Predictive Image Coding with Pseudo-Laplacian Edge Detector

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(ABSTRACT)

Several edge-adaptive dual-mode Predictive coding systems are proposed for encoding monochrome video signals. These algorithms use the Pseudo-Laplacian edge detector to switch between the textural coding and the edge coding. The one-dimensional Song DM coder and the two-dimensional weighted average prediction DM coder were used as the textural coding. The edge coding was done with either normal two-dimensional Song DM coder, DPCM schemes of Graham, or DPCM coder developed by the author. Nine different combinations of texture and edge coding techniques were developed and simulated. The bit rates of all the schemes were compared and the range varied between 2.28 - 3.46 bits/pixel without further compression of the edge information bits nor the correction bits. The subjective test on the selected images obtained with the developed schemes was carried out. The result showed that most of the pictures obtained with the techniques in this paper are superior to the pictures coded by the Song mode normal two-dimensional DM coder alone.

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Finally, the author wants to dedicate this work to his parents without whom this research could not be done.

Table of Contents

List of Illustrations

List of Tables

1.0 Introduction

Research on Predictive coding has now been carried out for about 30 years. One of the main advantages of Predictive Coding systems over other coding systems, such as transform coding, is its simplicity in algorithm and hardware. The field of Predictive Coding is divided mainly into two parts. One part is the Differential Pulse Code Modulation (DPCM) and the other is the Delta Modulation (DM).

The DPCM coder has a multi-bit quantizer in its feedback loop while the DM coder has a 1-bit quantizer in it. The other subtle difference is that the DPCM coder contains a more sophisticated predictor than that of DM coder. But the most significant difference can be found when we observe the predicted waveforms which follow the input signal to the coders. If the step size of the DM coder is fixed then the output of the coder cannot follow the input signal unless the sampling rate is increased to compensate the overload effect.

The researchers of DM have produced a more advanced technique called adaptive DM coding [17-21]. The system can vary its step size depending upon the previous outputs. This scheme seemed to a defiant challenger to the DPCM scheme but the accuracy in the reproduction of images was still inferior to that of DPCM. Song [6] has developed an analytical approach to the design of the DM coder and the result showed that many previous intuitive methods [18-21] could be derived from the equations he had developed.

Meanwhile, the researchers on the DPCM side continued improving the predictor and the quantizer parts. The primitive form of the predictor is made of a linear predictor which is obtained by minimizing the mean square prediction error (mse) between the actual sample and the predicted one. The predictor coefficients thus obtained can be fixed or adaptive. Also the number of picture elements for prediction was increased but gave no significant improvement in picture quality [22]. Some had developed two-dimensional predictors and could enhance the rendition of vertical edges which the one-dimensional predictors could not achieve [23]. The others concentrated on the interframe coding systems which used previous frame elements as well as present frame elements as reference pixels, but could not use them for high motion pictures.

There were schemes which let the prediction change based on the local properties of the picture signal. They consisted of several different predictors so that they could be switched depending upon certain neighborhood conditions [3,4,24]. A simple example is Graham's predictor [3], which selects either previous line or the previous element for the reference pixel.

The question arises at this point. Is DPCM coding really necessary for the whole part of the image? Is there any area in an image where accurate coding such as DPCM is not necessary? The multi-mode coding method may answer the question. If we can divide an image into a few areas, so that appropriate coding algorithms can be applied to each area, then we can eliminate the redundancy caused by the unnecessary high quality coding method. Usually, the region is divided by two parts : the high frequency region and the low frequency region. If the frequency is measured in one-dimension then the high frequency region can be found by one-dimensional edge detecting algorithm or just monitoring the large change of signal values. On the other hand, if the frequency is measured in two dimension a two-dimensional edge detector is used.

A method called a dual mode coding which was a combination of DPCM and DM coding methods was studied by Frei [13]. In this method the smooth areas with not much variation in gray level are coded in DM mode but when the coder encounters a sharp change in gray level, the coder switches to the DPCM mode. The predictor is one-dimensional so the reference pixel is always the previous pixel. The deviation between the present and the past sample is always monitored to switch the coder between the two coding schemes. The switching from DM mode to DPCM mode is done by detecting three equal DM bits within one sampling interval. On the other hand the transition from DPCM to DM coding occurs when the coder detects a smallest DPCM word preceded by a DPCM word of opposite sign. The conditon is interpreted as the DPCM idling state.

The DPCM codec (coder-decoder) using a switched quantizer was developed by Kaul [25]. The number of quantization levels can be increased substantially with this method. This system has just one DPCM coder and does not switch between different coding schemes but switches between two different modes in the code assigner. The idea is adapted from the sliding scale direct feedback PCM codec by Brown [26]. The system is made of a purely digital loop which means that the input to the loop must be a digital signal. The sample is classified as an edge if the magnitude of the difference signal exceeds some threshold. In the non-edge texture area, a certain number of least significant bits of the difference signal are transmitted. The two boundary levels of the non-edge signal are used to signal the receiver that it is an edge and the coder sends the same number of most significant bits to the receiver.

A different approach to the edge coding is done by Graham [10]. The edges were found with two-dimensional operators such as gradient or Laplacian. The locations of the contours were coded and sent to the receiver. The method exploited the psychophysical phenomenon that visual system accentuates the contours (***Mach phenomenon*** [11]) and brightness change is distorted in perception. Hence similar distortion in transmission can be tolerated by the human eyes. The locations of the contours were reproduced with a high frequency signal called ***synthetic high*** . The texture area was low-pass filtered to have a blurred look because the area is not the detail of principal interest to the observer and coded with low bit-rate PCM. At the receiver two-dimensional reconstruction filters are used to synthesize the high frequency picture from the decoded edge information. Finally, at the receiver, the ***synthetic highs*** signal is added to the low-pass filtered picture to yield a sharper looking picture.

The method developed by Hunt [14] shows a similar property with the previous schemes in that it divides the image into two areas, one with high spatial frequency and the other with low spatial frequency. The low frequency area is coded with low bit rate and the higher with high. He used a coding scheme called interpolated DPCM which extracts subsamples from the original image ,quantizes at a fixed number of bits, and transmit them. The subsamples are then interpolated at the receiver. Meanwhile, high frequency coding is done in high detail regions. The edge detector which he suggests using is a discrete optical sensor array and a simple digital processor. The switching is done between the subsampler-quantizer circuit and the single quantizer circuit by the edge detector. The resulting images had sharp reproduction of the edges but the texture areas were blurred too much, so that the method cannot be used in commercial systems.

The ultimate goal of this thesis is to devise an algorithm which can code the images efficiently without losing too much subjective quality. The dual-mode coding approach was used. The two modes consist of Delta Modulation (DM) and Differential Pulse Code

Modulation (DPCM). In the low detail area the DM technique was used while in the high detail area the DPCM or more accurate DM method was used. For partitioning the high frequency and low frequency regions, the Pseudo-Laplacian edge detector [1] was used. The edge detection method above requires a large window of a size 7x7 and it involves a large number of calculations. Also the detector takes up a huge circuit. So why use that kind of circuit to detect edges? With the advent of VLSI, the circuits which were impossible to apply to the communication systems can now be made in small chips. Hence the complexity of the circuits can no longer be an obstacle. The Pseudo-Laplacian edge detector circuit described by Deo [27] uses a pipeline structure and suggests that it can be easily implemented in VLSI.

Chapter 2 deals with the edge detection algorithms. The Pseudo-Laplacian edge detector [1] is explained in detail and the reason why it was selected for the combination with predictive coding is explained. The edge detector, having a capability of detecting two kinds of edges : ***black edge*** and ***white edge***, can improve the dual-mode coder performance significantly. Mainly, the overshoot, which is the primary defect in Adaptive DM technique, can be eliminated with this detector.

In Chapter 3, the predictive coding algorithms are reviewed and selected. In order not to make the system too complex, the simple predictor and quantizer was selected for the DPCM part in edge coding. For the texture coding, an Adaptive DM coder developed by Song [6] was reviewed in detail and applied.

In Chapter 4, many combinations of Predictive Coding methods are discussed. The main goal is to reduce the bit rate as much as possible without degrading the subjective quality of a picture. The edge coding and the texture coding methods are varied to give the satisfactory results. The texture coding is fixed to two kinds of DM coding to limit the bit rate on that part to 1 bit/pixel. Hence the one-dimensional and two-dimensional

DM coding methods were tried on the texture coding. For the edge coding many different methods of DPCM and DM were reviewed and developed. The quantization method for DPCM coding was adopted from Max's work [5].

Chapter 5 illustrates the simulation method and experiments with the results of the previously studied coding methods. In simulation, the critical point is the delays introduced by the use of edge detector. The methods of reducing the delay are discussed. The bit rates of all the developed coding schemes are obtained and compared. The equation for calculating the bit rates is shown. The subjective test on the coded images is done with rank ordering so that it could give the author some feedback on the reaction of viewers to the various coding methods. The study on obtaining some statistical relationships between DM bits and edges was done and the result is shown. The root-mean-square errors of the coded images are calculated and compared in order to know which coding method reproduces the original more faithfully. Finally, the difference images from each of the four major groups of coding methods were obtained and compared.

2.0 Edge Detection Algorithms

2.1 Conventional Edge Detection Algorithms

There are many edge detection algorithms which utilize difference operators that respond to changes in gray level or average gray level. For the purposes of this research, only two kinds of the edge detection mechanism, gradient and Laplacian, will be reviewed.

Consider Fig. 1 which shows the difference in performance between the one-dimensional gradient and Laplacian edge detection methods. G(t) is the gradient function expressed as follows;

$$G(t) = \frac{f(t+1) - f(t-1)}{2} \qquad [2.1]$$

L(t) is the Laplacian function with the expression;

$$L(t) = f(t+1) + f(t-1) - 2f(t) \qquad [2.2]$$

The gradient method responds to the first order directional derivative following the edge while the Laplacian approximates the second order directional derivative. The locations of the edges found by the two types above are quite different. The gradient type locates the edge in the middle of the transition zone while the Laplacian type can locate either in the brighter section or the darker section of the zone. Call the former the ***white edge*** and the latter the ***black edge***. Note that if the signal becomes noisy as on the right hand side of the figure, the Laplacian cannot detect the edges clearly.

As will be discussed later, the property of the Laplacian edge detector locating two kinds of edges can be utilized very efficiently in coding the image waveforms. According to experiments by Nadler [2], the Laplacian using the ***black edge*** works very well with human faces. It reproduces the nose and the whites of the eyes perfectly while other methods such as gradient and white edge Laplacian distort many important features of human faces.

2.2 Pseudo-Laplacian Edge Detector

We have noticed in the Fig. 1 that the normal Laplacian edge detection algorithm is useless when noise is present in an image. It is highly sensitive to the background noise which disturbs the viewers from recognizing important objects in an image.

As discussed before, the gradient type edge detector finds edges in the middle of transition ranges and is immune to noises such as spot noise, etc., where Laplacian type finds the edges of zonal change. Nadler [1] found an edge detector called Pseudo-Laplacian

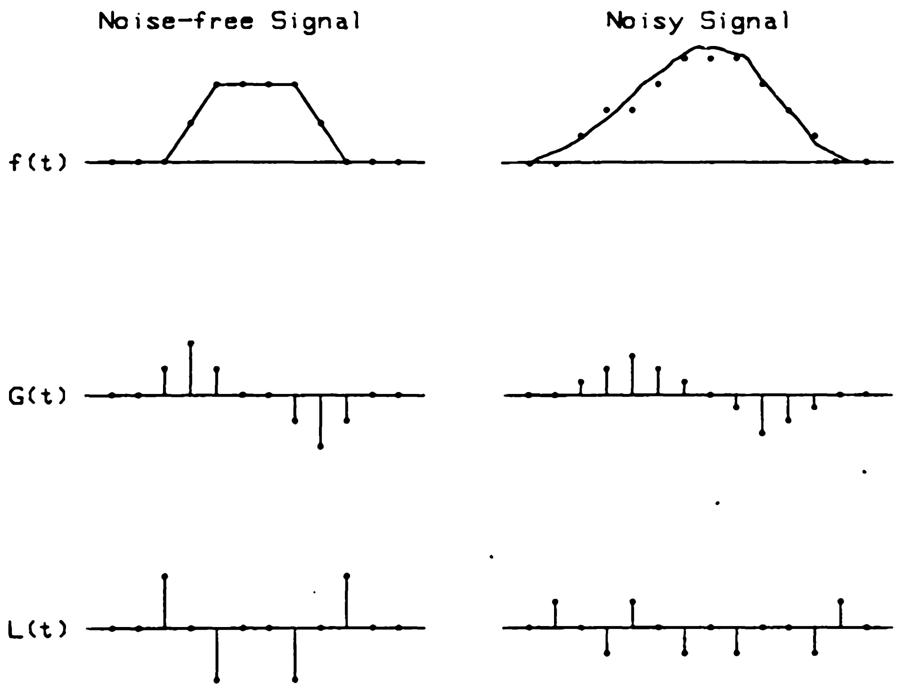


Figure 1. Comparison of the Gradient and Laplacian Edge Detectors

edge detector[1], which is a modification of a normal Laplacian edge detector that can reduce the noise significantly.

The basic process of finding the Pseudo-Laplacian edges is illustrated in Fig. 2. Let's consider the noisy signal in Fig. 1. First, the gradient vectors, G(t), are obtained. Then the vectors are normalized to 1's filtered by a threshold operation.

$$g(t) = 1 \qquad \text{if } G(t) \geq 1 \tag{2.3}$$

Hence only the gradient vectors which are above some given threshold survive. Next, the normal vectors are differentiated again to give a Laplacian of the point;

$$l(t) = g(t + 1) - g(t - 1) \tag{2.4}$$

The improvement of the function l(t) over the function L(t) in Fig. 1 in reducing the noise components is significant.

The basic theory above can be applied to the 7x7 window specified in Fig. 3 [1]. The large-window Pseudo-Laplacian edge detector works as follows. Around the center pixel of the window, obtain the gradients of the vectors specified. If the gradient has a positive value and is above some preset threshold, T_1, it contributes to the white edge because it is decreasing outward from the center. So add one to the ***white sum***, C(+). Otherwise, it contributes to the black edge so add one to the ***black sum***, C(−).

After summing up the arrays C(+) and C(−) for one window, check if the arrays C(+) and C(−) themselves have enough values to be assigned as a ***black*** or a ***white edge***. If only ***black edge*** is considered then compare in the following way.

---

[1] The edge operator which is discussed in this paper has no relation to the Schachter et al.'s Pseudo-Laplacian edge operator [31].

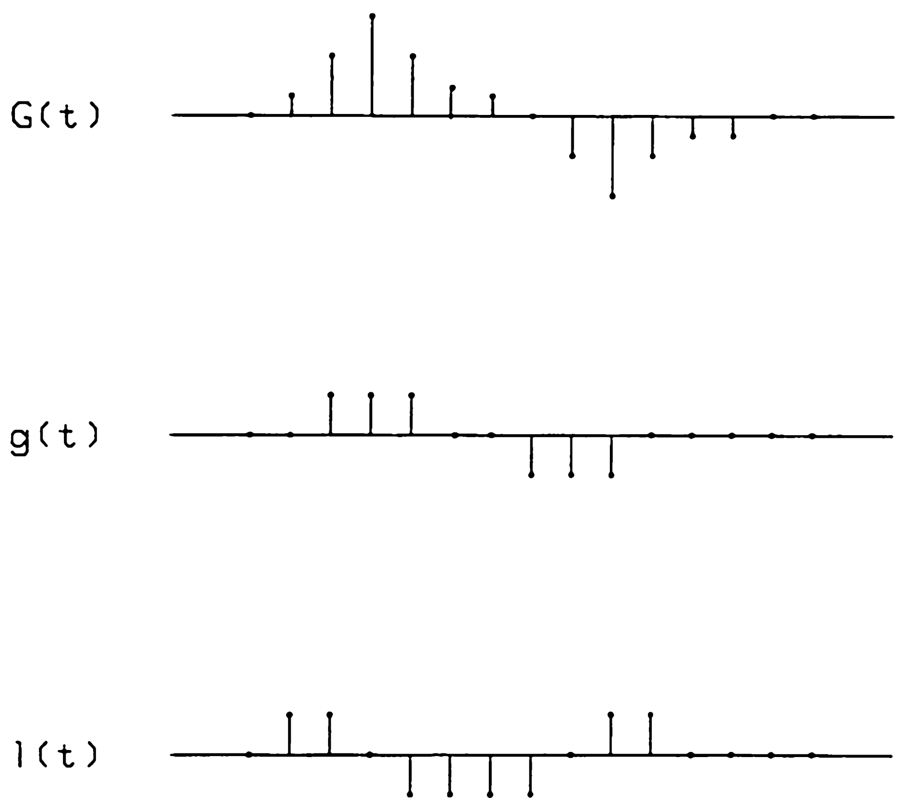


Figure 2. The Procedure of Pseudo-Laplacian Edge Detection

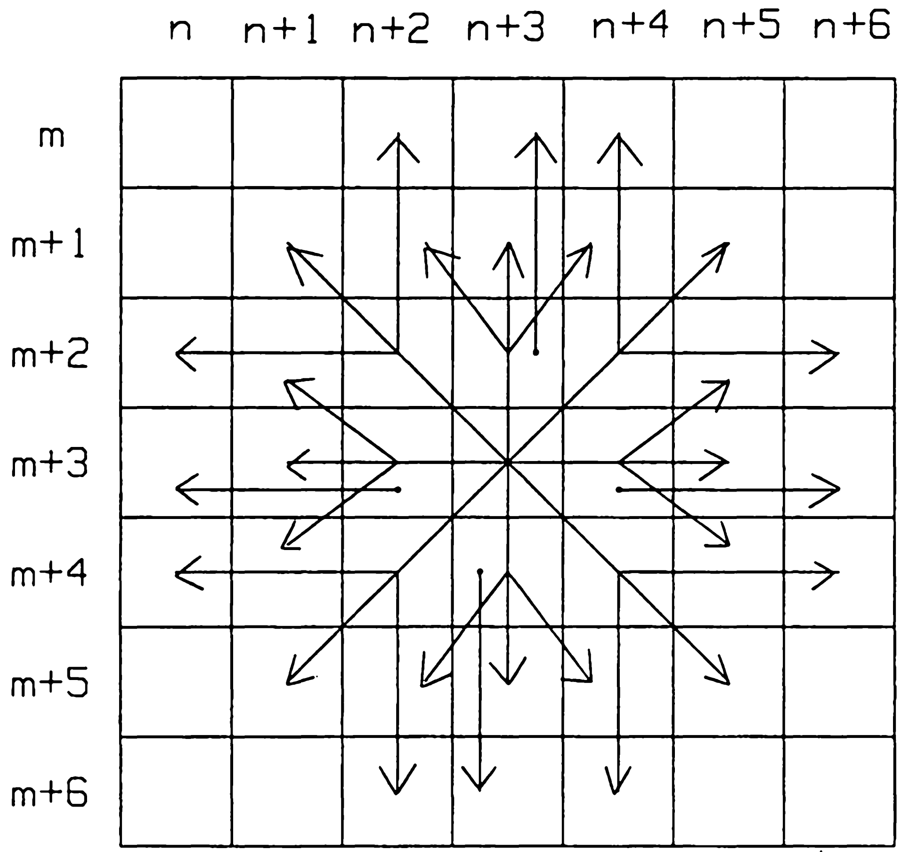


Figure 3. Gradient Window of Size 7X7 for Pseudo-Laplacian Edge Detector

$$C(-) > T_2 \qquad [2.5]$$

This scheme is different from the gradient edge detection scheme in that it requires T_2 first order directional differences greater than T_1 instead of requiring that the maximum be greater than a given threshold.

Next, the sums C(+) and C(−) are compared against a threshold T_3 in the following way.

$$C(-) - C(+) > T_3 \qquad [2.6]$$

This operation assures that the possibility of being a ***black edge*** is more than that of being a white edge. The procedure for finding the ***white edge*** is similar to the above method except that C(−) and C(+) are interchanged. The image obtained by ***black edge*** detection is shown in Fig. 4. The 7x7 gradient window was used.

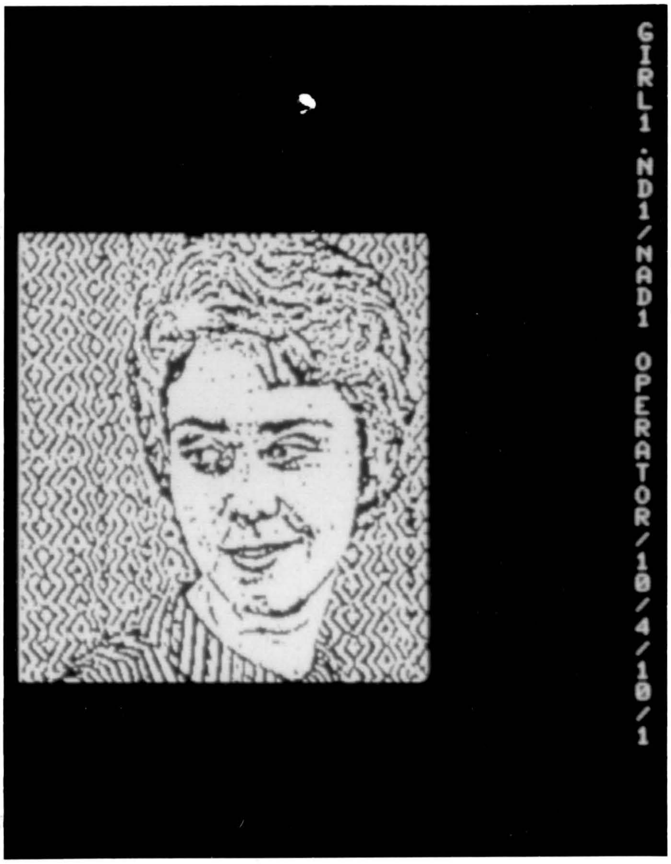


Figure 4. Edge Image Obtained with Pseudo-Laplacian Edge Detector: 7x7 window, black edge

3.0 Predictive Coding Systems

3.1 Differential Pulse Code Modulation (DPCM)

The differential Pulse Code Modulation (DPCM) coders constitute one of the most important examples of Predictive coding systems. The waveform redundancy is utilized to reduce the bit rate for a specified quality of digitization. The block diagram of the DPCM coder and decoder is shown in Fig. 5.

The predictive coder consists of three basic components: 1) predictor, 2) quantizer, 3) code assigner. The Delta Modulation (DM) system is realized by the one-bit quantizer and a simple predictor, as will be discussed in the next chapter.

3.1.1 Prediction

There are linear predictors which use the coefficients obtained by minimizing the mean square prediction error (mse) between the actual sample and the predicted sample. In this

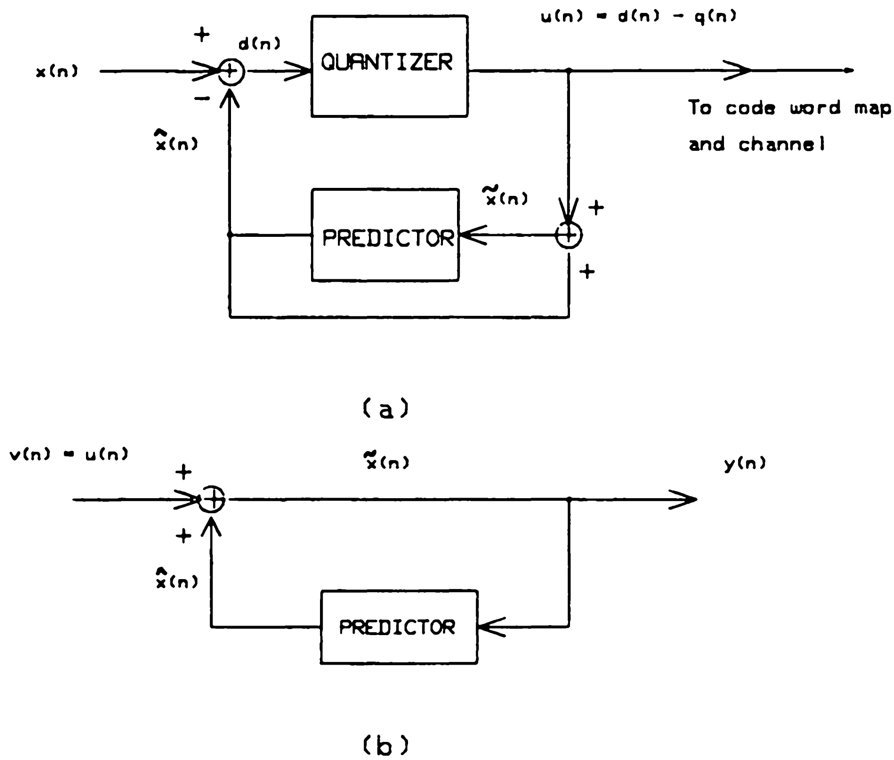


Figure 5. Predictive Coding System: (a) Coder, (b) Decoder

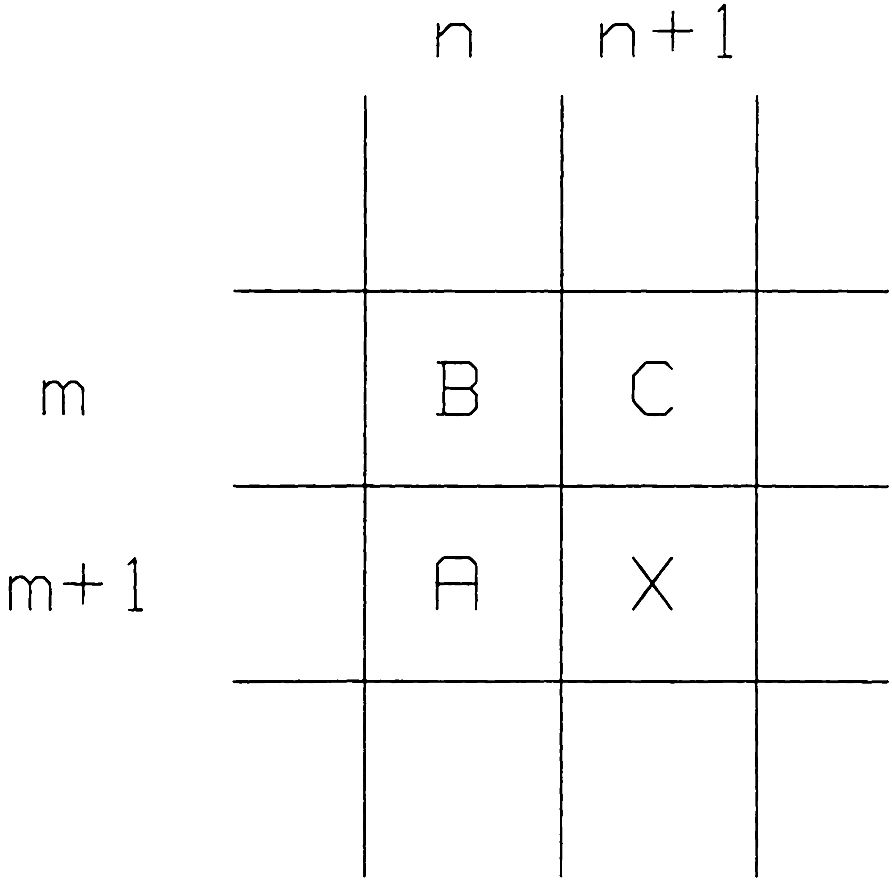
method the weighting coefficients for the predictor have to be determined by using the statistical information of the image so that they can be multiplied by the prescanned pixel values to form a predicted value. The differences between the actual and the predicted samples have lower variance than the original image samples. After the quantization the difference values are coded for transmission to achieve compression.

This DPCM scheme is rather sensitive to variations in image statistics. The images usually do not show stationary statistics while the DPCM weighting coefficients are fixed to optimize one kind of image statistics. Hence the problem with this predictor scheme is that the predictor coefficients should always be matched to the statistics of a picture, which is impossible.

The DPCM systems of high complexity may use the adaptive predictors matched to the short time input spectrum and/or use the distant-sample-memory for utilizing the waveform periodicities (interframe predictors). But these approaches are too complex to be applied to the schemes proposed in this thesis. The prediction must be carried out in a simple way and doesn't have to be very accurate, as most of the state-of-the-art DPCM predictors demand.

There are prediction schemes which compute measures of directional correlation, based on the local neighboring transmitted pixels and use it to select a predictor along the direction of largest correlation. One example is the Graham's predictor [3], which uses the either previous line or previous element for prediction. Figure 6, on page 18, shows how it selects the predictor depending upon the surrounding information.

As will be discussed in Section (3.2.4), this scheme is equivalent to the weighted average prediction scheme for the two-dimensional Delta Modulation coder.



$$
\begin{aligned}
\hat{X} &= \text{Predictor for X} \\
&= \begin{cases} A & \text{if } |C - B| \leq |A - B| \\ B & \text{Otherwise} \end{cases}
\end{aligned}
$$

Figure 6. Graham's Predictor

Also there is a more complex switched prediction scheme by Zschunke [4], which uses 4 neighbors of the previous pixel. If one of the neighbors of the previous pixel was chosen as the closest one to the previous pixel, then the direction to the chosen pixel is stored and it is used to pick the reference pixel of the present pixel. Hence the reference depends on the most likely direction of the image contour.

The determination of the direction is made on the basis of reconstructed pixels so that no information is needed to be transmitted to the receiver. This scheme might be suitable for coding the whole image but it is inefficient for coding of the edges which usually are thin horizontally.

The prediction schemes which will be used in this paper are the ones which are suitable for the characteristics of edges. The correlations between the edges must be considered as well as the correlations between edges and non-edge pixels. Sometimes the direction bit will be sent to allow the decoder to choose the reference pixel more accurately.

3.1.2 Quantization

To realize a DPCM coder, a quantizer is needed to send the discrete representation of the difference between the original and the predicted waveforms. The quantizer should be designed in the way such that the number of quantization levels is minimized while the object waveform can be reproduced faithfully.

The transfer function of a typical quantizer is shown in Fig. 7. The type of the quantizer shown is non-uniform midrise type. As can be seen from the diagram, the quantization levels are sliced nonuniformly, the step size increasing as the input signal gets larger. The amplitudes x_k, the inputs to the quantizer, are called decision levels and amplitudes y_k, the outputs from the quantizer, are called the reconstruction levels.

The uniform quantization does not represent the most effective conversion. The nonuniform quantization, however, chooses smaller decision intervals where the probability of occurrence of the random variable X is high, and chooses larger decision intervals otherwise.

3.1.2.1 PDF Optimized Nonuniform Quantizers : Iterative Solutions

The quantizer which is optimized to yield the minimum mean squared error (mmse) is called Max quantizer [5,9]. The procedures for finding the decision and reconstruction values are as follows.

Consider a stationary zero mean random sequence {X(n)} of variance σ_x^2. The quantization error variance σ_q^2 will be minimized to give a nonexplicit exact solution. Quantization error variance is given by the following expression;

$$\sigma_q^2 = \sum_{k=1}^{L} \int_{x_k}^{x_{k+1}} (x - y_k)^2 \; P_x(x)dx \qquad [3.1]$$

In order that the above expression attain a minimum, the following equations must be satisfied.

$$\frac{\partial \sigma_q^2}{\partial x_k} = 0, \;\; k = 2,3, \dots ,L \qquad [3.2]$$

$$\frac{\partial \sigma_q^2}{\partial y_k} = 0, \;\; k = 1,2, \dots ,L$$

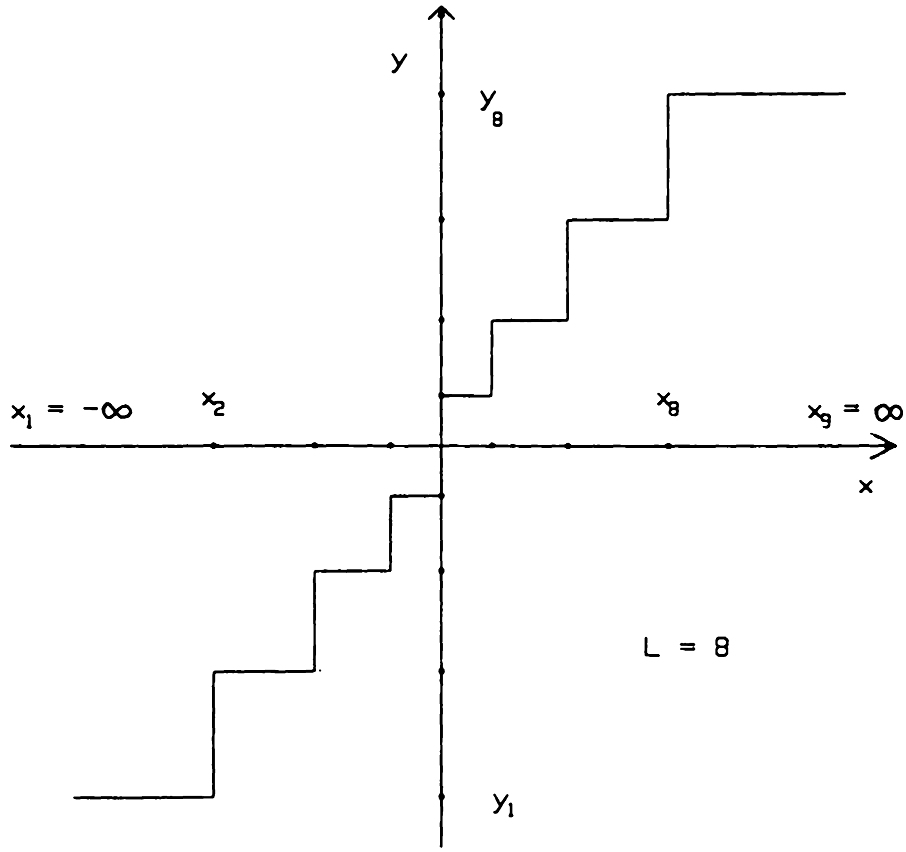


Figure 7. Tranfer Function Diagram of a Typical Non-Uniform Quantizer: x_i : decision levels, y_i : reconstruction levels

Calculating the above conditions leads to the results below [5].

$$x_{k,opt} = \frac{1}{2}\,(y_{k,opt} + y_{k-1,opt}), \quad k = 2,3, \ldots ,L \tag{3.3}$$

$$x_{1,opt} = -\infty, \quad x_{L+1,opt} = \infty$$

$$y_{k,opt} = \frac{\int_{x_{k,opt}}^{x_{k+1,opt}} x p_x(x)dx}{\int_{x_{k,opt}}^{x_{k+1,opt}} p_x(x)dx}, \quad k = 1,2, \ldots ,L \tag{3.4}$$

The first equation shows that the optimum decision levels are halfway between neighboring reconstruction levels and second equation shows that a reconstruction level should be the centroid (mean of the input signal on the given interval) of the pdf in the appropriate interval.

The procedure for finding the values y_i's and x_i 's starts by choosing a value for y_1, solves equation [3.4] for x_2, solves the equation [3.3] for y_2, ... and solves [3.3] for y_L. If y_L is not close enough to the right side of [3.4], then change the value y appropriately and continue iteration.

Table 1 on page 23 shows the optimum decision and reconstruction values as calculated by the method above. To the values in the table must be multiplied by the standard deviation σ_x for inputs to give the desired quantization levels.

As you can see from Table 1, there are four kinds of pdf's to which the quantizing levels are optimized. Due to the changing statistics of the input signal, the optimum quantizers are often not matched to the input signal statistics. According to the Fig. 4.14 in Jayant's book [29], the Gamma quantizer achieves a signal-to-noise ratio which is nearly independent of the type of pdf. Hence the Gamma quantizer was employed in the DPCM systems which are being studied.

Table 1. Optimum Decision Values for PDF-Optimized Nonuniform Quantizers

(**U** : Uniform, **G** : Gaussian, **L** : Laplacian, **Γ** : Gamma function)

R		1		2		3		4	
pdf	j	x(j)	y(j)	x(j)	y(j)	x(j)	y(j)	x(j)	y(j)
U	1	0.000	0.866	0.000	0.433	0.000	0.217	0.000	0.109
	2			0.866	1.299	0.433	0.650	0.217	0.326
	3					0.866	1.083	0.433	0.542
	4					1.299	1.516	0.650	0.759
	5							0.866	0.975
	6							1.083	1.192
	7							1.299	1.408
	8							1.516	1.624
G	1	0.000	0.798	0.000	0.453	0.000	0.245	0.000	0.128
	2			0.982	1.510	0.501	0.756	0.258	0.388
	3					1.050	1.344	0.522	0.657
	4					1.748	2.152	0.800	0.942
	5							1.099	1.256
	6							1.437	1.618
	7							1.844	2.069
	8							2.401	2.733
L	1	0.000	0.707	0.000	0.420	0.000	0.233	0.000	0.124
	2			1.127	1.834	0.533	0.833	0.264	0.405
	3					1.253	1.673	0.567	0.729
	4					2.380	3.087	0.920	1.111
	5							1.345	1.578
	6							1.878	2.178
	7							2.597	3.017
	8							3.725	4.432
Γ	1	0.000	0.577	0.000	0.313	0.000	0.155	0.000	0.073
	2			1.268	2.223	0.527	0.899	0.230	0.387
	3					1.478	2.057	0.591	0.795
	4					3.089	4.121	1.051	1.307
	5							1.633	1.959
	6							2.390	2.822
	7							3.422	4.061
	8							5.128	6.195

3.2 Delta Modulation (DM)

3.2.1 Theory of the Song Digital Variable Step Size Delta Modulator

Song et al. [6] has introduced an analytical approach to finding an optimum adaptive delta modulator-demodulator configuration. The algorithm uses two past samples to predict the next sample pixel in order to minimize the mean square error for Markov-Gaussian source. Until the invention of this modulator, many different schemes of delta modulators were introduced but most of the methods were empirical and did not involve much analytical approach.

The critical points in his analytical method will be reviewed. The criterion of finding the optimum predictor will be a mean square root function

$$E\{s_k - x_k\ (e^{k-1}, x^{k-1})\}^2 \qquad [3.5]$$

where s_k is the present input sample, x_k is the predicted sample, x^{k-1} is the past predicted sequence $x^{k-1} = x_{k-1}, x_{k-2}, \dots, x_1$ and e^{k-1} is the past output sequence of encoder, $e^{k-1} = e_{k-1}, e_{k-2}, \dots, e_1$.

If only two input samples are considered, we have to calculate

$$E\{s_k - x_k(e_{k-1}, e_{k-2}, x_{k-1}, x_{k-2})\}^2 \qquad [3.6]$$

On the other hand, the optimum estimator can be found by minimizing

$$E\{s_k - r_k(e_k, e_{k-1}, x_k, x_{k-1})\}^2 \qquad [3.7]$$

The results will have the following form.

$$
\begin{aligned}
x_k &= E\{s_k | x_{k-1}, x_{k-2}, e_{k-1}, e_{k-2}\} \\
r_k &= E\{s_k | x_k, x_{k-1}, e_k, e_{k-1}\}
\end{aligned}
\qquad [3.8]
$$

The input signal was assumed to be the Markov sequence generated from the equation

$$
s_k = \rho s_{k-1} + \lambda_{k-1} \qquad [3.9]
$$

where λ_{k-1} is uncorrelated, normal, zero mean with standard deviation $\sigma_{\lambda_{k-1}}$ and ρ is a correlation coefficient which indicates how the successive samples are correlated.

$$
\begin{aligned}
x_{k+1} &= E\{x_{k+1} | x_k, x_{k-1}, e_k, e_{k-1}\} \\
&= E\{\rho s_k + \lambda_k | x_k, x_{k-1}, e_k, e_{k-1}\} \\
&= \rho E\{s_k | x_k, x_{k-1}, e_k, e_{k-1}\} \\
&= \rho r_k
\end{aligned}
\qquad [3.10]
$$

It was found out that if the input samples are highly correlated ρ is approximately equal to 1.

In the two-past-sample case, using the estimator equation,

$$
r_k = \int_{-\infty}^{\infty} s_k \; P(s_k | x_{k-1}^{k}, e_{k-1}^{k}) ds_k \qquad [3.11]
$$

we can obtain very complex equations for four combinations of e_{k-1}, e_k values. To make calculations simpler and adaptable to hardware design, Song made many approximations and the results are as follows [6];

r_k can be written as

$$
\begin{aligned}
r_k &= x_{k+1} = x_k + g_1 + g_2 \\
g_1 &= g_1(e_k, x_k - x_{k-1}) \\
g_2 &= g_2(e_{k-1}, x_k - x_{k-1})
\end{aligned}
\qquad [3.12]
$$

The original equations of g_1 and g_2 are modified so that their slopes can be matched to the statistics of the incoming signal. Also the minimum step size was introduced because of the finite word length of the implemented digital system.

The resulting equations are

For $x_k - x_{k-1} > 0$

$$g_1(e_k = +1) = 0.08 + \alpha(x_k - x_{k-1} - 0.08)\ U(x_k - x_{k-1} - 0.08)$$

$$g_1(e_k = -1) = -0.08 - \alpha(x_k - x_{k-1} - 0.08)\ U(x_k - x_{k-1} - 0.08) \quad [3.13]$$

$$g_2(e_{k-1} = +1) = [0.04 + \beta(x_k - x_{k-1} - 0.08)]\ U(x_k - x_{k-1} - 0.08)$$

$$g_2(e_{k-1} = -1) = -[0.04 + \beta(x_k - x_{k-1} - 0.08)]\ U(x_k - x_{k-1} - 0.08)$$

For $x_k - x_{k-1} < 0$

$$g_1(e_k = +1) = 0.08 - \alpha(x_k - x_{k-1} + 0.08)\ U(-[x_k - x_{k-1}] - 0.08)$$

$$g_1(e_k = -1) = -0.08 + \alpha(x_k - x_{k-1} + 0.08)\ U(-[x_k - x_{k-1}] - 0.08) \quad [3.14]$$

$$g_2(e_{k-1} = +1) = [0.04 - \beta(x_k - x_{k-1} + 0.08)]\ U(-[x_k - x_{k-1}] - 0.08)$$

$$g_2(e_{k-1} = -1) = -[0.04 - \beta(x_k - x_{k-1} + 0.08)]\ U(-[x_k - x_{k-1}] + 0.08)$$

$$\text{where } U(z) = \begin{cases} 1 & z \geq 0 \\ 0 & z < 0 \end{cases} .$$

The slopes α and β were limited to the values 1/4, 1/2, 1, and 2 for ease of implementation. The experiments done by Song shows that for video information, using $\alpha = 1, \beta = 1/2$ had the greatest clarity.

If we substitute the above values in equations [3.13] and [3.14], the following equations result.

If $x_k - x_{k-1} \geq 0.08$

$$\begin{aligned} g_1(e_k &= +1) = 0.08 + (x_k - x_{k-1} - 0.08) = x_k - x_{k-1} \\ g_1(e_k &= -1) = -0.08 - (x_k - x_{k-1} - 0.08) = -(x_k - x_{k-1}) \\ g_2(e_{k-1} &= +1) = 0.04 + 0.5(x_k - x_{k-1} - 0.08) = 0.5(x_k - x_{k-1}) \\ g_2(e_{k-1} &= -1) = -[0.04 + 0.5(x_k - x_{k-1} - 0.08)] = -0.5(x_k - x_{k-1}) \end{aligned} \qquad [3.15]$$

If $x_k - x_{k-1} < -0.08$

$$\begin{aligned} g_1(e_k &= +1) = 0.08 - (x_k - x_{k-1} + 0.08) = -(x_k - x_{k-1}) \\ g_1(e_k &= -1) = -0.08 + (x_k - x_{k-1} + 0.08) = x_k - x_{k-1} \\ g_2(e_{k-1} &= +1) = [0.04 - 0.5(x_k - x_{k-1} + 0.08)] = -0.5(x_k - x_{k-1}) \\ g_2(e_{k-1} &= -1) = -[0.04 - 0.5(x_k - x_{k-1} + 0.08)] = 0.5(x_k - x_{k-1}) \end{aligned} \qquad [3.16]$$

Then from the equations [3.12], [3.15] and [3.16], when $e_{k-1} = -1, e_k = 1$ and $x_k - x_{k-1} \geq 0.08$

$$r_k = x_{k+1} = x_k + (x_k - x_{k-1}) - 0.5(x_k - x_{k-1}) = x_k + 0.5(x_k - x_{k-1}) \qquad [3.17a]$$

When $e_{k-1} = 1, e_k = 1$,

$$r_k = x_{k+1} = x_k + (x_k - x_{k-1}) + 0.5(x_k - x_{k-1}) = x_k + 1.5(x_k - x_{k-1}) \qquad [3.17b]$$

When $e_{k-1} = 1, e_k = -1$,

$$r_k = x_{k+1} = x_k - (x_k - x_{k-1}) + 0.5(x_k - x_{k-1}) = x_k - 0.5(x_k - x_{k-1}) \qquad [3.17c]$$

When $e_{k-1} = -1, e_k = -1$,

$$r_k = x_{k+1} = x_k - (x_k - x_{k-1}) - 0.5(x_k - x_{k-1}) = x_k - 1.5(x_k - x_{k-1}) \qquad [3.17d]$$

From the above equations, we notice that whenever the two consecutive difference signals are equal in sign, the step size increases by 1.5 and whenever they are not equal in sign, it decreases by 0.5. Hence if we have a video signal which has a large slope (edge) then the predicted signal increases nonlinearly to follow the input signal.

Especially, in the slope overload region, it was found out by Song that the system operates as Jayant's scheme [19] with P = 1.15 and Q = 0.5.

3.2.2 One-Dimensional Delta Modulator (1DDM)

The above equations [3.17] can be summarized as below [7,17].

$$E(k + 1) = \operatorname{sgn}[S(k + 1) - X(k + 1)]$$

$$X(k + 1) = X(k) + Y(k + 1) \qquad [3.18]$$

$$Y(k + 1) = \begin{cases} |Y(k)||[E(k) + 0.5E(k - 1)] & \\ & |Y(k)| \le \frac{Y_{max}}{1.5} \text{ and } E(k) = E(k - 1) \\ & |Y(k)| < Y_{max} \text{ and } E(k) \neq E(k - 1) \\ & 2\, Y_{min} \le |Y(k)| \\ 2\, Y_{min}\, E(k) & \text{when } |Y(k)| < 2\, Y_{min} \\ Y_{max}\, E(k) & \text{when } |Y(k)| > \frac{Y_{max}}{1.5} \text{ and } E(k) = E(k - 1) \end{cases}$$

Where,

E(k) = the digital output of the encoder

S(k) = the input analog sample to the encoder

X(k) = the encoder estimate of the input signal

Y(k) = the step size of the delta modulator

Y_{min} = the minimum step size of the delta modulator

Y_{max} = the maximum step size of the delta modulator

The equations above involves only the prediction with one pixel to the left. The image shown in Fig. 8 is the result of the above scheme with minimum step size 1/64 of the maximum peak to peak input signal and maximum step size 20 times the minimum step size.

Figure 8. **Image coded by One-Dimensional Song Delta Modulator:** 1 bit/pixel, sampling at Nyquist rate

As can be seen from the image, edge busyness and ringing along the high contrast edge is clearly visible. If the signal is sampled at a higher rate than the Nyquist rate, then the impairment visible in the image can be reduced. In this thesis, the sampling rate is not varied because of insufficient facilities and for comparison purposes.

3.2.3 Normal Two-Dimensional Delta Modulator (Normal 2DDM)

In the one-dimensional delta modulator discussed above, only one direction, the horizontal, was emphasized for the prediction. If we take the vertical direction as well as the horizontal into account, then the coding path can move freely and optimally in a two-dimensional domain.

The two-dimensional DM (2DDM) system proposed by Lei et al. [17], operates as follows. Suppose the center pixel is X and A, B, C, and D are corresponding neighborhood pixels in Fig. 9. It was found out that the 2DDM system utilizing the A-C pair gives the best result in terms of edge sharpness and contour smoothness [17].

The following equations describe the operation of the normal 2DDM system using the A-C pair. The basic equations are the same as the 1DDM case except that the predicted value, the previous step size and the previous difference signal have to be determined after the comparison of the surrounding two pixels with the center pixel. Let $D_{H,m+1,n+1}$ be the difference between the input sample and the estimate of A and let $D_{V,m+1,n+1}$ be the difference between the input sample and the estimate of C. $X_{ref,m+1,n+1}$, $Y_{ref,m+1,n+1}$ and $E_{ref,m+1,n+1}$ are the reference estimate, step size and encoder output, respectively. These values should be substituted for X(k), Y(k) and E(k) in equation [3.18] respectively. Then,

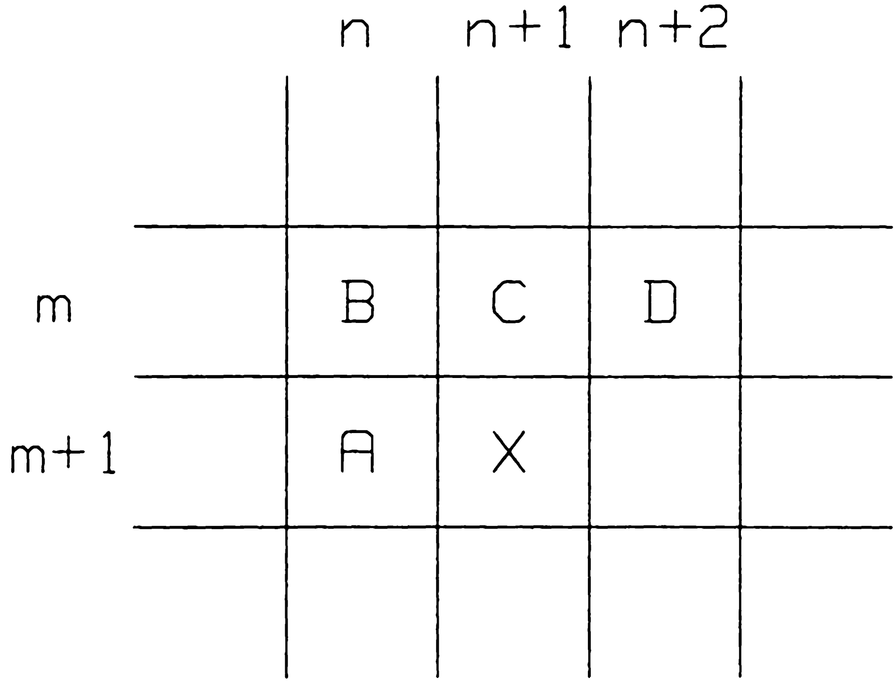


Figure 9. Reference Pixels in Two-Dimensional Song Delta Modulator

$$D_{H,m+1,n+1} = |S_{m+1,n+1} - X_{m+1,n}|$$
$$D_{V,m+1,n+1} = |S_{m+1,n+1} - X_{m,n+1}| \qquad [3.19]$$

If $D_{H,m+1,n+1} \le D_{V,m+1,n+1}$

$$X_{ref,m+1,n+1} = X_{m+1,n}$$
$$Y_{ref,m+1,n+1} = Y_{m+1,n} \qquad [3.20]$$
$$E_{ref,m+1,n+1} = E_{m+1,n}$$

If $D_{H,m+1,n+1} > D_{V,m+1,n+1}$

$$X_{ref,m+1,n+1} = X_{m,n+1}$$
$$Y_{ref,m+1,n+1} = Y_{m,n+1} \qquad [3.21]$$
$$E_{ref,m+1,n+1} = E_{m,n+1}$$

Hence the decision to use pixel A or C as the reference pixel is made after the comparison of D_H and D_V. The image in Fig. 10 shows that the edge busyness is reduced significantly, compared to the 1DDM case, because the reference of the delta modulator tends to follow the direction of the edge optimally.

This scheme needs one more bit per pixel to tell the receiver which direction to refer to because the receiver doesn't have the original pixel value. It follows that on the whole the normal 2DDM encoder sends 2 bits/pixel to the receiver if the signal is sampled at the Nyquist rate.

Figure 10. Image Coded by Normal 2DDM Coding: Direction bits are sent, 2 bits/pixel

3.2.4 Weighted Average Two-Dimensional Delta Modulator (2DDM)

In order to eliminate the extra bit needed to tell the direction of prediction, the original pixel itself can be estimated in the decoder as well as the encoder. The predicted value, $\overline{P}$, if the scheme by Lippman [8] is used, is

$$\overline{P} = 0.75\,\overline{A} + 0.75\,\overline{C} - 0.5\,\overline{B} \qquad [3.22]$$

where $\overline{A}$, $\overline{B}$, and $\overline{C}$ are the encoded estimates of A, B, and C respectively.

If we substitute $\overline{P}$ for the original pixel value $S_{m+1,n+1}$ in equation [3.22] and determine whether $\overline{A}$ or $\overline{B}$ is closer to the value $\overline{P}$, the direction of prediction can be determined independently at the decoder. We can simplify the comparison procedure by a simple derivation [17]. The result shows that comparison of $|\overline{A} - \overline{P}| < |\overline{C} - \overline{P}|$ is same as $|\overline{A} - \overline{B}| > |\overline{C} - \overline{B}|$. Using this result, pixel $\overline{B}$ is compared against the coded pixels, $\overline{A}$ and $\overline{C}$, and if $\overline{C}$ is closer to $\overline{B}$ than $\overline{A}$, then choose $\overline{A}$ as the estimate.

The derivation shows that this scheme is exactly same as the one proposed by Graham [3] as discussed in Section (3.1.1). This method finds the coding path very clumsily so that the error due to wrong prediction are visible in the image as shown in Fig. 11.

One of the advantages of this scheme over the normal 2DDM can be said that it sends only 1 bit/pixel at Nyquist rate. Also, in spite of the visible background noises, the vertical edges of the image are reproduced much better than the 1DDM method.

Figure 11. Image Coded by Weighted Average Prediction 2DDM: 1 bit/pixel, sampling at Nyquist rate

4.0 Pseudo-Laplacian Edge Detector Applied to Predictive Coding

Most video signals contain smooth areas of little change in gray scale over many sampling intervals. When there is a large change in gray level in one area there is high possibility that the area has more information than the smoother areas. If the edges can be isolated and reconstructed so as to appear sharp, then a picture will be of a good quality [12]. The background texture area contains low contrast detail and approaches a more random signal. Hence it is safe to say that more distortion can be introduced in these areas than the areas with high contrast change.

The above concepts lead to the dual-mode coding. The background texture can be coded in a lower bit rate, using the schemes which introduce more error, and the edges can be coded in higher bit rate, using accurate prediction schemes. For the lower bit rate coder we can use the DM coder, because it uses minimum number of bits among the various predictive coding schemes. The edge coding can be performed with any Predictive coding method which gives more accurate output waveforms than the background coding. Frei et al. [13], have studied a similar method, called dual-mode coding, but this scheme considered only one-dimensional edges found by differences between two adjacent pixels. In this paper various combinations of predictive coding schemes will be considered.

Figure 12 shows the image in which the edge pixels are reset to the original 8-bit value. This image shows the upper limit of the quality that we can achieve with the methods of this section. But the problem is that the bit rate becomes too high if the image is very edgy.

In the following sections, we introduce various methods of edge coding which can reduce the bit rate compared to resetting to 8 bits at the edge. But sometimes there seems to be too many edge pixels which must be coded at a higher rate. To reduce the number of pixels to be coded at a higher bit rate, the following method can be applied. If the predicted signal value from the background coder is close enough to the real signal value, then ignore the presence of edge at that point and code the pixel by the lower bit rate coder. This concept is applied to all the schemes to be discussed in this thesis.

4.1 1DDM-DPCM Combination

The background texture has been coded by one-dimensional delta modulation scheme originally found by Song et al. [6], as discussed in Section (3.2.2). The image coded by the one-dimensional Song modulator, as shown in Fig. 8, introduces displeasing noises, such as edge busyness. Edge busyness is the noise caused by the irregular oscillation of the signal value around the edges. If the edges can be found and the oscillations around them suppressed, the perceptual gain is enormous.

Figure 12. Image with Edge Pixels Resetted to 8-Bit Original Value

Figure 13 shows the increasing slope of the video signal. As we can see in the diagram, overshoot occurs at the upper end of the increasing slope. Hence ***white edge***, as defined in Section (2.1), has to be found. If the ***white edge*** is found at some point, then the step size of the adaptive coder is reset to its minimum value, so that the large adaptive step size can be reduced at the edge. In the case of the decreasing slope, the same procedure is executed except finding a ***black edge*** at the foot of the slope.

The example of the signal which was discussed before is the case when the signal is faithfully following the input signal. But there are cases that even an adaptive DM coded signal cannot follow the input. If the situation occurs the slope overload effect appears and the DM signal lags the input. In short, the DM signal follows the input few steps behind the rapidly changing input signal slope. This effect can be reduced when a ***white edge*** is found in the increasing input signal. The value at the edge pixel can be reset to the value closer to the original pixel value so that the DM signal can afterwards follow the input faithfully. The more accurate coding methods such as the normal Song mode two-dimensional DM scheme or the switched prediction DPCM schemes are applied to edge coding.

The system which was designed with these concepts is shown in Fig. 14. Note how the outputs of the DM and DPCM coders are switched by the edge detector. The memory for storing coded image samples is shared by the two coders to ensure the continuity of the image samples.

Use of the edge detector introduces one more bit to the overall bit rate of the coding scheme. One bit of information must be sent for every sample to tell the decoder whether the pixel is an edge or not. This edge information bit is the bottleneck which increases the bit rate of every coding method discussed in this paper. Hence one method which can contribute to decreasing the number of edge information bits has been devised.

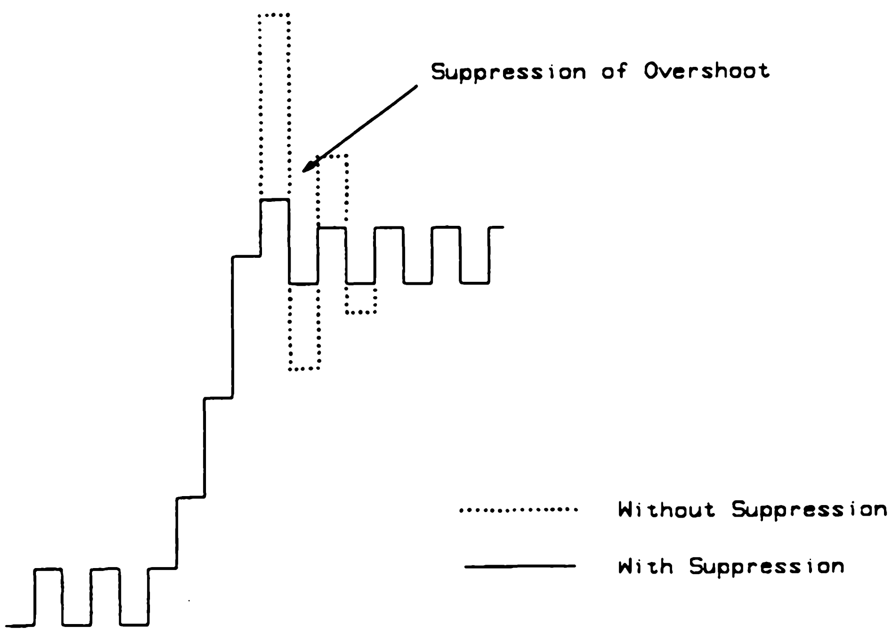


Figure 13. Adaptive DM Signal Response to the Abrupt Change in Gray Level

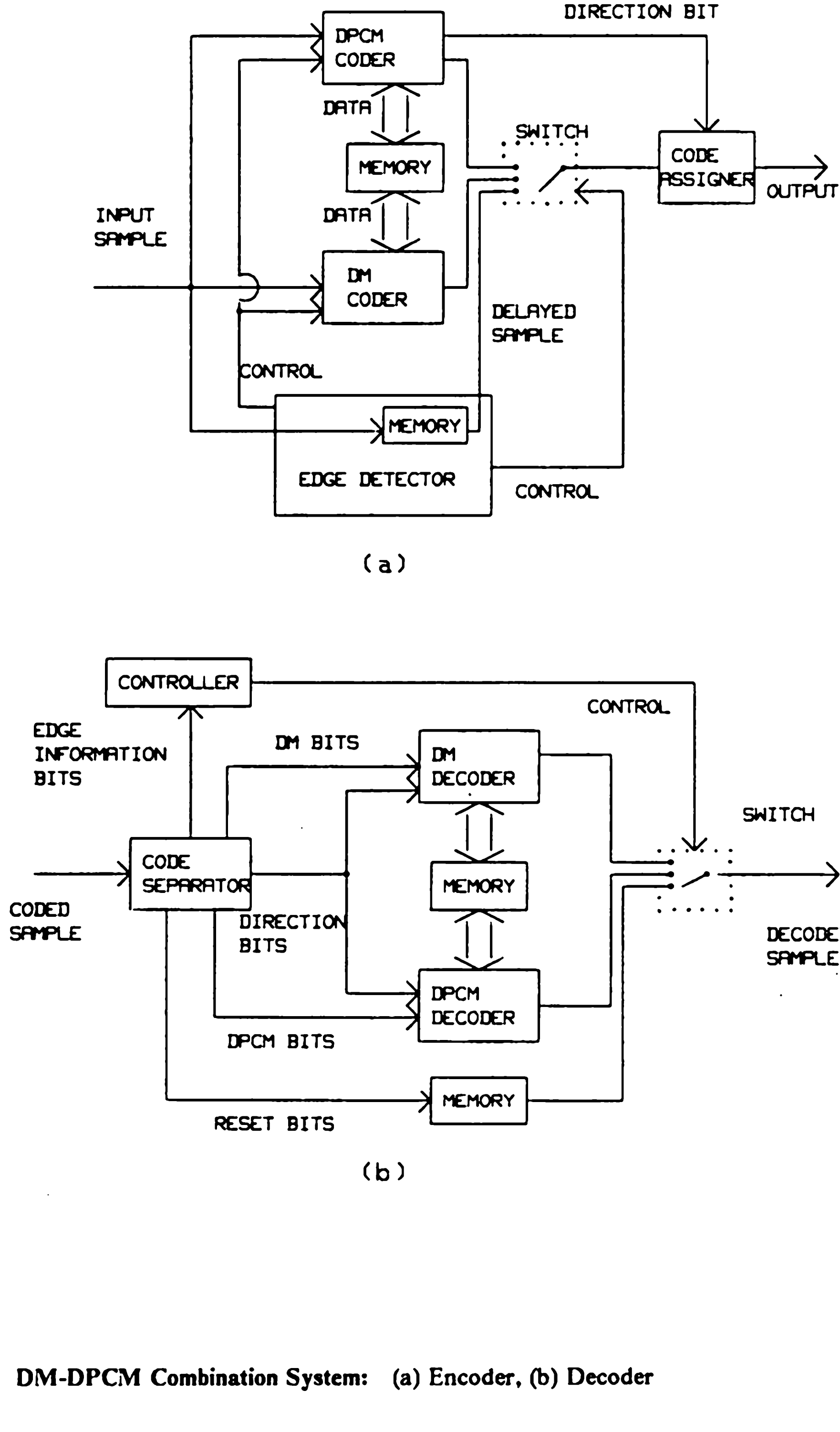


Figure 14. DM-DPCM Combination System: (a) Encoder, (b) Decoder

If the background non-edge coding is done in 1DDM, then the coder is looking for the one-dimensional edge most of the time. The edges found by the Pseudo-Laplacian edge detector can be totally irrelevant to the 1DDM coding. In other words, a vertical edge can be found while the prediction signal coded by 1DDM is following the input faithfully in horizontal direction. The edges at such points can be unnecessary.

If the two past DM bits are of the equal sign, then the signal can be assumed to be in a slope and there is a high possibility that a vertical edge exists at the point. From the assumptions above, a restriction was made in detection of edges. That is, to find the edge only when the two past difference bits - output of 1DDM coder - are of the same sign. This restriction can also be detected by the decoder. This scheme can degrade the performance of the coders slightly because this method can miss some of the diagonal edges which can be between vertical edges.

The value at the edge can be reset to the DPCM coded value. Many DPCM algorithms were reviewed for this application. But it may be appropriate to devise special algorithms which are matched to the characteristics of the edges. The various DPCM prediction algorithms which can be applied are as follows.

4.1.1 Average of the Surrounding Edge Pixels

If there are any edge pixels in the four neighborhood pixels: A, B, C and D in Fig. 9, they can be averaged to form a prediction value of the reference pixel. This algorithm is based on the assumption that the reference edge pixel should be closer to the surrounding edge pixels than the non-edge pixels. If there were no edge in the neighborhood, then the pixel is reset to the 8-bit original value.

The Max quantizer, as discussed in Section (3.1.2) was used for quantization of the DPCM coded edge signals. The standard deviation of the input signal was calculated after the observation of the difference signal histograms in many different types of predictors. Note that the only difference signals of the edge pixels, excluding 8-bit reset pixels and texture area pixel values, are considered. Then the standard deviation was multiplied to the values in Table 1 on page 23 to yield the appropriate slice levels for the quantizer. The quantizer was matched to the pdf of Gamma function.

Trials were made at 8 (3 bits) and 16 (4 bits) quantization levels ; it was found out that there was no visible difference between the two schemes. Hence the 3-bit Max quantizer, optimized to the statistics of the GIRL image, was used. The result image is shown in Fig. 15.

As discussed before, if we monitor the past two DM bits the image looks like Fig. 16. Note that there is no big difference from the previous image, except that some of the missed edges degrade the performance of the coder slightly. The most significant advantage of this method is that the number of edge information bits was reduced by half with the GIRL image. This means that we can save 0.5 bit/pixel in the bit rate.

4.1.2 Transmission of Direction Bits for Prediction

When the above system was used, there was a doubt that the averaged value may be farther away from the center pixel than one of the surrounding edge pixels. By examining some parts of the coded image, it was found out that many of the non-edge pixels were closer to the center pixel than the average. Hence to minimize the difference between the reference pixel and the center pixel, the direction bits which tell the direction of the reference pixel were sent. The normal DPCM schemes do not send the direction

Figure 15. Image Coded by 1DDM-DPCM Combination: The predicted value is the average of surrounding edge pixels. 3-bit quantization.

Figure 16. Image Coded by 1DDM-DPCM Combination: Predicted signal is the average of the surrounding edge pixels. 3-bit quantization. Two past DM bits monitored.

bits because it increases the bit rate too much. But in this case, the DPCM coding was applied to the edges only so it was thought that it would not increase the bit rate significantly.

Similarly to the scheme in Section (4.1.1), if there are no edge pixels in the neighborhood, then the pixel was reset to 8-bit original value.

The direction bits are sent in the following way. If there is no edge in the neighborhood the direction bit is not sent. The decoder can also detect the condition. If there is only one edge in the neighborhood then still no direction bit is needed to be transmitted because the decoder can detect that there is only one edge to refer to. In a similar way, if there are two edges 1 bit was sent and if 3 edges 2 bits, and if 4 edges 2 bits again. The method above can greatly reduce the bits required to send directional information.

On detecting an edge, the coding scheme is switched from the background 1DDM coding algorithm to the following algorithm.

If an edge is found at the pixel

1. Count the number of edges (CNT = CNT + 1)
2. If CNT = 0 ; Reset the pixel to 8-bit

   If CNT = 1 ; Do not send the direction bit

   Send Q($S_{m+1,n+1} - X_{i,j}$).

   where Q(.) is quantization,

   $S_{m+1,n+1}$, the center pixel and

   $X_{i,j}$, the neighborhood edge pixel

   in Fig. 9

   If CNT $\geq$ 2 ; Send direction bit

Send Min $\{Q(S_{m+1,n+1} - X_{i,j})\}$

3. Reset the step size to Y_{min} and the difference signal to 0

Note that $X_{i,j}$ has to be the value which is coded, not the original pixel value. The reason is that the decoder has to be able to get the same values which the encoder is using.

The result image is shown in Fig. 17. As may be seen, there is no significant difference from Fig. 15 in subjective quality. Also the picture obtained by monitoring past two DM bits is shown in Fig. 18. The picture shows no much degradation due to reducing the number of edge information bits. And the number of edge information bits to be sent to the receiver was about half of the original scheme so that we can save 0.5 bit/pixel in bit rate, as the previous section.

4.2 1DDM-2DDM Combination

Similar to the algorithms of previous sections, Delta modulation can be applied to the coding of the edge pixels. The idea was that the bit rate can be reduced significantly if we code the edge pixels by one bit, as in the case of DM.

Figure 19 shows the designed system. Note that the hardware can be reduced greatly, as the quantizer is shared by the two coding schemes. The predictors must be different to distinguish between one and two-dimensional DM.

Figure 17. **Image Coded by 1DDM-DPCM Combination:** The direction bits are sent to the decoder. 3-bit quantization on edge.

Figure 18. Image Coded by 1DDM-DPCM Combination: The direction bits are sent to the decoder. Past two DM bits were monitored. 3-bit quantization.

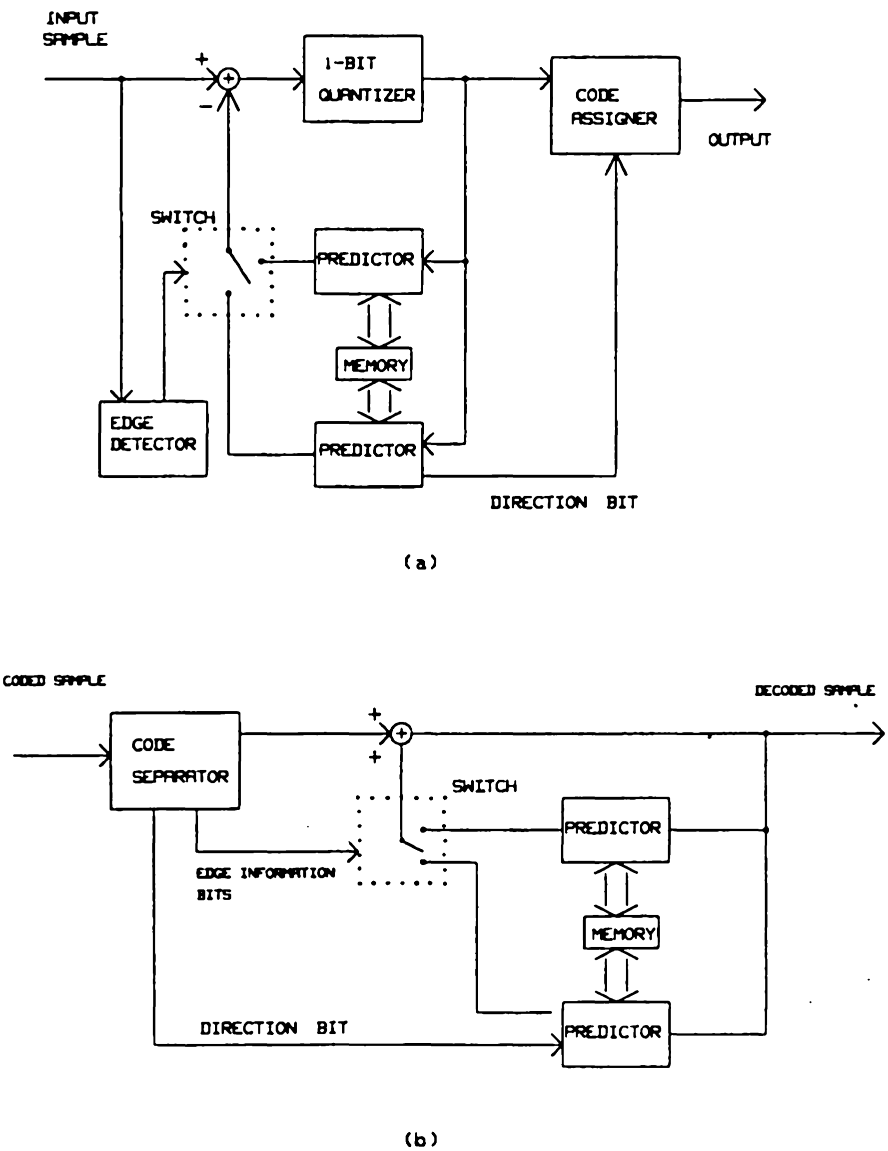


Figure 19. 1DDM-2DDM Combination System: (a) Encoder, (b) Decoder

The direction bits are sent as in the normal 2DDM system. After the direction has been determined by comparing original pixel value and neighborhood edge pixel values, the reference step size, the difference value, and the reconstructed pixel value were obtained from the pixel indicated by the direction. Then the same procedure follows as the normal adaptive DM coding.

If an edge is found at the pixel

1. Determine the direction by calculating Min $\{S_{m+1,n+1} - X_{i,j}\}$ for two neighborhood pixels, A and C in Fig. 9.
2. If X_A is the reference pixel, then $X_{ref} = X_A$, $Y_{ref} = Y_A$, $E_{ref} = E_A$
3. Use the Reference values $(X_{ref}, Y_{ref}, E_{ref})$ in calculating the next step size and prediction value at the center pixel.

This procedure was tested for the GIRL image as shown in Fig. 20. The image does not look too different from the DPCM edge coding systems. But we notice some noise in the reproduction of the edges.

4.3 2DDM-DPCM Combination

As discussed in Section (3.2.4), 2DDM with weighted average prediction, or Graham's predictor [3], can be used in the background non-edge coding. It has the same bit rate (1 bit/pixel) as the case of 1DDM. We have noticed that the image coded by just weighted average 2DDM had a lot of noise, caused by wrong predictions. But if we limit the wrong predictions to the rather smoother area without many edges, the result will

Figure 20. Image Coded by 1DDM-2DDM Combination Method: Normal 2DDM

be that one would not notice the noise in the area as clearly as that on the edges, because the area has less information than the edges.

The DPCM scheme can be used in coding the edge pixels as the previous sections. The background coding scheme is 2-dimensional ; if we use a similar prediction scheme in the coding of the edges, then the implementation of the coder will be simplified.

4.3.1 Transmission of Direction Bit for Prediction

The method of sending direction bits is quite different from the case in 1DDM-DPCM combination. The direction bit is sent after examination of the two neighborhood pixels: A and C in Fig. 9. Here, it does not matter whether the two surrounding pixels are edge pixels or not. One of the two pixels which is closer to the center pixel is selected and the corresponding direction information is sent to the decoder.

Hence, one extra bit is added at the edges. This scheme has been devised to make the implementation simpler. The two-pixel comparison method used for background coding can be reused here. As before, the quantization is realized in Max's method (3 bits). The algorithm is summarized as follows;

If an edge is found at the pixel

1. Find the closer of the two neighborhood pixels (up and left) from the center pixel.
2. Code the direction of the closer pixel in one bit and send to the decoder.
3. Quantize the difference between the reference pixel and the

center pixel and send to the decoder

4. Reset the step size to Y_{min} and the difference signal to 0

Figure 21 shows the image coded with the above method. On the whole, the image looks much sharper than the 1DDM texture coding methods. The reason can be said that some of the vertical edges which can be missed with the edge detector alone can be reproduced with the weighted average 2DDM itself. But when we look at the texture area closely noise like rashes on the face are observed. But the noises are less visible than the picture coded with a weighted average 2DDM method.

4.3.2 Transmission of Direction Bit and Resetting

This scheme is exactly the same as the previous one except that it sends 8-bit reset signals when there is no surrounding edge pixel. As in the 1DDM background coding case, the reset value can help the prediction signal to follow the input signal more accurately. The image in Fig. 22 shows that this scheme works a little bit better than the previous one. But one cannot see too much difference in quality.

4.3.3 No Direction Bit and Resetting

The extra direction bit will not be needed if we use the same prediction method with the background coding. In other words, we code the edge pixels with the weighted average prediction. The pixel is reset to 8-bit values if there is no neighborhood edge pixel. Figure 23 shows the system. We can see that the two coders share the same predictor to minimize the hardware.

Figure 21. Image Coded by 2DDM-DPCM Combination: Direction bits are sent for prediction. No pixel is reset to 8-bit original.

Figure 22. Image Coded by 2DDM-DPCM Combination: The edge pixel with no surrounding edge pixel is reset to 8-bit. One direction bit is sent.

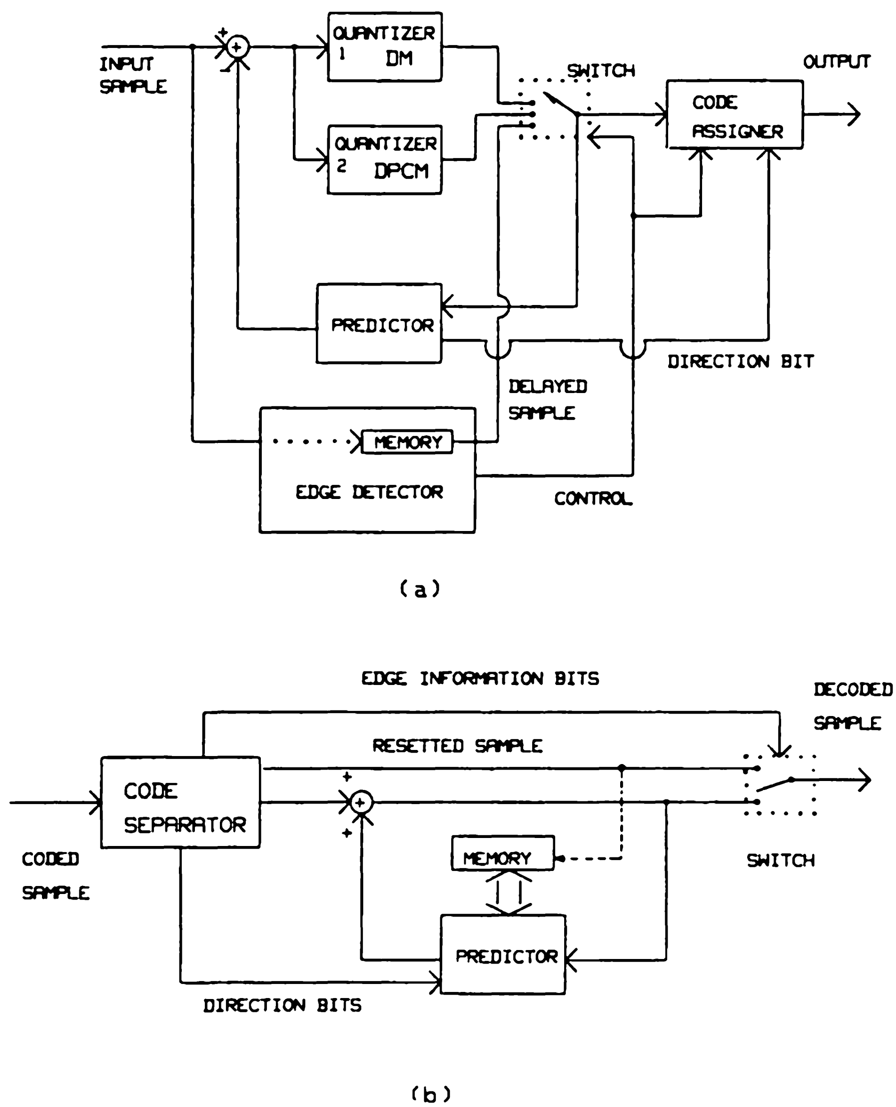


Figure 23. 2DDM-DPCM Combination System: (a) Encoder, (b) Decoder

The prediction scheme for the background coding might be unsuitable for DM coding of edges but may be acceptable for multi-bit DPCM edge coding. The DPCM coding is certainly not done in an adaptive way, so that the present step size will not depend upon the past ones. It can reproduce the edges more accurately although the prediction is not done in an optimum way.

The following is the summary of the procedure.

If an edge is found at the pixel

1. Count the number of edges among the 2 neighborhood pixels

   : CNT = CNT + 1

2. If CNT = 0 : Reset to 8-bit original

   If CNT $\geq$ 1 : Do the weighted average prediction

   If $|X_{m,n} - X_{m,n+1}| \leq |X_{m,n} - X_{m+1,n}|$

   Quantize $(X_{m+1,n+1} - X_{m+1,n})$

   Else

   Quantize $(X_{m+1,n+1} - X_{m,n+1})$

3. Send the Quantized or resetted signal to the decoder.

4. Reset the step size to $Y\min$ and the difference signal

   to 0

Figure 24 shows the image with the above algorithm, but the degradation due to the omission of direction bits cannot be noticed clearly.

Figure 24. **Image Coded by 2DDM-DPCM Combination Method:** The edge pixel is reset to 8 bits if no surrounding edge pixel. No direction bit is sent.

4.3.4 No Direction Bit, No Resetting

The question arises at this point. Is the resetting of the pixels with no neighborhood edge pixels really necessary? If the resetted pixels are not used much in enhancing the coded image, then the resetting can be said to be unnecessary. The object of the present image coding is to make the image look sharper, without taking closeness to the original picture much into consideration.

The result image with 3-bit quantization is shown in Fig. 25. There is not much degradation comparing to the previous schemes. But if we observe closely, we can see more noises introduced in the smoother part of the GIRL's face.

4.4 2DDM-2DDM Combination

As in 1DDM-2DDM case, if we code edges with 2DDM method, then the bit rate can be reduced further than the previous DPCM edge coding schemes. The designed system will look like Fig. 19 except that the 1DDM texture coder is replaced by the weighted average 2DDM coder.

4.4.1 Edge Following, One Direction Bit, Resetting

This method examines the two neighboring pixels: A and C in Fig 9. as before, and finds the edge pixels. If there is no edge pixel, reset the pixel to 8-bit original value; if there is one edge pixel, refer to the pixel for prediction; if there are two edge pixels,

Figure 25. Image Coded by 2DDM-DPCM Combination Method: No direction bit. No resetting.

then compare them with the center pixel and the closest edge pixel will become the reference pixel. The algorithm is as follows.

If an edge is found at the pixel

1. Count the number of edge pixels in the neighborhood

   : CNT = CNT + 1

2. If CNT = 0 : Reset the edge pixel to 8-bit

   If CNT = 1 : Refer to the edge pixel for prediction

   If CNT = 2 : Do the comparison below.

   If $|X_{m+1,n+1} - X_{m,n+1}| \geq |X_{m+1,n+1} - X_{m+1,n}|$

   Send direction bit : pixel C in Fig. 9

   Refer to the pixel one line above for prediction

   Else

   Send direction bit : pixel A in Fig. 9

   Refer to the pixel to the left for prediction

The result is shown in Fig. 26. We can see a slight degradation from the previous 2DDM-DPCM schemes, particularly in the texture area and the sharp edges.

4.4.2 One Direction Bit, No Resetting

This scheme can be called a mixture of a normal 2DDM scheme with a weighted average prediction 2DDM scheme, switched by a Pseudo-Laplacian Edge operator. This scheme was realized to be the minimum bit rate coder preserving the subjective quality. Although DM coding at the edge is clearly inferior to DPCM coding, the image can be improved with a more faithful reproduction at the edge which limit the errors caused by the wrong prediction in the background coding.

Figure 26. **Image Coded by 2DDM-2DDM Combination:** The reference pixel is chosen from the surrounding edge pixel. One direction bit is sent. No resetting to 8-bit original.

Figure 27. Image Coded by 2DDM-2DDM Combination: One direction bit is sent for prediction. No resetting at the edge pixel.

Figure 27, coded by the minimum bit rate method, does not seem to be much worse than the other schemes. The edges are well produced and the subjective quality is good enough, except there are more noises in the texture.

4.4.3 One Direction Bit, Resetting

This is the improved version of the previous scheme. To make the coded image closer to the original image, the edge pixels which have no surrounding edge points in the up or left position can be reset to 8-bit original values. As in the previous resetting methods, the step size is reset to the minimum value and the difference signal is reset to 0 at the edge points. The reason is to keep the next pixel which references the edge point from overshooting. But as can be seen from Fig 28., no significant difference from the previous scheme is there. In the latter figure, the noises are slightly less visible than the image with previous method.

Figure 28. Image Coded by 2DDM-2DDM Combination: One direction bit is sent for prediction. Edge pixel with no surrounding edge pixel is reset to 8-bit original.

5.0 Experiments and Discussion

The simulations and experiments were conducted on GIPSY (General Image Processing System) environment, which is implemented on VAX 11/780 in the SDA Laboratory of VPI & SU. The simulation programs were coded in RATFOR, a modified version of Fortran for image processing.

5.1 Simulation

The simulation with motion pictures could not be done with the facilities at hand. Instead, still pictures were used as one frame of the moving pictures.

The channel was simulated by the following way. As shown in Fig. 29, an image plane was used for each of the informations: edge information bits, correction bits, DPCM difference signals or reset values, and direction bits.

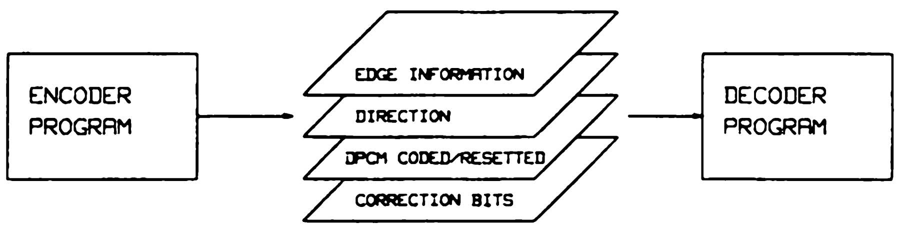


Figure 29. Simulation of the Channel

The encoder part consists of the texture coding module and the edge coding module. The texture coding part can be one the following schemes; 1DDM or 2DDM. Because of the complexity of the program, the different texture coding methods were implemented in different programs. The edge coding methods (2DDM, DPCM, and Reset) could be selected by the user. Usually the reset method was combined with DM or DPCM in edge coding.

The edge detector takes up a large portion of the program. The Pseudo-Laplacian edge detector works in the following way [28]. Figure 30 shows the modules in the program. There were originally five modules in the algorithm but one module is discarded because it is not used in this thesis. The four modules works as follows.

1. Find_Diffs : This module is designed to save the computing time of the gradient values. The differences of gray values are calculated along the four vectors for each pixel. Then the values are thresholded against some value, T_{DIFF}. Depending on the sign of the gradient values, if the magnitude of the gradient is above T_{DIFF}, one of the two locations for each sign is set.

2. Sum_Diffs : The vectors from the Find_Diffs module form a set of vectors as in the 7x7 window of Fig. 3. The vector element which has a direction going out from the center pixel is called a ***white*** element. And the one coming in is called a ***black*** element. Because the presence of vectors can be found from the previous module, we can add up the vector elements for each of the black or white sum.

3. Eval_Diffs : The sums that we have obtained in the Sum_Diffs module are evaluated against three thresholds. If the ***black sum*** has a significant value comparing to the ***white sum*** and over a threshold, then the pixel is designated as a ***black edge***. A ***white edge*** is found in a similar way.

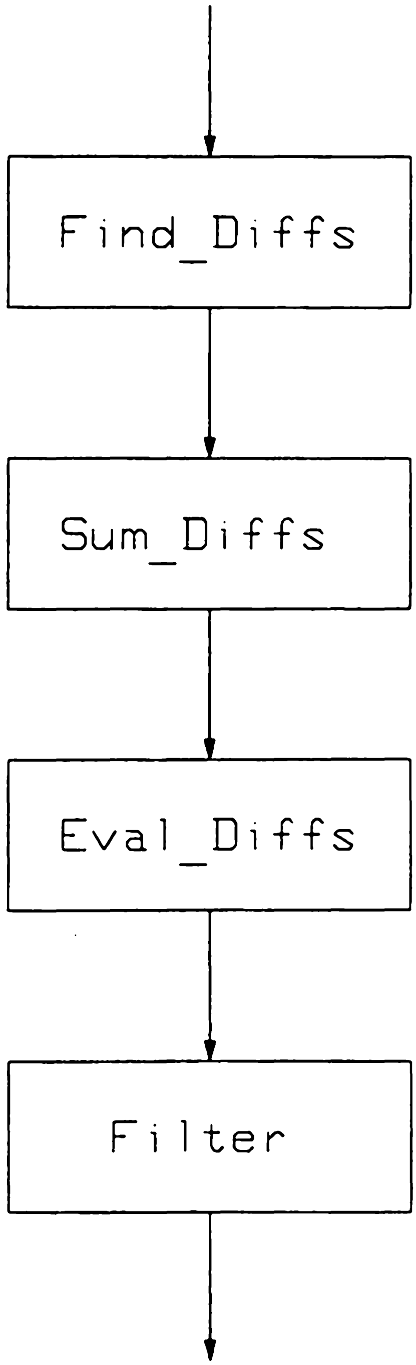


Figure 30. Modules in the Pseudo-Laplacian Edge Detector

4. Filter : The spot noises in the edge image from the Eval_Diffs module are discarded using the neighborhood connectivity criterion.

As can be seen from the above modules, there are inevitable delays which must be introduced into the coding methods discussed in this thesis. The modules described above operate in a line-by-line mode. After one line of an image is processed by one module the processed line goes into the next module. If the image is filtered the first result from the Eval_Diffs module is not transmitted even if it is an edge. The filter operation is done on a 3x3 window. Hence, as in Fig. 31, after three consecutive line operation of the three modules; Find_Diffs, Sum_Diffs, and Eval_Diffs, the result on the window from line #2 to #8 comes out from the Filter module. Hence the first result of the combined four modules will be on the pixel **b**, not on the pixel **a**. The total delay to give the result on the pixel **b** will be nine lines.

The algorithm shows that the edge is not detected in the first four lines, the last four lines, the first three columns and the last three columns of an image. If we still want to send the information on the missing pixels, we can send them only by background texture coding. This can be done by sending the texture coding signals after five lines of the edge detector operation. After five lines of delay, the texture coding on the fist four lines in the image frame will be started and will operate simultaneously with the edge detection operation.

If the filter module is eliminated, then time delay of one line can be be saved. The first output from the detector will be on the pixel 1, which means only seven lines of delay until the result. Also from the time the edge detector processes the fifth line, the texture coding on the first line can be started. But the result of the image without filter

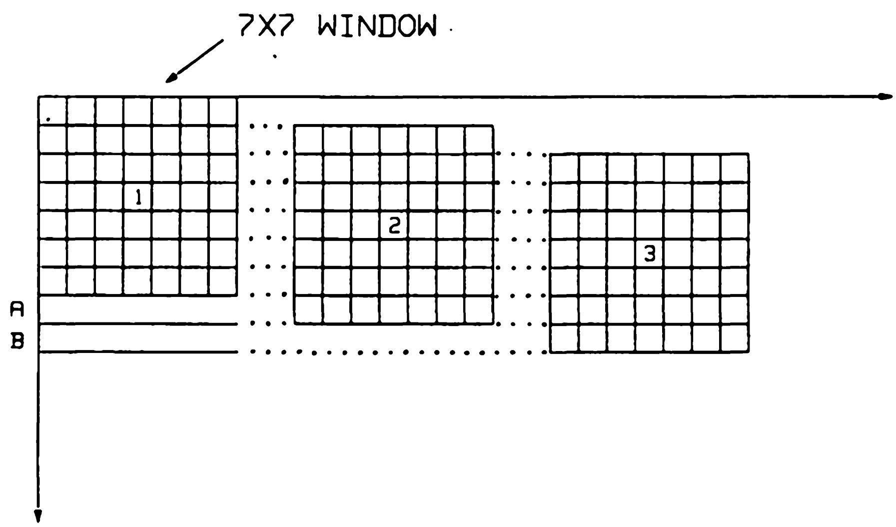


Figure 31. The Operation of the Gradient Window on a Image Frame

operation showed excessive edge pixels due to the noise components in the image, which can degrade the system performance greatly; in particular, the bit rate is increased.

If the boundary pixels look very different from the rest of the picture, then they can be discarded from coding. the size of the picture will be reduced by total of 8 lines vertically and total of 8 columns horizontally.

5.2 Comparison of the Bit Rates

The images which have been obtained with various algorithms were compared in bit rate. The equation below was used in finding the bit rate.

$$BR = \frac{n_e + n_c + n_d + n_r + n_p}{n_T} \qquad bits/pixel$$

where,

n_e : number of edge information bits

n_c : number of correction (DM) bits

n_d : number of direction bits

n_r : number of bits in 8-bit reset pixels

n_p : number of bits in DPCM coded pixels

n_T : total number of pixels in the image

n_e is required by all the schemes which are developed in this paper and no compression is assumed ($n_e = n_T$). The edge information bits can be reduced by the method in Section (4.1) or by various binary image compression methods. n_c is the number of

DM coded pixels which constitutes the background other than the edge coded area. Usually it is the difference between the number of pixels in an image and the edge pixels. n_d is the number of the bits sent if the scheme requires the transmission of directional information. The number varies from scheme to scheme and depends strictly on the number of the edge pixels. In most of the cases, the number is the same as n_e. n_r is required if some of the edge pixels are 8-bit reset. $n_r = 8 \times n_R$, where n_R is the number of pixels to be reset. n_p is expressed by the equation $n_p = n_x \times m_p$ where n_x is the number of bits for the DPCM output and m_p is the number of pixels to be DPCM coded.

In Table 2, the bit rates of various schemes are shown and compared. To find the values in the table, the threshold values and the window size of the edge detector, sampling rate of DM signals were the same in all of the methods in the table. The values of bit rate in the table were obtained assuming no overhead information, no compression of edge information bits, direction bits or correction bits. Hence the above bit rates should not be compared directly with the conventional methods because the extra bits mentioned above are not compressed and depend upon the methods to be applied.

We notice from the table that even if the 2DDM method is used in edge coding, when some of the edge pixels are reset to 8 bits, then the bit rate can be higher than the one with DPCM edge coding. The reason is that we are monitoring the predicted values in the encoder. When the predicted values are sufficiently close to the input sample values, then the point is declared as a non-edge point even if it is found to be an edge by the edge detector. The values coded by the crude DM method have less chance of being close to the input sample values than the ones coded by DPCM.

Table 2. Comparison of the Bit Rates

(M is for monitoring two past DM bits. A - D, G, H : Refer to Table 3.)

Background Coding	Edge Coding	Direction Bit	Reset to 8 bit	Prediction on Edge Pel	Quantization on Edge Pel	Bit Rate (bit/pel)	
1DDM	Reset	None	Yes	None	8 bits	4.41	
	DPCM	None	Yes	Average	3 bits	2.88 2.28 (M)	D
	DPCM	None	Yes	Average	4 bits	3.10	
	DPCM	0-2 bits	Yes	Edge Follow	3 bits	3.16 2.41 (M)	C
	DPCM	0-2 bits	Yes	Edge Follow	4 bits	3.46	
	2DDM	1 bit	No	Normal	1 bit	2.35	
2DDM	Reset	None	Yes	None	8 bits	4.21	
	DPCM	1 bit	Yes	Edge Follow	3 bits	3.44	H
	DPCM	1 bit	No	Edge Follow	3 bits	2.96	G
	DPCM	None	No	Graham	3 bits	2.65	A
	DPCM	None	Yes	Graham	3 bits	2.85	
	2DDM	1 bit	Yes	Edge Follow	1 bit	3.05	
	2DDM	1 bit	No	Normal	1 bit	2.34	B
	2DDM	1 bit	Yes	Normal	1 bit	3.05	

5.3 Rank-Ordering Tests

The object of this test is to know how the viewers respond to the images obtained by the new methods. There must be some comparison methods which measure the quality of the pictures. The rank-ordering test for images developed by Huang [15] was selected. The subjects consist of various nationalities and have not involved in this kind of subjective tests before. The test is aimed at getting the response of the normal viewers, not the specialists who have been used as subjects before. The procedure of the test is as follows.

First, we select a group of pictures to be tested. The pictures are chosen to represent each method in this paper and some of them are coded by conventional methods. If too many pictures were chosen for this test the subjects may not judge properly so only eight images were tested. Each of the subjects to be tested is asked to rank-order the pictures in the order of picture quality as affected by noise. With the rankings they have made, the best picture is given a rank of one, the second best a rank of two. The people are asked to judge on the overall appearance of the pictures, not just specific details.

The viewing distance is varied to see if the distance has any relation to the subjective quality of a picture. But if the distance was far from the set of pictures, nobody could judge well. The reason is thought to be the low quality of the Polaroid pictures which was used throughout the tests. Therefore the distance was fixed to 45 cm which is about 6 times the picture height. At the distance, everybody could rank the pictures without much difficulty.

The result of applying this procedure is shown in Table 3. Two kinds of images were tested. One of them is the GIRL image which have been used extensively throughout this thesis and the other is the HOUSE image, which is a natural scene with houses and trees.

For each of the images, GIRL and HOUSE, the average ranking [16] was obtained. That is, for each of the images coded by different coding methods, the sum of the ranks was obtained. The picture with the smallest sum was given a rank of one and the picture with the second smallest sum was given a rank of two, and so forth.

There is little difference between the judgments made by the subjects for the two different sets of image. One of the most notable things in the set of data is that the 2DDM background coded pictures had a good response from the subjects. Even if the backgound texture has a little bit of noise due to the wrong prediction, the 2DDM coding can reproduce the vertical edges more clearly than 1DDM case. The subjects tended to look for the quality of the vertical edges in the pictures. They rejected the picture when there was only a slight busyness on the edges. The normal 2DDM coded picture not combined with edge detection did not receive good points from the subjects, which means that most of the pictures coded with the methods in this thesis are subjectively better than the normal 2DDM method without edge detection.

We must be able to measure the reliability of the tests performed. The measure is called the concordance calculation [16]. The coefficient of concordance W must be obtained as follows.

Let m be the number of the rankings by subjects and let n be the number of the pictures to be ranked. The sum of the ranks in columns would be

$$\frac{mn(n + 1)}{2}$$

Table 3. Rank Ordering Tests

(The brackets are for ties.)

Test No.	Picture	Rankings	No. of Observers
1	GIRL	A H D G C F B E	9
2	HOUSE	H A G D C (B F) E	9

A : 2DDM-DPCM, Graham's Predictor on edge, 3-bit quantization

B : 2DDM-2DDM, No resetting to 8 bit

C : 1DDM-DPCM, Direction bit, 3 bit quantization, monitored two same DM bits

D : 1DDM-DPCM, Prediction on edge : average of edge pixels, 3-bit quantization

E : 1DDM

F : Normal 2DDM

G : 2DDM-DPCM, direction bit, no resetting to 8 bit, 3-bit quantization

H : 2DDM-DPCM, direction bit, resetting to 8 bit, 3-bit quantization

Obtain the sum of the squares of deviations from the mean $\frac{m(n+1)}{2}$, and call it S.

If the concordance is perfect, the sums of each rank will look like m, 2m, ..., nm and the summation of the terms is

$$\frac{m^2(n^3 - n)}{12.}$$

Hence the coefficient of concordance is

$$W = \frac{S}{\frac{m^2(n^3 - n)}{12}} = \frac{12S}{m^2(n^3 - n)}$$

where $0 \leq W \leq 1$.

The concordance coefficient in the test 1 was 0.768 while in the test 2 it was 0.617. It means that the subjects could not judge as well on the HOUSE image which is a natural scene. They could not judge on the small details as they did in the GIRL pictures.

5.4 Elimination of Edge Information Bits?

The edge information bits which must be sent to tell the receiver that the point in an edge is the major obstruction to the goal in reducing the bit rate. Also the edge detector used in this thesis is expensive to implement and it seems to be too complicated a system for a coder. Hence a way to eliminate the edge information was investigated.

If the edge can be detected with the DM correction bits, then we will not need the extra information bits. Therefore the statistics of the relations between correction bits and edges were measured. A window was designed as Fig. 32. There are $2^8 = 256$ configurations for the 3x3 window assuming that a binary number was assigned to each of the elements. For each configuration of the window the statistics of the pixel X being an edge was found.

The result showed that we cannot find any configuration which has a probability which is significant enough to be used. The statistics showed that the average probability of X being an edge is 0.364 with variance 0.00273 and only two configurations exceeds 0.5 in probability.

5.5 Root-Mean-Square Error

The root-mean-square errors between each of the images coded by the coding methods in this thesis and the original image were obtained. The figures in Table 4 show that there is more error in the 1DDM texture coded pictures. This result is due to the fact that the method reproduced the image very crudely in the vertical direction. It didn't consider the vertical correlation of the picture elements at all. 2DDM texture coding case in combination with various edge coding methods did a fine job in reproducing the images. Except the method of resetting all the edge pixels to 8 bit, the scheme with the lowest rms error is the one with DPCM on edge, 3-bit quantization and the edge following prediction. But from Table 2, it will be noticed that the method requires a high bit rate. Observing and comparing the two tables (Table 2 and Table 4) the most economical method while preserving the picture quality seems to be the one with 2DDM texture coding in combination with DPCM edge coding.

A	B	C
D	E	F
G	H	X

Figure 32. 3x3 Window: Finds the statistical relationship between correction bits and edge bits

Table 4. Comparison of RMS Errors

(M is for monitoring past two DM bits. A - D, G, H : Refer to Table 3.)

Background Coding	Edge Coding	Direction Bit	Reset	Prediction on Edge Pel	Quantization on Edge Pel	RMS Error	
1DDM	Reset	None	Yes	None	8 bits	15.91	
	DPCM	None	Yes	Average	3 bits	18.69 20.19(M)	D
	DPCM	None	Yes	Average	4 bits	18.40	
	DPCM	0-2 bits	Yes	Edge Follow	3 bits	18.48 19.99(M)	C
	DPCM	0-2 bits	Yes	Edge Follow	4 bits	18.33	
	2DDM	1 bit	No	Normal	1 bit	20.75	
2DDM	Reset	None	Yes	None	8 bits	13.03	
	DPCM	1 bit	Yes	Edge Follow	3 bits	13.13	H
	DPCM	1 bit	No	Edge Follow	3 bits	13.26	G
	DPCM	None	No	Graham	3 bits	13.73	A
	DPCM	None	Yes	Graham	3 bits	13.28	
	2DDM	1 bit	Yes	Edge Follow	1 bit	16.95	
	2DDM	1 bit	No	Normal	1 bit	16.72	B
	2DDM	1 bit	Yes	Normal	1 bit	14.96	

5.6 Difference Images

The difference images between the original image and the coded images were obtained. Within each of the combination groups ; 1DDM-DPCM, 1DDM-2DDM, 2DDM-DPCM and 2DDM-2DDM, the difference images looked very similar. Hence four pictures representing each group were picked for comparison purposes in this paper. All the difference images had low contrast so they were thresholded at 85 in the gray level range of 0 to 255. The differences are absolute values.

Figure 33 shows the difference image between the original and the image with 1DDM-DPCM coding. We can see that the vertical edges are not reproduced clearly. Figure 34 shows the difference image corresponding to 1DDM-2DDM coding and more noises in the texture area can be seen than DPCM edge coding case. Figure 35 is the difference image corresponding to 2DDM-DPCM coding. There are fewer noises than the 1DDM background coding cases and the vertical edge noises are not visible as previous coding schemes. Fig 36 is the difference image of 2DDM-2DDM coding. The image has a lot more noises than the DPCM edge coded image but the errors seem to be distributed throughout the entire image rather than confined to some areas as in 1DDM background coded pictures.

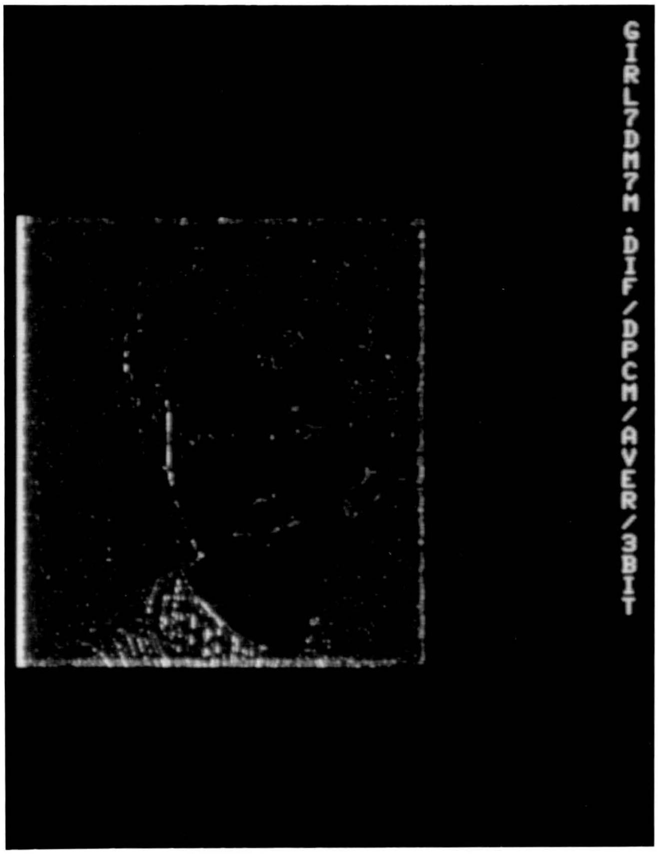


Figure 33. Difference Image: 1DDM-DPCM

Figure 34. Difference Image: 1DDM-2DDM

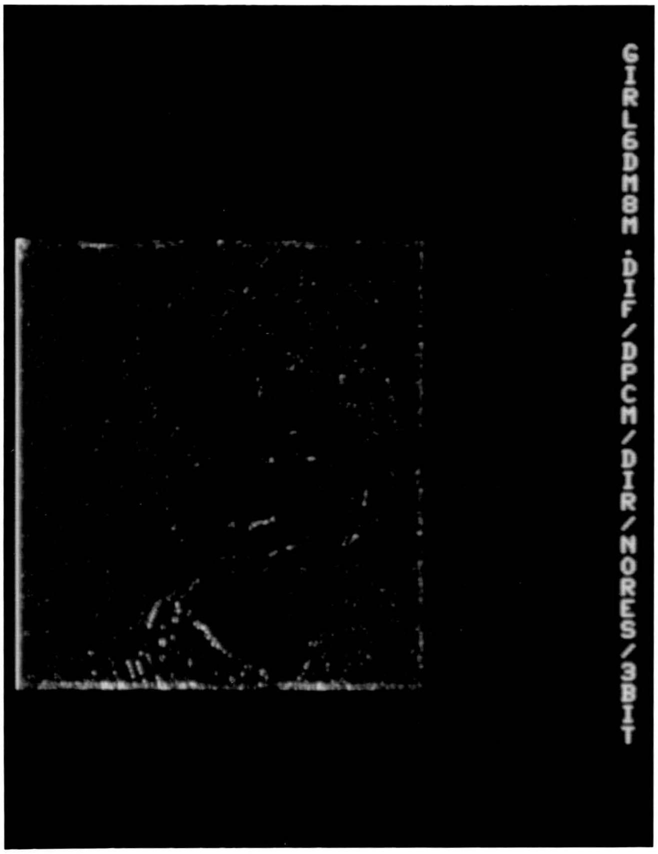


Figure 35. Difference Image: 2DDM-DPCM

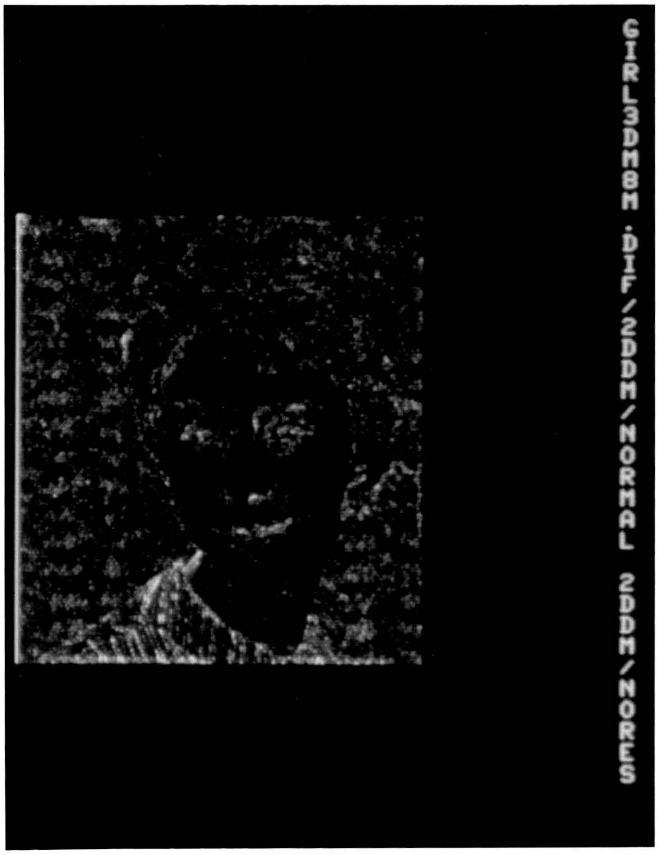


Figure 36. Difference Image: 2DDM-2DDM

6.0 Conclusions

Algorithms of dual-mode coding switched by Pseudo-Laplacian edge detector were presented and evaluated in this paper. The Pseudo-Laplacian edge detector was selected for the switching mechanism for its capability of finding black and white edges and its immunity to the noise present in an image. For the texture coding method, the Song one-dimensional delta Modulator and the weighted average prediction two-dimensional delta modulator were chosen for their simplicity and low bit rate. For the edge coding algorithms, many DPCM and DM coding methods were developed and tested. Some of the edge pixels can be coded with 8-bit original pixel value which makes the scheme triple-mode.

Among the many combinations which have been studied, the 2DDM textural coding systems proved to be more effective subjectively than the 1DDM textural coding systems. In the subjective quality tests, the system with only the normal Song 2DDM coder proved to be worse than most of the algorithms developed in this paper. The highest ranked pictures in subjectivity test for two kinds of image, GIRL and HOUSE, were types A and H in Table 2. This assures that 2DDM-DPCM schemes are superior to 1DDM-DPCM in subjectivity even though the bit rates are about the same in both of the cases. Also the effects of resetting some of the edge pixels to 8-bit original value enhanced the subjective quality as shown in the Table 2.

The bit rates of 1DDM texture coding systems can be saved by about 20 percent by monitoring past two one-dimensional DM bits. The number of edges are reduced by the method of filtering as above. Also the bit rate can be further saved by the method of disregarding the results of the edge detector if the predicted value is close enough to the input sample value. Hence the extra bits which are needed to code the edge pixels in more accurate methods than the textural coding were not needed.

The bit rates of the schemes developed in this paper are highly dependent on the number of edge pixels in an image frame. These schemes are very effective for the images which do not have much detail. The proposed usage of this technique is coding the video conference images which are not too edgy and have smooth backgrounds.

More studies have to be done on compressing the correction bits and the edge bits. Also the ideas represented in this paper can be applied to coding the color video signals. Furthermore, the interframe coding method can be combined to reduce the bit rate further.

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