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Entropy Measurements for Nonadaptive and Adaptive, Frame-to-Frame, Linear-Predictive Coding of Video-telephone Signals

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Linear predictive coding is an efficient method for transmitting the amplitudes of moving-area picture elements (pels) in a conditional replenishment coder for video-telephone signals. It has been conjectured that if the linear predictor can dynamically adapt to the speed and direction of motion in the scene, then greatly improved performance should result. To test this conjecture and to get a first-order estimate of the possible saving, computer simulations were carried out using pairs of video-telephone frames stored on digital discs. Using this data, picture quality could not be studied. However, differential signal entropies could be estimated, and this was done for several nonadaptive and adaptive linear predictors. Entropies (in bits per moving-area pel) for adaptive linear predictors were significantly lower than for nonadaptive predictors, indicating that substantial bit-rate savings should be possible. However, simpler implementations will have to be devised before adaptive prediction becomes practicable.

I. INTRODUCTION

In coding television pictures for transmission over a digital channel, it is well known that the required bit rate can be significantly reduced by removing various redundancies that exist in the signal, and in recent years methods for removing frame-to-frame redundancy have been investigated.[1] In a conditional replenishment[2] system, only the picture elements (pels) that have changed significantly since the previous frame are transmitted. Their amplitudes as well as their locations must be sent; however, most of the transmission capacity is used in sending the amplitudes. During periods of rapid motion, only every other moving-area pel need be transmitted, i.e., the moving area of the picture can be subsampled[3,4] at half-rate with the unsampled pels being replaced by the average of their neighbors.

Linear predictive coding is an efficient method of transmitting these amplitudes. Channel rates of 1 bit per pel and below have been obtained.[4–7] With this technique, a prediction is formed of each pel to be sent by computing a linear combination of previously transmitted pels. The difference between the actual value and prediction is then quantized and coded for transmission. Since the differential signal is small usually and large only occasionally, variable word-length coding can be used to good advantage in reducing the overall bit rate.

The entropy of the quantized moving-area differential signal provides an estimate of the average number of bits required to transmit a pel. Thus, it is a good yardstick for comparing the performance of various frame-to-frame predictive coders. The entropy will depend on the amount of detail (frequency and amplitude of brightness variations) in the moving area of a frame as well as on the speed of movement in the scene. The overall bit rate, however, is strongly dependent on the number of pels in the moving area which, in turn, is determined by the type of picture to be transmitted. See Ref. 8 for statistics on the number of moving-area pels per frame in typical video-telephone signals.

In Refs. 9 and 10, and by simple extension of the techniques of Ref. 11, it is suggested that if the predictor can dynamically adapt to the speed and direction of motion in the scene, then greatly improved performance should result. For example, if an object is moving left to right at a speed of about 1 pel per frame period (PEF) then for each moving-area pel of the present frame a very good prediction should be obtainable by going back to the previous frame and looking 1 pel to the left. Other types of adaptive linear prediction are described in Refs. 12 to 14. They suggest that the weighting coefficients in the linear predictor be varied adaptively to make the differential signal smaller.

II. COMPUTER SIMULATION

To get some comparison between nonadaptive and adaptive, frame-to-frame, linear predictors, computer simulations were carried out using about three dozen video-telephone picture sequences stored as 8-bit PCM* on digital disc (two successive frames per sequence). With only two frames available per sequence, picture quality could not be studied. However, moving-area differential signal entropies could be estimated, and this was done for several nonadaptive and adaptive predictors.

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* Characteristics: 30-Hz frame-rate, 271 lines, 2:1 interlace, 3 dB down at 1 MHz, 2-MHz sampling-rate, 8 bits/sample, 210 visible samples/line.

Frame-to-frame noise in the pictures was small—in most cases, less than 1.5 percent of black-to-white signal amplitude. Thus, detecting the moving-area pels was not difficult. This was done as follows:

(*i*) Frame-to-frame differences larger in magnitude than 4 out of a possible 255 were detected.
(*ii*) If a significant change had two insignificant changes directly to the left and two insignificant changes directly to the right, or if it had two insignificant changes directly above and two insignificant changes directly below, it was deemed to be insignificant, i.e., caused by noise rather than movement.
(*iii*) Finally, horizontal gaps of six pels or less between significant changes were deemed to be also in the moving area.

This procedure defines the moving-area very well. See Ref. 4, Figs. 1, 4, and 7 for pictorial examples.

Figure 1 shows some of the pictures used. Figures 1a to 1c are scenes containing a mannequin's head, which could be moved horizontally at various speeds. The smaller the head size, the more detail there is in the moving area. Thus, with these scenes results could be obtained for various speeds and for various amounts of moving-area detail.

About half of the picture sequences were of live subjects engaged in typical video-telephone conversations, such as shown in Figs. 1d and 1e. These scenes were important in comparing different linear predictors because they were more representative of what would normally be encountered in practice. The speed was not constant over the whole moving area as it was with the mannequin head, and there were more variations in lighting and picture detail. For these scenes the speed of movement could only be estimated to the nearest PEF (pels per frame period) by observing the frame-to-frame displacement of the edge of the moving area.

In video-telephone scenes, speeds range from slow (0.5 PEF) to very fast (4 PEF). Very rapid movement is rare, however, and in such instances the viewer is less critical of picture quality since he is already accustomed to seeing blurred moving-areas in cinema and television pictures.

III. NONADAPTIVE LINEAR PREDICTIVE CODING

Figure 2 shows two successive frames with interlacing fields (two interlaced fields per frame). Suppose Z is a moving-area pel we wish to transmit. Pels A, B, C, G, and H are in the field presently being scanned; pels D, E, F, R, S, and T are in the previous field; and the remaining pels are one frame period back from the present field. Pel M is the previous frame value of Z. The general linear prediction of

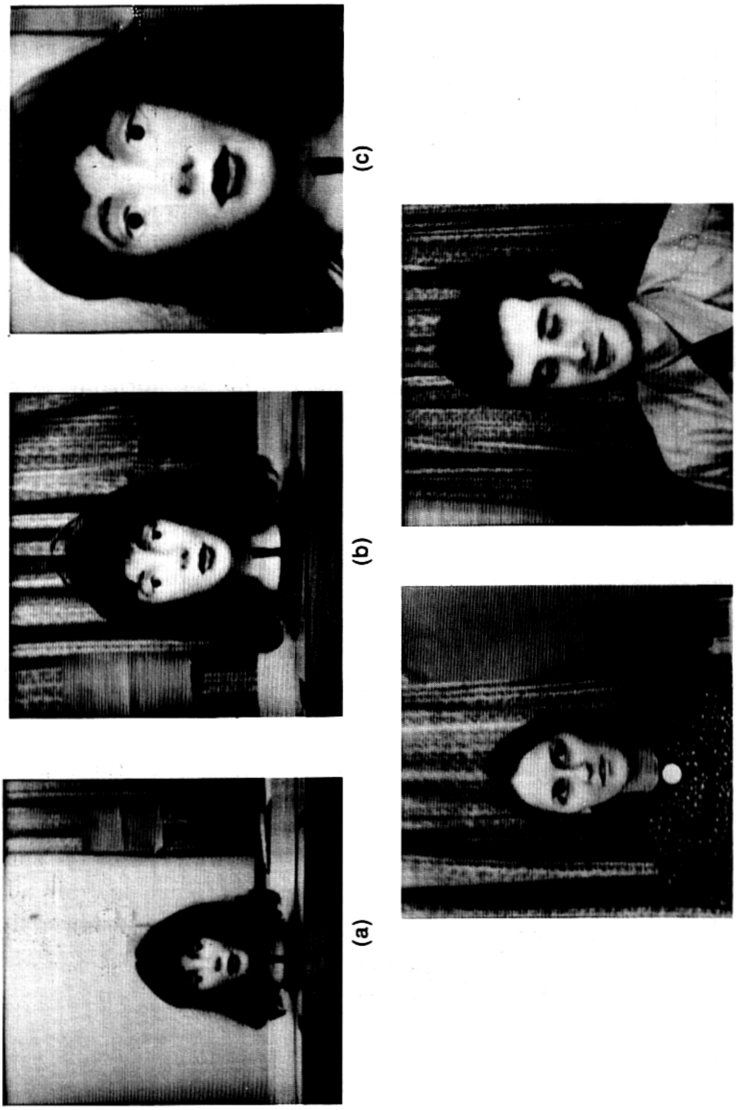

Fig. 1—Typical pictures used in the simulations. (a) Small head. (b) Medium head. (c) Large head. (d) and (e) Live subjects.

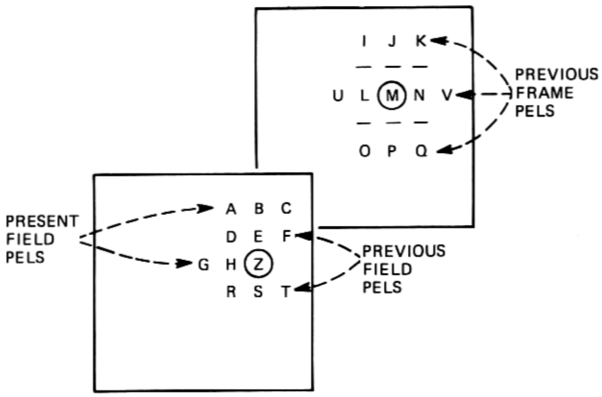

Fig. 2—Two successive television frames with interlacing assumed (two interlaced fields per frame). Pels Z and M are exactly one frame period apart.

Z based on the previously transmitted pels, which are nearby both spatially and temporally, is given by

$$P_Z = \alpha_1 A + \alpha_2 B + \alpha_3 C + \cdots + \alpha_{22} V, \tag{1}$$

where $\alpha_1, \alpha_2, \cdots, \alpha_{22}$ are the weighting coefficients.

Since Z is 8-bit PCM and P_Z is clipped to 8-bit PCM, the differential signal Z-P_Z can assume any of 511 levels. The entropy of the 511-level signal is a measure of the relative performance of different predictors. However, in practice, a more coarsely quantized signal (consistent with acceptable picture quality) would probably be transmitted to reduce the overall bit rate.

Picture quality could not be observed in the simulations. However, to get a rough estimate of bit rate for linear predictors with coarser quantization, a compromise 35-level* quantization scale was chosen that is slightly coarser than the quantizer of Ref. 4 for frame differences and somewhat finer than the one used in Ref. 7 during periods of movement for element differences. Using this quantization scale, slope overload rarely occurs, and the predominant picture degradation is granular noise in the moving areas. This has been verified in recent preliminary simulations using thirty consecutive frames stored on digital disc. Using the nonadaptive and adaptive linear predictors mentioned in this paper, there is little difference in picture quality in the limited picture sample studied. However, much work remains to be done in this area.

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* On a scale of 0 to 255, the levels are: 0, ±5, ±14, ±22, ±30, ±40, ±50, ±60, ±70, ±82, ±94, ±106, ±118, ±130, ±142, ±154, ±166, and ±178.

The effects of the predictive coder feedback loop are ignored in the entropy measurements. Feedback can affect results to a significant degree if quantization is extremely coarse. Even so, the entropy measurements reported here are in close agreement with those of Refs. 4 and 7.

For various nonadaptive linear predictors, Figs. 3 to 8 show the entropy (bits per moving-area pel) of the differential signal as a function of the speed of movement (pels per frame period or PEFs). Results are summarized in Table I. For these cases, more moving-area detail (smaller head) resulted in somewhat higher entropies, as would be expected, but moving-head results were still fairly close to each other. The live-subject entropies were close to the moving-head entropies for the most part, even though there was considerable variation in moving-area picture detail.

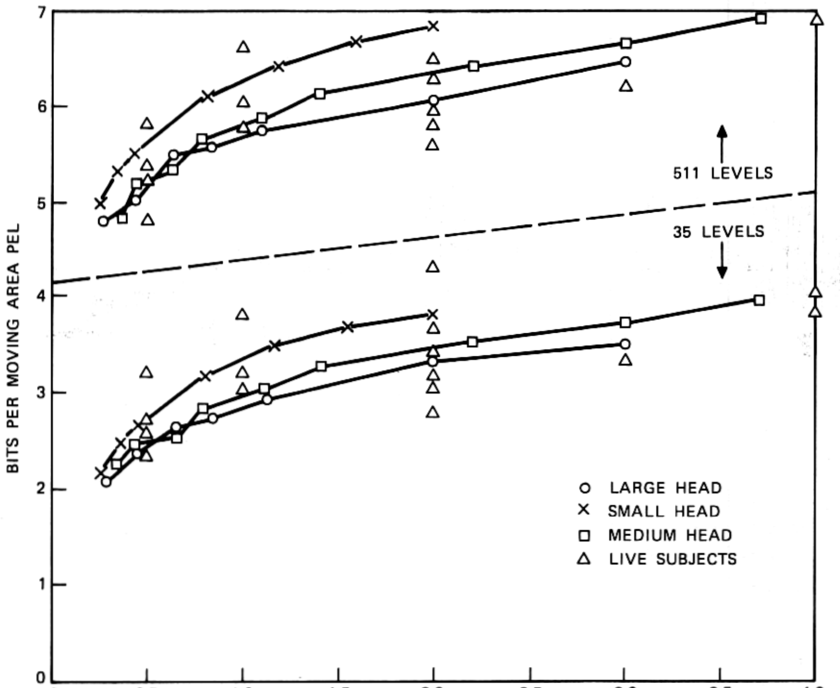

Fig. 3—Entropy of the frame difference signal in the moving area versus speed. $P_Z = M$. Starting with 8-bit PCM as was done in these simulations the differential signal could assume any of 511 levels. Results are also shown for coarser quantization to 35 levels which still gives very good picture quality. Solid curves are for the mannequin head at various distances from the camera. Unconnected points are for live subjects, such as in Figs. 1d and 1e.

Table I — Entropies of some nonadaptive linear predictors

Transmitted Signal $Z - P_Z$	P_Z (See Fig. 2)	Entropies in Bits Per Moving-Area Pel (35-Level Quantization)
Frame difference	M	≈2.1–3.9
Element difference	H	≈2.0–3.7
Element difference of frame difference	$M + H - L$	≈1.8–3.1
Line difference of frame difference	$M + B - J$	≈1.5–3.5
Field difference	$(E + S)/2$	≈1.8–3.2
Element difference of field difference	$H + (E + S)/2 - (D + R)/2$	≈1.5–2.5

The frame-difference[4] entropy (Fig. 3) increases with speed as expected. However, the element-difference entropy (Fig. 4) decreases as the speed increases, because of blurring introduced by the camera.[7] It drops below the frame-difference entropy at a speed of about 1

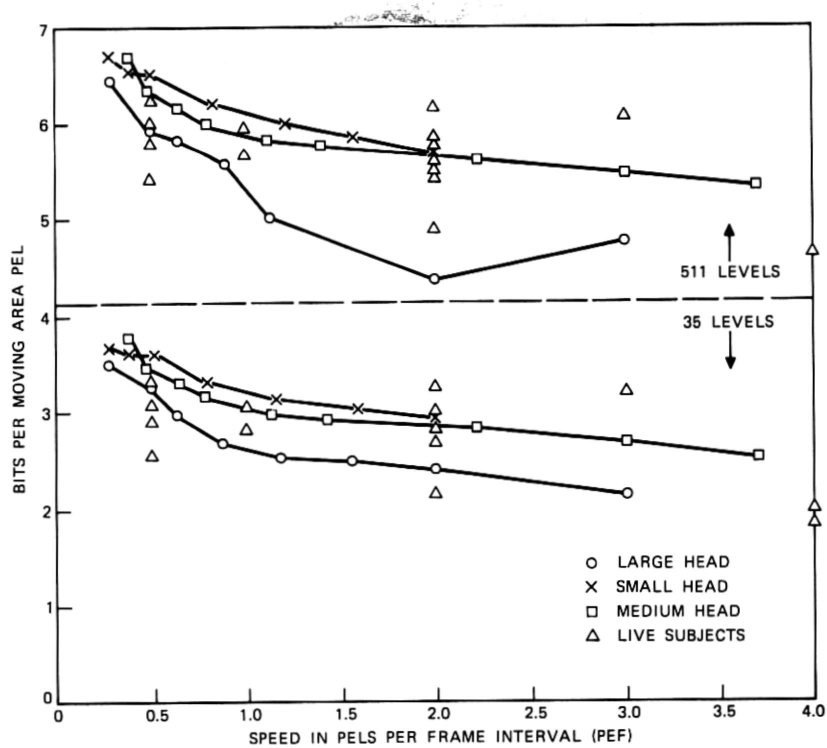

Fig. 4—Entropy of the element difference signal in the moving area versus speed. $P_Z = H$.

PEF.[7] Subsampling at half-rate, however, causes it to rise above the levels shown in Fig. 4.

The element difference of frame-difference entropy[15] and line difference of frame-difference entropy[16] (Figs. 5 and 6) are very close to each other even though with interlace (see Fig. 2) the previous line is further away from pel Z than is the previous element. D. J. Connor has pointed out that this occurs because movement in the scenes is mostly in the horizontal direction. However, the line-difference of frame-difference signal has the advantage of being unaffected by subsampling along the line.

The field-difference entropy[17] (Fig. 7) is lower than the frame-difference entropy, except at very slow speeds, because of the spatial and temporal closeness of the previous field pels. It compares well even with the double derivative signal of Figs. 5 and 6. The element difference of field-difference entropy (Fig. 8) is smaller than any of the others and, other factors ignored, would be the logical choice in a nonadaptive, frame-to-frame, linear predictive coder. However, sub-

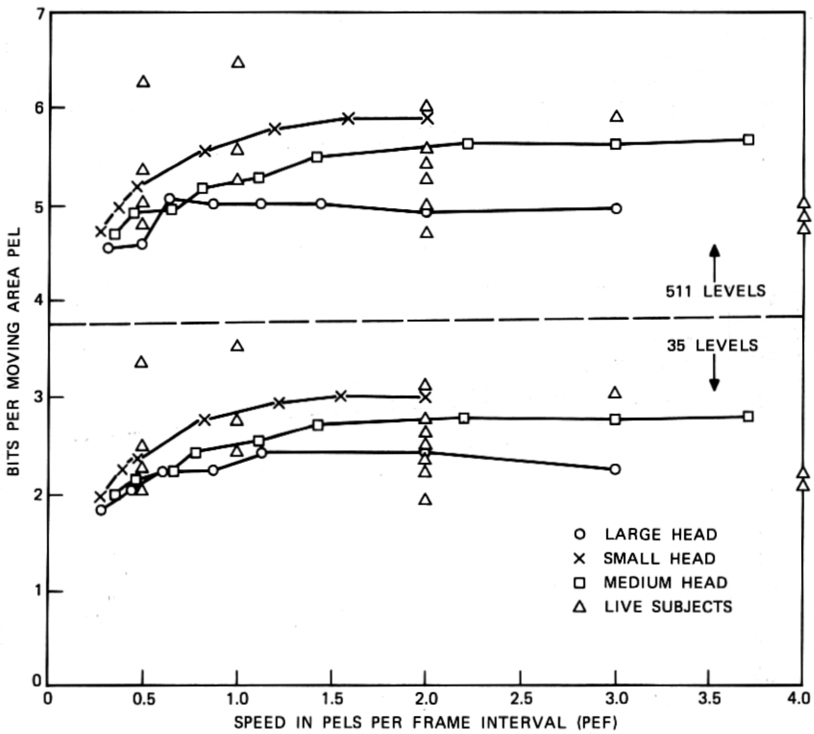

Fig. 5—Entropy of the element difference of frame-difference signal in the moving area versus speed. $P_Z = M + H - L$.

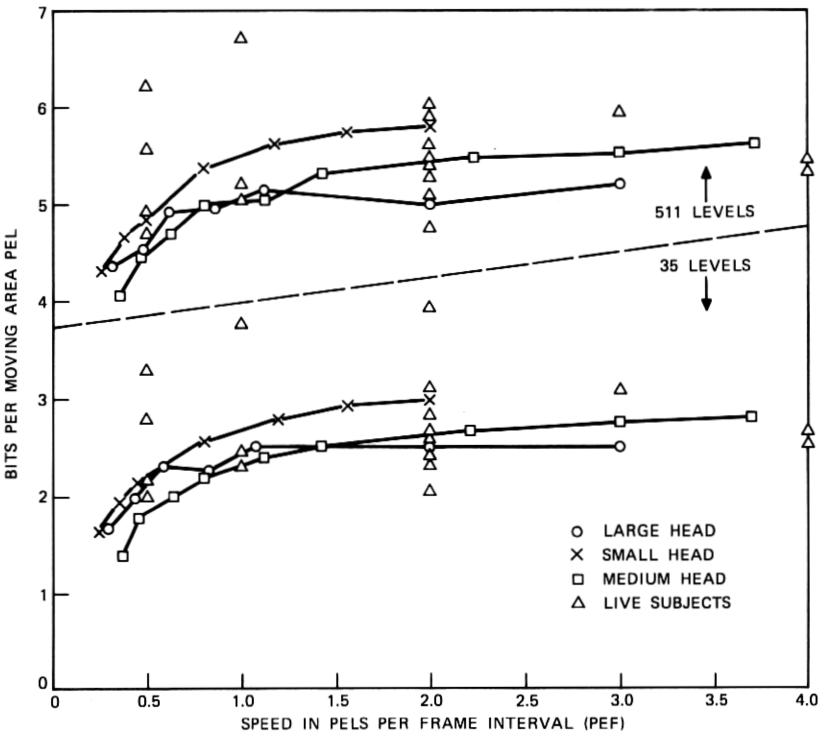

Fig. 6—Entropy of the line difference of frame-difference signal in the moving area versus speed. $P_Z = M + B - J$.

sampling along the line leads to a considerable increase in entropy, putting it above the line difference of frame-difference entropy. Furthermore, conditional vertical subsampling[18,6] makes impracticable the use of any predictive coder that uses previous field pels.

IV. ADAPTIVE FRAME-DIFFERENTIAL CODING WITH MOVEMENT COMPENSATION

In Refs. 9 and 10, and by simple extension of the techniques of Ref. 11, frame-differential coding is adapted to the speed and direction of movement in the scene. Thus, if in Fig. 2 the speed of the moving object is about 1 PEF left to right, then pel L is a much better prediction of Z than M is. Similarly, if movement is 1 PEF right to left, then pel N is a better prediction. Such a coder must first estimate the velocity (speed and direction) of the moving object and then transmit this estimate to the receiver before sending the quantized moving-area differential signal.

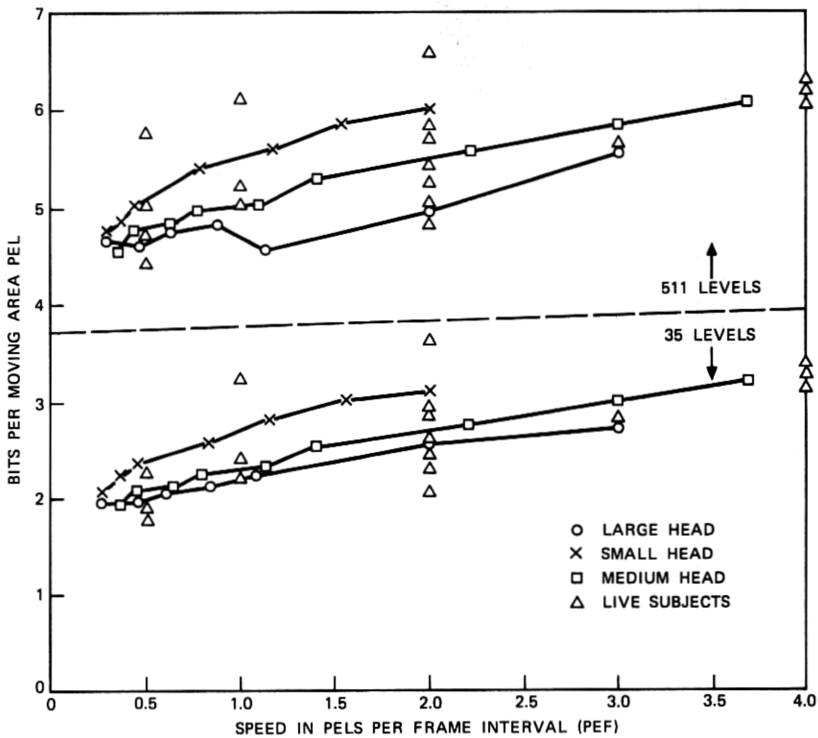

Fig. 7—Entropy of the field-difference signal in the moving area versus speed. $P_Z = (E + S)/2$.

Some computer simulations were carried out to test such schemes. First, each field was divided into 64 smaller blocks of 27 pels × 16 lines each, in an attempt to accommodate velocity variations within the field. Within a block the velocity was assumed constant. Then, for pel Z in the moving-area of a block, the 17 differences (see Fig. 2) Z-D, Z-E, $\cdots$, Z-Q were computed between Z and the six previous field pels and the 11 previous frame pels located relative to Z, as shown in Fig. 2. The magnitudes of these 17 differences were each summed over the moving area of the block. Following this, the 17 accumulated sums were examined to determine the smallest one. Then, for each moving-area pel Z, the pel in the relative position that yielded the smallest accumulated sum was used as a prediction within that block, and statistics of Z-P_Z were measured.

This technique always gave a prediction which corresponded to the correct direction of motion, and was fairly accurate with regard to speed for speeds $\leqq 2$ PEF. However, for a given block, the accumulated sums were all quite close to each other, reflecting the high pel-to-pel correla-

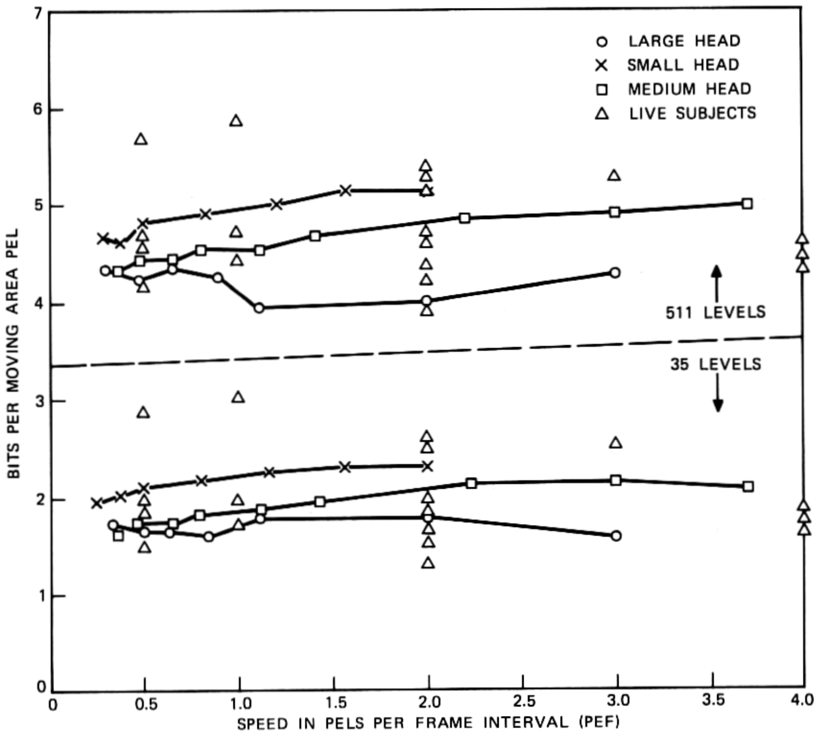

Fig. 8—Entropy of the element difference of field-difference signal in the moving area versus speed. $P_Z = (E + S)/2 + H - (D + R)/2$.

tion present in most television pictures. In low-detail moving areas, of course, tracking was less accurate; but in these regions choice of the pel to be used as a prediction was also less important since they all had approximately the same value anyway.

Entropies of the differential signal Z-P_Z are shown in Fig. 9, again with no additional quantization and with 35-level quantization. Results are comparable to those for the element difference of field difference, but they are much less regular. In addition, there is a sharp dip around 1 PEF where, for the moving head at least, pel L (see Fig. 2) should be a near perfect predictor of pel Z. There is another less sharp dip near 2 PEF. These results are encouraging, but they indicate that movement at a nonintegral number of PEF should be handled in some other manner.

V. MINIMUM MEAN-SQUARE-ERROR LINEAR PREDICTION

In the general case of adaptive linear predictive coding, the weighting coefficients of eq. (1) are changed periodically to obtain a small

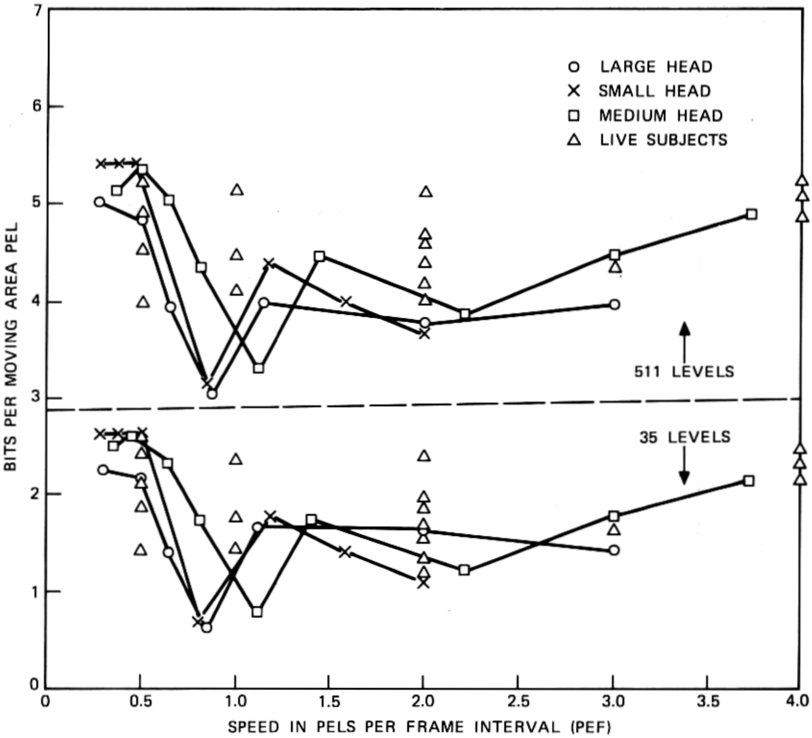

Fig. 9—Entropy of the differential signal in the moving area when movement compensation techniques are carried out. In this case, P_Z equals the pel in the previous field or frame that gives the smallest $|Z - P_Z|$ averaged over the moving area. A sharp dip in the entropy occurs near 1 PEF.

entropy for the differential signal $Z\text{-}P_Z$. If a block of pels is scanned before coding to derive an appropriate set of α's, then these would have to be sent to the receiver, followed by the moving-area differential signals $Z\text{-}P_Z$.

In general, it is not known how to find the α's that minimize the entropy of $Z\text{-}P_Z$. It is possible, however, to determine the α's that minimize the mean squared value of $Z\text{-}P_Z$. As will be seen later, the resulting entropy turns out to be smaller than with any of the previously discussed methods. In fact, using search techniques, it is not possible to find α's yielding entropies very much smaller than those obtained using minimum, mean-square-error (MSE), linear prediction.

Let $\mathfrak{M}$ be the set of moving-area pels in the block of pels presently being scanned, and let Z_i be the ith member of $\mathfrak{M}$. Let $Y_{i1} = A_i$, $Y_{i2} = B_i$, $Y_{i3} = C_i$, $\cdots$, $Y_{i22} = V_i$ be the pels located relative to Z_i, as shown in Fig. 2. Then, to minimize the mean squared prediction error over $\mathfrak{M}$ it is sufficient to minimize

$$Q = \sum_i (Z_i - P_{Z_i})^2 = \sum_i (Z_i - \sum_{j=1}^{22} \alpha_j Y_{ij})^2. \tag{2}$$

Set the partial derivatives with respect to $\alpha_1, \alpha_2, \cdots, \alpha_{22}$ all equal to zero, i.e., for $k = 1, 2, \cdots, 22$

$$\frac{\partial Q}{\partial \alpha_k} = - \sum_i 2(Z_i - \sum_{j=1}^{22} \alpha_j Y_{ij}) Y_{ik} = 0. \tag{3}$$

In matrix notation, these simultaneous equations can be written

$$\mathfrak{A}\boldsymbol{\alpha} = \mathfrak{B}, \tag{4}$$

where the jkth element of the square matrix $\mathfrak{A}$ is

$$\sum_i Y_{ij} Y_{ik}, \tag{5}$$

the kth element of the column matrix $\mathfrak{B}$ is

$$\sum_i Z_i Y_{ik}, \tag{6}$$

and the kth element of the column matrix $\boldsymbol{\alpha}$ is α_k.

Matrix $\mathfrak{A}$ is symmetric, and if it has an inverse, eq. (4) has a unique solution. Otherwise, many solutions exist. Furthermore, any solution to (4) will minimize the Q of (2) since Q is a convex downward function of α.

This procedure should take advantage of many types of redundancy in the picture. By tracking movement in the scene, frame-to-frame redundancy is removed. By using pels in the present and previous field, intraframe redundancy is also removed.

VI. ADAPTIVE CODING USING ONE SET OF α's PER FIELD

In the simulations to be described next, a set of α's was chosen to minimize the squared differential signal averaged over the moving area of the entire field. That is, in the preceding equations, summations with respect to i were over the entire moving area of each field. In this case the α's can be sent using negligible channel capacity.

Entropy results are shown in Fig. 10. Values are significantly less than all of the previously described results. The live subject results are not as good as those of the moving head, however, mainly because of the velocity variation within the moving area of a field. At speeds above about 2 PEF, results are surprisingly good given the pel configuration of Fig. 2, which would, at first, be expected to encompass

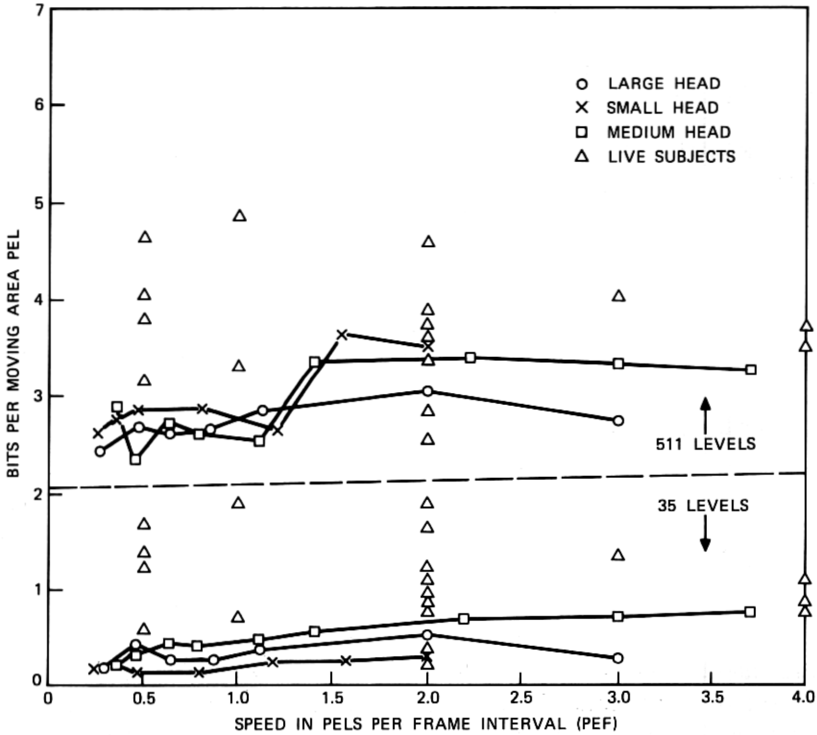

Fig. 10—Entropy of the differential signal in the moving area when minimum MSE linear prediction is carried out. In each field P_Z is the linear combination of the 22 pels shown in Fig. 2, which minimizes $(Z - P_Z)^2$ averaged over the moving area. Entropies are significantly smaller than any of the previous results; however, live subject results are, in general, above the moving area results.

only speeds less than 2 PEF. This may happen because at the higher speeds, significant blurring is introduced by the camera making interpolative predictions more efficient.

Figure 11 shows a representative set of derived weighting coefficients (multiplied by 100) arranged in the configuration of Fig. 2. The speed of the moving head is 0.63 PEF, left to right. Thus, the point on the moving object which is now at pel Z is in the previous frame 0.63 pel to the left of M. The linear predictor places very little weight on pels K, N, Q, and V, since motion is from left to right. It interpolates between pels L and M as it should for this speed, but numerous other differentiations are also present. For example, a form of element-difference of field-difference prediction is attempted in the present frame. Some weight is also placed on previous line pels.

A question which arises at this point is: how much of the removed redundancy is frame-to-frame, and how much of it is intraframe?

Thus, some simulations were carried out where the predictor was only allowed to use pels from the previous frame in its prediction. This is done by deleting in eq. (4) the rows and columns of matrix $\mathcal{A}$ and the elements of column vectors $\boldsymbol{\alpha}$ and $\mathcal{B}$ that correspond to the unused pels. Entropy results are shown in Fig. 12.

The results are practically the same as in Fig. 10 up to a speed of about 1.3 PEF which is nearly the range of speeds for which one should expect good performance, given the configuration of Fig. 2. Thus, most of the redundancy removed is frame-to-frame redundancy. Intraframe redundancy becomes important only when the speed is outside the tracking range of the algorithm.

Some simulations were also carried out to test the effect of subsampling at half rate. In this case the predictor is only allowed to use pels B, D, F, G, J, M, P, R, T, U, and V in the prediction. Entropy results are shown in Fig. 13 for the speed range of 1 to 4 PEF, which is where subsampling would normally be carried out.

Subsampling increased the entropy as one would expect, but the amount of the increase depended on how much detail there was in the moving area of the scene. With 35-level quantization, subsampling increased the entropies by factors ranging from 1.5 to 2.3 for the large head, 1.7 to 2.9 for the medium head, and 3.2 to 4.6 for the small head. As the size of the head decreases, the amount of detail increases and, thus, so does the detrimental effect of subsampling. Of course, if the entropy is more than doubled by subsampling, then subsampling at half rate does not pay.

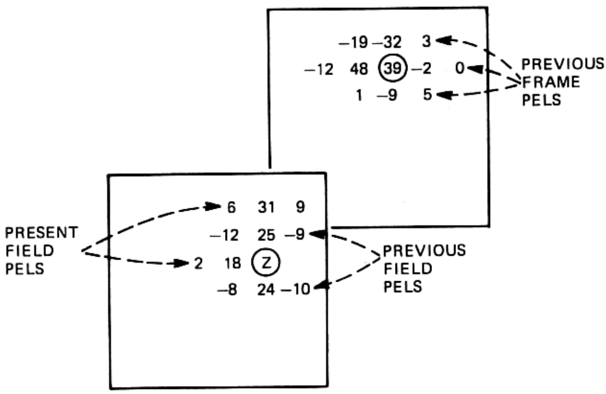

Fig. 11—A representative set of 22 minimum MSE weighting coefficients multiplied by 100 (see Fig. 2). The mannequin head was moving at 0.63 PEF. Thus, a moving object point which is at Z in the present frame was 0.63 pels to the left of M in the previous frame.

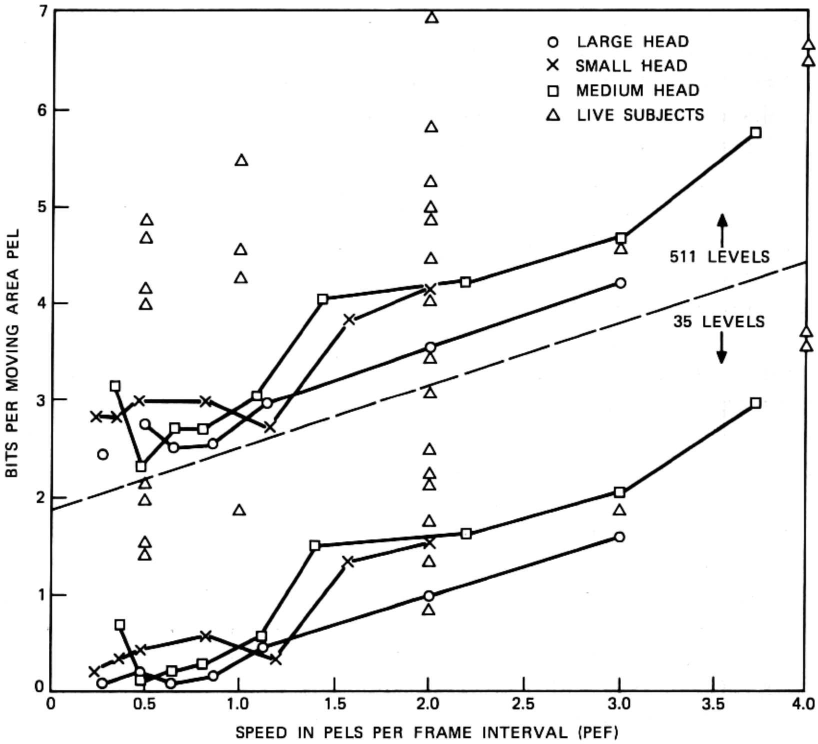

Fig. 12—Entropy of the differential signal in the moving area with minimum MSE linear prediction; P_Z is a linear combination only of the 11 pels in the previous frame. Results are about the same as those in Fig. 10 up to a speed of 1.3 PEF. Thus, in this range, the coder is removing mostly frame-to-frame redundancy.

VII. SUBDIVISION OF THE FIELD INTO SMALLER BLOCKS

In Fig. 10, where one set of weighting coefficients is used for the entire moving area of the field, the entropies corresponding to the live subjects are, in general, larger than those of the moving head because the head moves with pure translation, whereas different parts of live subjects move with different velocities. Velocity variations within a field can be accommodated by first dividing the field into smaller blocks, and then using a different set of weighting coefficients within each block. The α's which give the minimum mean square prediction error over the moving area of a given block can be computed from eq. (4) exactly as before.

Some simulations were carried out to determine the effect of using smaller blocks. A slightly different set of pictures was used for these computations than was used for the previous results. The mannequin head was slightly larger than in Fig. 1b, but the live subjects were

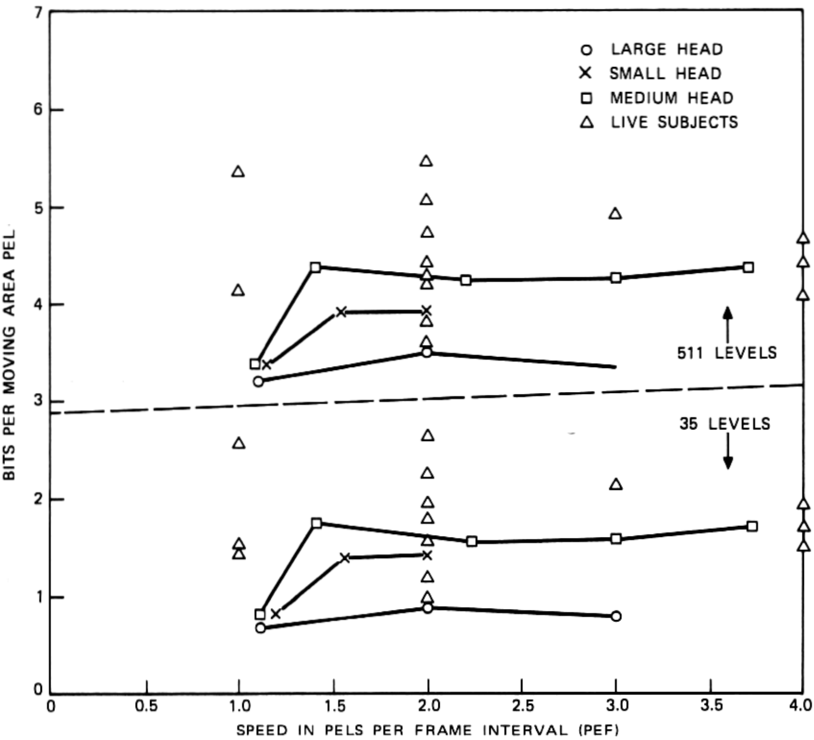

Fig. 13—Entropy of the differential signal in the moving area with minimum MSE linear prediction with subsampling, i.e., P_Z is a linear combination only of pels B, D, F, G, J, M, P, R, T, U, and V.

about the same as in Figs. 1d and 1e. It was found in the simulations that the determinant of matrix $\mathcal{A}$ in eq. (4) was frequently zero, indicating nonunique solutions, i.e., one or more of the α's could be chosen arbitrarily. In this case, the arbitrary α's were set equal to zero and, whenever possible, they were chosen to correspond to pels in the present frame.

Figure 14 shows entropies for 511-level differential signals. The uppermost curve and its associated live-subject points are obtained with no subdivision, as in Fig. 10. The single points are all above the moving-head curve, as before.

The middle curve and points are the entropies which result from subdividing the field into 120 blocks (10 horizontal $\times$ 12 vertical) and using a different set of weighting coefficients for each block. Each block is 21 pels $\times$ 10 lines. Not only are the single points closer to the moving-head curve, but all of the points are considerably below those obtained using no subdivision. Using smaller blocks, therefore, not only ac-

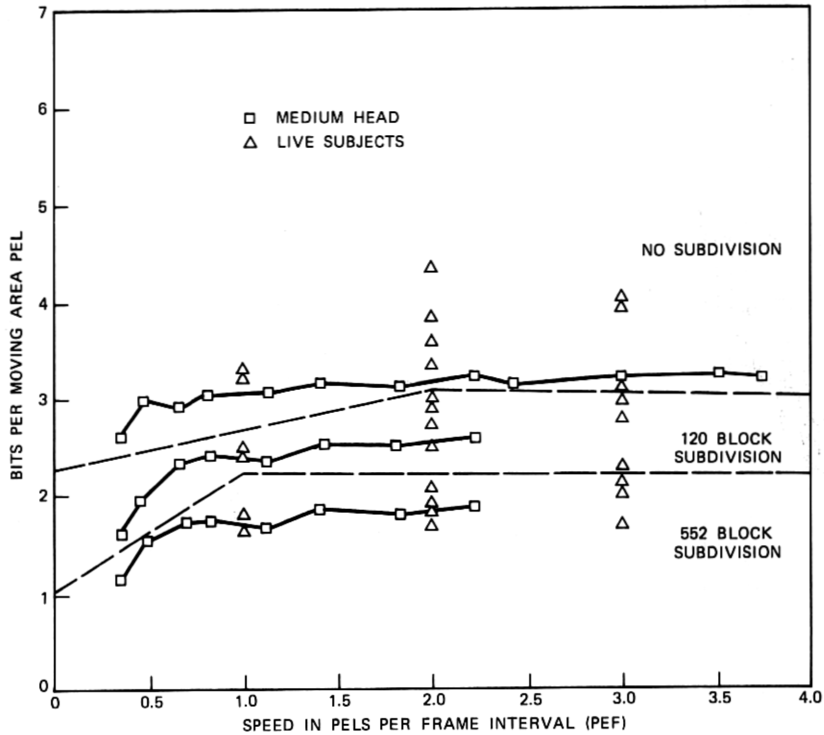

Fig. 14—Entropy of the differential signal in the moving area with minimum MSE linear prediction and prior subdivision of each field into smaller blocks. A different set of weighting coefficients is used in each block. As the block size is reduced, the live-subject results come closer to the moving-head results because variations in velocity within a field are accommodated. In addition, all entropy figures are reduced because more intraframe redundancy is removed.

commodates variations in velocity within the field, but it also removes some in-frame redundancy that could not be removed previously.

There is a penalty to pay, however. The α's of each block in which there is movement must be transmitted to the receiver so that it can correctly decode the received differential signal. If the α's are sent via 8-bit PCM, and movement occurs in 50 percent of the blocks, then $22 \times 8 \times 60 = 10{,}560$ bits (or about 0.84 bit per moving-area pel) must be transmitted just to send the α's. Clearly, some alternate method of transmitting the α's should be used. For example, they might be estimated from the minimum MSE α's of some nearby previously transmitted block, or the vector $\boldsymbol{\alpha}$ might be chosen from some predefined finite set of vectors known both to the coder and decoder.

With even smaller blocks the entropies are further reduced. The bottom curve and points of Fig. 14 result from subdividing the field into 552 blocks (23 horizontal × 24 vertical). Each block is 9 pels × 5 lines. Coarse quantization of the differential signal in this case gives zero nearly always. Thus, nearly all of the information about the pels is carried in the weighting coefficients which, with 50 percent of the area moving, require 48,576 bits for transmission using 8-bit PCM. So if the blocks are made too small, the algorithm is inefficient because of the bits required to send the α's.

VIII. CONCLUSION

In a conditional replenishment system for transmitting video-telephone pictures, the moving-area picture elements can be coded for transmission in many ways. Sending frame-to-frame differences and subsampling at half rate during active movement is simple, reasonably efficient, and does not fail catastrophically with an occasional transmission error. Sending line-to-line differences of frame-differences and subsampling during active motion is even more efficient and is reasonably simple, but it is somewhat less impervious to transmission errors.

Adaptive linear predictive coding, which takes into account the speed and direction of movement in the scene, results in much greater coding efficiency, indicating that substantial bit-rate savings should be possible. However, system complexity and vulnerability to transmission errors are increased accordingly. This means that some kind of error detection-correction scheme is absolutely necessary if adaptive coding is to be used.

Adaptive coding, which handles speeds of a nonintegral number of PEFs, performs better than if an integral number of PEFs is assumed. Relatively good results are obtained if for each block in the picture the weighting coefficients are chosen to minimize the mean squared moving-area differential signal. This technique requires transmission in some way of the weighting coefficients so that the decoder can correctly decode the received differential signal. Thus, if the block size is too small, then the system is inefficient because of the number of bits required to send the coefficients. However, even using only one set of weighting coefficients per field (block size = entire field), significant reductions in differential signal entropies are measured compared with nonadaptive coding.

Much work remains to be done before these techniques can be used in a practical coder. For example, the subjective aspects of interframe coders which track moving objects are as important as the statistical aspects which are discussed in this paper. Also, many short cuts in implementation must be developed before these methods are economical. Nevertheless, these results provide a valuable yardstick with which simpler and more practical adaptive frame-to-frame coders can be compared.

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