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PRAGMATIC TRELLIS CODED MODULATION: A HARDWARE IMPLEMENTATION USING 24-SECTOR 8-PSK

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ABSTRACT Trellis Coded Modulation (TCM)[2,3], combines convolutional encoding with PSK or QAM signalling to provide spectrally efficient communication with forward error correction. Pragmatic TCM[4], uses the industry standard, 64-state, binary convolutional code. This paper presents a hardware implementation of a pragmatic TCM system for 8-PSK. This system associates each sector of a quantized phase receiver[7] with a pair of weights to be used as soft decision inputs of the Viterbi decoder. This system approaches 3dB of coding gain at bit error rates of 10^{-5} and less.

I. INTRODUCTION

In the decade of the 90's, there will be a need for high quality, high data rate, spectrally efficient communication systems. In quadrature amplitude modulation (QAM), or phase shift keyed (PSK) systems, the bandwidth requirement is roughly proportional to the rate at which discrete signals are transmitted. Increasing the level of modulation, the number of discrete signals allowed, increases the amount of information per symbol, although greater energy is needed to maintain the same distance between signal vectors. Currently, satellite links are almost entirely BPSK (two signals of opposite phase) or QPSK (four signals of 90 degree phase difference), but anticipated spectral crowding is motivating research into higher levels of signalling for space communications. Because satellite transceivers employ a nonlinear travelling wave tube amplifier, constant envelope signalling is required. For this reason, the logical next move would be from QPSK to 8-PSK, and possibly later to 16-PSK.

Forward error correction coding reduces the signal to noise level necessary to maintain a specified bit error rate (BER). The difference (in dB) in signal to noise ratio (SNR) necessary to maintain the same BER for both a coded and uncoded system is referred to as the coding gain. Forward error correction requires redundancy, which may be obtained by reducing the data rate, increasing the symbol rate, or increasing the level of modulation. Trellis Coded Modulation (TCM) [2,3] combines convolutional encoding with higher level modulation (M>4) to obtain coding gain without bandwidth expansion or reduction in data rate.

In a typical TCM system, codebits are generated by a convolutional encoder and used to select a vector from a QAM or PSK signal set. The signal vectors are transmitted over a noisy channel to a receiver, where the Viterbi algorithm[1] is used to select the maximum likelihood sequence. A complete tutorial description of the properties of convolutional codes is given by Forney[6]. An important characteristic of convolutional codes is that in general, the probability of error declines with minimum distance between code sequences. In binary codes, the distance is the Hamming distance, the number of bit positions in which the two sequences differ. In TCM, the distance used is the Euclidean distance, the sum of the squares of the geometric distances between corresponding symbols in the two sequences.

Optimal binary convolutional codes, ranging from 4 to 256 states have been known since the late seventies. To date, the defacto industry standard the rate 1/2 64-state code of Ungerboeck[2,3]. The improvement in error correction performance in using codes of more than 64 states is in general not worth the additional decoder complexity and Viterbi decoders for the 64-state code, on a single chip, are currently available from a number

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of vendors, and are widely used in modems and other applications. Ungerboeck[2] has pointed out that the problem of finding an optimal TCM code is distinct from that of finding an optimal binary convolutional code, and has conducted exhaustive searches to find the best TCM codes for a variety of code rates, code complexities, and signal constellations.

Although the optimal TCM code is not necessarily the same as the optimal binary code of the same code rate and code complexity, a system proposed by Viterbi[4], known as pragmatic TCM, uses a rate 1/2 binary encoder to produce rate k/(k+1) TCM codes which are nearly as good as the best 64-state TCM codes, for a variety of signal constellations. This assumption is based on predicted performance of the codes, using the analytical techniques of Zehavi and Wolf[5]. This paper presents the construction and test results of a system which implements pragmatic TCM for rate 2/3 encoded 8-PSK.

II. PRAGMATIC TCM

In pragmatic TCM, one of k data bits, referred to as the convolutional bit, is fed into a rate 1/2 64-state convolutional encoder. The k - 1 uncoded data bits, known as the outboard bits, and the two codebits from the convolutional encoder are mapped onto a PSK or QAM signal, generating a rate k/(k+1) TCM code. The signal vectors are transmitted over a noisy channel, and the Viterbi algorithm[1] is used to determine the maximum likelihood sequence of convolutional bits. Once the convolutional bits are recovered, threshold decisions are used to determine the outboard bit. At SNR's at which operation is practical, the probability of incorrectly decoding the convolutional bit is less significant, so the probability of error reduces to the probability of making an incorrect outboard decision. To minimize the probability of error, signal vectors which represent the same codebits but different outboard bits are made to be as far apart as the signal constellation will allow. The argument in favor of using pragmatic TCM, as opposed to the best 64-state TCM code, is as follows: pragmatic TCM is straightforward to implement, uses a currently available industry standard decoder, and uses the same decoder for a variety of modulation schemes, while sacrificing very little in coding gain compared to the optimal code.

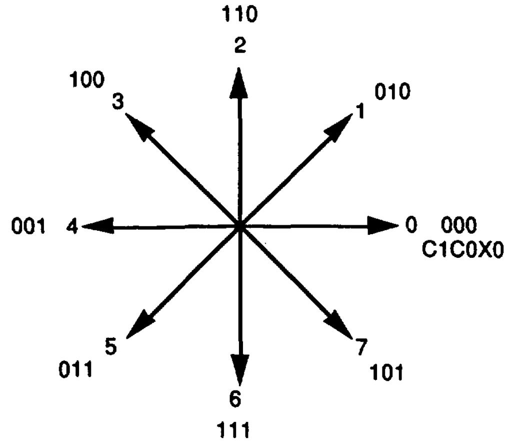

Fig.1 8-PSK signal constellation.

This paper is concerned with the specific case of rate 2/3 encoded 8-PSK, which provides constant envelope signalling, and the same spectral efficiency as uncoded QPSK The signal constellation is shown in figure 1. As explained earlier, the probability of error for pragmatic TCM is expected to reduce to the probability of an incorrect outboard decision. In pragmatic 8-PSK, the distance between signal vectors having the same codebits but different outboard bits are separated by a distance of $\sqrt{4E_S}$, whereas in QPSK, nearest neighbors are separated by $\sqrt{2E_S}$, thus the energy saved by 8-PSK pragmatic TCM is expected to be about 3dB. This is only approximate because pragmatic TCM has a non-zero probability of decoding error, and because the QPSK vector has more than one nearest neighbor. Simulations done previously, as well as the test results presented in this paper, show that at a bit error rate of 10^{-5}, the approximation is very good, andpragmatic TCM achieves close to the expected 3dB of coding gain over uncoded QPSK. At this operating point, the best rate 2/3 8-PSK 64- state Ungerboeck code is predicted to achieve 3.6 dB of coding gain[4], so that only 0.6dB is sacrificed by using the pragmatic system.

353.2.2

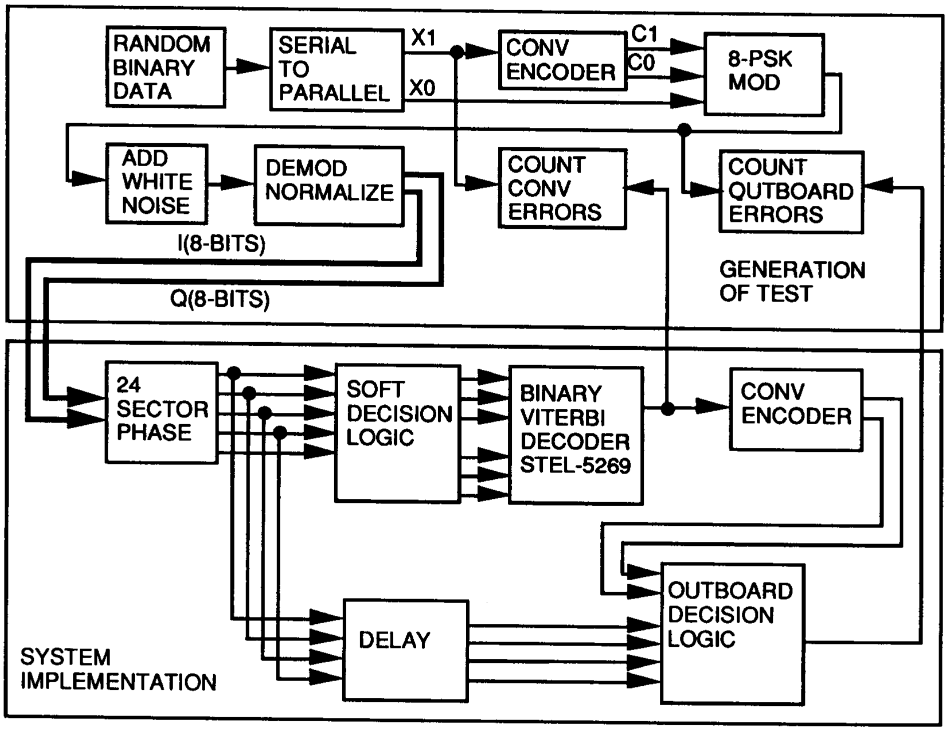

Fig. 2. Complete system.

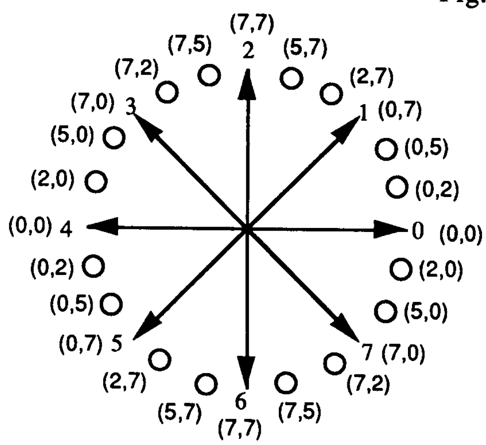

Fig. 3. Soft decision assignments

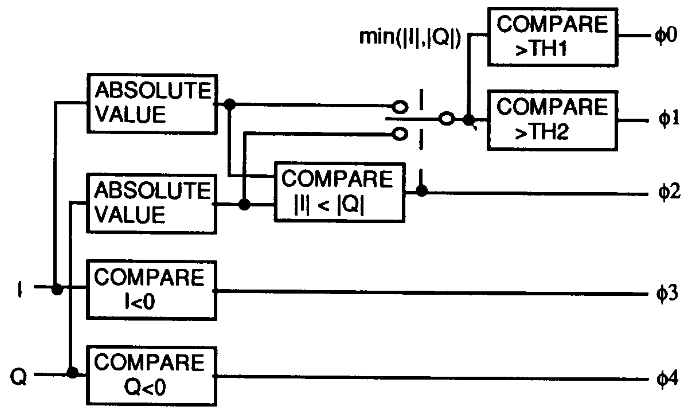

Fig 4. 24-sector phase quantizer.

III. IMPLEMENTATION OF PRAGMATIC TCM

A system to decode 8-PSK pragmatic TCM, as shown in figure 2, was built and tested to determine bit error rates. The decoding system consists of a commercially available Viterbi decoder, designed for use on a binary channel, with external circuitry to adapt the decoder to the 8-PSK channel.

The system operates by making use of the soft decision inputs of the Viterbi decoder, which allow the decoder to accept not only a hard zero or one but also a relative weight indicating the likelihood that the received codebit was a zero or a one. The Viterbi algorithm is well suited to use this information, and it is known that on a binary channel, the use of soft decisions will result in a performance gain of 2dB over hard decisions[10]. In adapting the binary decoder to the 8-PSK channel, the use of the soft decisions is crucial. The particular Viterbi decoder used in this system accepts soft decision inputs on a scale of 0 thru 7, with a soft decision 7 indicating the strongest binary 1, and a soft decision 0 indicating the strongest binary 0. With this in mind, the signal vector space is quantized, and a pair of soft decisions (one for each codebit), is assigned to each quantization point. In this case it has been decided to use 24-sector phase quantization, which has already been shown (in simulations) to work well with 8-PSK TCM [7,8,9]. Through simulation, the soft decision assignments of figure 3 were found to yield the best performance among reasonable alternatives.

The 24-sector phase quantizer was designed with the assumption that the in-phase and quadrature components of the received, noisy signal vectors will be converted to 8-bit numbers, after the length of the received vector has been normalized. Normalization of the received vector may be omitted, resulting in a performance loss of about 0.5 dB. The circuit, shown in figure 4, uses five comparators (8-bit), two absolute values (8-bit) and an 8-gang switch to generate a five bit phase code indicating one of 24 sectors. Each of the five phase bits gives information about the location of the received vector: ϕ_4 and ϕ_3 indicate the quadrant, the remaining three bits indicate the location within the quadrant. When $|I| < |Q|$, $|I|$ is compared to threshold 1 and threshold 2 to generate ϕ_1 and ϕ_0. When $|Q|<|I|$, $|Q|$ is used to generate ϕ_1 and ϕ_0. This phase code allows relatively simple logic to generate the soft decisions.

Once the convolutional bit has been determined by Viterbi decoding, it remains to determine the outboard bit. This is accomplished by making a threshold decision. Clearly, which threshold should be used depends on the codebits. Maximum likelihood codebits are generated by reencoding the output of the encoder. Due to the structure of the Viterbi algorithm, every Viterbi decoder delays the data by a fixed number of symbol periods. The decoder used in this system introduces a delay of 35 symbol periods, so the phase information used by the outboard decision logic must be delayed by 35 symbols to match up with the reconstructed code sequence.

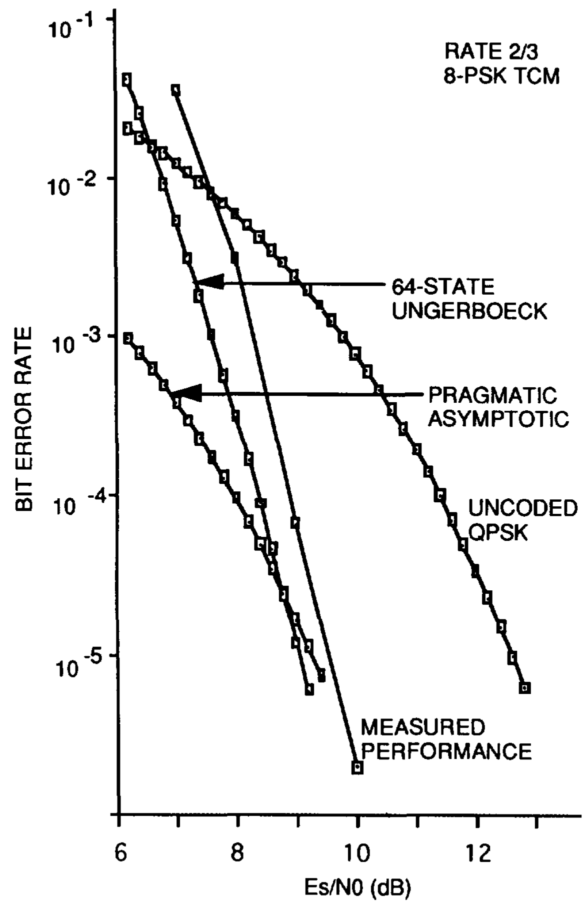

Fig. 5. Test results.

IV. CONCLUSION

The system was tested by using a computer to generate the eight bit I and Q components, as they would be received in the presence of additive white gaussian noise, at as specified signal to noise ratio. The phase quantizer, soft decision logic, and outboard decision logic were constructed out of TTL gates and connected to a commercially available Viterbi decoder chip. Random data was generated and encoded into a TCM sequence by the computer, and then decoded by the hardware system. The decoded data was compared to the original data, and errors were counted. Figure 5 shows the test results along with the asymptotic error rate for pragmatic 8-PSK TCM, and the theoretical error rate for the 64-state rate 2/3 code of Ungerboeck. The error rate for uncoded QPSK is calculated as $2Q\left(\sqrt{\frac{E_s}{N_0}}\right)$ where Q() is the tail of the Gaussian distribution. The asymptotic error rate is the theoretical lower limit on the error rate for pragmatic 8-PSK. This is the probability of error based on the assumption that only outboard errors will occur, and is calculated as $Q\left(\sqrt{\frac{2E_s}{N_0}}\right)$. At higher SNR's, the true error rate approaches the asymptotic error rate. The error rate for the Ungerboeck code was calculated by analytical means. In theory it is possible to achieve a coding gain closer to 3dB by using finer quantization of the received signal, however, the quantization method used here allows the system to be implemented in relatively simple logic. At a bit error rate of 10^{-5}, the coding gain of this system is 3 dB, demonstrating the effectiveness and feasibility of 8-PSK pragmatic TCM.

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