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PRAGMATIC TRELLIS CODED MODULATION: A SIMULATION USING 24-SECTOR QUANTIZED 8-PSK

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ABSTRACT Trellis Coded Modulation (TCM)[2,3,4], combines convolutional encoding with PSK or QAM signalling to provide spectrally efficient communication with forward error correction. Pragmatic TCM[1], uses the industry standard, 64-state, binary convolutional code. This paper presents a simulation of a pragmatic TCM system for 8-PSK. This system associates each sector of a quantized phase receiver[9] 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. This will be especially true if the extensive use of video signals is desired. 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 symbols 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 the use of higher level modulation in space communications. Because satellite transceivers employ a nonlinear travelling wave tube amplifier, constant envelope signalling is required. For this reason, the most logical next move would be a move from QPSK to 8-PSK, and possibly later to 16-PSK,

Forward error correction coding reduces the signal to noise ratio necessary to maintain a specified bit error rate. The difference in 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 (thereby increasing the bandwidth), or increasing the level of modulation. Trellis coded modulation (TCM) combines convolutional encoding with higher level modulation (M>4) to obtain coding gain without bandwidth expansion or reduction in data rate.

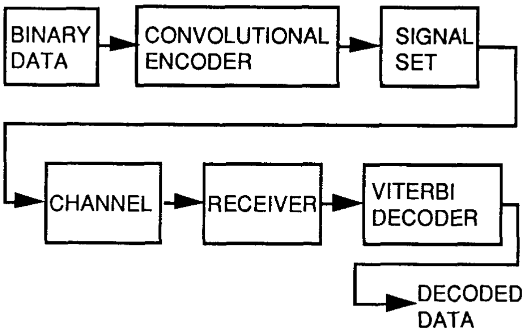

Fig.1 Typical TCM system.

A typical TCM system is shown in figure 1. Codebits are generated by a convolutional encoder and used to select a signal vector from a QAM or PSK signal set. The signal vectors are transmitted over a noisy channel to a receiver, where the Viterbi algorithm is used to select the maximum likelihood sequence. A complete tutorial description of the Viterbi algorithm is given by Forney[8]. An important characteristic of convolutional codes is that in general, the probability of error declines with the minimum distance between code sequences. In binary codes, the distance used 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.

Ungerboeck[2,3,4] conducted exhaustive searches to find the best codes, using the minimum distance criterion, for various

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constellations and code complexity. The complexity of the code and the size of the required decoder grow with the number of states that the decoder is able to realize. From Ungerboeck's search, it may be concluded that for rate 2/3 8-PSK, very little coding gain is to be expected from increasing the complexity of the code to more than 64 states. Viterbi[6] has predicted that a relatively straightforward mapping of the industry standard 64-state binary convolutional code onto a PSK or QASK signal constellation, referred to as pragmatic TCM, will perform nearly as well as the best 64-state code found by Ungerboeck's exhaustive search. The pragmatic system, employing a current industry standard decoder, is expected to obtain near optimal performance with less system complexity than would be required to implement the true optimal code. This paper presents the logic design and simulation results for a system which effectively implements pragmatic TCM for rate 2/3 encoded 8-PSK.

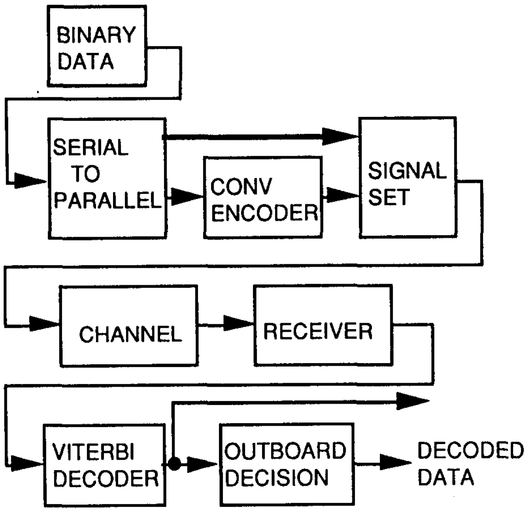

Fig.2 Pragmatic TCM system.

II. PRAGMATIC TCM

Pragmatic TCM, introduced by Viterbi[6], is illustrated here in figure 2. One of k data bits, referred to as the convolutional bit, is fed into a rate 1/2 convolutional encoder, which generates two codebits. The convolutional encoder is the industry standard 64-state encoder shown here in figure 3. The uncoded data bit(s), referred to as the outboard bits, together with the codebits, select the signal vector, so the coderate of pragmatic TCM is always k/(k+1). (Ungerboeck[4] has pointed out that for TCM in general, little is to be gained by reducing the coderate to less than this anyway). In this paper, the term partition is used to refer to a set of signal vectors having the same codebits but different outboard bits. When pragmatic TCM is received, the decoded sequence is used to identify the most likely partition, then threshold decisions are used to identify the most likely vector from the selected partition. At SNR's at which operation is practical, the probability of incorrectly decoding the convolutional bit becomes insignificant, so the overall probability of error reduces to the probability of making an incorrect outboard decision. To minimize the probability of error, the signal vectors of a partition are made to be as far apart as the signal constellation will allow. As an example, the signal constellation for rate 2/3 TCM is shown in figure 4. As can be seen, there are four partitions: {000, 001}, {010, 011}, {110, 111}, and {100, 101}. Each partition consists of two vectors which differ by 180 degrees of phase, the maximum distance possible in the 8-PSK constellation.

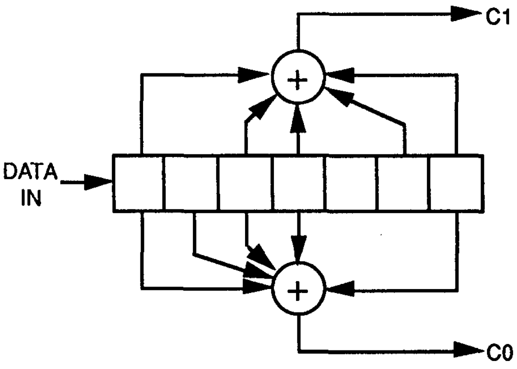

Fig.3 Industry standard convolutional encoder.

The benefit of coding is determined by comparing the error probability of the coded system to that of an uncoded system with the same number of bits per symbol, so that the two systems have equal spectral efficiency.

In this case, we are comparing coded 8-PSK to uncoded QPSK, both of which carry two bits per symbol. As explained earlier, the probability of error for pragmatic TCM reduces to the probability of an outboard decision error. In the case of 8-PSK, this is the probability of incorrectly selecting between two vectors at a distance of $\sqrt{4Es}$ from each other. The most likely error in QPSK is that of incorrectly selecting between two vectors which differ by $\sqrt{2Es}$. Therefore, the performance of coded 8-PSK is expected to be approximately equivalent to that of uncoded QPSK with twice the energy. Since the number of bits per symbol is the same, and therefore the energy per symbol is equivalent, this amounts to a coding gain of 3 dB. The approximation is not exact because 8-PSK has a nonzero probability of incorrectly decoding the convolutional bit, and QPSK has more than one vector at a distance $\sqrt{2Es}$ from the correct vector. Simulation, however, shows that pragmatic TCM does indeed achieve close to 3 dB of coding gain at higher signal to noise ratios.

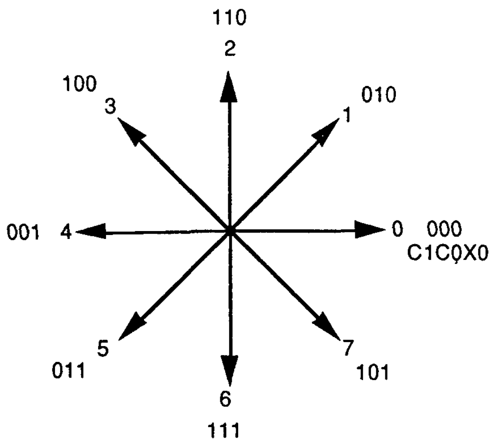

Fig.4 8-PSK signal constellation.

The argument in favor of using pragmatic TCM as opposed to the best found 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. In the case of rate 2/3 8-PSK, Viterbi[6] has used the analytical technique of Zehavi and Wolf[7] to evaluate the best 64-state Ungerboeck code and found an expected coding gain of 3.6 dB, so that only 0.6 dB is sacrificed by using the pragmatic system. This provides the motivation to develop specific implementations of pragmatic TCM.

III. IMPLEMENTATION OF 8-PSK PRAGMATIC TCM

The standard Viterbi decoder chip will accept inputs in either of two modes: hard decision, in which the receiver makes a binary determination that the received codebit is a "0" or a "1", or soft decision, in which the receiver indicates, on some specified scale, the relative likelihood that the received codebit is a zero or a one. When Viterbi decoding is used with binary signalling, the use of soft decisions can improve performance by as much as 2 dB over hard decisions[8]. Typically, the soft decision is generated by the quantization of an antipodal signal received in the presence of additive white Gaussian noise, as shown in figure 5. Usually, a scale of 0 through 7 (3-bit soft decision) would be used, although decoders which use a scale of 0 through 15 (four bit soft decision) are currently available. The decoder uses the soft decisions to calculate a branch metric to associate with each combination of codebits resulting from a state transition of the convolutional encoder. The branch metrics are then used to determine the maximum likelihood sequence.

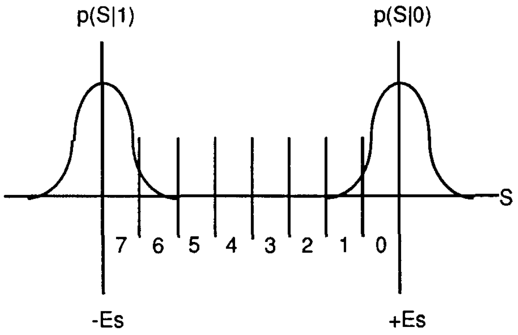

Fig.5 Soft decisions.

In order to make a binary decoder work with an 8-PSK channel, it is necessary to use soft decisions. The use of hard decisions will result in unsatisfactory performance. The key to making the system work is to understand that the decoder will perform well as long as the soft decision inputs are reasonably accurate indications of the codebit likelihoods. Since the decoder requires the soft decision inputs to be discrete, a reasonable approach is to quantize the signal set space, then assign a pair of soft decision weights to each quantization point. two soft decision weights are necessary, since each signal vector represents two codebits. Simulations[9,10,11] have proven the effectiveness of circular quantization (phase quantization) for use with TCM, and shown that for 8-PSK, circular quantization to 24 sectors is sufficient. The signal constellation for 24-sector 8-PSK, with soft decision assignments, is shown in figure 6. The assignments were made according to the following principles:

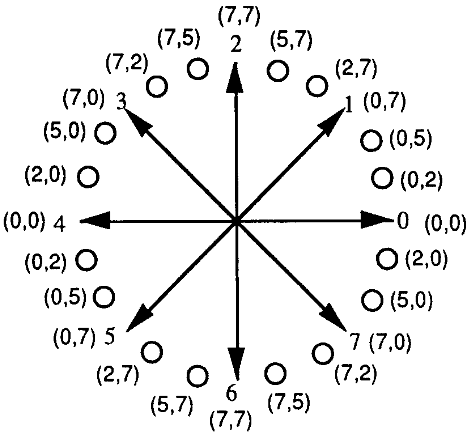

Fig.6 Soft decision assignments.

1. As required by the decoder, the soft decision weight indicates the relative likelihood of a zero or a one, with a weight of zero indicating the greatest likelihood of a binary zero and a weight of seven indicating the greatest likelihood of a binary one.

2. The soft decision assignments are made in a way which reflects the symmetry of the signal constellation.

Figures 7 and 8 are alternative assignments which also conform to principles 1 and 2 above, however, the assignment shown in figure 6 has been experimentally found to be the best.

The complete system is shown in figure 9. Rate 2/3 8-PSK pragmatic TCM is generated as described earlier, transmitted over an additive white Gaussian noise channel, and received by a 24 sector quantized phase detector. The phase detector outputs a five bit code indicating which of the 24 sectors includes the received vector. The soft decision logic generates the soft decision assignments of figure 6, which are used by the Viterbi decoder to make the maximum

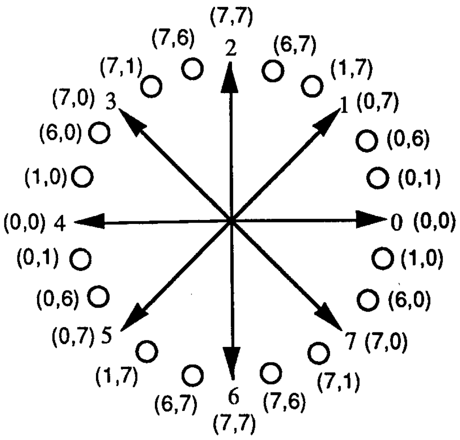

Fig. 7 Alternative soft decision assignments.

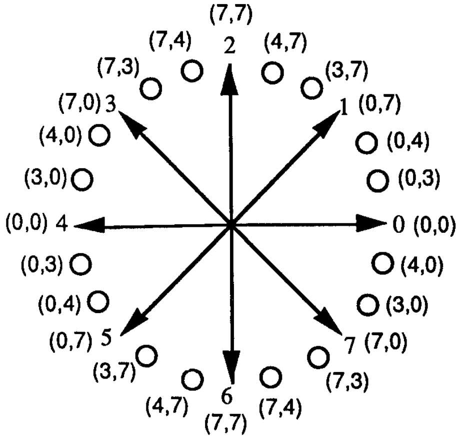

Fig.8 Alternative soft decision assignments.

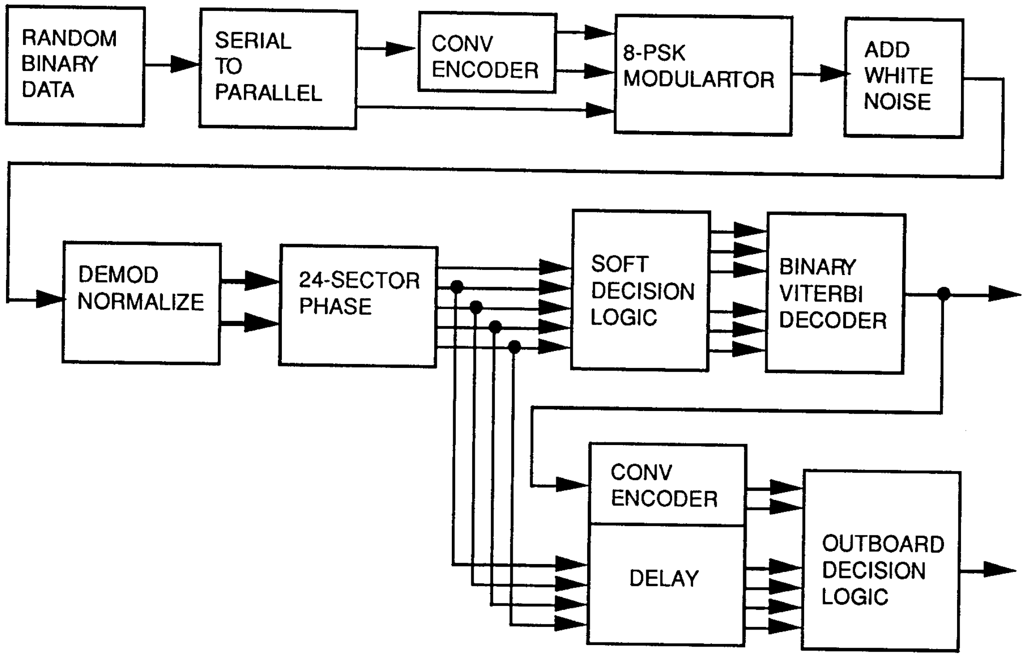

Fig.9 Complete system

likelihood determination of the convolutionally encoded sequence. As explained previously, the decoded sequence is used to determine the most likely partition,

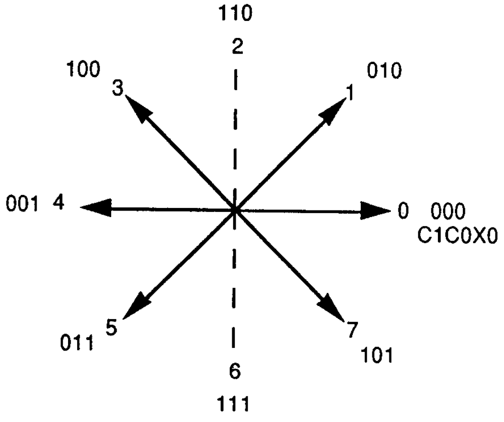

Fig.10 Optimal threshold, C1C0=00.

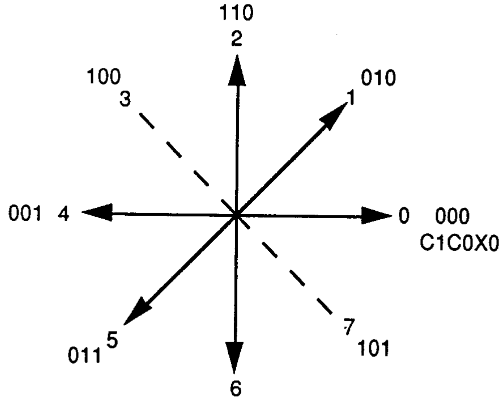

Fig.11 Optimal threshold, C1C0=01.

which in this case is a pair of vectors of opposite phase. Once the most likely partition is identified, a threshold decision is needed to identify the most likely vector from the partition. This is the function of the outboard

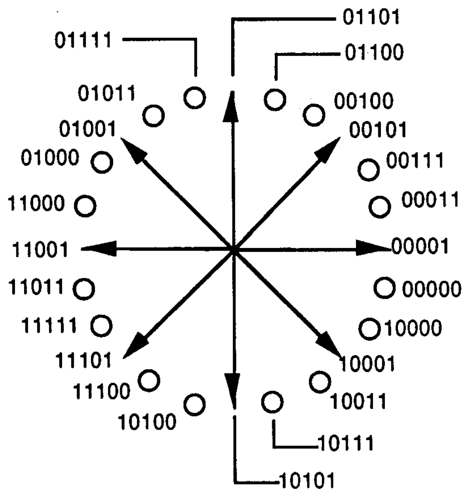

Fig.12 Phase code assignments.

decison logic. The outboard decision logic requires the decoded sequence as input, because the optimal threshold depends on the selected partition. For example, if it is most likely that the two codebits were 00, then the most likely partition is {000, 001}, and the optimal threshold is a line through the origin at 90 degrees to the *X* axis (figure 10). Alternatively, if it were most likely that the two codebits were 01, then the optimal threshold would be a line at 135 degrees (figure 11). A Viterbi decoder has a latency period of between 35 and 80 symbols, depending on the specific design and the mode of operation. Because the decoded sequence is needed to make the outboard decision, the information from the phase detector to the outboard decision logic must be delayed to match the data delay introduced by the Viterbi decoder. The soft decision logic generates the soft decision weights required by the Viterbi decoder. The soft decision

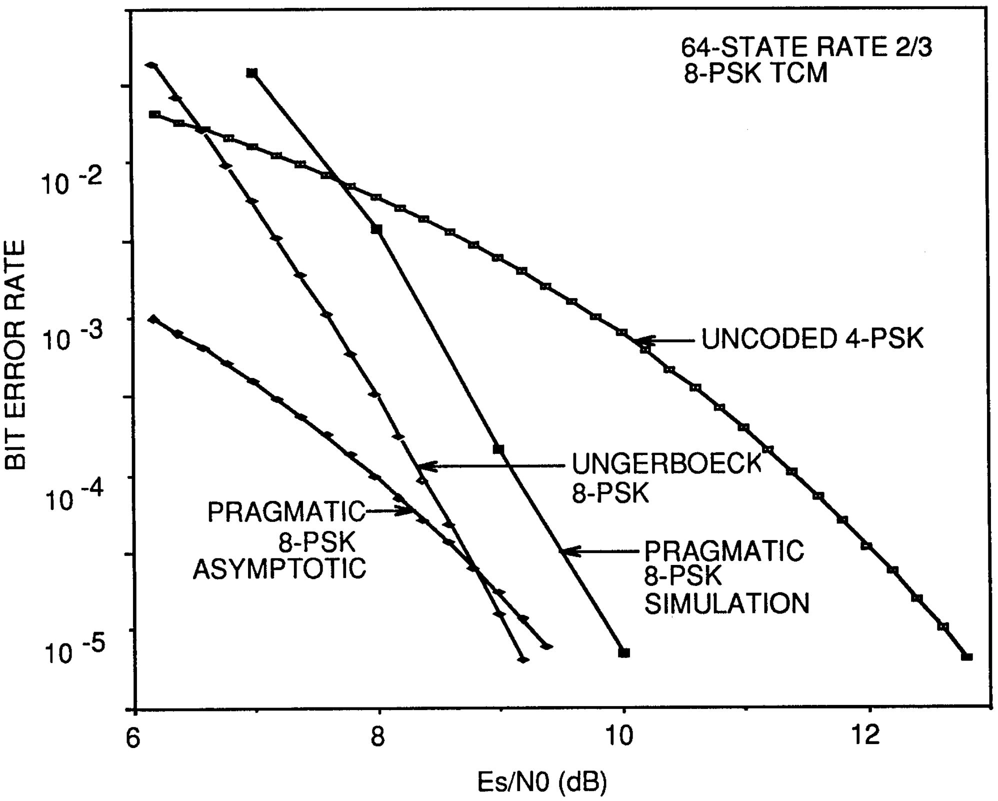

Fig.13 Simulation results.

weight is an integer represented by three bits. A soft decision is required for each of the two codebits. By listing the five-bit phase code along with the required soft decisions for each of the 24 phase sectors, it is possible to derive and reduce the canonical expressions for each of the six soft decision bits, using standard Boolean algebra. As long as the phase codes are assigned in an orderly way, the logical expressions which generate the soft decisions will be relatively simple. For the simulations discussed in this paper, a threshold detector was designed to generate the phase code illustrated in figure 12, and the soft decision logic was realized with five gates.

V. CONCLUSION

Figure 13 shows the simulation results, along with the asymptotic error rate for pragmatic 8-PSK TCM, and the theoretical error rate for the 64-state, rate 2/3 8-PSK code of Ungerboeck. The error rate for uncoded 4-PSK is calculated as $2Q\left(\sqrt{\frac{Es}{N0}}\right)$ where Q() is the complementary Gaussian error function. The asymptotic error rate for pragmatic TCM is calculated as $Q\left(\sqrt{\frac{2Es}{N0}}\right)$. The error rate for the Ungerboeck code was calculated by analytical means. In theory, it is possible to achieve a coding gain closer to 3 dB by using finer quantization of the received signal, however, the quantization method used in this paper allows the system to be implemented by relatively simple logic. At a bit error rate of 10^{-5}, the coding gain of this system is 2.6 dB, demonstrating the effectiveness and feasibility of pragmatic TCM, for 8-PSK.

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