Performance of Digital Modulation Methods in Cable Systems

Leo Montreuil
William Wall

Scientific Atlanta

Abstract

Four digital Modulation Techniques; QPSK, QPR, 4-VSB-AM, and 16-QAM; capable of providing data rates between 10 MBPS and 20 MBPS in a 6 Mhz channel have been studied. A time domain simulation program has been written that allows accurate modeling of the modulation-transmission-demodulation process. Error performance vs. thermal noise has been calculated as a function of amplitude tilt, amplitude ripple, phase noise, quadrature offset, and timing offset. Finally a "typical" cable channel and demodulator have been modeled and error performance calculated.

I. Introduction

Recently introduced new digital audio services and the promise of highly compressed digital video in the near future instigated this study of digital modulation methods for cable applications. Digital modulation offers many potential advantages over analog transmission, such as lower transmission power, more services in a given bandwidth, essentially perfect noise free reproduction of the original source when above some threshold C/N, and unbreakable signal security. In order to utilize these potential advantages a modulation method must be selected that provides reliable reception in a cable environment, a data rate appropriate for the service, and economical demodulation in the subscriber's home. While numerous theoretical analyses of digital modulation performance exist in the literature, a practical comparison under signal conditions typical of cable systems was not found. Further, a method for simulating specific channel conditions and measuring performance for a variety of modulation techniques with those specific channel conditions was desired. To that end a computer simulation has been developed that accurately models digital modulation / demodulation methods in the time domain, adds a variety of controlled impairments, and measures the resultant bit error rate. This simulation technique has been found to be highly accurate and greatly reduces the time to test system design changes as well as test competing modulation methods.

This paper provides a brief overview of digital modulation techniques and the important parameters used in quantifying them, and discusses the major types of channel impairments and their effect on the signal as well as the effects of real (non-ideal) demodulator's performance. The specific modulation methods, QPSK, QPR, 16-QAM, and 4-VSB-AM, modeled in this paper are discussed.

A description is provided of the simulation technique as well as the channel model it simulates.

A model for a "typical" cable channel is discussed along with the performance variation that may be "typical" for a consumer grade demodulator. Simulation results for this model are presented and discussed.

II. Methods of Digital Transmission

As a brief review, digital transmission is accomplished by modulating an RF carrier to a discrete value (or state) that represents one or more bits of information. Each successive discrete state is called a **symbol** and the rate at which they are sent is the **symbol rate**. The modulation may be AM, FM, phase modulation (PM), or a combination of modulation types. If a symbol has only two discrete states, then each symbol represents one bit of data and the symbol rate and data rate are equal. A symbol may represent more than one bit by having multiple values; two bits may be encoded into four discrete values, three bits into eight values, etc. In this manner the symbol rate may be less than the data rate, and the occupied bandwidth of the modulated signal is less. If the transition from one symbol to the next was instantaneous then wide bandwidth modulation sidebands would be created, therefore the modulation must be filtered to limit the bandwidth and control the transitions from one symbol to the next. The key to this filtering is that it must allow the signal to reach the precise discrete value at the proper time independent of the values of the previous symbols. (In one type of modulation discussed, QPR, the current symbol depends on the previous symbol but the current value still must be attained.) A large class of filters, known as **Nyquist** filters meet this requirement. Figure 1 shows the possible trajectories for a four valued signal (QPSK) that is Nyquist filtered. Notice that at the sampling points all trajectories have converged to one of the four discrete values. For a given symbol rate there is a minimum bandwidth known as the **Nyquist bandwidth**, equal to one half the symbol rate at baseband, that a filter can achieve and still not produce any intersymbol interference (**ISI**). This bandwidth cannot be achieved in practice since it requires a perfectly square filter and as one approaches this bandwidth the sensitivity of the signal to distortion and timing errors increases dramatically. The measure of the filter bandwidth is known as **alpha** and varies between zero percent, equal to the Nyquist bandwidth, and one hundred percent, equal to twice the Nyquist bandwidth. Typical values range from 20% for a very spectrum efficient system to 100% where spectrum efficiency is less of a concern than sensitivity to distortion. Figure 2 shows trajectories for a two level signal, one filtered with an alpha of 20% and the other with an alpha of 100%. These diagrams, known as **eye diagrams** for their obvious resemblance, show how the eye becomes narrower due to filter ringing with lower alpha.

The total channel filtering must be Nyquist, that is the product of the transmit filtering plus receive filtering must meet the Nyquist criteria. This objective can be met in a number of ways; one way is to place half of the filter at the transmit side and half at the receive side. The resultant filter, **square root Nyquist**, at each end provides optimum performance for additive gaussian noise but requires a precision filter at each end. A second alternative is to place the entire Nyquist filter at the transmit end and a wider less precise filter at the receive end. Though this has a small noise penalty (approx. 2 dB) associated with it, it may be very cost effective in situations such as cable where there is a single transmitter and many receivers. This approach exhibits less sensitivity to tuning errors and filter imperfections.

Turning now to the receive side, the demodulator must try to make an optimum **estimate** of the state of the transmitted symbol. Depending on the modulation type, the demodulator may be **coherent** or **non-coherent**. Coherent demodulators require a phase reference that tracks the transmitter phase prior to modulation. This phase reference can be derived from a pilot tone or reconstructed from the modulated signal. Since coherent demodulators offer significantly better performance than non-coherent demodulators, only coherent demodulators will be considered here.

Many different forms of modulation are used for digital transmission that vary significantly in their noise performance as well as bandwidth efficiency. These variations have been cataloged elsewhere[1]. For cable applications we have limited the number of techniques studied to those that can provide the relatively high bandwidth efficiency required to deliver between 10 MBPS to 20 MBPS data rate in a 6 MHz channel bandwidth. All of the studied techniques are either AM or PM or combinations of the two. FM techniques do not in general meet these bandwidth efficiencies.

Quadrature Phase Shift Keying (QPSK) is a Phase Modulation technique that has four phase states per symbol located 90 degrees apart. QPSK may be alternately described as a suppressed carrier AM technique where two independently AM modulated signal components in phase quadrature (90 degrees apart) each have two amplitude states. These two components, known as the **in-phase (I)** and **quadrature (Q)** components are orthogonal and may be demodulated separately without mutual interference in the ideal case. Figure 3 shows a phase state diagram for QPSK (alpha 20%) with the I axis horizontal and the Q axis vertical. The four areas of highest density are the four phase states; the remaining lines indicate the trajectories between phase states. With an alpha of 20%, QPSK can achieve a data rate of 10 MBPS in a 6 MHz bandwidth. The noise performance of QPSK is the best of any digital modulation technique.

By adding controlled ISI to QPSK one can effectively generate a third level to each of the quadrature AM components such that the interpretation of that third level depends on the estimate of the previous symbol state, creating a nine state modulation format known as Quadrature Partial Response (QPR). An eye diagram for one component of a QPR signal is shown in Figure 4. QPR provides a higher bandwidth efficiency allowing a data rate of 12 MBPS in a 6 MHz channel bandwidth, with a slight noise performance penalty.

Another modulation method is created by the encoding of two bits in four levels in each of the quadrature AM components which allows the transmission of a total of four bits per symbol. The four by four states gives a total of 16 states per symbol, hence the name 16 state Quadrature AM (16-QAM). Using an alpha of 20%, 16-QAM allows the transmission of 20 MBPS in a 6 MHz channel. Again the addition of the additional states degrades the noise performance.

Taking only the in-phase four level AM component and transmitting it as vestigial sideband AM improves the bandwidth efficiency, allowing a data rate of 12 MBPS to be sent in a 6 MHz channel bandwidth. This technique, unlike the double sideband AM techniques which allow reference carrier regeneration from the transmitted signal, requires the transmission of a carrier or pilot component for a reference carrier regeneration. Referred to as 4-VSB-AM, the noise performance is similar to 16-QAM.

III. Qualitative Effects of Transmission Impairments

There are six main processes that contribute to errors in the demodulated data: thermal noise, phase noise, ISI, timing errors, crosstalk between I and Q, and threshold errors. In most modulation methods thermal noise is gaussian and is additive to each state of a symbol. The demodulator will incorrectly estimate the modulation state if the noise caused the instantaneous received signal to be closer to another state than the actual transmitted state. The "tails" of a gaussian distribution extend far so that even at high signal to noise ratios there is still a measurable error rate. Clearly for a given signal level, the fewer the states in a symbol, the greater the distance between states, and the lower the probability of error; that is the fewer bits per symbol, the better the noise performance. Similarly, the lower the **noise bandwidth** of the receive filter the better the performance assuming that the filter causes no ISI.

Phase noise, either introduced in the transmission path by frequency converters or in the reconstructed reference carrier, degrades performance by introducing apparent thermal noise on the received symbol and by causing crosstalk between in-phase and quadrature components in a given symbol, which reduces the effective distance between states. Inter-symbol interference (ISI) is caused by improper filtering or reflections within the transmission path causing previous symbols to interfere with the current symbol, again reducing effective distance between symbol states (closing the eye).

Nominally the state estimate is made when the eye has the greatest opening, or the distance between states is the greatest. Timing errors in the clock recovery part of the demodulator cause the state estimate to be sampled either before of after the nominal time where the distance between states has been reduced, degrading the demodulator performance. Modulation techniques that use in-phase and quadrature AM components may be degraded by crosstalk between components that reduce effective distance between states. Similarly static bias errors in either phase or amplitude that offset the decision threshold of some symbol states relative to their nominal position will degrade the noise performance of the demodulator.

IV. The Simulation Program and Channel Model

To evaluate the effects of the channel and the filter distortion on various modulation types, a simulation program was written in MATLAB language; MATLAB is an interactive program for numerical linear algebra, matrix computation, and signal processing. The simulation was done using the complex baseband representation of the bandpass modulated signal, meaning a carrier frequency of 0 Hz. The complex baseband representation permits us to sample the time waveform of the studied modulation at a lower rate than what would be necessary if we were using a high carrier frequency. This is done without losing generality and keeping the same properties as a band-limited signal modulating a high frequency carrier. All the parameters of the simulation are normalized to the symbol rate and the filter bandwidths are specified as a ratio of the symbol rate instead of Hz.

The modulator block is an information source which, in the program, is composed of multiple Pseudo Random Binary Sequence (PRBS) generators and two digital to analog converters (D/A), one in-phase (I) and one in quadrature (Q). The simulation being numerical, frames of 4096 complex samples is formed by the sampling of 512 symbols with 8 samples per symbol.

The filters and the channel in the system are modeled as finite impulse response (FIR) digital filters and the coefficients for these filters are real for symmetric filters or complex for asymmetric filters. The filtering is done in the time domain if both the input signal and the filter coefficients are real by convolving the signal with the filter coefficients; if the signal or the filter coefficients are complex the filtering is done in the frequency domain by using a 512 point Fast Fourier Transform (FFT) and the overlap-and-add method for processing long records, instead of doing 2 or 4 convolutions in the time domain. The program also generates all the conventional filter responses plus raised-cosine [2], square-root raised-cosine, partial response and various channel distortions. The group-delay of the designed filters can be specified independently of the magnitude response enabling us to simulate any type of filter technologies like SAW filters, digital filters, or LC filters.

After the signal is passed through the filters and the channel, the signal is demodulated synchronously. In a complex baseband signal, the carrier frequency is zero but the phase of the received signal is unknown and is function of the delay between the modulator and the demodulator. The demodulator extracts the I and Q components along two orthogonal axis offset in phase relative to the modulator phase reference in order to minimize the cross-correlation between I and Q components. The demodulated samples are then resampled by the symbol clock. If the sampling instant falls between demodulated samples, the values at that sampling instant are then estimated by linear interpolation which gives accurate results for a sampling rate to symbol rate of 8 or more.

The Bit Error Rate (BER) measurement is based on the Quasi-Analytical (QA)[3] instead of the direct Monte-Carlo simulation. For linear systems this technique permits accurate measurements of low BER without excessive computation. In the QA technique, also referred to as the hybrid simulation, a simulation is done without the addition of noise and with a source data pattern long enough to obtain all the possible combinations of Inter-Symbol Interference (ISI). A histogram of the clock sampled data is then built, the noise is added analytically to the bins of the histogram, and the average symbol error rate is calculated. To convert the average symbol error rate to BER versus Energy per bits normalized (Eb/No), we need to calibrate our system by measurements of the signal power in the channel, the receiver noise bandwidth, and the number of bits per symbol.

V. Quantitative Effects of Transmission Impairments

We considered the following impairments to a digital signal and divided them in two categories; hardware imperfections and channel distortions.

Hardware imperfections:
- Quadrature error
- Phase error
- Symbol timing error

Channel distortion:
- Linear slope across passband
- Sinusoidal ripple across passband

The quadrature error is the deviation from orthogonality of the transmitter or the receiver, the symbol timing error is the deviation from the optimal sampling instant. These two errors are usually due to initial adjustment error or drift caused by components aging or temperature change. The phase error is an indirect measurement of the system sensitivity to phase noise, if the component of the phase noise is a sinusoidal waveform with a frequency less than the symbol rate, the BER degradation due to the untracked RMS phase noise give similar results to the same static phase error in the recovered carrier relative to the optimal carrier phase. This result was verified by simulating both degradations as well as by comparing our data with the results of Tranter, et al.[4]

To simulate the channel distortions encountered in a cable plant we designed two linear phase filters, a linear slope filter and a ripple filter.[5] The slope is defined as the number of dB. variation in a 6 MHz bandwidth. The ripple error is generated by a three tap FIR filter. This filter simulates three path propagation and can simulate the effect of reflection due to mismatch and the triple transit in SAW filters.

The bit rate and the filters for each modulation method in the simulation are selected to have a null-to-null bandwidth of 6 MHz using sharp filters that are today's state of the art. The resultant RF spectrum for each of the modulation methods simulated is shown in Figure 5. The bit rate and filters used are shown in Table 1.

Theoretical performance for each of these modulation methods is shown in Figure 6. Examining these results would suggest that while QPSK is the most robust, there is not much difference among the rest. These results do not take into account the relative sensitivities to distortions and demodulator imperfections.

VI. Results for a "Typical" Cable Channel

Elsewhere in the literature (Ref. 1) results are presented showing the BER degradation of the four modulation types studied in the presence of a single non-optimal condition. In an actual system all forms of degradation will be present in varying degrees simultaneously. The results of each impairment do not linearly contribute to the total system performance degradation, thus it is necessary to model the system with all impairments included. In an attempt to understand the performance of these modulation methods in a "typical" cable environment a set of parameters were chosen to represent a consumer grade tuner and demodulator along with reasonable system performance. These parameters are not intended to be interpreted as worst case conditions. Table 2 lists' these parameters.

The ripple of 0.5 dB peak is typical of triple transit response of a good consumer grade SAW filter. It could also be produced by a reflection 24 dB down on a drop produced by a typical splitter. We included no other frequency response anomalies since most channels are quite flat. The phase noise of 5 degrees rms residual is the total contributed by all sources. The 3 degree quadrature error and 5% timing error are typical of alignment accuracy achieved in consumer products. Drift could increase this number.

The simulation results are shown in Figure 7. These results are presented in Eb/No; to convert to equivalent C/N in a video channel, the ratio of the bit rate to a video channel noise bandwidth of 4.2 MHz converted to dB is added to the Eb/No. This is summarized in Table 3. Also shown is the degradation from ideal performance at a BER of 10^-6.

From these results it is clear that even in this rather benign environment that 16-QAM and 4-VSB-AM require a C/N close to that of video, and that adding margin to account for amplitude tilt and delay distortion may require a higher C/N than existing video services. At slightly higher levels of impairment they may not achieve 10^-6 BER at any C/N. Examining the sensitivity of 16-QAM and 4-VSB-AM to demodulator imperfections indicates that much closer tolerances in manufacturing would be required than for QPSK or QPR. QPR on the other hand appears to be an attractive alternative to QPSK, providing 20% greater data rate with a relatively small penalty in C/N and very little additional complexity in implementation.

VII. Conclusion

Four digital modulation techniques; QPSK, QPR, 4-VSB-AM, and 16-QAM; capable of providing data rates between 10 MBPS and 20 MBPS in a 6 MHz bandwidth, and that are suitable for transmission of digital audio or compressed digital video have been studied. A time domain simulation program has been written that allows accurate simulation of the entire modulation-transmission-demodulation process and calculates error performance. The simulation allows imperfect filters, timing errors, quadrature errors, phase noise, and bias errors to be included explicitly. The results suggest that QPSK and QPR are significantly more rugged than 4-VSB-

AM or 16-QAM. QPR offers 20% greater bandwidth than QPSK with only a minor increase in signal power. Since 4-VSB-AM does not offer any advantages over QPR and is much less rugged, it does not appear to be an attractive alternative. If the higher data rate offered by 16-QAM is essential, a significantly more complex demodulator would be required to provide acceptable performance, and then only with an 11 dB higher signal than QPR.

1. John D. Oetting, "A Comparison of Modulation Techniques for Digital Radio", IEEE Transactions on Communications, Vol. COM-27, No. 12 December 1979.

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3. Michael J. Jeruchim, "Techniques for Estimating the Bit Error Rate in the Simulation of Digital Communications Systems", IEEE Journal on Selected Areas in Communications, Vol. SAC-2, No. 1, January 1984, pp. 153-170.

4. Walter R. Braun, et al., "CLASS: A Comprehensive Satellite Link Simulation Package", IEEE Journal on Selected Areas in Communications, Vol. SAC-2, No. 1, January 1984, pp. 129-137.

5. William H. Trantor, et al., "Simulation of Communications Systems Using Personal Computers", IEEE Journal on Selected Areas in Communications, Vol. SAC-6, No. 1, January 1988, pp. 13-23.

Table 1: Modulation Parameters

Modulation	Data Rate	Transmit Filter	Receive Filter
QPSK	10 MBPS	Square Root Raised Cosine, alpha 20%,	Square Root Raised Cosine, alpha 20%, Noise BW= 5 MHz
QPR	12 MBPS	Partial Response class 1	Maximally Flat, 6 MHz BW Noise BW= 6 MHz
16-QAM	20 MBPS	Square Root Raised Cosine, alpha 20%,	Square Root Raised Cosine, alpha 20%, Noise BW= 5 MHz
4-VSB-AM	12 MBPS	Square Root Raised Cosine, alpha 40%,	Square Root Raised Cosine, alpha 40%, Noise BW= 3 MHz

Table 2: Typical Cable Performance Parameters

Channel Impairment	Amount
Phase Error	5.0 Deg.
Quadrature Error	3.0 Deg.
Clock Timing	5.0 %
Linear Amplitude Slope	0.0 dB
Amplitude Ripple	0.5 dB Peak

Table 3: Comparison of "Typical" Cable Performance at 10^-6 BER

Modulation Type	Eb/No (dB)	Rate/BW (dB)	C/N* (dB)	Degradation (dB)
QPSK	12.2	3.8	16.0	1.6
QPR	16.2	4.6	20.8	2.7
16-QAM	25.2	6.8	32.0	10.1
4-VSB-AM	26.1	3.8	29.9	10.9

* Note: Equivalent C/N in 4.2 MHz noise bandwidth video channel.

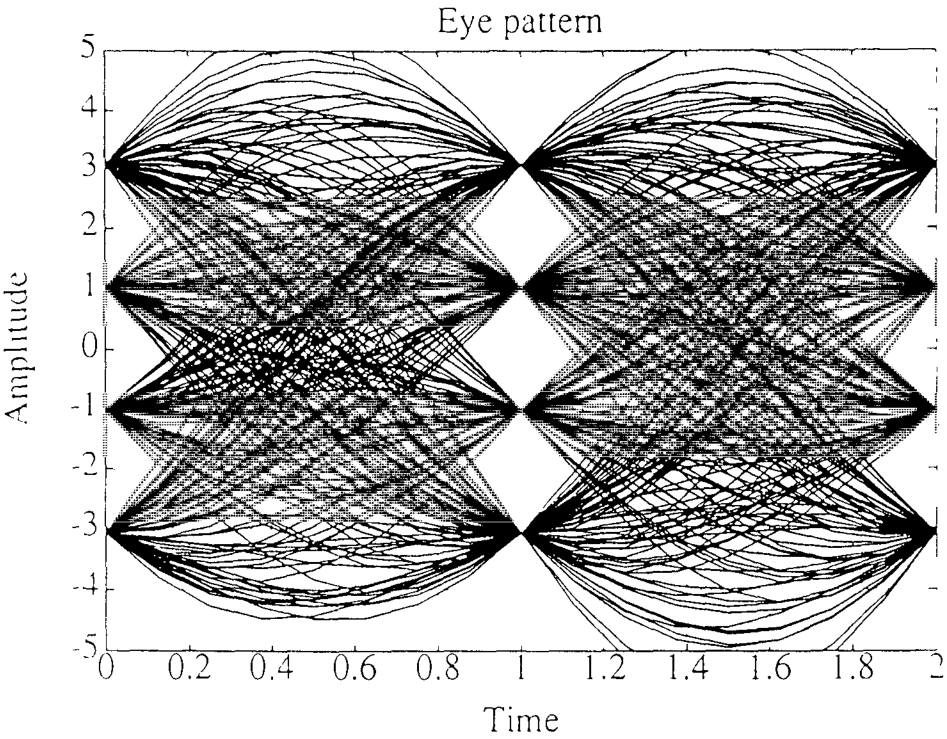

Figure 1. 16-QAM anphase eye pattern, alpha = 20%

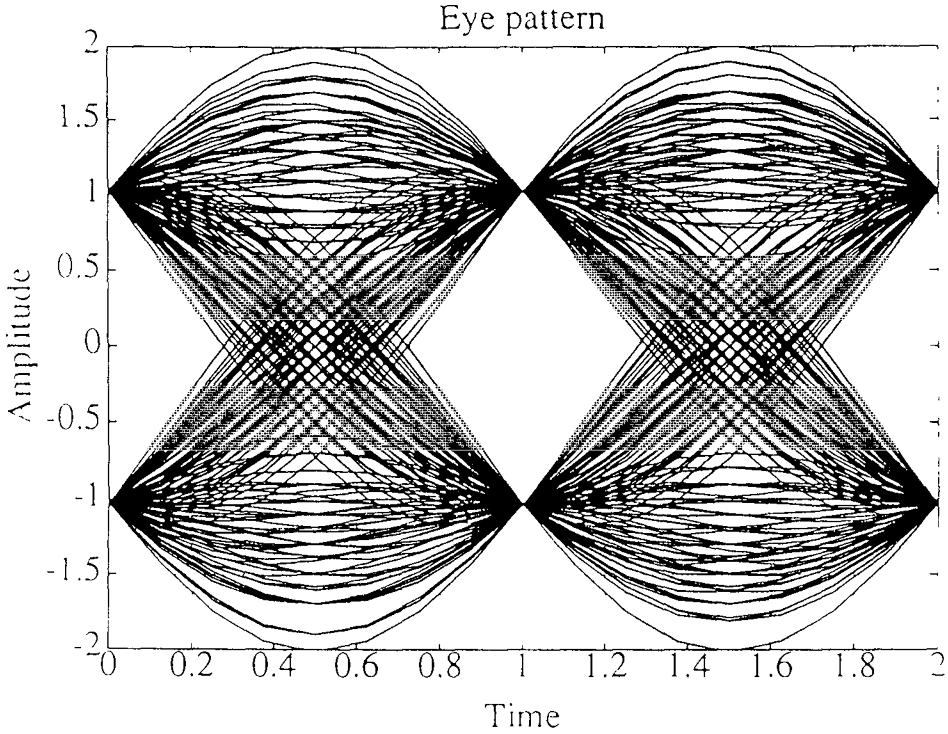

Figure 2a. QPSK inphase eye pattern, alpha = 20%

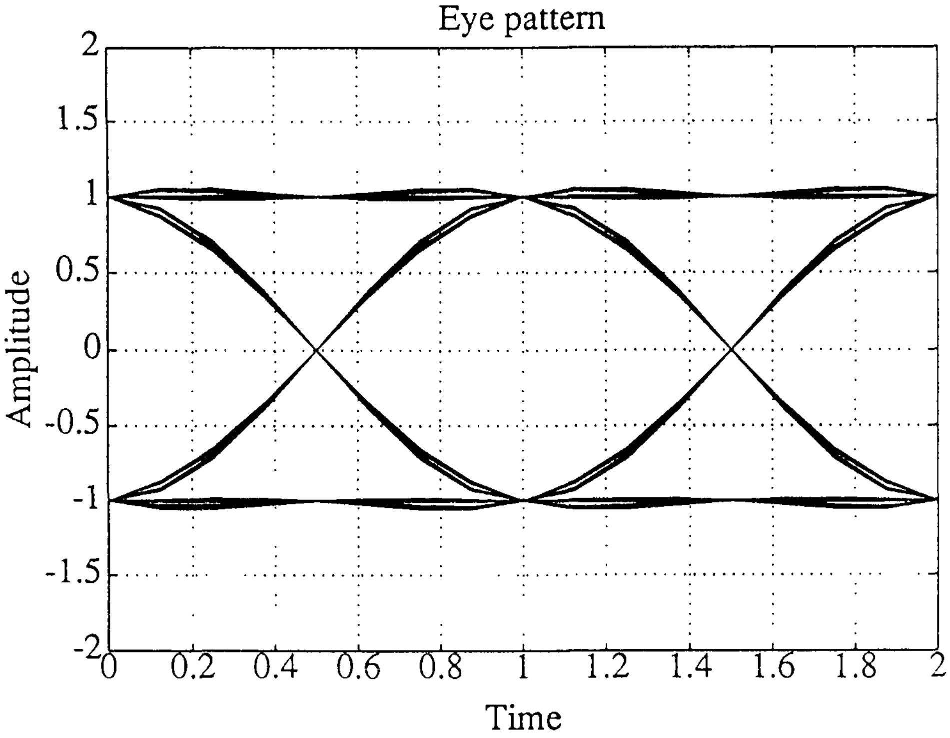

Figure 2b. QPSK Inphase Eye Pattern, alpha = 100%

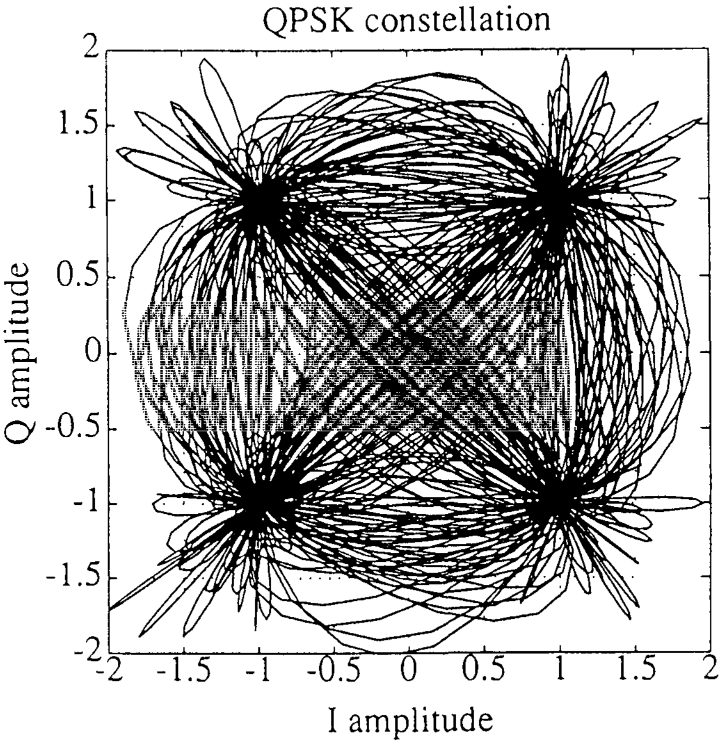

Figure 3. QPSK Phase State Diagram, alpha = 20%

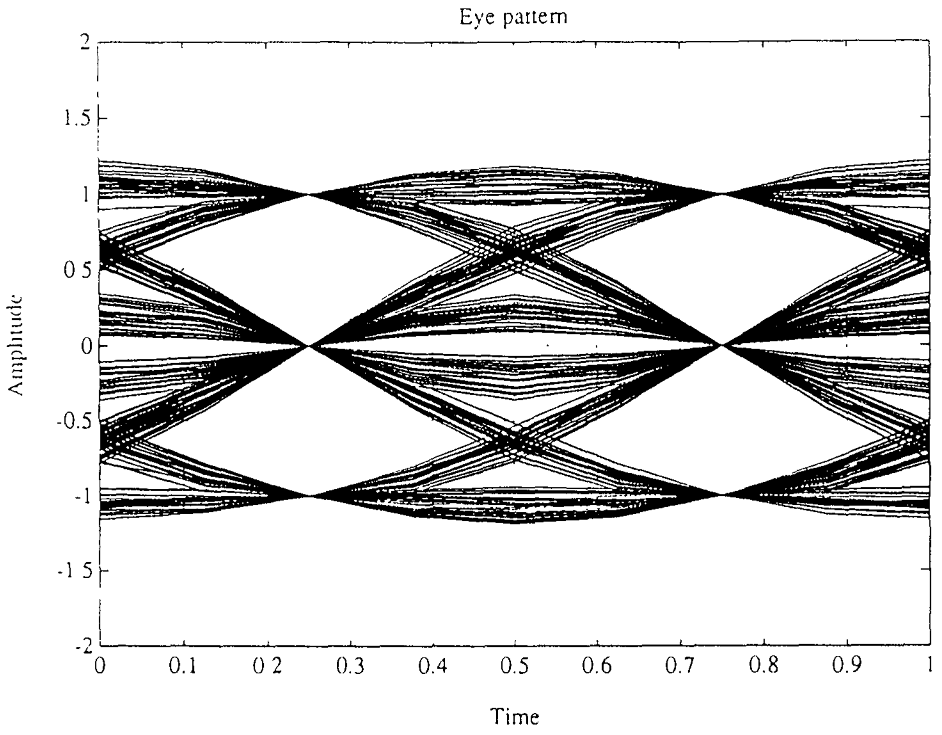

Figure 4. QPR Eye Diagram

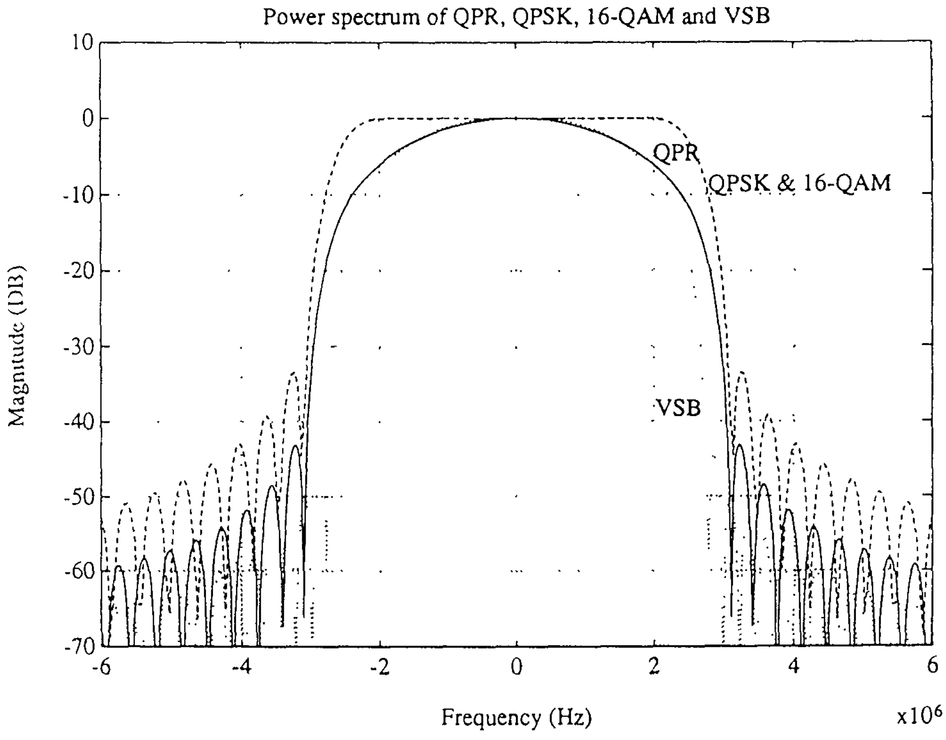

Figure 5. Power Spectrum of the various modulation studied

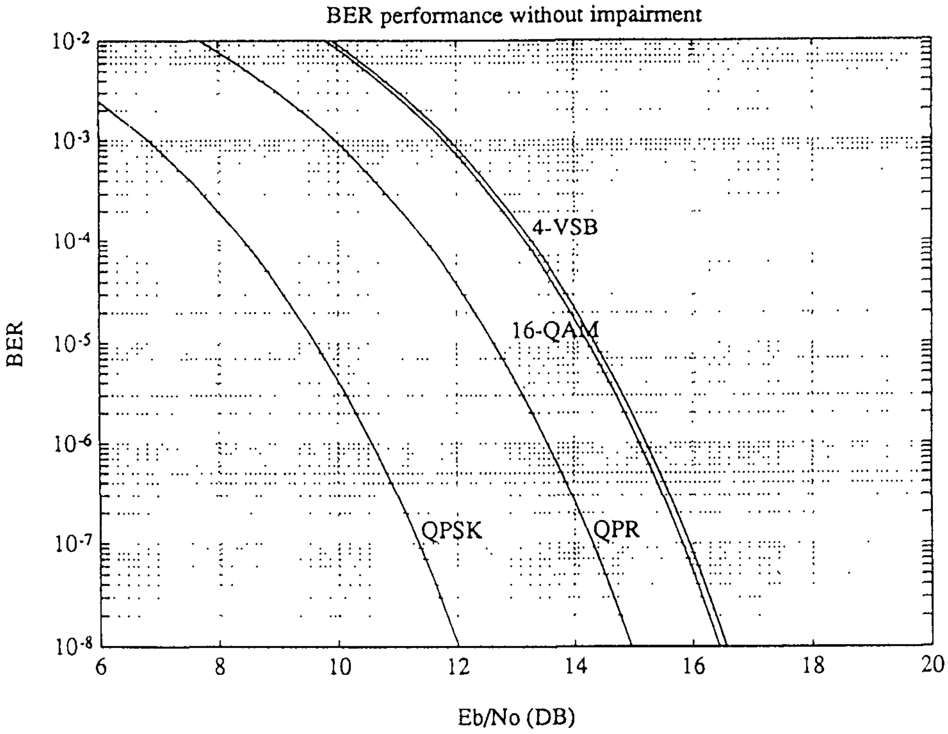

Figure 6. Theoretical Performance of QPSK, QPR, 16 QAM, and 4-VSB-AM

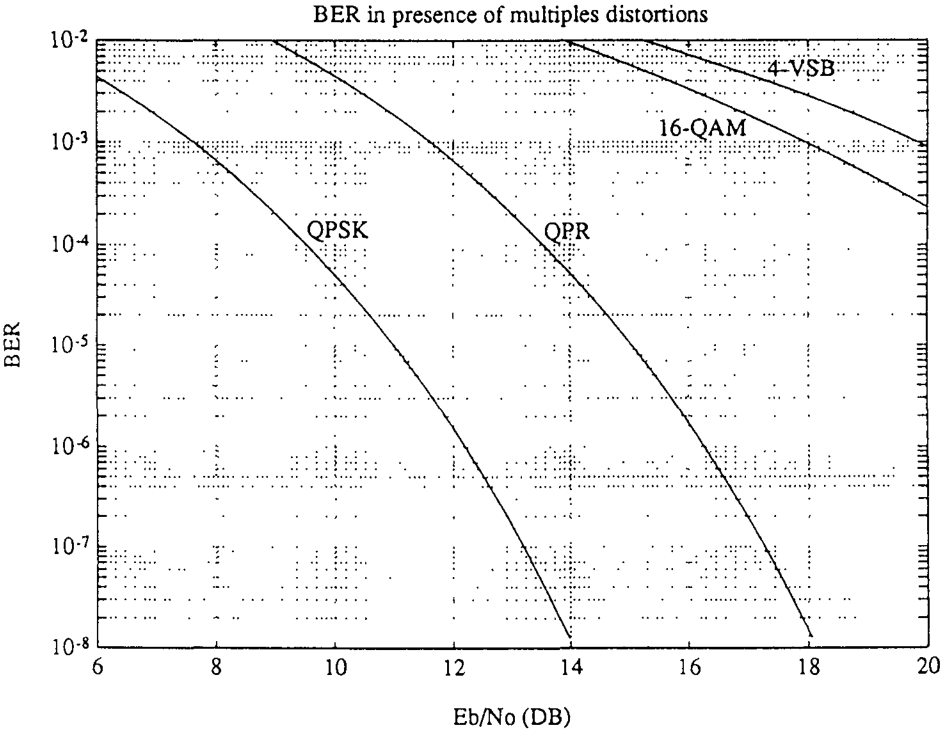

Figure 7. BER performance of QPSK, QPR, 16-QAM and 4-VSB in presence fo the following impairments; Phase error = 5 degrees, Quadrature error = 3 degrees, timing error = 5%, ripple = 0.5 dB peak to peak.