

A COMPARISON OF DIGITAL MODULATION METHODS  
FOR SMALL SATELLITE DATA LINKS

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ABSTRACT

The selection of a good modulation scheme for a satellite data link should involve careful consideration of several factors. Bit-error-rate (BER), initial cost, power consumption, circuit complexity, channel linearity, reliability, and bandwidth must be considered and weighed in the selection process.

This paper examines and compares various modulation methods applicable to small satellite data links. The performances of frequency-shift keying (FSK), bi-phase-shift keying (BPSK), quadrature-phase-shift keying (QPSK), offset QPSK (OQPSK), minimum-shift keying (MSK), and on-off keying (OOK) are compared.

The use of a non-linear transmitter amplifier is normally desirable because of its power efficiency. Because of this, a near constant envelope modulation scheme is desired. Power efficiency and bandwidth efficiency may also be important. In regards to these and other criteria, OQPSK has good characteristics and is recommended.

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## INTRODUCTION

When choosing the modulation type for a small satellite digital modem, several factors, such as power efficiency, spectral efficiency and circuit complexity, must be considered. These and other factors such as size, cost, and reliability will need to be weighed by the designer when choosing a modulation scheme.

This paper will compare the following modulation types in terms of their suitability for small satellite use:

1. Frequency-shift keying (FSK), continuous-phase case
2. On-off keying (OOK)
3. Bi-phase-shift keying (BPSK)
4. Quadrature-phase-shift keying (QPSK)
5. Offset-quadrature-phase-shift keying (OQPSK)
6. Minimum-shift-keying (MSK)

The modulation schemes are compared with respect to ideal performance, spectral properties, complexity and the effects on performance of a bandlimited channel and a non-linear channel (such as a traveling-wave tube [TWT] transmit amplifier).

## A COMPARISON OF MODULATION TYPES

### Spectral Efficiency

Spectral efficiency refers to the ratio of the data rate to the bandwidth of the modulated signal. This ratio then expresses the data rate per Hertz of bandwidth and is expressed in bps/Hz. High spectral efficiency can be obtained by the use of elaborate M-ary modulation schemes (e.g. 16-ary QAM), but the implementation of these methods is complex and will not be considered here.

In theory, the bandwidth occupied by any of the above listed signals is infinite. In practice the transmitted signal is filtered to reduce interference to adjacent channels. If the filtering is done properly, intersymbol interference (ISI) will not occur at the bit sampling instant and no loss in performance will occur. This requires that the transmit and receive filters be carefully designed so as to minimize the ISI. Although proper filtering can significantly increase spectral efficiency, the filter design is complicated and can be difficult to implement, especially at higher frequencies. In addition, spectral distortion caused by non-linearities in the transmit power amplifier (PA) may "undo" the effect of the filter unless the filtering is done after the PA.

Because of these difficulties, the filters that will be considered here will be slightly wider than the width of the main lobe of the signal spectrum. Thus, spectral efficiency will be sacrificed to the gain of simplicity in implementation. Nevertheless, insight can be gained by looking at some data obtained from heavily filtered signals. The spectral efficiencies and the corresponding bit error rates (BER) are listed in table 1, after [2]. Note that this data comes from various sources and no attempt was made to achieve an optimal BER.

Modulation Method	Maximum Speed, (bps/Hz)	Corresponding $E_b/N_o$ (dB) for BER = $10^{-4}$
----- Amplitude-shift keying -----		
OOK - coherent detection	0.8	12.5
----- Frequency-shift keying -----		
FSK continuous phase, non-coherent detection	1.0	10.7
MSK, differential encoding	1.9	9.4
----- Phase-shift keying -----		
BPSK	0.8	9.4
QPSK	1.9	9.9

Table 1. Signal Speed of Representative Modulation Methods

Although the theoretical bandwidths of the different signal spectrums are infinite, the fractional out-of-band power for the different spectra varies considerably. A comparison of BPSK, QPSK, and MSK is shown in figure 1. Note that for these unfiltered spectra, the power outside of the main lobe is significantly less for MSK than for BPSK or QPSK [4].

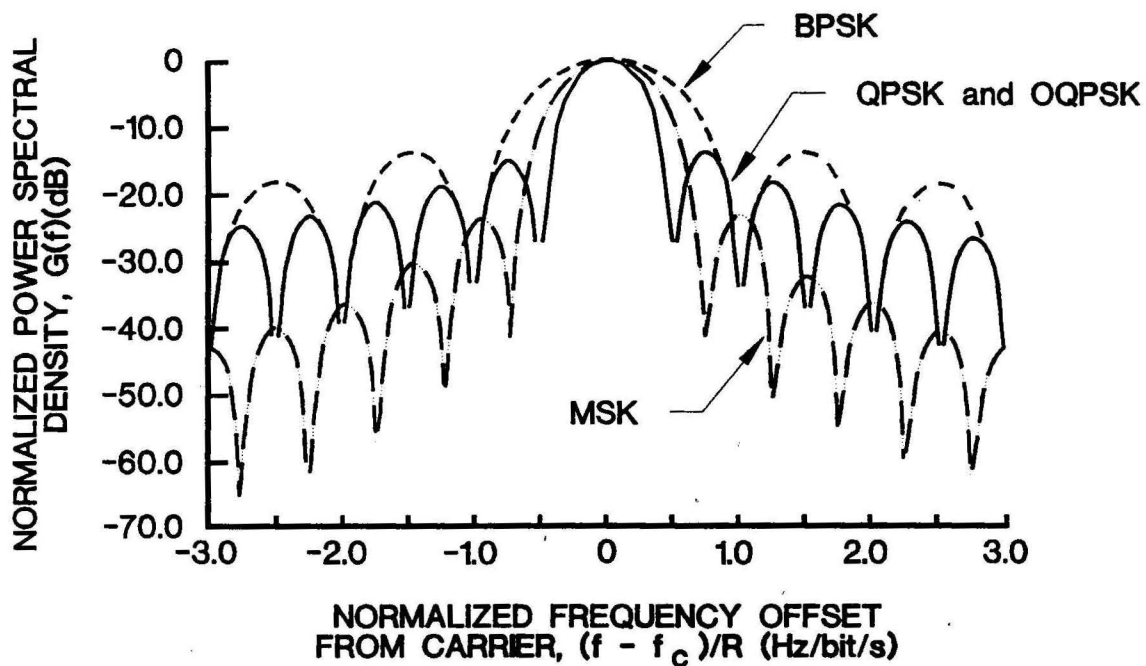


Figure 1. Normalized power spectra for BPSK, QPSK, OQPSK, and MSK.

Consider the signals in terms of sidelobe strength, using an arbitrary distance of  $8/T$  ( $T$  is the symbol duration) from the center frequency. With AM schemes (such as OOK) the sidelobes are down by about 25 dB, with phase modulation (PM) schemes (BPSK, QPSK) the sidelobes are down by about 33 dB, and with continuous phase FM (FSK, MSK) the sidelobes are down by 60 dB or more [2]. Thus, the FM schemes have an advantage in terms of unfiltered spectral efficiency although with modest filtering, the other schemes can be made spectrally efficient with minimal degradation to performance.

### Power Efficiency

Power efficiency refers to the energy required in each bit to transmit the data at a specified bit error rate (BER). The theoretical performance of the modulation schemes is shown in table 2. The required signal-to-noise ratio is listed for a BER of  $10^{-4}$ . BPSK, QPSK, OQPSK, and MSK are theoretically optimal if detected properly and have an inherent 3 dB advantage over coherently detected FSK or coherently detected OOK.

The criterion for the OOK comparison assumes that the average power is used. This is one half of the peak power. If an amplifier is limited by peak rather than average power then

OOK is actually 6 dB worse than BPSK, QPSK and MSK and 3 dB worse than FSK. If a saturated power amplifier (such as a class C or a TWT amplifier) is used, then peak power will be limited, and OOK will have relatively poor performance. Another disadvantage of OOK as compared to the other schemes is that when envelope detection is used (as is normally the case for demodulator simplicity when using OOK), we are faced with the dilemma of a decision threshold that must change with signal-to-noise ratio. Because of these disadvantages, OOK is not normally used for satellite links.

Modulation method	$E_b/N_o$ (dB) for BER = $10^{-4}$
----- Amplitude-shift keying -----	
OOK - coherent detection (assumes average power)	11.4
OOK - envelope detection (assumes average power)	12.3
----- Frequency-shift keying -----	
FSK - non-coherent detection	12.3
FSK - coherent detection	11.4
MSK	8.4
----- Phase-shift keying -----	
BPSK - coherent detection	8.4
DE-BPSK (differentially encoded BPSK)	8.9
QPSK	8.4
OQPSK	8.4

Table 2. Ideal power efficiency of representative modulation methods.

### The Effects of Filtering Then Limiting

Filtering the transmitted signal is normally a must, or interference to adjacent-channel signals will likely result -- possibly forcing the offending system to cease operations. Unfortunately, filtering the signal can have a negative effect on the BER performance. This is partially due to the ISI introduced by the filters finite rise and fall times. In constant amplitude modulation types such as PSK and FSK, filtering causes amplitude variations to appear in the filtered signal's envelope. This normally undesirable effect is due to the finite rise and fall times of the filter. The amount of envelope variation will vary considerably with the type of modulation used.

BPSK and QPSK signal envelopes are the most severely effected by filtering. At the  $180^\circ$  phase transitions the signal

envelope goes through zero amplitude. (In QPSK these transitions occur when both the in-phase and quadrature (I and Q) channels change phase simultaneously.) Since the transitions in FSK (continuous phase) and MSK are less abrupt, their signal envelopes are only mildly affected by filtering. The effect of filtering on the OOK envelope will simply be to round off the rectangular pulses.

In order to eliminate the possibility of a  $180^\circ$  phase transition in the QPSK case, the two data streams (I and Q channel data) can be offset in time by one-half of a bit period. This means that the phase can only change a maximum of  $90^\circ$  at any given transition. When this is done the maximum envelope variation of the filtered signal will be 3 dB. This is called offset-QPSK or staggered-QPSK (OQPSK or SQPSK).

The importance of trying to maintain a constant signal envelope amplitude after filtering is important if one is concerned with transmitter power efficiency. Generally speaking, an amplifier is more efficient when operated in a saturated mode such as class C (TWTs are also frequently operated in a saturated mode). In this mode any amplitude variations introduced by the filter will be greatly reduced by the amplifier's non-linear response. This will cause the unwanted spectral sidelobes to be regenerated if filtering is done before amplification. Post-amplifier filtering is generally more difficult than pre-amplifier filtering. This is because of the need for low loss filters in the post-amplifier case, and because the filtering may be difficult at the operating frequency.

To illustrate the effect of filtering and then limiting, three computer simulations were done using an 8th order Butterworth filter followed by a TWT amplifier. Three modulation types were simulated: BPSK, QPSK, and OQPSK. For each of these types, the signal spectrum (FFT estimate) is shown for the signal before filtering, the signal after filtering, and the signal after being amplified by the TWT (figure 2). The simulations were performed using the SPW package from COMDISCO Systems, Inc.

Note that for the unfiltered signals shown, even though the bulk of the power is in the frequency band spanned by the main lobe, the sidelobes do not fall off rapidly and will likely cause interference to other users. The effect of sidelobe regrowth due to the TWT is most pronounced with BPSK and QPSK. The sidelobe regrowth for OQPSK is much less severe because, as mentioned earlier, its filtered envelope has less variation than for the other two cases.

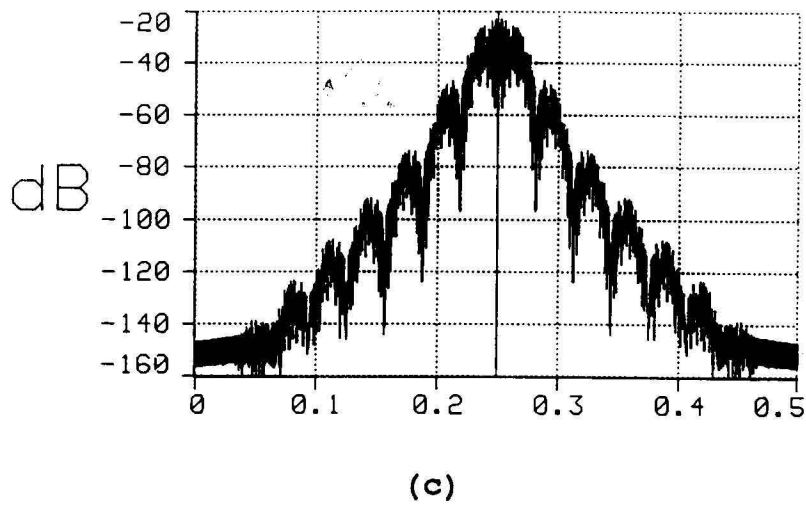
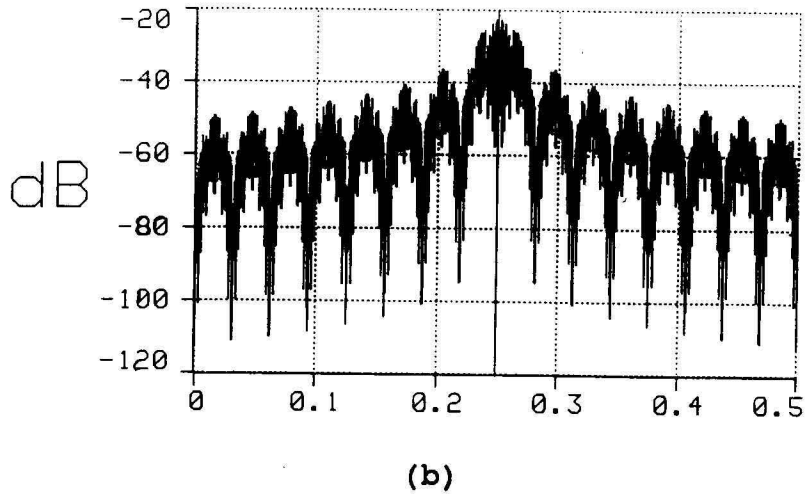
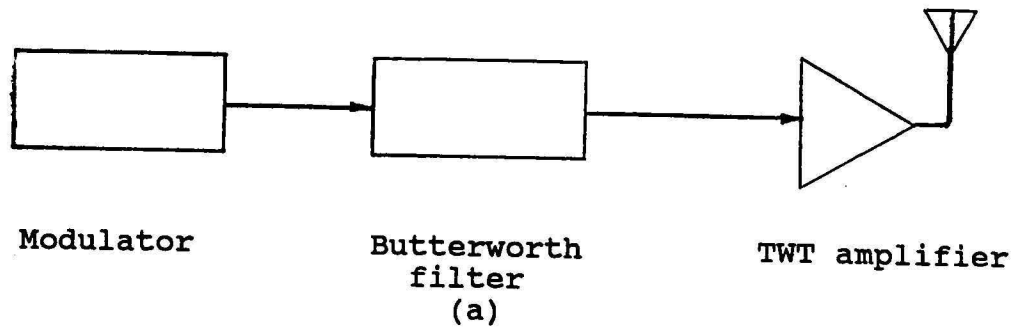


Figure 2. Signal spectra for BPSK, QPSK and OQPSK computer simulations. (a) Block diagram; (b) unfiltered BPSK; (c) filtered BPSK; (d) TWT output, filtered BPSK; (e) unfiltered QPSK; (f) filtered QPSK; (g) TWT output, filtered QPSK; (h) unfiltered OQPSK; (i) filtered OQPSK; (j) TWT output, filtered OQPSK

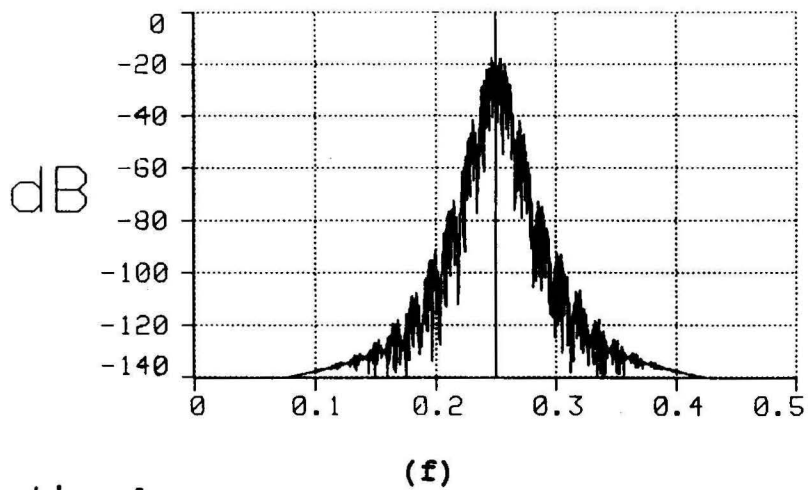
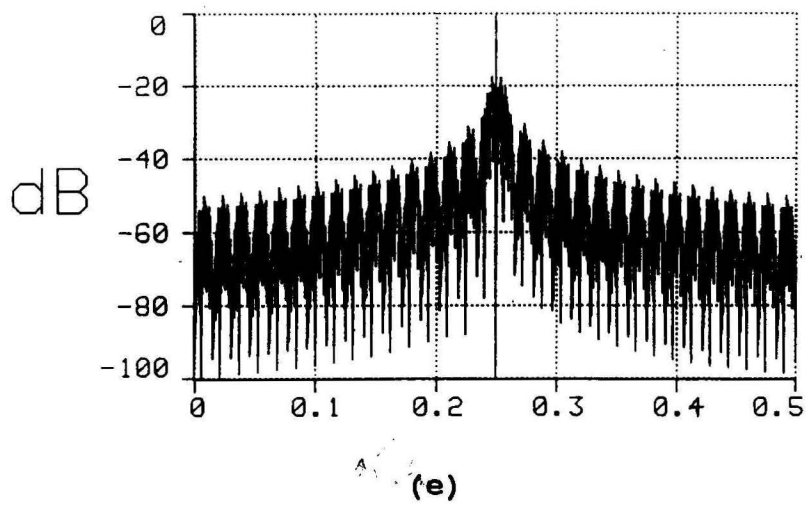
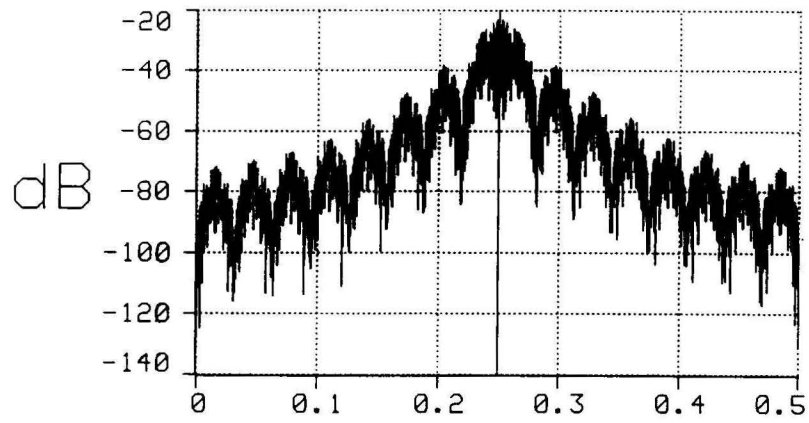
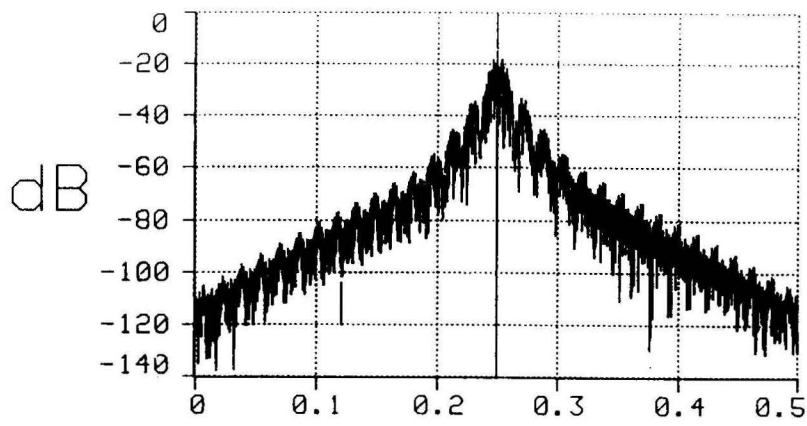
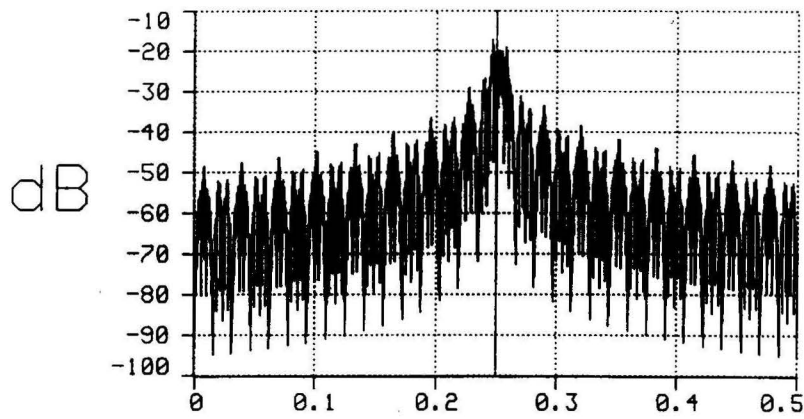


Figure 2 continued.

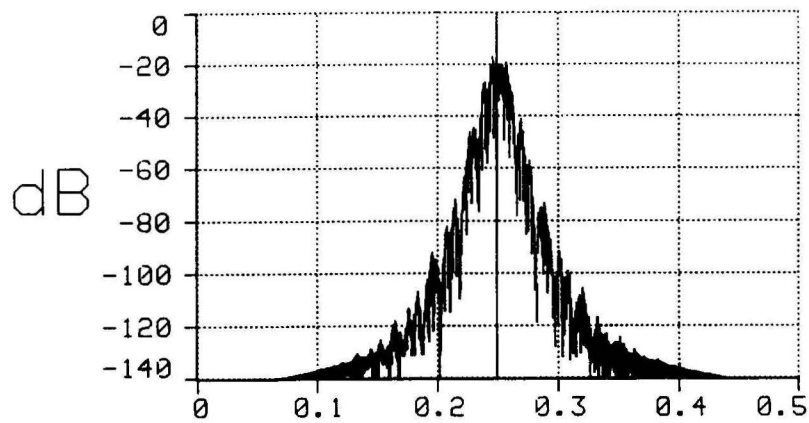




(g)

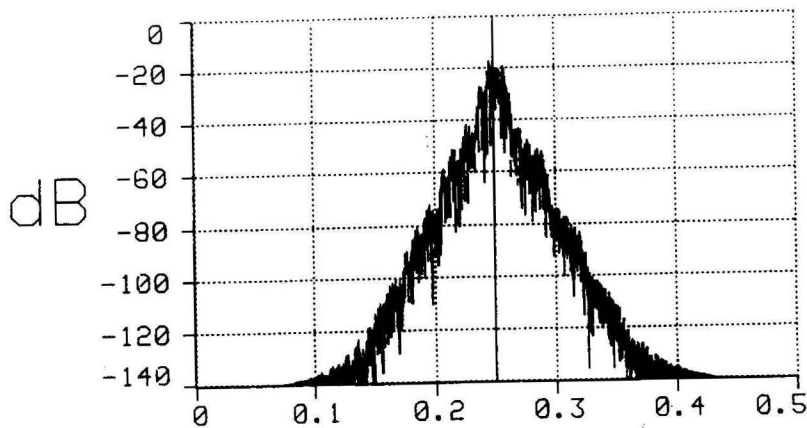


(h)



(i)

Figure 2 continued.



(j)

Figure 2 continued.

We would also like to know the degradation in BER caused by filtering and then limiting (figure 3). (The limiter is an approximation to a non-linear amplifier such as a class C or TWT amplifier.) The filter is a 4-pole Chebyshev and a raised cosine filter with  $\alpha = 0.5$  follows the limiter. The degradation of the SNR is determined as a function of  $BT_b$  relative to the unfiltered case where the  $BER=10^{-4}$ . For the case  $BT_b=1$ , the degradation is negligible for the 3 cases considered [1].

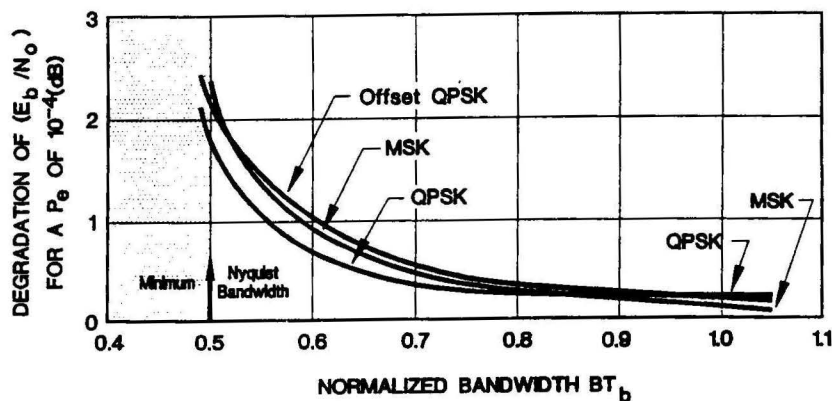
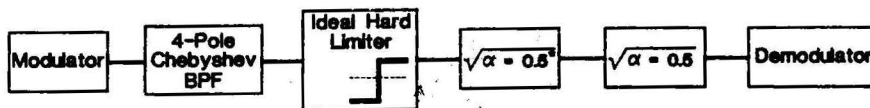


Figure 3. The degradation caused by filtering and then limiting versus normalized prefilterer filter bandwidth.

The use of a non-linear amplifier with filtered QPSK or OQPSK signals can cause cross-talk between the I and Q channels. This will cause some degradation but it is normally not severe.

### Circuit Complexity

Circuit complexity for the various modulation schemes varies greatly, especially for the demodulator. Depending on the system constraints, different modulation types may be chosen for the up-link and the down-link. This could allow a simple demodulator to be used in the satellite where reliability and low power consumption are important. If, for example, a simple, power efficient modulation scheme such as BPSK were used for the downlink, and a less power efficient scheme, but one that would allow for a simple demodulator, used for the uplink, power would be saved on both the transmit and the receive side in the satellite. The loss in performance due to using a less power efficient scheme for the uplink could be compensated for by increasing power or the antenna gain of the ground station.

The modulation types in terms of circuit complexity are described below:

FSK. FSK has a relatively simple modulator. Normally the FSK signal is obtained from a voltage-controlled oscillator (VCO). The demodulator is fairly simple especially in the non-coherent case where a simple discriminator may be used.

OOK. OOK has a very simple modulator structure. The demodulator is the simplest of all the schemes considered if non-coherent detection is used. The demodulator in this case is simply an envelope detector.

BPSK. BPSK also has a very simple modulator. The BPSK demodulator can be moderately complex since a carrier recovery circuit is needed and a  $180^\circ$  phase ambiguity in the recovered carrier must be resolved.

QPSK and OQPSK. These two schemes require more modulator circuitry than any of those listed so far. Both an I and a Q channel must be generated and combined making it similar to 2 BPSK modulators with the two oscillators phases  $90^\circ$  apart. The demodulator is also complex because, like the BPSK case, a carrier reference must be recovered and a  $90^\circ$  phase ambiguity in the recovered carrier must be resolved.

MSK. MSK has the most complicated modulator and demodulator structures of the schemes considered. The signal can be created in a similar fashion to QPSK. This requires that an I and Q channel be generated, but the rectangular symbol pulses must be replaced by half-sinusoidal symbol pulses complicating the

circuitry. The demodulator is also more complex than QPSK since the unique pulse shapes must be properly detected.

Any demodulator will normally have clock recovery circuitry (bit synchronization). The recovered clock is used by the decision circuitry when deciding whether a bit is a "1" or a "0."

#### SUMMARY AND CONCLUSIONS

The representative modulation schemes, FSK, OOK, BPSK, QPSK, OQPSK and MSK, have been discussed from the following viewpoints: power efficiency, spectral efficiency and circuit complexity. Circuit complexity is also related to reliability and power consumption.

In terms of power efficiency, BPSK, QPSK, OQPSK and MSK are theoretically optimal. FSK and OOK are 3 dB worse if coherent detection is used and about 4 dB worse if non-coherent detection is used. If peak power is limited, OOK is actually 6 dB worse than optimal.

BPSK, QPSK, and OQPSK have sidelobe spectral properties that would likely cause adjacent channel interference. This requires that the signal be filtered to reduce the sidelobe strength. Unfortunately the sidelobes "regrow" if the signal is then passed through a non-linear amplifier (such as a TWT or a class C power amplifier). This effect is much less severe in the OQPSK case.

In terms of circuit complexity, OOK has the simplest overall modulator/demodulator structure if envelope (non-coherent) detection is used. FSK is more complex but it is relatively simple when compared with PSK and MSK especially if non-coherent demodulation is used. In order of complexity, BPSK, QPSK, OQPSK and MSK require a coherent carrier reference in the demodulator. This will increase complexity and the circuits will require more DC power.

Because of its simplicity, and its minimal envelope variations, FSK should be considered for small satellite communication systems. FSK may be more advantageous for the uplink where ground station effective radiated power can be increased to compensate for FSK's inherent 3 dB inferiority to BPSK, QPSK, OQPSK and MSK.

Because of the drawbacks discussed, OOK is not recommended unless perhaps simplicity is the most important constraint on the system design.

OQPSK should be given serious consideration for small satellite communication system downlinks. It has a 3dB advantage over FSK and good signal envelope and spectral characteristics allowing the use of a non-linear amplifier without significant

sidelobe regrowth. OQPSK has advantages over QPSK in the presence of reference carrier phase jitter [5]. OQPSK may be an especially good choice for the downlink because of its power efficiency, and because the more complex demodulator will be in the ground system.

BPSK may also be a good choice for the downlink although the effects of sidelobe growth must be considered if a non-linear transmit amplifier is used. Relatively efficient class B linear amplifiers are available as alternatives to non-linear amplifiers.

MSK, because of its complexity, may not be a good choice for a small satellite link. Although MSK has good spectral characteristics, OQPSK, with proper filtering, should perform about as well.

As digital implementations of modulation schemes become faster and consume less power, the circuit complexity limitations of the more complicated modulation types will be eliminated. Practically any modulator and demodulator can be implemented using digital signal processors (DSPs). The limitations are speed, cost and power consumption of the DSP implementation.

Until DSP implementations of small satellite data links become more viable, standard modem implementations, such as those discussed, may be the best choice. Of these types, OQPSK has good spectral characteristics, is theoretically optimal, and should be considered for small satellite data links.

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