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A COMPARISON OF MODULATION SCHEMES IN BANDLIMITED AWGN CHANNELS

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Abstract

In recent years, as data rates rise for seemingly decreasing available bandwidths, a great deal of research has been directed toward finding bandwidth efficient modulation schemes. Two such methods are Partial-Response Signaling and Trellis-Coded Modulation. Both of which promise performance gains in a bandlimited channel when compared to uncoded systems. This paper will compare the performance of these schemes, when applied to a QPSK system over various channel bandwidths.

Introduction

As data rate demands increase, the need for bandwidth efficient modulation schemes has driven a great deal of research. As a result, a number of complex systems have been developed. Partial-Response Signaling (PRS) [1,2,3] and Trellis-Coded Modulation (TCM) [4,5] are two methods promising increased performance over bandlimited channels, thus allowing higher data rates through the channel or better performance in the same channel. This paper will investigate the performance of relatively simple implementations of each of these techniques — a QPSK PRS and an 8PSK TCM system — in channels of different bandwidths. By doing so, it will be determined whether or not these implementations live up to their promised performance gains.

Bit error rates are estimated through baseband Monte Carlo simulation using the Signal Processing WorkSystem® (SPW™) software package. Each system compared transmits at a rate of two information bits per channel symbol. Channel bandwidth is specified by a 6th order Butterworth filter without phase-equalization. Simulations are performed with no bandlimiting and at bandwidths equal to 3, 1.5 and 1.0 times the symbol rate, generating varying degrees of ISI.

Both modulation schemes transmit symbols representing two data bits. Therefore, their performance will be judged for equal symbol rates — equal information rates — over channels of equal bandwidth. For comparison purposes, the performance of an uncoded QPSK system, which also transmits symbols representing 2 information bits, will also be evaluated. A well known result for the bit error rate of such an ideal QPSK system is

$$P_b = Q\left(\sqrt{\frac{2 \cdot E_b}{N_o}}\right),$$

where Q(x) is the complimentary error function, E_b is the energy per bit and N_o is the single-sided power spectral density of the AWGN [5].

Uncoded QPSK

A reference must be established to measure and compare performance gain. The chosen reference will be uncoded QPSK, representing the performance of an equivalent system without implementation of either technique.

The uncoded QPSK simulation model (Figure 1) consists of two random data sources, a QPSK modulator, the channel filter, an AWGN source, a matched filter and QPSK demodulator. The data sequences $\{xi_n\}$ and $\{xq_n\}$ consist of binary symbols with amplitude {-1,+1} with equal probability. Comparisons are made between these data sequences and the estimated data sequences $\{\hat{x}i_n\}$ and $\{\hat{x}q_n\}$ to generate a probability of bit error for both the I and Q channels. The system error rate is then approximated by the average of the I and Q error rates.

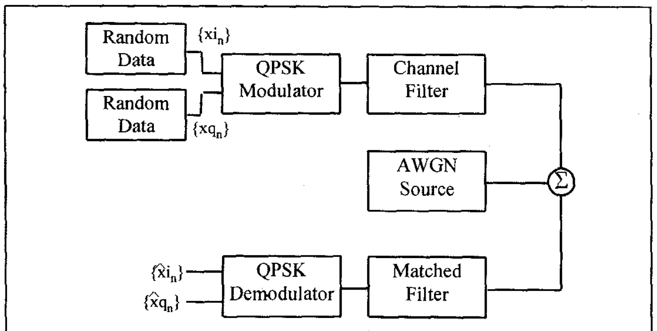

Figure 1/ Uncoded QPSK Model

The results of the simulations for the uncoded QPSK system are presented in graphical form in Figure 2. The probabilities of bit error for different channel

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bandwidths are plotted versus E_b/N_0. Although this system is able to perform reasonably well — less than 2dB of degradation at an error rate of 1×10^{-4} — for channel bandwidths of 1.5·Rs or greater, there is significant performance loss as the bandwidth approaches the symbol rate. This is the performance against which the TCM and PRS systems will be judged.

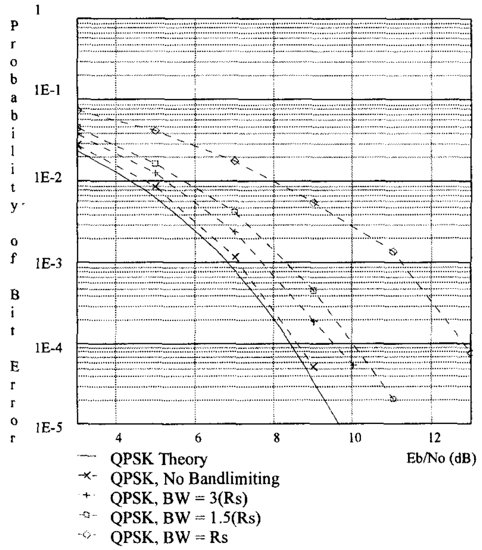

Figure 2 / Performance of Uncoded QPSK

QPSK with Partial-Response Signaling (PRS)

Duobinary PRS was first presented by Lender [3] as a method of high-speed data transmission. The addition of a Viterbi processor for maximum likelihood sequence estimation was made by Forney [2], in 1972. And, in 1975, Kabal and Pasupathy [1] presented a unified study of PRS.

PRS systems operate based on the idea of controlled ISI. Since the ISI is known, its effects can be removed by the receiver. This allows the shaping of the signal spectrum, narrowing the signal bandwidth or placing nulls in the power spectrum of the transmitted signal. This narrower spectrum will presumably be able to pass through a narrowband channel with less distortion than is experienced by the wider spectrum associated with QPSK and TCM signals. The Viterbi algorithm can then be used to make the optimum sequence estimates, based upon the known ISI.

PRS systems are usually denoted by their system polynomial F(D), of the form

$$F(D)=\sum_{n=0}^{N-1} f_n D^n,$$

where $\{f_n\}$ are the samples of the desired impulse response h(t), N is the smallest number of contiguous samples that span all the non-zero samples, and D is the delay operator [1]. If the input and output sequences are denoted $\{x_n\}$ and $\{y_n\}$ respectively, then

$$Y(D)=X(D)F(D),$$

where

$$X(D)=\sum_{n=0}^{\infty} x_n \cdot D^n \quad \& \quad Y(D)=\sum_{n=0}^{\infty} y_n D^n .$$

The system polynomial can be chosen such that the frequency response closely matches the channel frequency response, thereby minimizing the ISI encountered. Duobinary, with a system polynomial F(D) = 1 + D was chosen for this study because of its lowpass frequency characteristics [1].

The simulation model consists of two independent duobinary PRS channels corresponding to the in-phase and quadrature QPSK channels. The two data streams $\{xi_n\}$ and $\{xq_n\}$ are independent binary symbols taking on values {-1,1} with equal probability. Although the system consists of two Viterbi processors, this choice of system polynomial reduces their complexity to only two states.

The resulting simulation model is shown in Figure 3 and is made up of two data sources, two PRS F(D)=1+D filters, a QPSK modulator, the channel filter, a matched filter and the two Viterbi processors performing maximum likelihood sequence estimation.

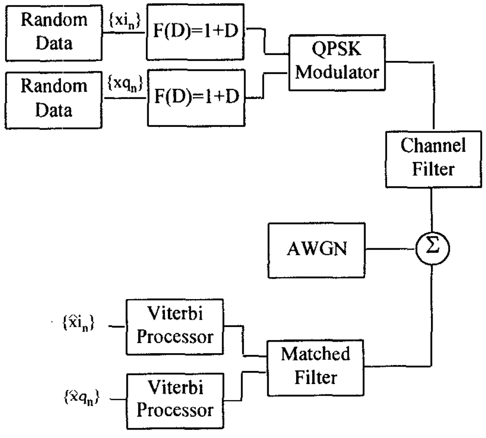

Figure 3 / QPSK-PRS Model

As in the uncoded QPSK simulations, the in-phase and quadrature estimated data sequences are compared to the corresponding transmitted data sequences for estimation of bit error rates. The system bit error rate for a given signal -to-noise ratio is then the average of the two independent error rates. Figure 4 presents the results in graphical form. The performance of this system degrades in a manner similar to that of the uncoded QPSK system — system performance is degraded by about 1.5dB at a bandwidth of 1.5·Rs and by close to 2.5dB at a bandwidth equal to the symbol rate. Note however that the error rates were significantly worse than ideal QPSK, even when there was no bandlimiting.

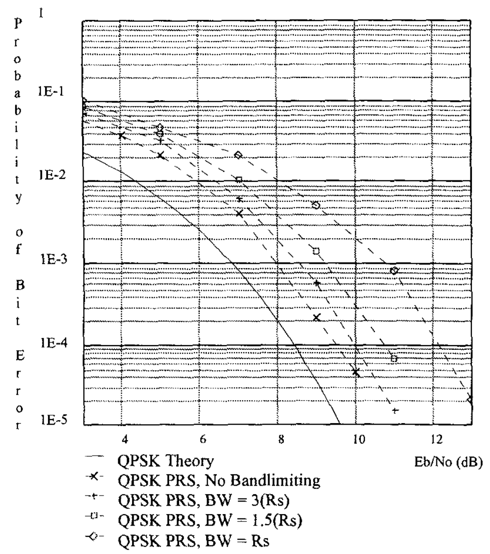

Figure 4 / Performance of QPSK-PRS

8PSK TCM

One obvious method of combating errors generated by ISI is the addition of coding to the system. However, in many cases, coding comes at the cost of bandwidth expansion. Thus any gains from the coding must overcome the loss generated by the increased ISI. In 1976, Ungerboek [6] demonstrated that Trellis Coded Modulation (TCM), in which the modulation and coding are unified, exhibits significant coding gains without requiring more bandwidth. Source data is convolutionally encoded to generate the code symbols to be transmitted directly over the channel. The received data is then decoded using the Viterbi algorithm.

TCM systems can be extremely complicated, sometimes applying multidimensional trellis diagrams with large numbers of states and varying code rates. Complexity in general increases with the number of states in the trellis. This paper focuses on a relatively simple 4-state, rate 2/3 (2 data bits for each 3 bit 8PSK symbol) 8PSK TCM system [5, pp. 374-378]. Even though the complexity of the system chosen is low, the theoretical asymptotic coding gain over uncoded QPSK is 3dB, showing the power of TCM.

The 8PSK TCM simulation model (Figure 5) operates on a single data stream, $\{x_n\}$. The data is buffered and supplied to the TCM modulator in pairs. For every data pair, one code symbol is transmitted by the modulator through the channel filter. Noise is then added from an AWGN source. The receiver structure consists of a matched filter and TCM Viterbi decoder, which generates parallel data estimates. These estimates are converted to a serial stream before comparison with the transmitted data stream.

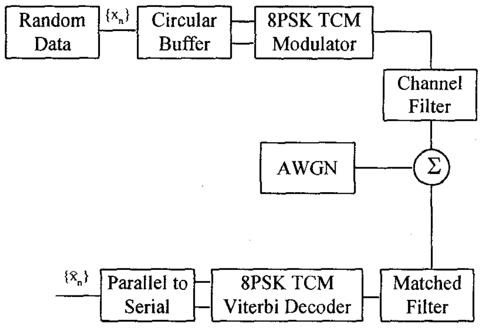

Figure 5 / 8PSK TCM Model

Although this system is the most complex of the three listed here, it is still relatively simple. Convolutional encoding is a simple operation while the 4-state Viterbi processor is not very much more complicated than the two 2-state Viterbi processors present in the QPSK-PRS system. The small increase in complexity produces a significant increase in performance (Figure 6). For channel bandwidths at or below 1.5·Rs, the system exhibits a performance gain over ideal uncoded QPSK. Although the system performance degradation is close to 4.5dB for a bandwidth equal to the symbol rate at an error rate of 1×10^{-4}, there is less than 2.5dB of degradation compared to ideal uncoded QPSK.

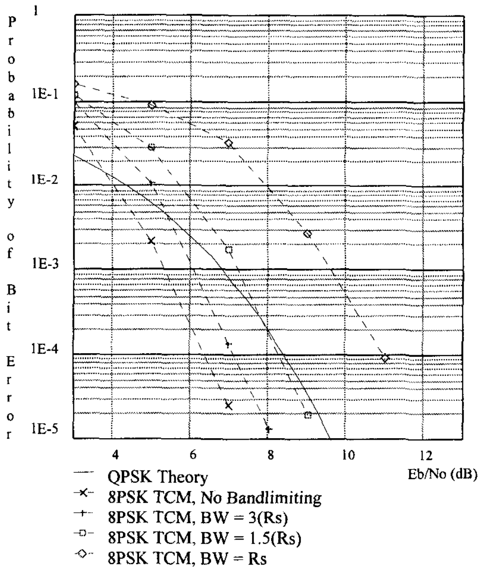

Figure 6 / Performance of 8PSK TCM

Performance Comparison

Up to this point, each system has been judged individually by its performance over a range of bandwidths. The performance of the different systems in a common channel bandwidth has not yet been compared. This section will make direct comparisons between the systems in the two most bandlimited channels studied.

The bit error rate of each system, over a range of signal to noise ratios, for a channel bandwidth of 1.5·Rs is shown in Figure 7 below. This set of curves is representative of all of the data presented for channel bandwidths at or below 1.5·Rs.

For the wider bandwidths studied — no bandlimiting, 3·Rs and 1.5·Rs — there is clearly no advantage to choosing the QPSK PRS system over uncoded QPSK in such situations. Such a decision would result in both increased complexity and performance degradation. However, the use of 8PSK TCM instead of uncoded QPSK will result in a gain of almost 2dB in system performance at an error rate of 1×10^{-4}. The gain is also increasing with smaller error rates.

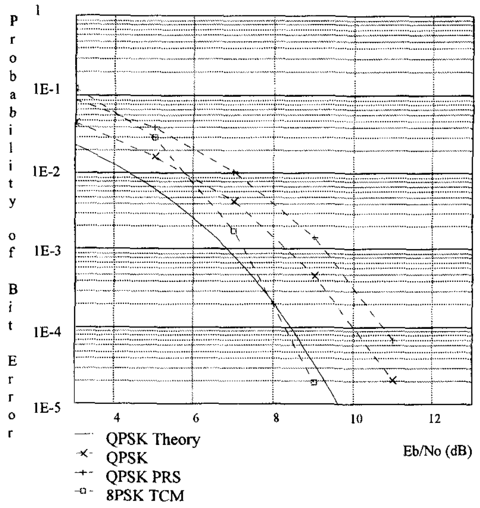

Figure 7 / Performance Comparison, BW = 1.5·Rs

Figure 8 compares each of the system's performances in the severely bandlimited channel in which the bandwidth is equal to the symbol rate. Here, the PRS system begins to show a slight advantage over uncoded QPSK. However, the gain is not more than 1dB at 1×10^{-4} bit error rate. The gain does seem to be increasing with decreasing error rates, but only slightly.

Again, the performance of the TCM system is superior to that of the other two systems. Even in the most severely bandlimited channel studied, the 8PSK TCM performance exhibits around 2dB of gain at an error rate of 1×10^{-4}.

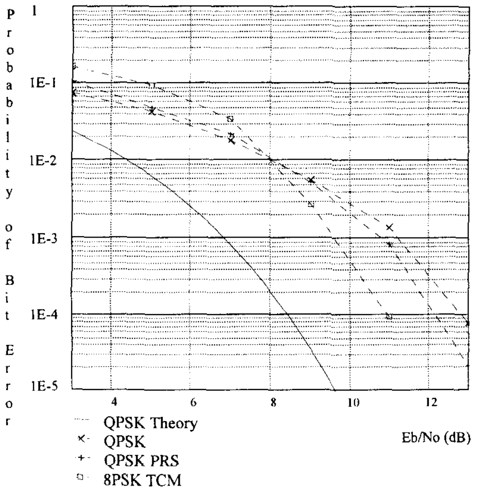

Figure 8 / Performance Comparison, BW = Rs

Conclusion

For the simple but practical systems studied, it appears that 8PSK TCM does provide the performance gain promised — it will provide coding gain over uncoded QPSK in the same channel bandwidth.

On the other hand, the duobinary PRS scheme does not appear to deliver on its promise of maintaining ideal QPSK performance levels in a narrowband channel. In fact, for any channel bandwidth greater then Rs, uncoded QPSK actually outperforms duobinary.

This demonstrates that one must be very careful in drawing conclusions about the likely performance of signaling schemes in narrow channels based upon the power spectrum of the transmitted signal. It also raises many questions about the performance, of the many bandwidth efficient schemes being touted in the literature today, in realistic communications channels — channeis with bandwidths limits, phase distortion and non-linearities.

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