Performance of Coded Modulation on Intersymbol Interference Channels*

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ABSTRACT

The bandwidth efficiency of coded modulation coupled with high coding gains over equivalent uncoded schemes has rendered the concept attractive for application in many practical communication systems. In this paper, we examine the performance by simulation, of TCM, MTCM and BCM on ISI channels. Simulations were performed assuming the receiver operates on the received signal using decision feedback equalization in conjunction with the Viterbi decoder. Results indicate that coded modulation schemes may be viable in systems that require low throughput rates. Coded schemes experience performance losses, however, in systems that require higher throughput rates mainly because the equalization process cannot adequately reduce the distortion induced by the channel, and the Viterbi decoder is unable to operate on the distorted signal.

1. INTRODUCTION

In 1982, Ungerboeck [1] introduced the concept of coded modulation when he proposed Trellis Coded Modulation (TCM), a system in which convolutional coding and modulation are combined to achieve bandwidth efficient signaling. Coded modulation schemes are attractive for many practical applications, because they provide coding gains over uncoded modulation without increasing bandwidth requirements. Since the introduction of TCM, other forms of coded modulation have appeared in the literature. Sayegh [2] presented implementations of Block Coded Modulation (BCM). Divsalar and Simon [3] proposed Multiple Trellis Coded Modulation (MTCM) and Forney [4,5] introduced the concept of coset codes, a more general approach to coded modulation that encompasses all the aforementioned schemes.

Time dispersive channels are encountered in many practical communication systems. Examination of the performance of modulation schemes on these channels is therefore of immense importance. The severity of impairments induced by transmitting a signal through these channels varies greatly with the impulse response of the channel. For example, a channel that contains spectral nulls severely degrades the quality of the transmitted signal to the point that even complex equalization techniques are not able to substantially reduce the induced distortions. Apart from several studies on the performance of TCM on time dispersive channels [6,7], there have been no studies on the performance of MTCM and BCM schemes on these channels.

In this paper we are concerned with the performance of TCM, MTCM, and BCM, on the intersymbol interference channel by simulation analysis. Section 2 provides a description of the main characteristics of each coded modulation scheme and Section 3 presents the system model used in the simulations. Results on the performance of the coded schemes are reported for two ISI channels on Section 4. Finally Section 5 provides a discussion and conclusions.

2. CODED MODULATION

2.1. Trellis Coded Modulation

The design of TCM schemes entails two concepts: a) expansion of the signal set and b) mapping by set partitioning. In a TCM system, the source information is first processed by a convolutional encoder of rate $\tilde{m}/\tilde{m}+1$ (Fig. 1). The $\tilde{m}+1$ binary symbols at the output of the encoder combined with the $m-\tilde{m}$ uncoded symbols are then input to the mapper/modulator where they are used to select a signal point from an expanded 2^{m+1} - ary signal set. The concept of mapping by set partitioning relies on a set of rules in determining the assignment of symbols to the various trellis transitions so as to achieve the largest possible squared Euclidean distance between the transmitted sequences [1]. This process produces a sequence of channel symbols at a throughput rate of $m/m+1$ bits per symbol that are dependent on the structure (trellis) of the convolutional code used in the encoding process.

2.2. Multiple Trellis Coded Modulation

In an attempt to improve the performance of trellis coded systems on AWGN and fading channels, Divsalar and Simon [3] proposed the concept of MTCM. This ap-

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proach to coded modulation increases the squared Euclidean distance between transmitted sequences of signals, over that of TCM, by assigning more than one signal point to each trellis transition. The multiplicity of signal points k, i.e., the number of points per trellis transition, is the key to this approach. TCM forms a special case of MTCM with $k = 1$.

2.3. Block Coded Modulation

BCM evolved as a natural extension to TCM. Block codes are combined with modulation to attain the benefits of bandwidth efficiency and large coding gains over uncoded modulation. The idea was presented in terms of the coded modulation theory by Sayegh [2], few years after the introduction of TCM.

A BCM system uses m coders each characterized by an (n, k_i) block code $(i = 1, 2, \ldots, m)$ and a mapper/modulator (Fig. 2). The block coders are ordered in a hierarchical fashion with the ith coder producing n binary symbols that form the i th row in a binary array of size $m \times n$. Each array column represents a binary label of a point in the signal constellation of the modulation scheme. Assume that the i th block code, denoted as C_{b_i} comprises of 2^{k_i} n-tuples taken from GF(2). The resulting BCM code can be represented in terms of its components codes as,

$$C = C_{b_1} + 2\,C_{b_2} + \cdots + 2^{m-1}\,C_{b_m} \quad , \tag{1}$$

where m is the number of block codes comprising the encoding section. This expression defines C as comprising of sequences with symbols taken from $GF(2^m)$. In fact, these symbols represent the columns of the aforementioned binary array. The BCM transmitter processes the source information at the throughput rate of $\Sigma k_i/n$.

3. SYSTEM MODEL

All simulations were carried out using the baseband equivalent model of Fig. 3. Three major blocks comprise this model, realizing the functions of the transmitter, the dispersive channel, and the receiver.

In Fig. 3 the binary source information denoted as $\{x_n\}$ enters the encoding/modulating stage producing a sequence of channel symbols $\{a_n\}$. The encoding and mapping sections are realized according to the coded modulation scheme used. For TCM and MTCM, a k/n convolutional encoder is used along with the mapper/modulator. The encoding section for the simulation of BCM employs m block codes and its output is mapped into one of the signal set points.

Two channel models were chosen to simulate the time dispersive channel. These have the following impulse responses [8]:

$$H_1(z) = 0.3 + 0.9z^{-1} + 0.3z^{-2} \tag{2}$$

$$H_2(z) = 0.408 + 0.816z^{-1} + 0.408z^{-2}. \tag{3}$$

The response in (2) is characteristic of a channel with no in-band spectral nulls, while the response in (3) represents a channel that contains spectral nulls and causes severe distortion.

The receiver section consists of a Decision Feedback Equalizer (DFE) in conjunction with a Viterbi decoder to optimally decode the TCM and BCM signals. Decision feedback equalization is best attained when the feedback section of the equalizer operates on symbols produced by the detector. However, in a coded system that uses the Viterbi algorithm to decode the code trellis, decisions are delayed and thus they are not useful to the feedback filter of the equalizer. Eyuboglu's [9] equalization technique overcomes the problems associated with the coupling of the DFE and the Viterbi decoder. Following the same technique Zhou *et al.* [8] proposed a more robust equalization process that is suitable for highly dispersive channels. This method is used in the set of simulations carried out in this paper.

4. SIMULATION RESULTS

The simulations were carried out for coded modulation schemes that use the 4-PSK and 8-PSK signal sets. Decoding was performed on the code trellis of the TCM, MTCM, and BCM schemes using the Viterbi decoder. Equalization was performed under the condition that the two DFE filters were fed back with the correct symbols.

Fig. 4 demonstrates the performance of rate 1/2 TCM 4-PSK and rate 2/4 MTCM 4-PSK ($k = 2$) systems operating on the channels described by (2) and (3). While both systems have a two-state trellis, the MTCM trellis differs from that of TCM in that it has two parallel transitions and two symbols per transition. For reasons of comparison the equivalent – same bandwidth efficiency – uncoded BPSK system is also shown on the figures. The simulation for the uncoded system was performed on the dispersive channels mentioned above using decision feedback equalization and maximum likelihood decoding.

On the AWGN channel, the rate 1/2 TCM 4-PSK system attains an asymptotic coding gain of 1.76 dB over uncoded BPSK while the rate 2/4 MTCM 4-PSK system provides a gain of 3.0 dB over BPSK. This trend is carried over on the dispersive channel as shown in Fig. 4 where both coded schemes outperform uncoded BPSK by even larger gains. For instance, at a BER of 10^{-3}, and on the channel with no spectral nulls, the TCM and MTCM schemes yield gains of approximately 2 dB and 3 dB respectively, over uncoded BPSK. On the channel with spectral nulls and for the same BER, TCM attains a gain of 3 dB while MTCM provides a gain of 3.8 dB. It is interesting to note that the performance of all schemes illustrated in Fig. 4 degrades in the channel of (3) due to the inability of the DFE to successfully compensate for the induced ISI.

The performance of the 8-state rate 2/3 TCM, 2-state rate 2/3 TCM and the 2-state rate 4/6 MTCM ($k = 2$) 8-PSK systems is depicted in Fig. 5. On the AWGN channel, these schemes obtain asymptotic coding gains of 3.6 dB, 1.1 dB and 2 dB respectively. On the dispersive channel the 8-state TCM scheme yields only marginal performance gains over uncoded 4-PSK. The other two coded systems, however, even with the aid of decision feedback equalization, they fail to sustain any gain over the uncoded 4-PSK system. The severity of impairments introduced by the channel are not compensated either by the equalization process or by the Viterbi decoder and thus the performance is severely degraded.

The general observations made above hold also for systems that use block coded modulation. Figs. 6 and 7 illustrate the performance of BCM systems operating on the two dispersive channels under examination. All codes used for this set of simulations feature an asymptotic coding gain of 3 dB over equivalent uncoded PSK systems on the AWGN channel. The block coded 4-PSK schemes perform well on both channels providing gains over equivalent uncoded BPSK. BCM 8-PSK schemes suffer on both channels with the worst performance observed on the channel with spectral nulls.

5. DISCUSSION

The performance of coded modulation on the dispersive channel has been obtained in this paper using simulations. Coded systems provide substantial gains over uncoded schemes on the AWGN channel. As our simulations show, this is not necessarily true on the dispersive channel. In low transmission rate situations, results indicate that coded schemes provide gains over uncoded systems and in fact the performance gain is further increased. This suggests that coded schemes compensate for imperfect equalization at these lower rates. Additional simulations not included in this paper have demonstrated that the performance gain can be reduced or even eliminated if a more advanced equalizer is used in conjunction with the uncoded system.

Coded modulation does not improve the performance of systems with high throughput rates operating on a dispersive channel. This was demonstrated by the results obtained for various coded 8-PSK schemes. Equalization does not provide any substantial reductions in ISI and the Viterbi decoder is not able to compensate for the residual distortion. It can therefore be concluded that coded systems depend heavily on the equalization process to sustain coding gains over equivalent uncoded systems.

The system of equalization adapted here for the coded modulation systems has some disadvantages. The introduction of the interleaver/deinterleaver pair and the requirements for the degree of interleaving to be equal to the Viterbi depth, imposes large decoding delays that may be unacceptable for some real time applications. Moreover, the insertion of a reference symbol every P symbols reduces the transmission rate by $1/P$ symbols. Nevertheless, the approach allows the feedback section of the equalizer to operate on the output of the Viterbi decoder and not on tentative decisions.

References

[1] G. Ungerboeck, "Channel coding with multilevel/phase signals," *IEEE Trans. Inform. Theory*, vol. IT-28, pp 55–67, Jan. 1982.

[2] S. I. Sayegh, "A class of optimum block codes in signal space," *IEEE Trans. Commun.*, vol. COM-34, no. 10, pp.1043–1045, Oct 1986.

[3] D. Divsalar and M. K. Simon, "Multiple Trellis Coded Modulation (MTCM)," *IEEE Trans. Commun.*, vol. COM-36, no. 4, pp. 410–419, Apr. 1988.

[4] G. D. Forney, "Coset Codes–Part I: Introduction and Geometrical Classification," *IEEE Trans. Inform. Theory*, vol IT-34, no. 5, pp 1123–1151, Sep. 1988.

[5] G. D. Forney, "Coset Codes–Part II: Binary Lattices and Related Codes," *IEEE Trans. Inform. Theory*, vol IT-34, no. 5, pp 1152–1187, Sep. 1988.

[6] L. N. Wong and P. J. McLane, "Performance of Trellis Codes for a Class of equalized ISI Channels," *IEEE Trans. Commun.*, vol. COM-36, no. 12, pp. 1330–1336, Dec. 1988.

[7] C. J. Carlisle, D. P. Taylor, M. Shafi, and W. K. Kennedy, "Performance Bounds for Trellis-Coded Modulation on Time-Dispersive Channels," in Proceedings of GLOBECOM '91, pp. 1176–1181.

[8] K. Zhou, J. G. Proakis, and F. Ling, "Decision-Feedback Equalization of Time-Dispersive Channels with Coded Modulation," *IEEE Trans. Commun.*, vol. COM-38, no. 1, pp. 18–24, Jan. 1990.

[9] M. V. Eyuboglu, "Detection of Coded Modulation signals on Linear, Severely, Distorted Channels Using Decision-Feedback Noise Prediction with Interleaving," *IEEE Trans. Commun.*, vol. COM-36, no. 4, pp. 401–409, Apr. 1988.

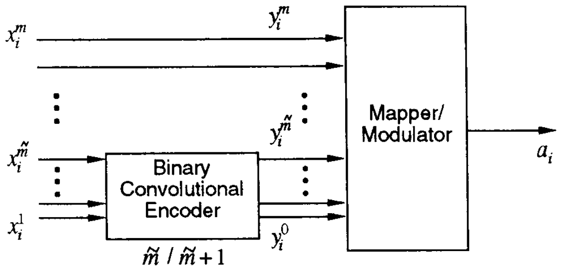

Figure 1: TCM Transmitter

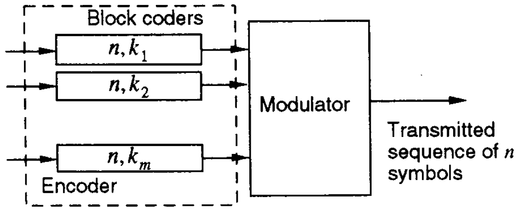

Figure 2: BCM Transmitter

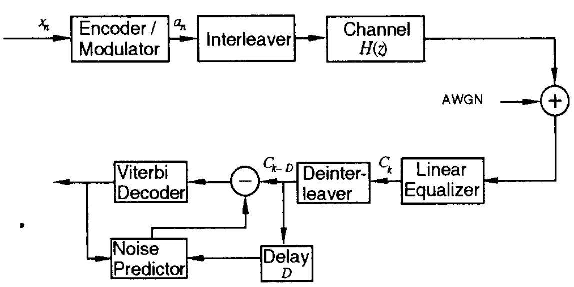

Figure 3: System Model

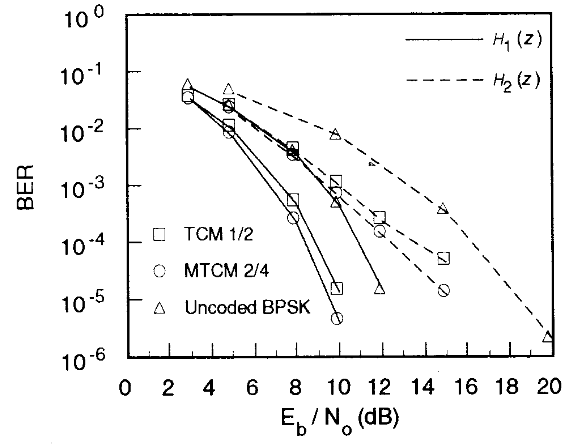

Figure 4: Performance of trellis coded 4-PSK schemes on the dispersive channels of (2) and (3).

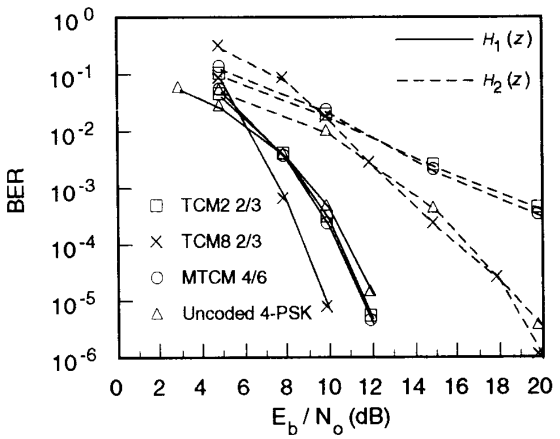

Figure 5: Performance of trellis coded 8-PSK schemes on the dispersive channels of (2) and (3); TCM2–2state, TCM8–8-state.

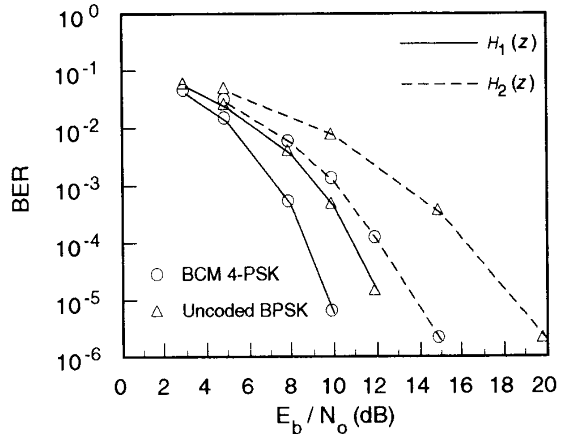

Figure 6: Performance of block coded 4-PSK schemes on the dispersive channels of (2) and (3).

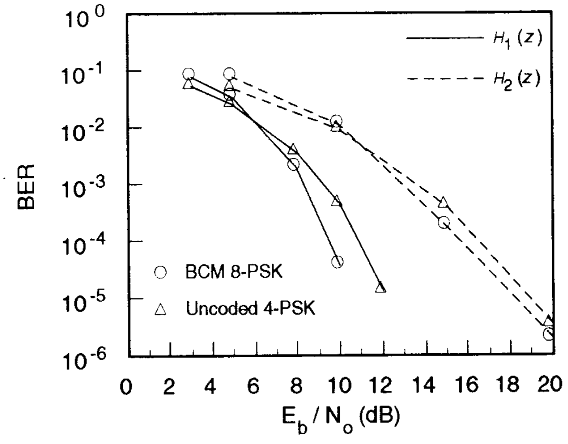

Figure 7: Performance of block coded 8-PSK schemes on the dispersive channels of (2) and (3).