellite performed the functions of Doppler and symbol timing correction and demodulation of each uplink. Additional filtering mitigated intersymbol interference (ISI) deliberately introduced for spectral shaping by prolate spheroidal data windows. Even when the received power in each satellite signal was 10 dB above the desired signal, 16 kbps rate-1/2 coded QPSK satellite signals on odd 12.5 kHz centers could coexist with line of sight (LOS) signals on 25 kHz centers.

These results are applicable to the ever growing problems deriving from increased spectral occupancy.

INTRODUCTION

This paper is a synopsis of approximately two years of parallel effort on two satellite communications problems requiring extensive computer simulation. The first problem involved the modeling and simulation of a hard-limiting frequency translating repeater satellite channel with the objective of estimating error rate performance for several digital constant envelope modulation schemes. The second problem addressed an approach to fitting several bandwidth efficient digital signals into a crowded UHF band where they

* This paper is based on work performed at Lincoln Laboratory, M.I.T.

might coexist with previously allocated analog signals and still be successfully demodulated in an advanced processing satellite. In this case a considerable amount of analysis as well as modeling and simulation was involved.

We will present the treatment of each of these problems by summarizing the mathematical model of the physical system, the unique simulation characteristics, and the performance results. As a start we will discuss some simulation procedures which are generally common to both efforts. We will conclude with a flavor of special difficulties encountered and a few suggestions which might be helpful to communications systems analysts without much simulation experience.

SIMULATION APPROACH

Although a few smaller computing facilities were available, we decided to employ an IBM 360/168 via a local time sharing system using FORTRAN-IV. This provided flexibility and a familiar language but required a considerable investment ($5-10 per minute) in CPU time. Consequently, our philosophy was to test many promising ideas with a fairly modest number of trials per simulated datum rather than increasing performance confidence levels but limiting the scope of the investigation. We felt the more successful schemes could be refined later with a special purpose software processing facility or laboratory experimentation with prototype hardware.

All the simulations were performed digitally and at baseband with complex signals and noise. This reduced the necessary sampling rate to a reasonable level and simplified mathematical representation and programming. For convenience an integral number of samples per symbol was guaranteed.

The transmitted data and Gaussian noise sequences were selected using the nearly uniformly distributed pseudorandom number generator

$$K_{n+1} \equiv 11^5 K_n \text{ (modulo } 2^{31} - 1) \tag{1}$$

where K_1 is a 9-digit integer, and a polar method of normal deviates. The same sequences were invariably used in comparing different modulation and filtering techniques.

Both performance simulations were aimed at counting decision errors in the bit error probability range $10^{-3} \lesssim P_b \lesssim 10^{-2}$, corresponding to energy contrast ratios (E_b/N_o's) of roughly 4 to 12 dB depending on the scenario. Very little data was gathered below a 10^{-3} error rate because of the amount of computer time required.

BANDPASS-LIMITED SATELLITE CHANNEL

This simulation was an attempt to predict the performance of a typical bandpass hard-limiting Navy Fleet Satellite Communication System (FLTSATCOM) channel.[1]

Model

We modeled the satellite as a narrowband filter followed by an ideal bandpass limiter that preserves the phase but removes the envelope information of its input (Figure 1). Although the space segment was well past the design stage, we simulated several filters to study sensitivity to roll-off, phase nonlinearity and center frequency offset.

Since the terminals could be modified, we tried six different antipodal constant envelope modulation schemes (Figure 2), including binary phase shift keying (BPSK), offset QPSK (SQPSK and MSK which yield the same coherent matched-filter bit error rate

$$P_b = (1/2)\operatorname{erfc}\left(\sqrt{(E_b/N_o)\mathrm{eff}}\right) \tag{2}$$

in additive white Gaussian noise (AWGN). The approximate (within 1 dB ignoring ISI effects) <u>effective</u> energy per bit per noise power density was defined in terms of the energy contrast ratios on the uplink and downlink and the data rate R as

$$(E_b/N_o)\mathrm{eff} = (E_b/N_o)\mathrm{up}\cdot(E_b/N_o)\mathrm{down}/((E_b/N_o)\mathrm{up} + (E_b/N_o)\mathrm{down} + B/R). \tag{3}$$

With this definition simulation results for both uplink and downlink noise could be plotted in two dimensions as P_b vs- (E_b/N_o)eff in a traditional way using (2) as a theoretical optimum.

We were interested in estimating the highest data rates feasible (R > B) for tolerable amounts (1 or 2 dB) of intersymbol interference and nonlinear distortion. The coherent receiver was not optimized to the channel but was matched to the transmitted signals.

Simulation

There were options for bypassing either the filter or bandpass limiter or both. Figure 3 illustrates how the ideal limiter transforms all baseband input samples of the form x(n) + jy(n) to a circle of fixed radius.

The complex sampling rate W must be significantly larger than either the filter bandwidth B or the signal bandwidth B_s in order to insure a reasonable approximation to the bandpass situation. We decided on the rule-of-thumb

$$W \tilde{>} 4 \max \{B, B_s\} \qquad (4)$$

as an adequate analysis bandwidth.

Several different digital filters were employed in the simulation: Chebyshev, Butterworth and elliptic infinite impulse response filters implemented in cascade canonical form in the time domain, and three finite impulse response (FIR) filters realized by frequency sampling techniques and fast convolution via the frequency domain; all but one of the FIR filters had nonlinear phase responses.

A typical simulation required about 30 sec of CPU time for each datum representing 2000 bit decisions. The program consisted of just under 2000 statements including comments.

Results

Of the six modulation techniques simulated, BPSK performed far worse than the others. MSK and SQPSK proved to be the best modulations overall, followed closely by QPSK, and more distantly by "alternating" QPSK (AQPSK) and continuous phase "quadrifrequency" shift keying (CPQFSK).

The effective signal to noise ratio (SNR) losses at $P_b \approx 0.005$ are shown in Figure 4 for MSK and various channel filters; the SQPSK performance was not significantly different. Since we took the nominal 3 dB bandwidth of the FLTSATCOM filter to be 25 kHz, the two estimation curves correspond to data rates of 32 kbps and 48 kbps.

Thus, the estimated FLTSATCOM performance losses for MSK or SQPSK at these data rates were about 0.5 dB and 2.5 dB, respectively. The similarly estimated losses for BPSK were about 1 dB and 4 dB for 19.2 kbps and 25 kbps, respectively. Larger degradations should be expected at lower error rates primarily because of filter induced ISI distortions.

BANDWIDTH EFFICIENT FDMA CHANNEL

This simulation was used to evaluate ways of fitting 16 kbps uplink signals to a processing satellite among LOS allocations spaced by 25 kHz in the UHF band.[2]

Model

The system model that was simulated digitally is shown in Figure 5. The terminals are assumed to be mutually unsynchronized or uncoordinated in symbol timing, Doppler, and transmitter power control, as might be the case with mobile platforms. User signals were separately processed at the satellite in the presence of crosstalk, ISI and channel noise. Spectral shaping was accomplished by digital filtering at both the terminals and the satellite, where deliberately introduced ISI was mitigated by a simple linear recursive filter.

The filtering for bandwidth conservation was applied in the time domain by amplitude weighting (windowing) the signals. For the problem considered this was more efficient than convolutional filtering, and since the data windows were finite in extent any induced ISI could be precisely confined and determined.

In particular, for M-ary PSK, if A_u is the amplitude of the signal received from the uth user, if $x_{u\xi}$ is the current received complex data symbol from the uth user, and if $\phi_{st}(r)$ is the crosscorrelation function between the satellite and transmitter windows, where the shift r is measured in symbols, then

$$f_{ISI} = A_u \sum_{r \neq 0} x_{u,\xi+r}\, \phi_{st}(r) \tag{5}$$

is the ISI at the output of the satellite discrete Fourier transform (DFT) operation. If N_c is the intersymbol distance, i.e., the number of samples per symbol, if N_t and N_s denote the length of the transmitter window t(m) and satellite window s(m), assumed common to all users, then

$$\phi_{st}(r) = \sum_{m=0}^{N_s-1} s(m)t(m - rN_c), \; r = 0, \pm 1, \cdots . \tag{6}$$

From (5) and (6), ISI is introduced whenever either window is longer than the intersymbol distance ($N_t > N_c$ or $N_s > N_c$). In the special case s(m) = t(m), the satellite window acts as a matched filter.

We found that this ISI could be nearly removed with a two stage digital filter (Figure 6) which was designed (also through simulation) using the standard minimum mean squared error (MMSE) criterion. That is, if $x_{u\xi}$ is the complex filter output symbol for the uth user we found the filter which minimized

$$\varepsilon_{u\xi} = \overline{|X_{u\xi} - x_{u\xi}|^2}. \tag{7}$$

This was accomplished by solving a nonlinear system of equations resulting from the partial differentiation of (7) with respect to the filter coefficients. These equations were solved iteratively with the computer for every window combination simulated.

Although MSK was also modeled digitally and simulated, no windows were applied at the transmitters, and the satellite windows were restricted to those that would not introduce any ISI. These restrictions on windows yielded promising results, nevertheless, for MSK exhibits relatively small crosstalk between unsynchronized and unwindowed MSK waveforms.[3]

Two classes of windows were selected for simulation: The Dolph-Chebyshev windows[4] and the prolate spheroidal windows.[5] For a given length and cutoff frequency these windows are optimum in the following senses: a Dolph-Chebyshev window has a minimum equiripple response outside of the main lobe of its frequency response, and a prolate spheroidal window has minimum energy out of band.

Simulation

The Dolph-Chebyshev windows were eventually abandoned during the simulations because the equiripple sidelobes contributed too much crosstalk interference from other user signals regardless of center frequency separations. Unfortunately, the prolate spheroidal windows were more difficult to generate; they were found with the computer, employing a standard numerical method of finding the eigenfunction associated with the largest eigenvalue λ of the set of equations, n = 0, 1, ..., N_w - 1

$$\lambda w(n) = (1/\pi) \sum_{m=0}^{N_w-1} \Big(w(m) \sin \omega_c (n-m)\Big) / (n-m) \tag{8}$$

where w(n) is a real sample of the window of length N_w and ω_c defines the bandwidth.

The windows were normalized for a peak power limited transmitter so that a rectangular window of length N_w would have unit energy. Hence, a non-rectangular window resulted in an average received signal energy loss of

$$L_t = -10 \log_{10} \phi_{tt}(0) \text{ dB}. \tag{9}$$

A typical prolate spheroidal window with L_t = 3.07 dB, and the magnitude of its digital frequency response is shown in Figure 7. Since this 76-sample window was applied so that its center coincided with the center of a data symbol 50 samples long, the window spanned all of that symbol and 13 samples of the two adjacent symbols. The resulting ISI governed by (5) is specified by $\phi_{st}(-1) = \phi_{st}(1) \approx 0.09$ (with $\phi_{st}(0) \approx 0.49$) for the matched case s(m) = t(m).

The N_c = 50 samples per symbol arose from the assumptions of a 500 kHz uplink bandwidth with 20 satellite user signals located at odd multiples of 12.5 kHz (LOS users at

25 kHz centers), a symbol rate of 16 ksps, an integral number of samples per symbol, and a number N of DFT points that was the least power of two which would accommodate the uplink bandwidth, i.e.,

$$N = 16 \text{ ksps} \cdot N_c / 12.5 \text{ kHz} \tag{10}$$

or $N_c = 25N/32$; N = 64 was the least power of two allowing at least 20 satellite channels on odd 12.5 kHz centers. Hence, the analysis bandwidth was $N \cdot 12.5$ kHz = 800 kHz.

BPSK, QPSK, MSK and CPQFSK modulations were simulated. The Forney scheme[6] which uses the Viterbi algorithm to obtain a maximum likelihood estimate of the transmitted data sequence in the presence of AWGN and ISI was investigated as an alternative to the MMSE filters. LOS users, when present, were modeled as colored Gaussian noise generated by passing AWGN through a narrowband Chebyshev digital filter. A typical simulation run consumed in the order of one minute of CPU time for every datum representing 1000 symbol decisions. The principal programs consisted of a total of roughly 4000 statements including comments.

Results

From extensive sets of simulations we prepared a performance summary (Table 1) for rate 1/2 coded QPSK and uncoded MSK for a 16 kbps precoded bit rate, ten satellite users spaced by 25 kHz, and two LOS users adjacent to the satellite user signal being demodulated. The receiver power in each of the interfering satellite user signals was E(dB) above that of the desired signal. The nominal bandwidth of the LOS user signals was about 3 kHz, and their pre-filtered mean-square signal amplitude was set approximately 8 and 11 dB above the desired signal for QPSK and MSK, respectively, assuming a rectangular transmitter window.

The coded QPSK performance of Table 1 was estimated from the theoretical and uncoded simulation curves of Figure 8 using a previously known technique.[7] This example illustrates how an E_b/N_o of about 6.8 dB is required for a 10^{-5} bit error rate with soft decisions and E = 10 dB interfering satellite users. This results from adding a 2 dB degradation in the uncoded simulations to the theoretical coding performance of E_b/N_o = 4.8 dB at $P_b = 10^{-5}$.

It was concluded that with relatively little degradation, 20 unsynchronized 16 kbps satellite users could be packed into a 500 kHz UHF uplink bandwidth shared with terrestrial LOS users spaced by 25 kHz. Signal strengths might vary by as much as 10 to 15 dB at the satellite without the need for transmitter power control. Peak-power-limited QPSK with a rate 1/2 convolutional code was slightly inferior to uncoded MSK for bit error rates larger than 10^{-3}. Spectrally shaped and coded QPSK, however, was needed for lower error rates and would be more attractive if the transmitters were not peak-power-limited.

LESSONS LEARNED

Unfortunately, it is difficult to maintain restraint at the beginning of a simulation when one is primarily interested in obtaining results. In addition to making the fundamental decision as to what computational facility to utilize, it should be well worthwhile to devote more than the usual attention to the quality of the output estimates and the number of trials required. One should also strive to eliminate unnecessary programming code where possible if its impact can be determined analytically with high confidence separately from simulation. It is expedient to learn as the simulation progresses but this can be costly in computer time because it is so tempting to let the computer do the “thinking” in resolving discrepancies.

The main troubles we encountered were generally related to the proper realization of digital filters and windows. The main worries had to do with setting noise levels, sampling rates, padding with zeros in the proper place, and determining the actual filtering delays to achieve the best receiver correlation. It certainly helps to have digital signal processing and Monte Carlo experts on hand as well as substantial programming support. As usual in anything related to software, it surely would be easier to do a far better job a posteriori - but that’s the simulation challenge.

CONCLUSIONS

These simulations added evidence to substantiate MSK as a versatile and attractive modulation performer. It is not only bandwidth efficient but behaves well when passed through nonlinearities. Nevertheless, spectrally shaped QPSK signals can share an allocated band on a non-interfering basis if constant envelope modulation is not required. These results may encourage further work in bandwidth efficient modulation techniques which are becoming so important in conserving the world’s spectral resource.

ACKNOWLEDGMENT

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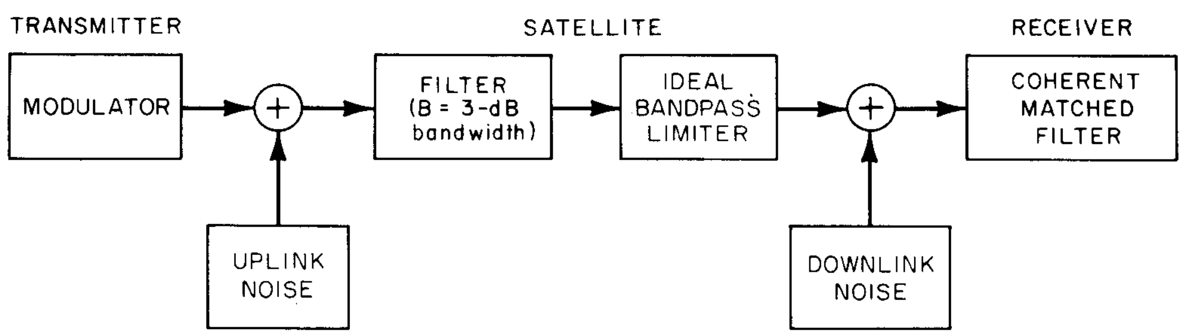


Figure 1. Bandpass-Limited Satellite Channel Model

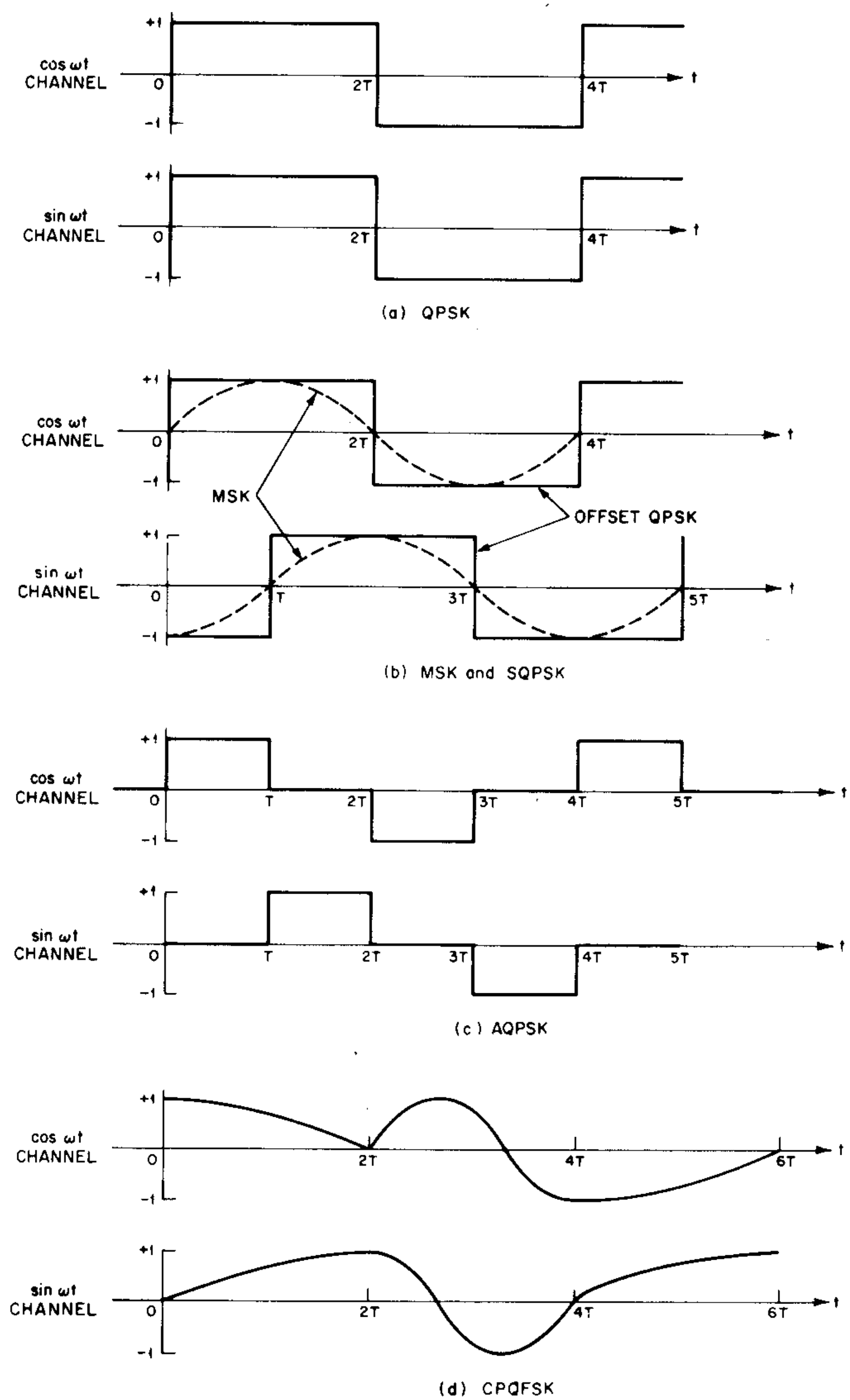


Figure 2 . Modulation Waveforms (BPSK One Channel of QPSK)

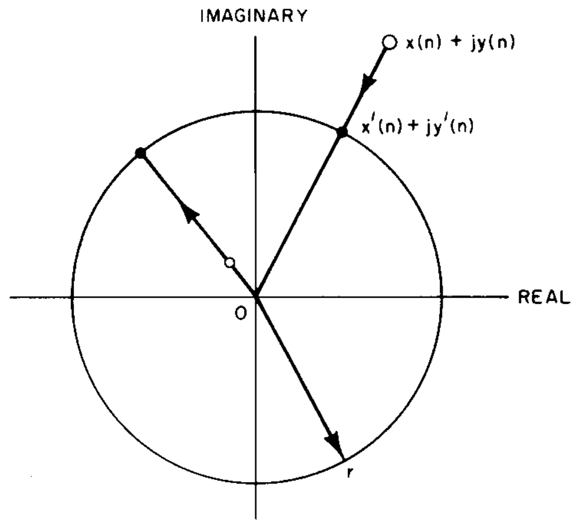


Figure 3. Ideal Limiting Operation

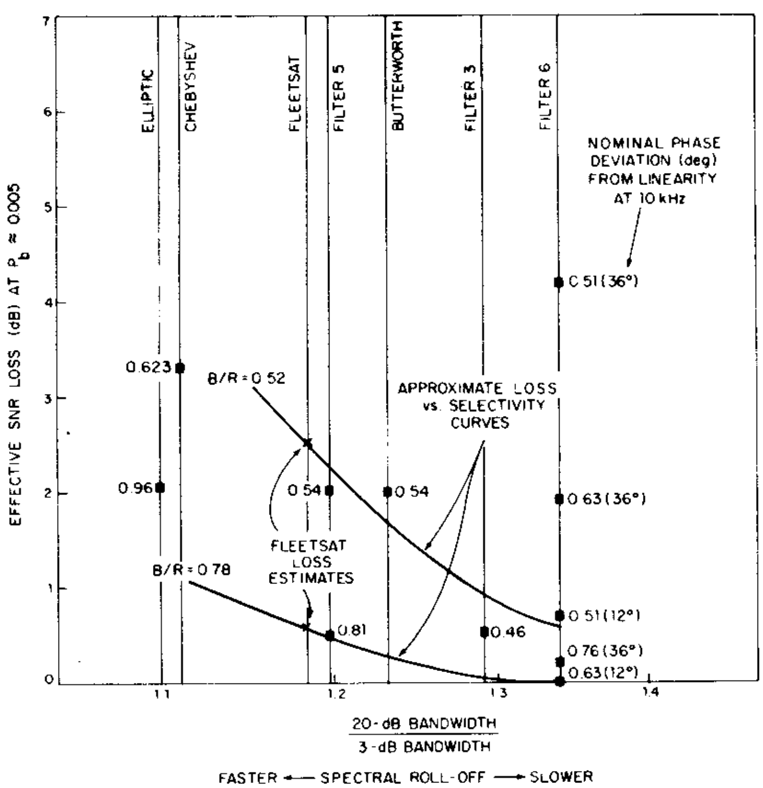


Figure 4. MSK Performance for Equal Uplink and Downlink SNRs

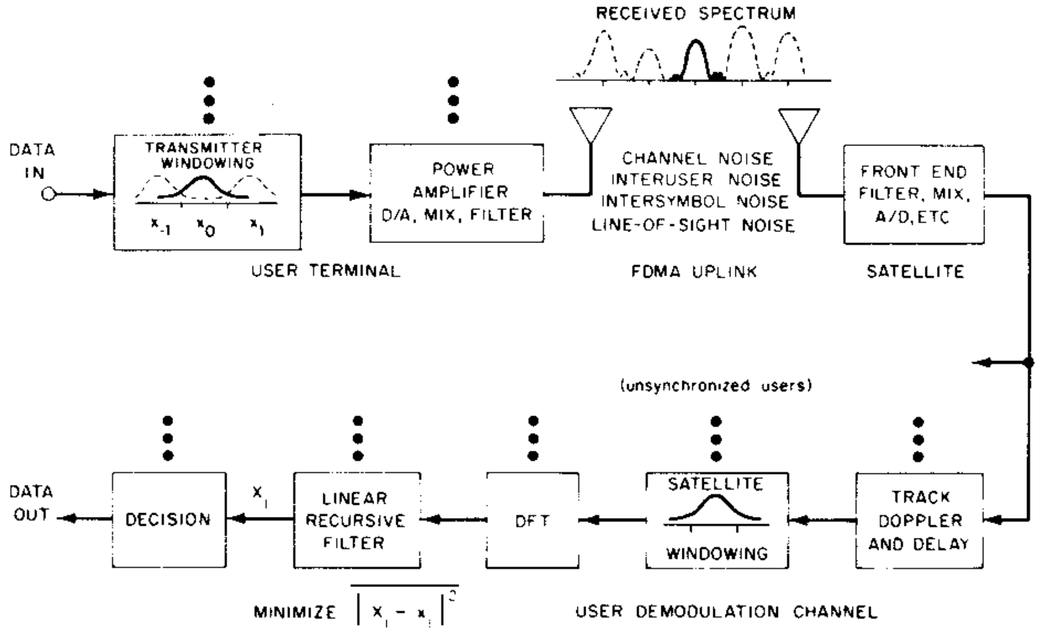
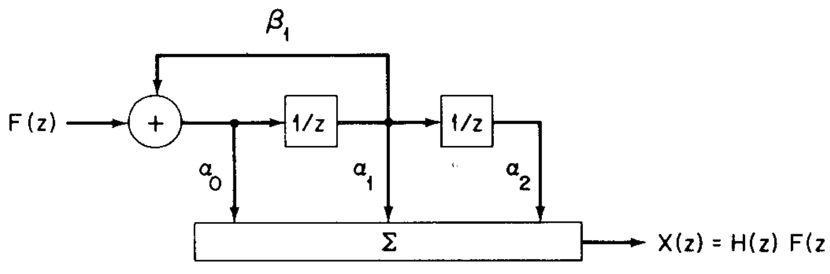


Figure 5. Basic Approach Using Data Windows



$$H(z) = \frac{\alpha_0 + \alpha_1/z + \alpha_2/z^2}{1 - \beta_1/z}$$

Figure 6. Canonical Digital Filter

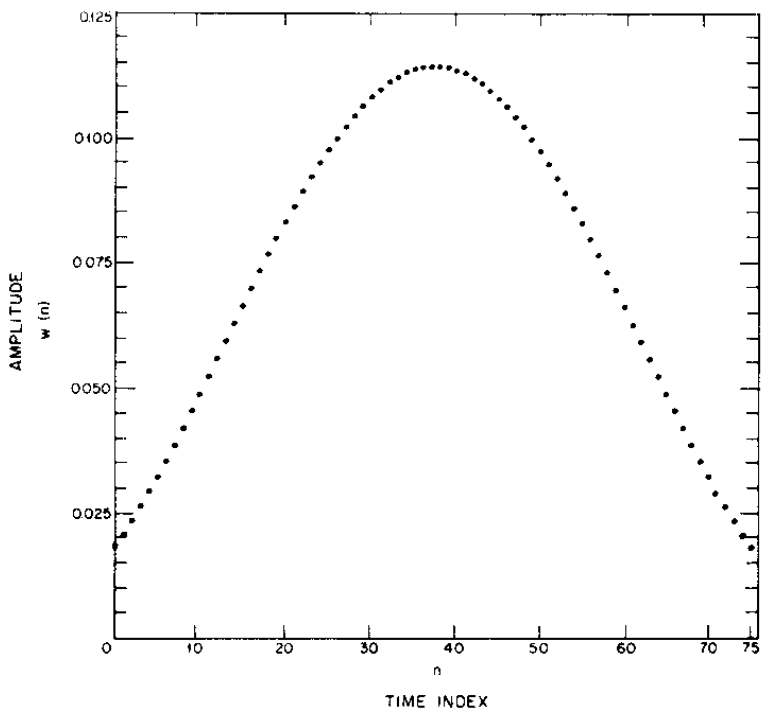


Figure 7. Prolate Spheroidal Window for Analysis Bandwidth of 800 kHz

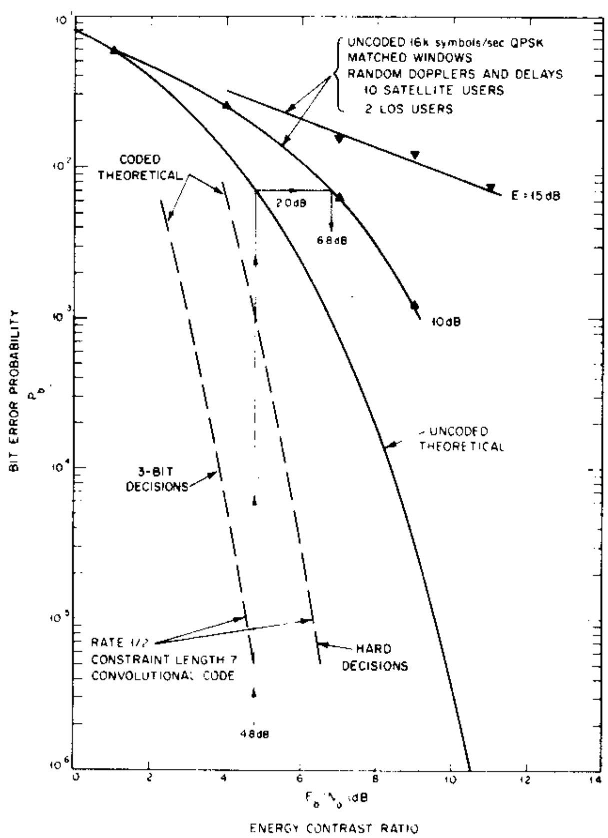


Figure 8. Coded QPSK Performance With Windows of Figure 7

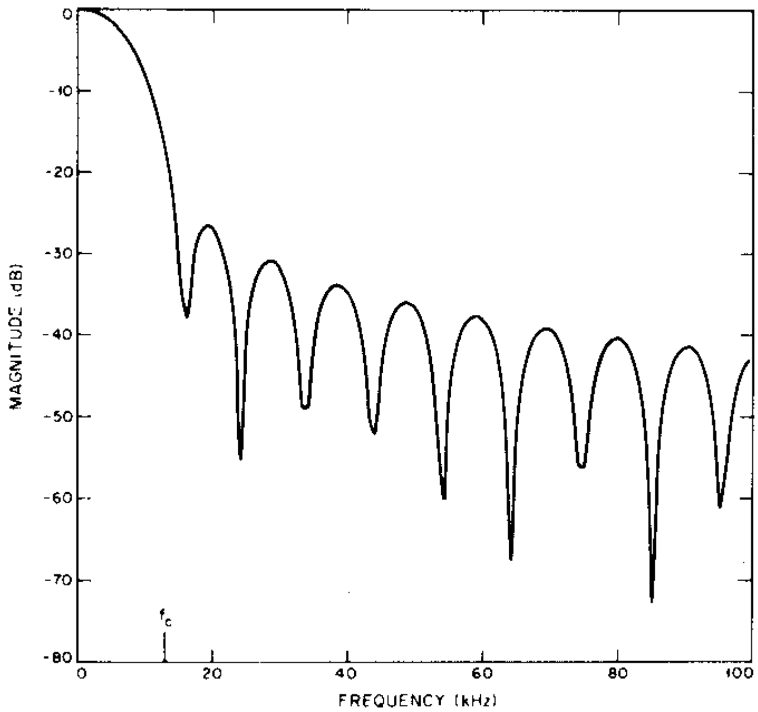


Table I - Coherent Performance from Figure 8 and all MSK Simulations