Entropy Coded Differential Pulse-Code Modulation Systems for Television

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Abstract—This concise paper describes experiments with a television source encoder which consists of a differential PCM encoder followed by entropy coding. This encoder converts analog television signals into a digital bit stream for digital transmission or storage. When optimized, this type of system is known to perform very close to the rate distortion bound. The differential PCM encoder has a 16-level quantizer during low entropy areas of the picture (quiet areas) but switches to a 6-level quantizer in high entropy (busy) areas of the picture which tend to fill up the buffer. This strategy avoids buffer overflow and has the desirable property that it produces low noise in quiet areas of the picture and higher noise in busy areas of the picture.

INTRODUCTION

Differential PCM (DPCM) combined with entropy coding forms a source encoding system for continuous stationary signals which is only 1.5 dB away from the rate distortion bound [1]. This means that if a minimum mean-square encoder could be constructed, its signal-to-quantizing-noise ratio, as predicted by Shannon’s rate distortion bound, would only be 1.5 dB greater than what we can now achieve by entropy coding the output of a DPCM system.1 This difference is very small—for speech or television 1.5 dB is not far away from a liminal unit. In other words, an untrained observer would not notice much difference between DPCM plus entropy coding (DPCM + EC) and the minimum mean-square encoder which performed at the rate distortion bound. Thus, DPCM + EC is very nearly optimum for practical transmissions as far as signal-to-quantizing-noise ratios are concerned.

Just because a source encoder operates near Shannon’s rate distortion bound does not necessarily mean it is the best possible encoder. Noise power, the distortion measure usually used in the bound, is not a definitive measure of picture quality. Furthermore, the rate distortion bound applies to signals which are assumed to be Gaussian. If a source encoder operates near Shannon’s rate distortion bound does not necessarily mean it is the best possible encoder. Noise power, the distortion measure usually used in the bound, is not a definitive measure of picture quality. Furthermore, the rate distortion bound applies to signals which are assumed to be Gaussian.

In this concise paper we describe experiments with a hardware DPCM + EC system for television signals. The DPCM part of the system is suboptimum—it contains only a one tap predictor in the feedback loop. Thus, its performance is not close to the rate distortion bound as described above. Optimizing the DPCM part of the system to take advantage of line-to-line and frame-to-frame redundancy is a complicated procedure [4],[5] and would require hardware beyond the scope of this research. However, systems using line-to-line and frame-to-frame feedback could benefit from the entropy coding schemes described here.

The source encoder we describe has the desirable property that it gives low noise in quiet areas of the picture and higher noise in busy areas of the picture.2 This is quite desirable because the human observer is more sensitive to noise in quiet areas than in busy areas. The observer, in fact, makes use of a context dependent fidelity criteria [6], i.e., the degrading effect of noise in a picture is determined by the picture content in the region where the noise occurs. The noise occurring in areas where the entropy of the picture is large (busy areas) is less disturbing than noise in low entropy areas (quiet areas) of the picture.

Whenever entropy (Huffman) coding [7] is used, a buffer is required and distortion caused by buffer overflow is a paramount concern. In the DPCM + EC system described here, a buffer full condition causes the DPCM system to use a modified encoding rule which reduces the entropy of the DPCM output. When in the buffer full mode the DPCM system uses a six-level quantizer and the buffer begins to empty and return to the buffer normal condition. High entropy areas of the picture cause the buffer to become full, resulting in fewer DPCM quantizing levels and more quantizing noise. Low entropy areas of the picture do not cause the buffer to fill, and the DPCM system uses all 16 quantizing levels. The buffer never overflows, regardless of its size.

DPCM + EC

Fig. 1 is a block diagram of a standard one tap DPCM system followed by an entropy coder and a buffer. In our experiments the DPCM system had a 16-level quantizer and a feedback constant of α = 0.96. The DPCM hardware is described by Agrawal [8],[9]. It is completely digital and consists of an 8-bit PCM encoder and various digital logic circuits which perform the feedback operation.

The entropy coder converts the DPCM quantizer levels into a Huffman code [7]. The buffer is required because the bit rate coming out of the Huffman coder is not constant but varies from one time interval to the next, depending on the activity of the signal. Since the bit rate required by the channel is constant, a buffer is needed between the entropy coder and the channel.

We found the block diagram of Fig. 1 to be impractical because it does not degrade the picture gracefully during the “buffer full” condition. This condition arises when the information rate of television signal is greater than the output bit rate of the digital channel. Our final design, however, was determined by a study of the system of Fig. 1 and its performance with three typical television signals.

Monochrome National Television System Commission (NTSC) television signals were derived from the three scenes in Fig. 2. These signals were bandlimited by a second-order Butterworth filter which was 3 dB down at 3 MHz, sampled at 6 MHz and then passed through the 16-level DPCM system. Without entropy coding

1 A quiet area of a picture is an area of relatively constant brightness. A busy area is characterized by frequent changes of brightness usually giving the area a textured appearance.
the digital channel required to transmit the DPCM output would be 24 Mbit. The DPCM quantizer used equally spaced levels because this can result in optimum performance when entropy coding is used [1]. In accordance with previous research results [4], we designed the 16-level quantizer to span 1/4 of the peak-to-peak range of the composite television input signal. The quantizing levels were, therefore, $1/16 \times 1/4 = 0.0156$ times the peak value of the composite video input to the system.

The probabilities of exercising each of the 16 quantizing levels are shown in Table I. These are the average probabilities for the three pictures and are computed from the measured data. Also shown in this table is a Huffman code derived for this set of first-order probabilities. This code assignment converts each DPCM quantizing level into a variable length codeword. This Huffman code is similar to codes derived by Chow [10] and Budrikis et al. [11].

The first- and second-order entropy measurements are shown in Table II as $H(i)$ and $H(i,j)$, respectively. These computations were made using the standard formulas [12].

If a Huffman code was not used, the 16-level DPCM output would require $\log_2 16 = 4$ bits per sample for its transmission. Table II shows the advantage to be gained from entropy (or Huffman) coding the DPCM output using the Huffman code of Table I, e.g., for "test chart," the first-order entropy is 2.88 bits/sample and the average code length (ACL) is 2.94 bits/sample. This means that the

![Fig. 1. DPCM with entropy coding.](image1)

![Fig. 2. Pictures for statistics measurements.](image2)
TABLE I
Entropy Code for a Practical 4-Bit DPCM Signal
(Sampling Frequency = 6.0 MHz)

<table>
<thead>
<tr>
<th>Level Number</th>
<th>DPCM Code</th>
<th>Probability</th>
<th>Huffman Code</th>
<th>Code Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>-8</td>
<td>1000</td>
<td>0.03352</td>
<td>0 1 0 0 0 0</td>
<td>5</td>
</tr>
<tr>
<td>-7</td>
<td>1001</td>
<td>0.00598</td>
<td>0 1 0 0 1 1</td>
<td>7</td>
</tr>
<tr>
<td>-6</td>
<td>1010</td>
<td>0.00758</td>
<td>1 0 1 1 1 1</td>
<td>6</td>
</tr>
<tr>
<td>-5</td>
<td>1011</td>
<td>0.00999</td>
<td>1 0 1 1 0 1</td>
<td>6</td>
</tr>
<tr>
<td>-4</td>
<td>1100</td>
<td>0.01511</td>
<td>1 0 1 1 1 1</td>
<td>6</td>
</tr>
<tr>
<td>-3</td>
<td>1101</td>
<td>0.02917</td>
<td>1 0 1 0 1 0</td>
<td>5</td>
</tr>
<tr>
<td>-2</td>
<td>1110</td>
<td>0.04787</td>
<td>0 1 0 1 1 0</td>
<td>4</td>
</tr>
<tr>
<td>-1</td>
<td>1111</td>
<td>0.17372</td>
<td>1 1 1 1 0 0</td>
<td>6</td>
</tr>
<tr>
<td>0</td>
<td>0000</td>
<td>0.12108</td>
<td>0 1 1 1 0 0</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>0001</td>
<td>0.03788</td>
<td>1 0 0 1 0 0</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>0010</td>
<td>0.02458</td>
<td>1 0 0 1 1 0</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0100</td>
<td>0.01335</td>
<td>1 0 1 1 0 0</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>0101</td>
<td>0.00927</td>
<td>1 0 1 1 1 0</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>0110</td>
<td>0.00740</td>
<td>0 1 0 0 1 1</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>0111</td>
<td>0.04043</td>
<td>1 0 0 1 0 0</td>
<td>4</td>
</tr>
</tbody>
</table>

TABLE II
Measured Entropies, Conditional Entropies, and Average Code Lengths

<table>
<thead>
<tr>
<th>Picture</th>
<th>$H(i)$ First-Order Entropy</th>
<th>$H(j/i)$ Conditional Entropy</th>
<th>$H(i) - H(j/i)$ Difference</th>
<th>Average Code Length (ACL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test chart</td>
<td>2.88</td>
<td>2.63</td>
<td>0.25</td>
<td>2.94</td>
</tr>
<tr>
<td>Girls</td>
<td>2.87</td>
<td>2.59</td>
<td>0.28</td>
<td>2.92</td>
</tr>
<tr>
<td>Aerial view</td>
<td>3.04</td>
<td>2.58</td>
<td>0.47</td>
<td>3.09</td>
</tr>
</tbody>
</table>

The simple entropy code of Table I could transmit the DPCM output at a rate of 2.94 bits/sample. This represents a savings of $4 - 2.94 = 1.06$ bits/sample for this code. There is approximately a one bit savings for each of the three pictures. The column marked $H(i) - H(j/i)$ gives the additional savings that an entropy code could achieve if it were designed to encode pairs of quantizing levels. These data indicate that the more complicated entropy code could give an additional improvement of 0.33 bits/sample, but this was not pursued further. On the basis of the ACL data in Table II, we decided to test the entropy code of Table I and determine buffer requirements for the DPCM + EC system of Fig. 1.

Fig. 3 shows a plot of the number of samples stored in the buffer for the first field of the three pictures when the digital transmission rate is 3 bits/sample or 18 Mbits. The buffer contents start from zero and are plotted against the number of sample values taken. Since the sampling rate is 6 MHz and one field of the picture lasts 1/60 s, 100 000 samples represent one field. The sharp decrease in the buffer contents at approximately 100 000 samples is due to the occurrence of the horizontal blanking pulse. For "aerial view" the transmission rate (3 bits/sample) is less than the ACL (3.09 bits/sample), and the buffer would eventually overflow regardless of its size. For the other two pictures the transmission rate is more than the ACL (2.94 and 2.92) and a buffer size can be selected which will prevent overflow.

One obvious method of reducing the desired buffer size or the probability of its overflow when the size is fixed is to increase the rate of transmission. Fig. 4 shows the buffer contents versus number of samples taken for the picture "girls" for several different transmission rates. As expected, increasing the bit rate decreases the required buffer storage, because this increases the rate at which bits are taken out of the store while the rate at which bits go in is not changed. It was found that the probability of overflow is very much reduced if the transmission rate is slightly higher than the ACL. This is in agreement with the behavior suggested by Budrikis [11].

Examination of Figs. 3 and 4 gives some idea of the buffer length required for these three pictures at various transmission rates. If the standard DPCM + EC system of Fig. 1 was used at a transmission rate of 3.0 bits/sample, buffer lengths of 19 000 and 13 700 would be required to prevent buffer overflow for the pictures "girls" and
Buffer overflow can lead to catastrophic failure of the encoding system. For any finite buffer length, buffer overflow will occur whenever the information rate of the DPCM output signal is greater than the transmission rate of the digital line for a long enough period of time. Thus, any system which uses an entropy coder must have a strategy to deal with buffer overflow. We studied various strategies to deal with this problem. One which seemed promising is to change the bandwidth of the television signal whenever the buffer becomes full. Reducing the bandwidth reduces the information content of the signal and therefore the DPCM output. Furthermore, bandwidth reduction is a graceful way to degrade the picture. Unfortunately, we found that the information content of the DPCM system was very weakly dependent on the television signal bandwidth. This is illustrated in Fig. 5 which shows a plot of buffer contents versus number of samples for several different bandwidths for the picture “girls” encoded by the DPCM + EC system of Fig. 1.

We found no better way to deal with buffer overflow than to reduce the number of DPCM quantizing levels when the buffer became full. This strategy produced an encoder which degrades gracefully when picture information is too high. Furthermore, it produces noise in the high information regions of the picture where it is least disturbing to a viewer. We call this encoder a dual mode DPCM + EC system.

THE DUAL MODE DPCM + EC SYSTEM

Fig. 6 is the block diagram of the DPCM + EC system which avoids buffer overflow. The encoder has two modes of operation: buffer normal and buffer full. In the buffer normal mode the 16 DPCM levels are encoded into the Huffman code of Table I by the entropy coder. When the buffer is full, a buffer status signal causes the two switches $S_1$ and $S_2$ in Fig. 6 to be thrown into the “full” position. The DPCM quantizer now operates as if it had only six quantizing levels. Actually, the 16 levels of the DPCM quantizer are combined into 6 levels as shown in Table III. The 6 quantizing levels in the buffer full mode are levels 1, 3, 6, -1, -3, and -6.

The design and hardware details of the system are given in [13].
The other levels are mapped into these levels, e.g., when the buffer is full, the quantizer levels 5–8 are combined into level 6 which is represented by the code word 011.

In the buffer full mode the entropy coder for six input quantizer levels is used. It can be seen from Table III, that all code words for this 6 word code have 3 bit or 2 bit length. Since three bits are removed from the buffer at each sample time, buffer contents in this condition either remain the same or decrease. This gradually decreases the number of bits stored in the buffer. When the buffer contents decrease to some predetermined value, the buffer is declared normal and a buffer status signal causes the system to switch back to 'normal' 16-level operation.

Of primary consideration are the length of the buffer and the buffer gap. The buffer gap is that number of bits which separates the buffer full condition from the buffer normal condition. For example, in the results which follow we use a buffer length of 4048 bits. When the buffer contents reach 4048 bits, the buffer is full and a buffer status signal causes the DPCM system to operate as if it had a 6-level quantizer. This reduces the average input to the buffer and causes the buffer to gradually empty itself. When the buffer contents are reduced to 4048 – 32 = 4016 bits, we declare the buffer normal and switch to ‘normal’ operation with the 16-level quantizer. The 32 bits between the buffer full and buffer normal conditions is what we call the buffer gap. We varied both the buffer length and the buffer gap in our experiments and found both to be important parameters [14].

The number of samples in the receive buffer plus those in the transmit buffer must always equal a constant. These samples represent the delay required by the use of entropy coding. Because of the variable length coding, the total number of bits in these buffers may not be the same but the total number of coded samples will be. When the transmit buffer is approximately full, the receive buffer is nearly empty and vice versa. The status of the transmitter buffer is always known by the receiver, provided there are no errors in the transmission medium (channel). No buffer status signals need be transmitted, though it may be desirable to do so under certain circumstances. The single exception to this occurs when the transmit buffer is empty and its input is at a rate less than that demanded by the digital channel. In this case, the buffer must transmit a dummy signal to mark time until it has enough information to transmit.

The retrace period can be very effectively utilized for clearing the buffer. In television transmission the blanking signals are deterministic, the only uncertainty being in the timing of the synchronizing pulse. Therefore, normal signal transmission can take place.

The design of buffer supervisory signals, framing, etc., are not considered here.

The retrace period can be very effectively utilized for clearing the buffer.
until the leading edge of the sync pulse, after which the period corresponding to the width of the sync pulse and the back porch of the blanking pulse can be utilized for clearing the buffer. According to NTSC television standards for monochrome television transmissions, this gives a minimum period of 8.26 μs during horizontal blanking. In normal transmission the code length for the sample values corresponding to these time intervals will be two bits because the constant level of blanking pulse causes a small prediction error. This implies that for a sampling frequency of 6.0 MHz the buffer is cleared by 48 bits at the end of each line and by 4991 bits at the end of each field. With 30 079 extra bits cleared every field, most of the pictures can be transmitted on an entropy coding system with a buffer of reasonable size without overflow. Furthermore, special circuits could be constructed which would allow almost all of the blanking interval to be used for buffer emptying purposes. This would permit the buffer to be emptied of about $6 \times 3 \times 8 = 144$ additional bits during each horizontal blanking period.

EXPERIMENTAL RESULTS WITH THE DUAL MODE ENCODER

The experimental results we present here are for the DPCM + EC system with a smaller buffer of 4048 bits. We chose a small buffer so we could observe the performance of the system when the buffer is full. The buffer gap we used was 32 bits. Using longer buffer gaps increased the regions of buffer full operation and had no concomitant advantage. Switching between the full and normal modes of operation was done during the horizontal blanking interval. At the end of each horizontal line the buffer contents were observed. If the buffer contents at the end of a line were 4047 bits or less, the system operated in the normal mode with the 16-level quantizer. If the buffer contents at the end of a line were 4048 bits or more, the system switched to the buffer full mode of operation with the 6-

*Actually, the buffer size needed for this system is somewhat greater than 4048 bits; about 5000 bits is adequate.*
level quantizer. The system remained in this full mode of operation until the buffer contents decreased to 4016 bits (buffer gap of 4048 bits — 4016 bits = 32 bits) at the end of a line. During high information parts of the picture, the system switched between the buffer full and normal modes of operation on alternate lines. Special circuits for buffer clearing during retrace were not employed.

Typical of the results we achieved is the picture of "girls" shown in Fig. 7. It was sampled at 6 MHz, encoded by the DPCM + EC system of Fig. 6 and transmitted at a rate of 3 X 6 = 18 Mbits, or 3 bits/sample value. The top of the picture was transmitted with 4 bit quality (i.e., 16-level DPCM). Near the middle of the picture the buffer became full as indicated in Fig. 7(a) and the system begins to switch back and forth between 16-level and 6-level operation on alternate lines. This is the busy region of the picture. Near the bottom the information content of the picture is smaller, the buffer empty, and buffer normal operation is resumed for the remainder of the picture. The picture very closely resembles a 4-bit DPCM picture. Since noise is added in the busy area of the picture where the buffer becomes full it is not very noticeable.

Similar results were obtained for the picture "test chart" and "aerial view." The "Test chart" had one relatively small area where the buffer was full and for "aerial view" the buffer full condition covered almost all of the picture. Fig. 7(b) shows a relatively quiet picture entitled "Judy" which produced several noncontiguous areas of buffer full operation. If a buffer length of 10 000 samples had been used as suggested by Chow [10], the buffer full condition would not have occurred on any of the pictures tested except "aerial view."

CONCLUSION

The dual mode system we described herein is an effective way to combat buffer overflow whenever entropy coding is used in conjunction with DPCM. The system we built and tested had a simple one-tap predictor in the feedback loop. The dual mode technique could easily be incorporated in more advanced DPCM systems which may contain line and/or frame feedback. It can also be used in speech DPCM systems. Regardless of the DPCM configuration the dual mode coder will tend to have these features:

1) It avoids buffer overflow.
2) It provides graceful degradation of the picture when the picture information content is too great for the transmission system.
3) It distributes the "information overload" noise in the high information regions of the picture where it is less noticeable.

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REFERENCES


Analysis of Synchronous Digital-Modulation Schemes for Satellite Communication

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Abstract—The multipath communication channel for space communication is modeled as a multiplicative channel. This paper discusses the effects of the multiplicative channel processes on the symbol error rate for quadrature modulation (QM) digital modulation schemes. An expression for the upper bound on the probability of error is derived and numerically evaluated. The results are compared with those obtained for additive channels.

INTRODUCTION

In a recent paper, Lyon and Holsinger [1] presented an analysis of synchronous—digital modulation and demodulation schemes and derived expressions for upper bounds on the probability of error for various modulation schemes when the received signal was observed in additive white noise. The effect of carrier phase offset was also considered. Here we consider the quadrature modulation (QM) digital modulation schemes, for use in satellite communication, and derive an expression for the probability of error. The upper bound on the probability of error is numerically evaluated and the results are compared with those reported earlier [1] for additive channels.

TRANSMITTER

A general model of a synchronous—digital modulation and demodulation system for QM schemes [1] is shown in Fig. 1. Let $T$ symbol interval
$a_i$ "in-phase" modulator input
$a_q$ "quadrature" modulator input

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