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1. Introduction

This document describes the Hybrid Extended MPEG (HEM) coding system, where the coder, decoder, various functionalities and their complexities are analyzed in detail. This coding system is being proposed as a standard for compression and decompression of moving pictures as addressed by the second phase of the MPEG work. This document is aimed at fulfilling the requirements of the ISO/MPEG proposal package description (MPEG 91/100).

The basic algorithm shares many similar features with the video coding system specified in the MPEG Simulation Model (SM) [1]; therefore, the syntax is also very similar to the one described in the CD 11172-2 [2]. HEM exceeds the SM quality in coding pictures at higher rates by modifying the SM algorithm. In particular we believe that the following new features contribute significantly to quality over that achievable by the SM:

— Hybrid field-frame based approach (field-based motion compensation and frame-based Discrete Cosine Transform).

— Optimized bit allocations and quantizer assignment.

— Adaptive Huffman code tables (according to JPEG standard).

The HEM has a hybrid coding structure with field-based motion compensation (MC) and frame-based Discrete Cosine Transform (DCT). Motion estimation is first performed on pairs of 4:2:0 subsampled fields. After motion compensation, odd and even fields are merged by interleaving the rows into one frame, and the DCT is applied to the residual signal on a frame basis. Bit allocation is done for the entire frame, and the quantizers are assigned on the Macroblock level based on the bit allocation. After quantization, the DCT values are encoded using the adaptive Huffman code table as in the JPEG standard.

2. Description of the Hybrid Extended MPEG Algorithm

2.1 Overview of HEM

The compression algorithm starts with preprocessing where each CCIR601 field is converted to a 4:2:0 subsampled field with 240x720 pixels of Y and 120x360 pixels of Cr and Cb. The encoder operates on the subsampled sequence at 60 fields/sec. Details of the preprocessor are given in section 2.2.

Since each subsampled frame (fields merged) has dimensions four times the size of a SIF picture, the processing complexity is slightly more than four times that of MPEG I. HEM performs source coding in intraframe, predictive, and bidirectionally predictive modes. It also has a similar, yet modified set of data structures as compared to MPEG I. The data structures include Groups of Pictures (GOPs), Super Slices (SSs), Super Macroblocks (SMBs), and Macroblocks (MBs). Each GOP has 12 frames with two bidirectionally coded pictures between two predicted frames (M=3) (Fig.1). A Super Slice consists of one row of Super Macroblocks, and each Super Macroblock has two Macroblocks spatially oriented in the vertical dimension (Fig.2).

The structure of the encoder is similar to the algorithm in the SM with the parameters set differently, affecting the controls of various coding operations. The principal compression techniques used in the encoder are still 2-dimensional Discrete Cosine Transform, Motion Compensation, and Variable Length Coding (VLC). To improve motion prediction, motion estimation is performed field by field on the same parity; i.e., even fields are used to predict even fields, and odd for odd. The DCT is still applied on each 8x8 block after the two motion compensated fields have been merged. The Macroblock Quantizers (MQUANTs) are selected through an iterative process such that the total bit count generated in a frame is within some margin of the bit allocation. Finally the DCT quantized values are encoded using a Huffman table adapted to the statistics of the quantizer outputs. The decoded pictures are converted back to the CCIR601 format through postprocessing.

Details of each module of the compression algorithm are described in the following sections. The issues of compatibility to existing standards, complexity of the coder-decoder, and other functionalities are covered in subsequent sections. The algorithm block diagrams, flow charts, VLC tables, and syntax diagrams are also given. Finally, the listing of bit stream files and the coding statistics are appended.

2.2 Preprocessing

The source video is converted from the CCIR601 format into a sequence of 4:2:0 subsampled fields through preprocessing. The sampling rate of the chrominance signals is reduced vertically by a factor of 2. Since each CCIR601 field contains 243 lines of luminance and chrominance signals, the last three lines out of those 243 in all three components are dropped. Each of Cr and Cb arrays of size 240x360 is then vertically decimated to get arrays of size 120x360 which are used in the coding. The decimation is carried out by processing the Cr and Cb input arrays along each column with a symmetric eleven-tap FIR filter and computing only 120 output samples per column. The output (column) signal $y[n]$ is given by:

$$y[n] = 1/S \sum_{i=-5}^{5} h[i]x[2n-i], \quad 0 \leq n < 120, \tag{1}$$

where the input signal $x[n]$ is extended by five samples at each end. The filter coefficients are given by:

$$h = [3,0,-25,0,150,256,150,0,-25,0,3];$$

and the scaling factor $S = 512$.

2.3 Postprocessing

The decoded video is converted from the 4:2:0 subsampled format back to the CCIR601 format through postprocessing. The sampling rate of the chrominance signals is increased vertically by a factor of 2. Each of Cr and Cb decoded field arrays of size 120x360 is vertically interpolated to get arrays of size 240x360. The interpolation is carried out by processing the Cr and Cb input arrays along each column to insert a sample after every input sample. The interpolated output (column) sample $y_o[n]$ is given by:

$$y_o[2n+1] = 1/S_g \sum_{i=-1}^{2} g[i]x_d[n-i], \quad 0 \leq n < 120, \tag{2}$$

where the decoded signal $x_d[n]$ is extended by one sample at the beginning and two samples at the end of the column. Note that $y_o[2n] = x_d[n]$, $0 \leq n < 120$. The filter coefficients are given by:

$$g = [-1,9,9,-1];$$

and the scaling factor $S_g = 16$. Since each CCIR601 field contains 243 lines of luminance and chrominance signals, three (black) lines are appended to the 240 lines in all three components.

2.4 Predictive/Transform Coding Loop

Figure 3 summarizes the core of the compression algorithm. It shows tremendous resemblance in structure to the SM hybrid coding loop. This coding loop is based on temporal predictive coding with motion compensation and transform coding. It also contains an embedded decoder to recover the coded pictures. A simple mechanism in the loop allows the encoder to switch among the intraframe, the predictive, and the bidirectionally predictive modes. One distinctive feature of the HEM which is different from the SM is that motion estimation/compensation is performed field by field on the same parity, while all other operations including the DCT and quantization are performed frame-based (Fig.4). A Macroblock is the basic processing unit in most operations, where the MBs are scanned within the SMBs down each Super Slice throughout the entire frame.

2.4.1 Intraframe Coding

Intraframe coding is used to encode the first frame (encoding order) of each GOP. It is done like the SM intra-coding where DCT is performed once on every 8x8 block in the source picture. After DCT, an MQUANT is assigned to every MB based on the statistics of the DCT outputs. Then quantization is done utilizing the MQUANTs and a non-uniform 8x8 matrix. The process of MQUANT assignment and quantization is reiterated until certain requirements are met. Then a VLC table is generated based on the statistics of the quantizer outputs to encode the quantized DCT coefficients. The intraframe (I-frame) is reconstructed through inverse quantization and inverse DCT. The decoded image is stored in a coded picture memory as reference picture for future motion compensation.

2.4.2 Predictive Coding

Predictive coding is used once every three frames except on the first frame of a GOP. This coding scheme requires motion prediction from a previously coded I-frame or P-frame (predicted frame). Motion estimation is performed on the original luminance components of both the current picture and a reference picture. Since motion estimation is more accurate when performed on the same parity field, the even field of the reference frame is used to predict the even lines of the SMBs in the current frame, and the odd field is used to predict the odd lines. The motion compensated even and odd lines are then interleaved to produce a motion compensated frame. Then the intra/non-intra decision is made for each MB in the P-frame based on the criterion in the SM algorithm [1]. According to this decision, either the prediction error or the original data (in the case of an intra MB) is encoded through the DCT. DCT is actually performed twice, once on the luminance of the original picture, and once on the difference picture. The result of the first transform is used to evaluate MQUANTs. Again, the assignment of MQUANTs and quantization are repeated until some criterion is reached. A new VLC table is then generated to encode the quantized output. Each P-frame is also reconstructed by adding the prediction back to the decoded difference picture. This recovered picture is used to predict the B-frames (bidirectionally predicted frames). In addition to the P-frame Macroblock types used in the MPEG I standard, a new MB type is defined. A non-coded MB with zero motion vectors, formerly considered as skipped, is now defined with a 7-bit codeword. More on Huffman coding will be described in a separate section.

2.4.3 Bidirectionally Predictive Coding

Bidirectionally predictive coding is used twice consecutively between two non-B-frames. In this coding mode, motion estimation is performed twice, with forward prediction referencing a past frame, and backward prediction referencing a future frame, where both reference pictures must have been previously coded and decoded in either the intraframe or the predictive mode. Again, motion estimation is field-based on the same parity. MB type decisions for the B-frame are the same as the SM and their VLCs apply. As in predictive coding, DCT is performed once on the luminance of the original picture, and once on all three components of the difference frame. The result of the first transform is used to evaluate MQUANTs. After some iterations of MQUANT assignment and quantization, a new VLC table is generated for the DCT quantized coefficients.

2.4.4 Motion Estimation

Motion estimation is performed on the luminance component of the original picture. Specifically, it is applied to each 16x16 block in a field. If the current frame is a P- or B-frame, the 16x16 block in the even (odd) field is found a best-matched block from the even (odd) field of the previous I- or P-frame, and a set of motion vectors (horizontal and vertical components) is obtained correspondingly. Note that there are two sets of motion vectors for each 32x16 block in a frame where the odd and even lines are block-matched independently. For a B-frame, an additional set of motion vectors is obtained from the next I- or P-frame with the same process. All the motion vectors are with half-pixel resolution, and are obtained by full search. The maximum search range is related to the field distance. Given a field distance of F, the search range used in the proposal is [-(max{21,7F}+0.5), max{21,7F}+0.5] subject to the constraint of image boundary.

2.4.5 MQUANT Assignment

MQUANTs are assigned to all MBs in a way to stablize the compressed quality in the spatial-temporal domain. Their values are also adjusted iteratively to keep the bit rate output under control. In this section, only the MQUANT assignment is described. The rate control is left for a following section.

As described previously, all three coding modes require DCT to be performed on the luminance component of the original picture. For every 16x16 luminance Macroblock, the value $ACsrc$ is evaluated according to the following:

$$ACsrc = ACav * \frac{128}{\max(DCav, 96)} \tag{3}$$

where $ACav$ is the absolute AC average over the 4 8x8 blocks of DCT coefficients, $DCav$ is the average DC coefficient, 128 is a normalizing factor, and 96 is used to decrease the sensitivity of the DC term for $DCav$ values below 96. $ACsrc$ is a factor that explores the invisible distortion of a MB. MQUANT is proportionally assigned based on this value:

$$MQUANT = 2^{c} * ACsrc, \quad \text{for } I \text{ and } P \textit{ frames}; \tag{4}$$
$$MQUANT = 2^{c+g} * ACsrc, \quad \text{for } B \textit{ frames}; \tag{5}$$

where c is determined by rate control, and g is a preset value so that the quantizers for B-frames are slightly larger. According to this equation, MBs with higher texture are assigned larger MQUANTs and vice versa. Since every new MQUANT comes with an overhead in MB type and extra bits to specify the new value, some measure is taken to limit the occurrence of new MQUANTs. After DCT has been applied on the original picture, $ACsrc$ is calculated for every 16x16 block of the entire frame. Based on the statistics of the $ACsrc$s, one particular value ($ACflat$) is selected where the $ACsrc$ of a MB is changed to $ACflat$ if any one of its neighbors has a value less than or equal to $ACflat$. This step attempts to assign MQUANTs of flat regions to the surrounding edges. Then again based on the statistics of $ACsrc$s, $ACmax$ and $ACmin$ are selected to limit the range of $ACsrc$, with $ACmin$ greater than $ACflat$. Any value outside of this range is cropped by the max or the min. This step attempts to fix MQUANT in regions with $ACsrc$s that fall outside of the range. These two steps not only control the usage of MQUANT, but also helps to reduce the artifacts associated with coarse quantization of edges.

2.4.6 Quantization and Inverse Quantization

Quantization and inverse quantization are done very similarly as in the SM. They utilize both the Macroblock Quantizer and a Quantization Matrix (QM). As in the MPEG I standard, the QM is downloadable in the sequence layer, and separate matrices can be used for intra- and non-intra-quantization. The QM used in the simulations takes on intermediate shape between the two default matrices in the SM. The only different feature introduced is the expansion of end-of-block area before the intra-quantization. Each 8x8 block of an intra MB is zig-zag scanned to obtain a one-dimensional array of increasing frequencies. Then a variable threshold (Th) is applied on every element starting from the last coefficient and ending on the fourth coefficient of lower frequency. The variable thresholding is performed this way:

```
for (i=63; i>=3; i-=1) {
   Th[i] = (2*MQUANT*QM[i])/16;
   if (DCT[i]>Th[i] || DCT[i]<-Th[i]) break;
   DCT[i]=0;
}
```

where MQUANT is the Macroblock Quantizer assigned to the current MB, QM[i] is the ith entry of the Quantization Matrix, and 16 is a normalizing factor. Any element in the zig-zag scanned array with an absolute value lower than its corresponding threshold will be set to zero. This thresholding proceeds from the coefficient of highest frequency and terminates upon an element that exceeds the threshold. The purpose of this thresholding is to expand the end-of-block area of each 8x8 block within an intra MB to cut down the number of bits used for high frequency signals.

2.4.7 Rate Control

Rate control is achieved by adjusting the value of c which is used to evaluate MQUANTs (Eq. 3). Large cs contribute to coarse quantization and lowering of current bit rate. The process of MQUANT assignment and quantization reiterates during the coding of a frame until an optimal c is selected for the frame. This value of c is carried over to the next frame so that a stable quality can be achieved in the temporal domain.

This rate control scheme begins by assigning target bits for I-, P-, and B-frames such that these target values meet the bit rate constraint. The variable c is initialized for the first iteration in the MQUANT-quantization loop. It is also re-adjusted in each iteration in order that the final number of bits produced by the current frame is within some δ of the target value. This δ is a small fraction of the desired bit rate. To prevent indefinite looping, some terminating conditions are used and are summarized in a flow chart (Fig.5). If none of those conditions applies, c must be adjusted before the next iteration. The adjustment of c is summarized in another flow chart (Fig.6).

After the last iteration, c should have been changed more or less from its initial value. Since this new c will become the initial value for the following frame, the projected value of bits generated for each frame type can be calculated based on this new c. If these projected values were to be used as target bits, the resulting bit rate will eventually deviate from the desired bit rate. Therefore the target bits used in the terminating conditions must be updated based on the rate of change in bits due to the change in c. Also, at the end of each GOP, the buffer occupancy must return to the initial state at the beginning of the GOP to achieve a fixed delay. Since the actual number of bits generated per frame varies in time, the buffer state at the end of a GOP is indeterminate before the coding of the entire GOP is complete. Therefore, the projected difference in this final buffer state must be monitored and the target bit updating should absorb the buffer difference in advance.

In predictive coding, a simple switch is used to detect a scene change. If the number of intra MBs in a P-frame is greater than half the total number of MBs in a picture, a scene change is signaled. The initial value of c will be raised by a small step for the current P- and the following two B-frames to accommodate the increase of bit consumption. This switch helps to speed up the iteration process that seeks for an optimal c.

2.5 Parameter Selection

The assignment of parameters is automatic, and no single parameter in the simulations has been optimized for any particular video sequence. However, there are three small sets of parameters whose values differ for bit rates above and below 6 Mbits/sec. The first set handles the initial assignment of target bits among different picture types. The second set determines the shapes of the intra- and non-intra-quantization matrices. The third set selects the max and the min *ACsrc* based on the distribution of the *ACsrc* on the current frame.

2.6 Entropy Coding

Because of the great resemblance in structure between this algorithm and the MPEG I simulation model, the set of symbols produced is coded in a similar manner; we only describe the differences below.

Macroblock Addressing and Coded Block Pattern from the MPEG I standard are not used since not many MBs are skipped at high bit rate coding. The start codes and the header information used in different layers remain the same. Those symbols that are handled differently include the following :

— The intra DC coefficients are differentially coded as in CD 11172-2, while the zero-runs and non-zero amplitudes for all other quantized DCT coefficients are coded using the JPEG approach. This approach optimizes the VLCs locally according to the symbol statistics in each frame. Some data regarding the codebook information will be sent along for the decoder to reconstruct the customized VLC table, and this information is inserted as the extension data in the picture layer.

— Two pairs of motion vectors must be coded for each motion-compensated Super Macroblock because the odd and even lines of an SMB are motion estimated independently. The differential motion vectors (DMVs) are encoded as in CD 11172-2 with the prediction being the motion vector of the most recently motion-compensated even MB. In other words, the prediction for an even MB motion vector will be that of the previous even MB and the prediction for the odd MB motion vector will be that of the current even MB. The motion vector prediction is reset at the beginning of a Super Slice. For a P-frame, it is again reset if both MBs of an SMB are of types No MC or intra, or if either one has type No MC while the other has type intra. For a B-frame, it is only reset if both MBs are intra. No change in syntax from CD 11172-2 is required to encode the DMVs.

— Macroblock types VLC tables for the three coding schemes remain the same except that a new MB type is introduced in the P-frame. A No-MC and Not-Coded MB will be encoded as type "0000001".

— The Macroblock Quantizer of the first MB in a Super Slice will be coded as the Super Slice Quantizer. This value will be used by the Super Slice until it is over-ridden by a different MQUANT. All Super Slice Quantizers as well as the new MQUANTs are coded with 5 bits as in the CD 11172-2.

3. Compatibility Feature

The coder and decoder of the HEM algorithm shares many common elements with the MPEG I system. These elements include the 8x8 DCT, zig-zag scan, quantization, inverse quantization, 16x16 motion estimation/compensation, and most of the VLC tables. This system cannot claim total compatibility with MPEG I because the data structure has been changed in the SMB level (see syntax diagrams). The MBs are scanned in a slightly different order, and the motion vectors are predicted differently. However, these two systems are compatible up to the building blocks. Furthermore, the issues of forward, backward, upward, and downward compatibility have become less important due to the implementation of programmable chips which can operate as different systems by loading the corresponding firmware. Given such technology, the key issue now seems to rest upon the commonality of processing elements.

4. Random Access Feature

Random access is achieved by periodic reset to intraframe coding. Since intraframe coding does not rely on the previous frame for decoding, an intraframe is readily accessible. The degree of random accessibility depends on the frequency at which intraframe coding is invoked. If a P- or a B-frame is requested, the decoder will start decoding from the previous intraframe until the requested frame is reached, ignoring all the intermediate B-frames. Presently our encoder invokes the intraframe mode once every 12 frames which is determined by the GOP structure. The amount of time to reach a given frame is given by the time to read the amount of bits representing the predictively coded frames of the GOP anterior to the given frame. The worst case of random access time is thus given by the time it takes to read the entire predictive part of a GOP structure.

5. Coding/Decoding Delay

Fig.7 shows the complexity block diagram of the Hybrid Extended MPEG (HEM) encoder. Each module is labeled with a block number. Block number 1 down-samples the incoming pictures from 4:2:2 to 4:2:0 using an 11-tap filter, and the results are being stored into frame memories 2, 3, 4, and 5. Blocks 2 and 3 are used to store B-frames, and blocks 4 and 5 are used for I- and P-frames which will be used as reference pictures for motion estimation. Blocks 6 and 7 perform backward and forward motion estimation respectively. Blocks 22 and 23 store the corresponding odd-field motion vectors while block-matching on the even fields is being performed. Block 8 performs DCT on the luminance signal and block 10 stores the output of block 9, the *ACsrc* of each luminance Macroblock (MB). Blocks 19 and 20 perform motion compensation based on the motion vectors and the reconstructed reference frames (blocks 18 and 17). Then block 11 performs DCT on the prediction error; the coefficients are saved in block 12. These coefficients are quantized and the adaptive VLCs are generated in an iterative process with a maximum number of 5 iterations. The final set of quantized values are reconstructed through blocks 15 and 16. The timing requirement of each module is shown in Fig.8. In Fig.8 the number attached to the arrow identifies the processed frame number and the letter 'e' or 'o' represents its field parity. The length of the arrow implies the time duration for processing. The dash arrow associated with a memory implies the reading of data being held. Since a B-frame has the longest delay among the three frame types, the delay of the first B-frame (frame 1) is analyzed. Due to the nature of bi-directional prediction, a delay of M frames is imposed. Besides this M-frame delay, there is also a computational delay. The delay associated with the preprocessor is 1/20 of a frame.

Since the HEM encoder does not perform quantization until DCT of the entire frame is finished, a one-frame delay is expected before quantization. Furthermore, since this algorithm uses a frame adaptive VLC, VLCs cannot be assigned until quantization of the entire frame is done. Assuming that the quantization iterations of the entire frame are completed within 1/4 frame, the total computational delay is 1.3 (1/20+1+1/4) frame. Therefore, the encoding delay is M+1.3 frames (with M >= 2).

Fig.9 shows the block diagram of the HEM decoder. The structure looks exactly like the MPEG I decoder except for the merge and separate fields modules which are simply address generators. The post-processor performs chrominance vertical up-sampling from 4:2:0 to 4:2:2 using a 4-tap filter and converts each frame into interlaced fields. Each module in this block diagram performs its operation according to the timing requirements shown in Fig.10. The expected delay is 1/2 of a frame due to the conversion from the interleaved structure to the interlaced structure.

Since we are assuming an encoder output buffer of 6 frames, the worst case delay is 360 ms.

Overall Delay = Encoder Delay + Buffer Size + Decoding Delay
= 3 + 1.3 + 6 + 0.5
= 10.8 frames

6. Coder/Decoder Complexity

Each module in the encoder timing diagram (Fig.8) has its required performance/capacity. Table 1 shows the number of operations in the worst case for each Macroblock. Motion estimation is performed twice per MB (forward and backward directions). The 8x8 DCT is performed 10 times for each MB (4 times on the luminance MB in block 8 of Fig.7 and 6 times on the prediction error in block 11). Quantization of 8x8 DCT is performed 30 times due to the worst case iteration. VLC assignment is done 5 times (worst case iteration). Inverse quantization and 8x8 IDCT are performed 6 times each for each 8x8 block in a MB. Table 3 shows the requirements of each module. The pre-processor contains memory for 26 lines of the CCIR 601 input picture. Blocks 2, 3, 4, 5, 19, and 20 each contains 1 frame memory (240x720+120x360+120x360 pixels per frame). Block 10 contains 1350 floating points for *ACsrc* s, one for each MB. Block 12 contains all the DCT coefficients of an entire frame. Blocks 22 and 23 contain 675 pairs of motion vectors (x and y components) of a field. Blocks 6 and 7 complete motion estimation for one field in 1/2 a frame time or 1/60 of a second. Block 8 performs DCT on luminance only, while block 11 performs DCT on all 3 components. Each must be completed in 1/2 a frame. Block 13 has to complete 5 iterations of quantizations of 8x8 DCT on an entire frame in a 1/4 frame or 1/120 of a second. Blocks 15 and 16 perform 8100 (1350 MBs x 6 8x8 blocks) operations in 1/2 a frame.

Similarly, the number of operations of each module per MB in the decoder (Fig.9) is shown on Table 2. VLC decoding on each MB is done once. Inverse quantization and inverse DCT of 8x8 block are performed 6 times in each MB. Table 4 lists the corresponding required performance/capacity. The inverse operations in blocks 3 and 4 on the entire frame are completed in one frame time. The decoder requires 2 frame memories to store the reconstructed pictures and 1 frame memory in the post-processor to hold the output frame for scanning of odd and even lines.

7. Additional Functionalities

7.1 Fast Searches

Fast search is achieved by playing the sequence at a reduced frame rate and decoding only the intraframes at the decoder end. Fast search is essentially constrained by the amount of information to be read from the channel since the coded intraframes require significantly more bits than when motion compensated prediction or interpolation is used. At 4 Mbits/sec, the number of bits required by an intra-coded picture is typically less than 600 kbits. Therefore, at most 6 intraframes can be decoded every second given this bit rate. A factor of 4 speedup is achieved by decoding every other I-frame and displaying it 6 times. This amounts to decoding 5 intraframes per second with the resulting bit rate of 3 Mbits/sec. Fast search in either forward or reverse direction is implemented in the same way. The demo tape shows a video sequence in fast forward and fast reverse with a speedup factor of 4. The DC-picture mode from MPEG I could also be used to implement fast search without adding complexity.

7.2 Low Delay Mode

Shorter delay may be achieved by changing some parameters in the HEM encoder. In the low delay mode, there is only one B-frame coded between two P-pictures (M=2). To reduce the necessary buffer size, the periodic reset of the I-frame is eliminated. The GOP header is still inserted every 12 frames to report the time codes, but the first frame of a GOP will no longer be an I-frame except for the first GOP of a sequence. To terminate predictive error propagation, every 2 out of 15 Super Slices in P-frames are coded in intramode; i.e., each P-frame will have 2 Super Slices coded without temporal prediction, and these MBs are coded with type intra. Hence there is no need to send extra information to define these "Intra-Slices". This implementation will sacrifice random accessibility, but such functionality is usually not necessary where low delay pictures are required.

Scene change is detected in P-frames only. When such condition occurs, no DCT coefficient will be sent for the following B-frame until the next P-frame is coded. Also, if the buffer occupancy exceeds three quarters of the buffer capacity, the same measure will be applied for the following B-frame.

Assuming a buffer size of 2 frames for the low delay mode, the overall delay is 193 ms.

$$\begin{aligned}\text{Overall Delay} &= \text{Encoding Delay} + \text{Buffer Size} \div \text{Decoding Delay}\\ &= 2 + 1.3 + 2 + 0.5\\ &= 5.8 \text{ frames}\end{aligned}$$

If the first I-frame is not available to the decoder as in the case of channel-hopping or delayed access, the decoder will fill up its reconstructed frame memories with the value 128 (the default reference DC values in intramode), and start decoding and displaying the reconstructed pictures once synchronization is established. The image quality will gradually build up in about 1/2 a second because the picture will be fully replenished by intracoding in 8 P-frames.

7.3 Cell Loss Resilience

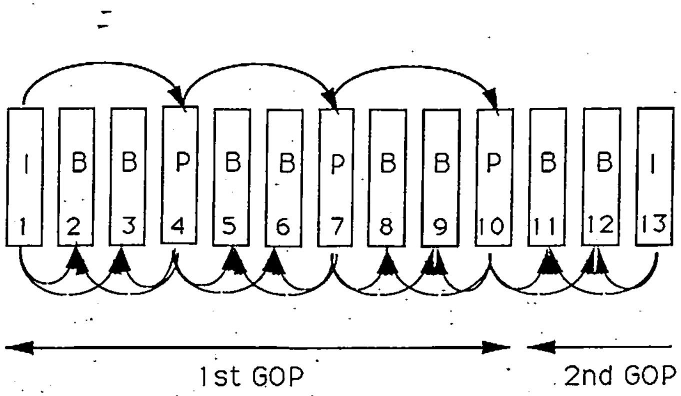
The cell loss resilience characteristic of the algorithm has been demonstrated by the following simulation. The bit stream of a coded sequence is packetized into cells and each cell contains 48 bytes. No link between the cell boundary and the bit stream syntax is made. A uniform distribution of packet loss is simulated by simply dropping a packet at a ratio of 1E-4. When a cell loss occurs, the decoder continues to decode the bit stream until it cannot go on. The decoder then looks for unique codewords (marks) to resynchronize. The undecodable blocks will be replaced with the corresponding segments from the previous frame according to the encoding order.

References

[1] "MPEG Video Simulation Model Three", Document MPEG 90/41, ISO/MPEG Simulation Model Editorial Group.

[2] "Coding of Moving Pictures and Associated Audio – for Digital Storage Media at up to about 1.5 Mbit/s – Part 2 Video", CD 11172-2.

8. Figures, Tables, Flowcharts, and Syntax Diagrams



I = Intraframe
B = Bidirectionally predicted frame
P = Predicted frame

Fig.1 A Group of Pictures (display order)
The first GOP has 10 frames only.
Other GOPs have 12 frames each.

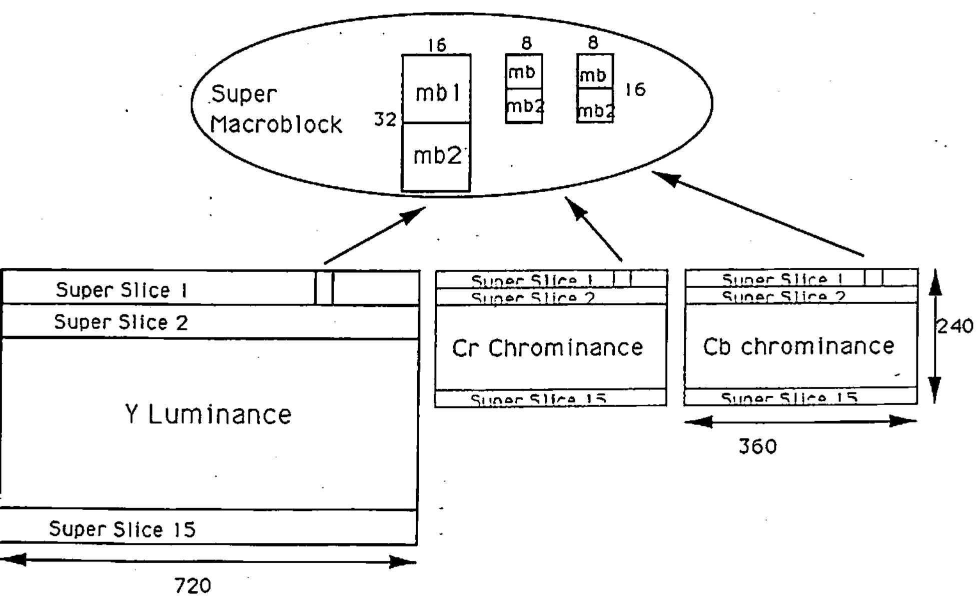
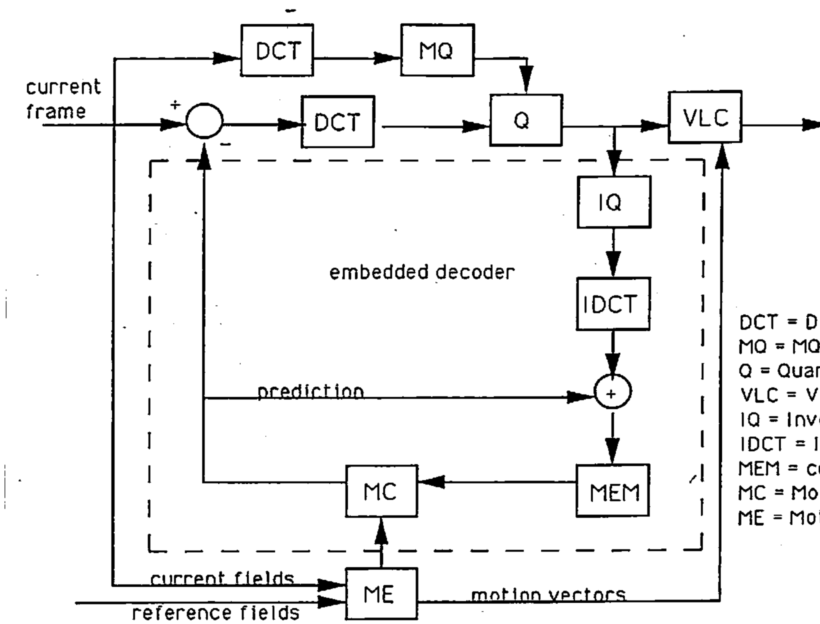


Fig.2 Data Structures --- Super Slice, Super Macroblock, Macroblock



DCT = Discrete Cosine Transform
MQ = MQUANT assignment
Q = Quantization
VLC = Variable Length Coder
IQ = Inverse Quantization
IDCT = Inverse DCT
MEM = coded frame memory
MC = Motion Compensation
ME = Motion Estimation

Fig.3 Predictive/Transform Coding Loop

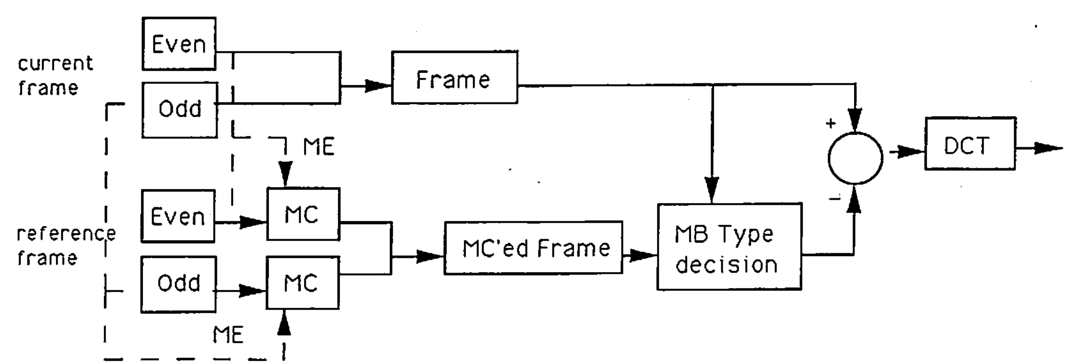


Fig.4 Field-based motion estimation/compensation

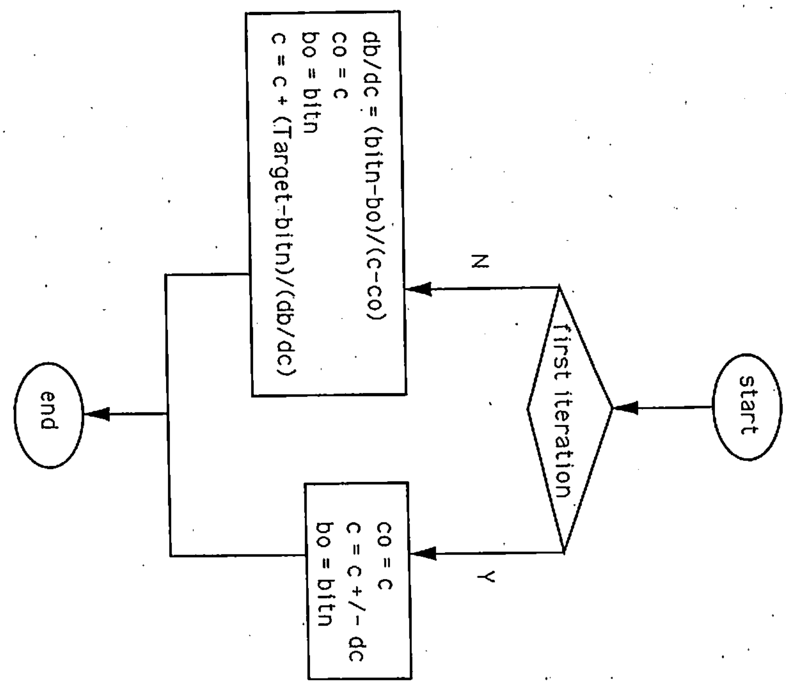


Fig. 6 Adjustment of c

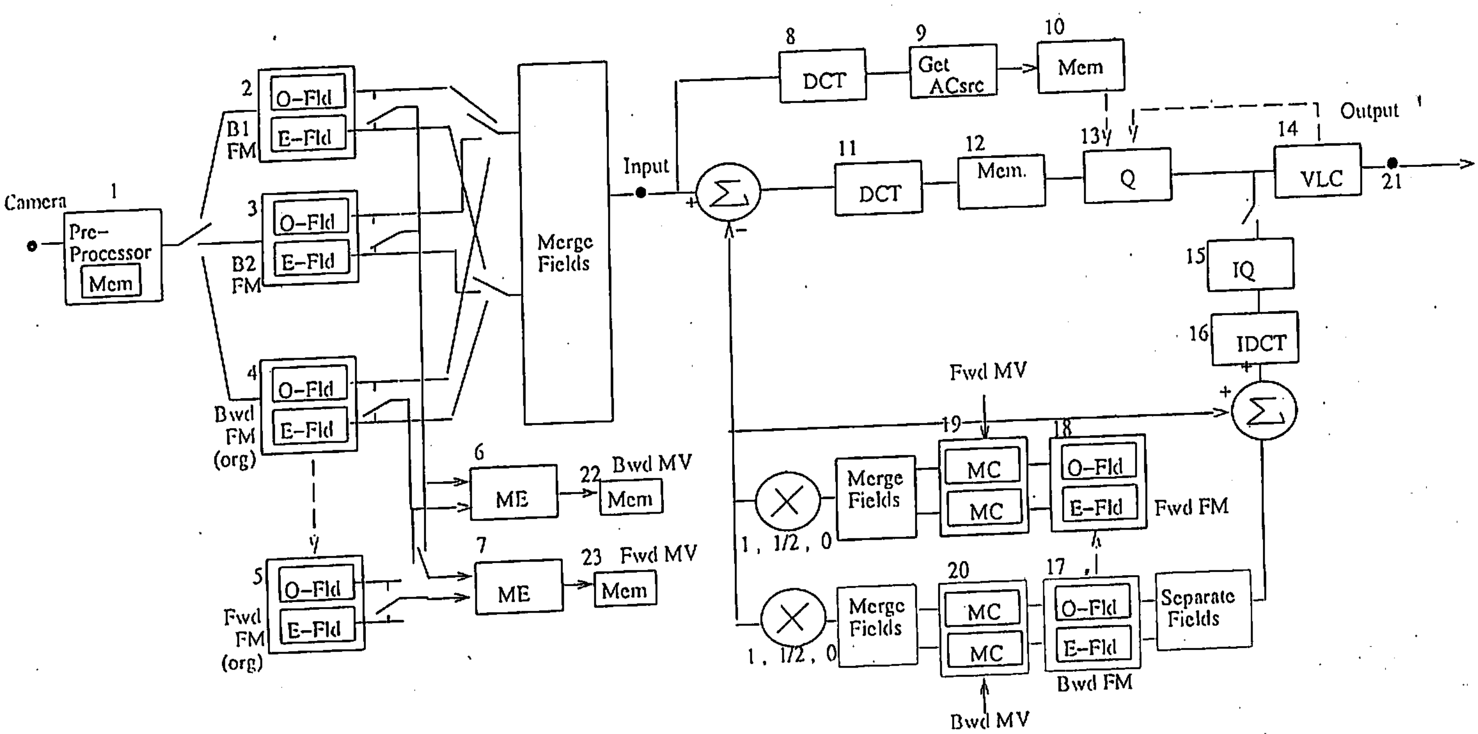


Fig.7 Encoder Complexity Block Diagram

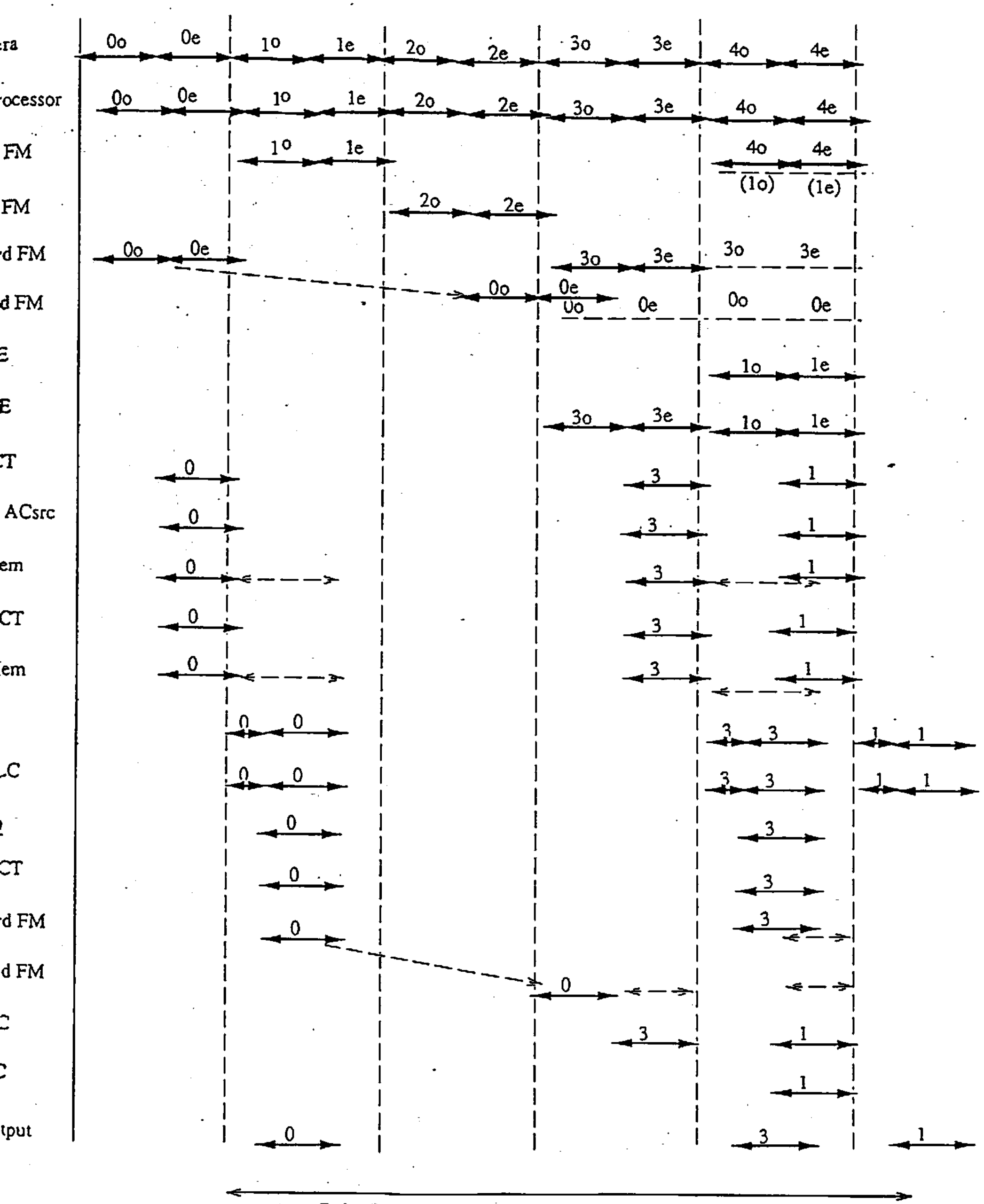


Fig 8 Encoder Timing Chart

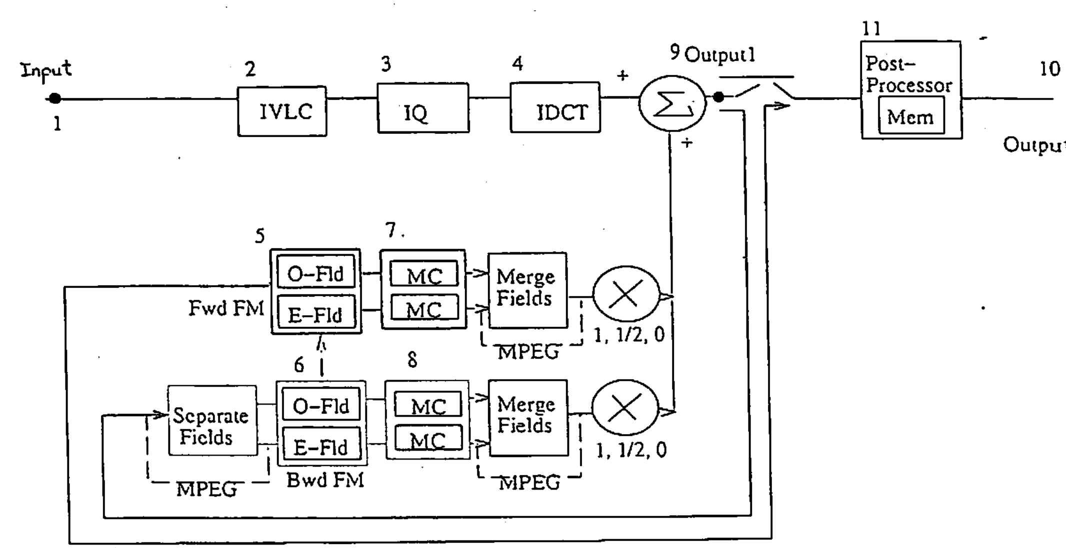


Fig. 9 Decoder Complexity Block Diagram

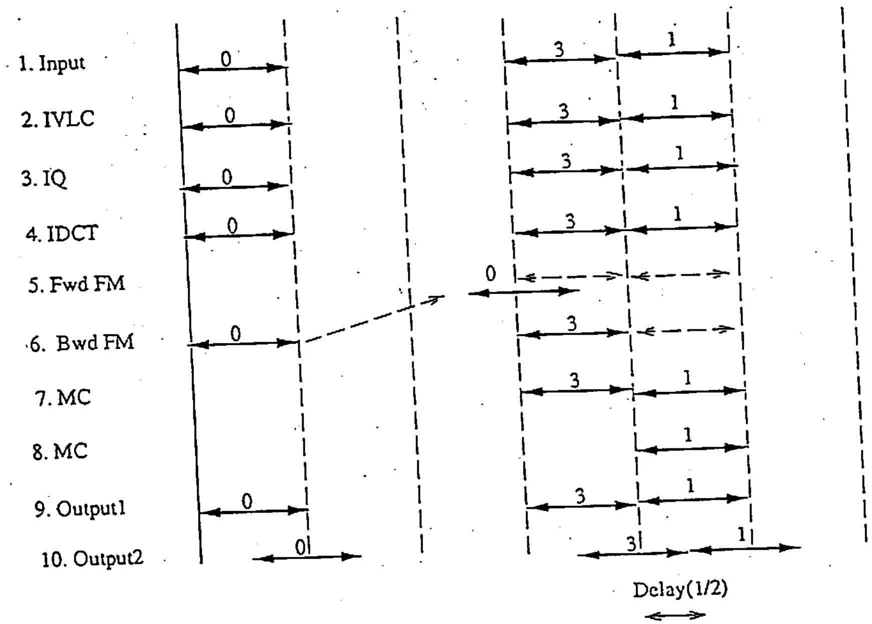


Fig. 10 Decoder Timing Chart

The number of operations per macro block

Table 1: Encoder

Operation	Times
Motion Estimation	2 (1/2 x 2 x 2)
8x8 DCT	10 (6 + 4)
Quantization of 8x8 DCT	30 (6 x 5)
VLC Assignment	5
Inverse Quantization	6
8x8 IDCT	6

Table 2: Decoder

Operation	Times
VLC Decoding	1
Inverse Quantization of 8x8 IDCT	6
8 x 8 IDCT	6

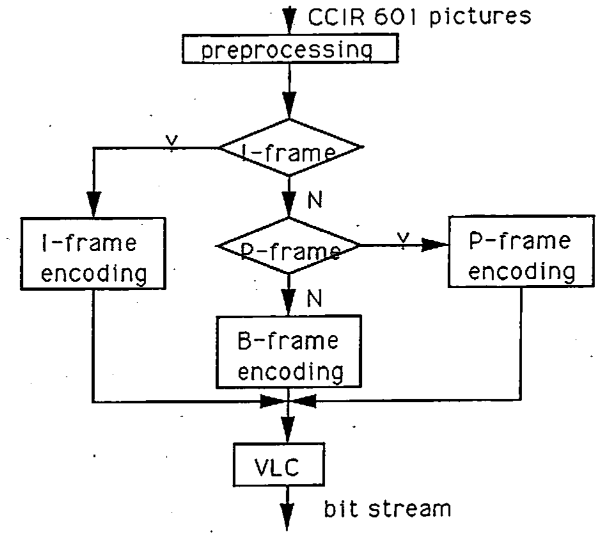
The performance/capacity requirements for each block

Table 3: Encoder

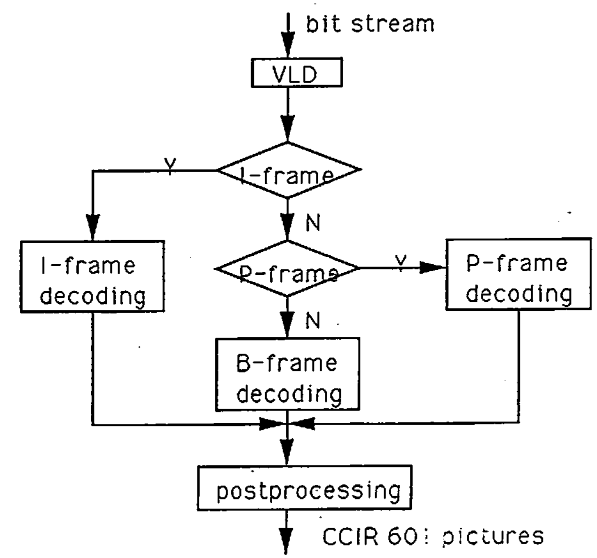
Block No.	Item	Performance/Capacity Requirements
1	Memory in Pre-Processor	37440 x 8[bit]
2	Memory	259200 x 8[bit] x 2
3	Memory	259200 x 8[bit] x 2
4	Memory	259200 x 8[bit] x 2
5	Memory	259200 x 8[bit] x 2
6	Motion Estimation of 16x16 block	675 in 1/60[sec]
7	Motion Estimation of 16x16 block	675 in 1/60[sec]
8	8x8 DCT	5400 in 1/60[sec]
10	Memory	1350 x 32[bit]
11	8x8 DCT	8100 in 1/60[sec]
12	Memory	518400 x 12[bit]
13	Quantization of 8x8 DCT	40500 in 1/120[sec]
15	Inv-Quantization of 8x8 DCT	8100 in 1/60[sec]
16	8x8 Inv-DCT	8100 in 1/60[sec]
19	Memory	259200 x 8[bits] x 2
20	Memory	259200 x 8[bits] x 2
22	Memory	675 x 16[bit]
23	Memory	675 x 16[bit]

Table 4: Decoder

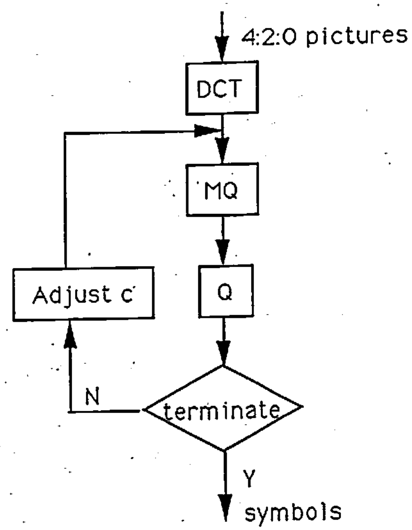
Block No.	Item	Performance/Capacity Requirements
3	Inv-Quantization of 8x8 DCT	8100 in 1/30[sec]
4	8x8 Inv-DCT	8100 in 1/30[sec]
5	Memory	259200 x 8[bit] x 2
6	Memory	259200 x 8[bit] x 2
11	Memory	518400 x 8[bit]



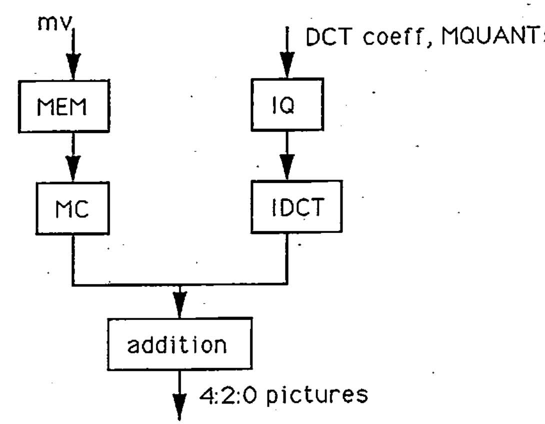
Encoder Flow Chart



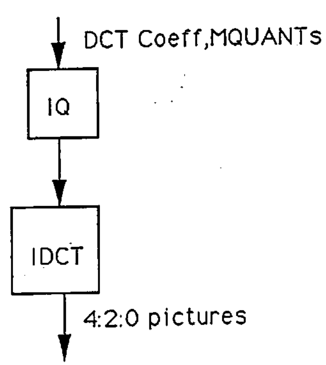
Decoder Flow Chart



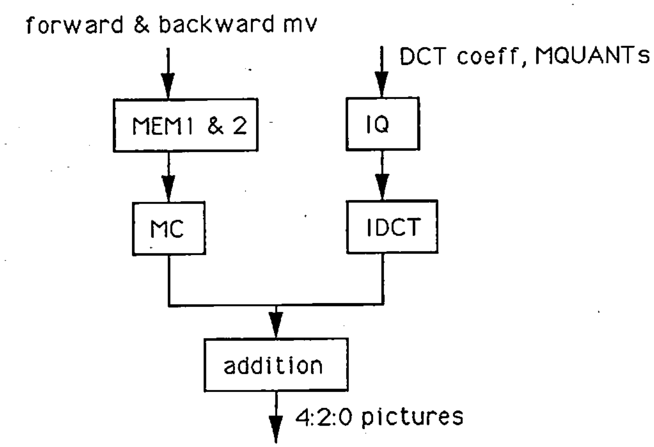
I-frame encoding



P-frame decoding



I-frame decoding



B-frame decoding

Macroblock Types for P-frames				
VLC code	New MQ	Forward Motion	Coded	Intra
1	0	1	1	0
01	0	0	1	0
001	0	1	0	0
00011	0	0	0	1
00010	1	1	1	0
00001	1	0	1	0
000001	1	0	0	1
0000001	0	0	0	0

9. Unix Listing of Coded Bitstreams and Statistics

```
:t 15 11:02 1991   Page 1

otal 29066
:wxr-xr-x  2 ctc         512 Oct 15 09:30 ./
:wxrwxrwx  6 ctc        1024 Oct 15 09:29 ../
:wxr-xr-x  1 ctc     2470312 Oct 14 17:23 GARDEN4*
:wxr-xr-x  1 ctc     5575523 Oct 14 17:44 GARDEN9*
:wxr-xr-x  1 ctc     2475177 Oct 14 17:59 MOBILE4*
:wxr-xr-x  1 ctc     5568348 Oct 14 18:32 MOBILE9*
:wxr-xr-x  1 ctc     5561873 Oct 14 18:47 POPPLE9*
:wxr-xr-x  1 ctc     2473335 Oct 14 17:40 TENNIS4*
:wxr-xr-x  1 ctc     5554939 Oct 14 18:13 TENNIS9*
```

Oct 17 09:38 1991   /u/ctc/MPEG2/binary/stat/GARDEN4.tbl2 Page 1

**** FILE = GARDEN4.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	34.01	568872	568872
1	P	30.72	216416	785288
2	B	30.78	43592	828880
3	B	29.88	35560	864440
4	P	29.45	237352	1101792
5	B	29.16	35136	1136928
6	B	28.84	32760	1169688
7	P	29.33	240760	1410448
8	B	29.26	37264	1447712
9	B	28.85	35968	1483680
10	I	31.39	491000	491000
11	B	28.27	53232	544232
12	B	28.53	56264	600496
13	P	29.35	235592	836088
14	B	29.06	35552	871640
15	B	28.80	34000	905640
16	P	28.64	238872	1144512
17	B	27.74	45248	1189760
18	B	27.39	47856	1237616
19	P	28.35	236256	1473872
20	B	28.20	32536	1506408
21	B	27.86	32296	1538704
22	I	30.47	440368	440368
23	B	28.76	29752	470120
24	B	28.41	32848	502968
25	P	30.56	280304	783272
26	B	29.02	57288	840560
27	B	29.63	42496	883056
28	P	29.81	253584	1136640
29	B	29.45	34632	1171272
30	B	28.96	34032	1205304
31	P	29.54	265048	1470352
32	B	29.06	35096	1505448
33	B	28.69	40352	1545800
34	I	31.25	500608	500608
35	B	29.08	40760	541368
36	B	29.93	31088	572456
37	P	30.16	263736	836192
38	B	30.11	35128	871320
39	B	29.63	39688	911008
40	P	29.04	259312	1170320
41	B	29.50	33152	1203472
42	B	28.71	32224	1235696
43	P	28.78	251544	1487240
44	B	27.85	40480	1527720
45	B	27.66	40752	1568472

46	I	30.44	495224	495224
47	B	28.92	29928	525152
48	B	29.48	27944	553096
49	P	29.79	262000	815096
50	B	28.99	37536	852632
51	B	28.72	40752	893384
52	P	29.36	224624	1118008
53	B	27.13	57256	1175264
54	B	27.34	56824	1232088
55	P	28.65	222424	1454512
56	B	28.24	35704	1490216
57	B	28.20	33744	1523960
58	I	29.83	440536	440536
59	B	29.02	25760	466296
60	B	29.43	25176	491472
61	P	29.23	260792	752264
62	B	28.18	47376	799640
63	B	28.05	45008	844648
64	P	28.67	238664	1083312
65	B	29.24	37848	1121160
66	B	28.47	40080	1161240
67	P	29.65	257944	1419184
68	B	28.93	32944	1452128
69	B	29.08	33712	1485840
70	I	31.44	547272	547272
71	B	30.54	36288	583560
72	B	30.05	37488	621048
73	P	29.74	262544	883592
74	B	29.57	40088	923680
75	B	29.41	39144	962824
76	P	29.79	258736	1221560
77	B	29.38	37440	1259000
78	B	29.68	35624	1294624
79	P	29.82	235928	1530552
80	B	29.61	35544	1566096
81	B	29.30	34672	1600768
82	I	31.69	550504	550504
83	B	29.27	42424	592928
84	B	29.85	36792	629720
85	P	30.02	243440	873160
86	B	30.54	34296	907456
87	B	30.00	36960	944416
88	P	29.80	239544	1183960
89	B	30.04	35376	1219336
90	B	29.74	35792	1255128
91	P	28.97	244864	1499992
92	B	29.34	28888	1528880
93	B	28.65	31632	1560512
94	I	31.16	537320	537320
95	B	29.73	32496	569816
96	B	29.27	38832	608648

97	P	29.38	278824	887472
98	B	27.87	51200	938672
99	B	27.67	48896	987568
100	P	28.19	230496	1218064
101	B	27.02	51792	1269856
102	B	27.02	56144	1326000
103	P	27.12	207320	1533320
104	B	26.43	50072	1583392
105	B	26.00	58920	1642312
106	I	28.61	424120	424120
107	B	26.33	55632	479752
108	B	26.69	45040	524792
109	P	27.98	237608	762400
110	B	27.39	39056	801456
111	B	27.19	39680	841136
112	P	27.61	234944	1076080
113	B	26.58	46600	1122680
114	B	26.79	36912	1159592
115	P	27.51	231600	1391192
116	B	26.90	39408	1430600
117	B	26.67	40232	1470832
118	I	29.63	480224	480224
119	B	28.57	25840	506064
120	B	28.69	25648	531712
121	P	29.22	279624	811336
122	B	28.49	40304	851640
123	B	28.49	38960	890600
124	P	29.44	260776	1151376
125	B	29.11	33328	1184704
126	B	29.00	34272	1218976
127	P	28.39	256576	1475552
128	B	27.82	34808	1510360
129	B	27.56	32960	1543320
130	I	29.90	506048	506048
131	B	28.98	23872	529920
132	B	29.16	24032	553952
133	P	29.46	267448	821400
134	B	29.30	34520	855920
135	B	29.13	35304	891224
136	P	30.07	266016	1157240
137	B	29.56	34024	1191264
138	B	29.65	35720	1226984
139	P	30.07	267776	1494760
140	B	29.50	32440	1527200
141	B	29.11	35400	1562600
142	I	31.20	571464	571464
143	B	30.85	25240	596704
144	B	30.45	24824	621528
145	P	28.78	251944	873472
146	B	28.92	30208	903680
147	B	28.52	29672	933352
148	P	29.74	270640	1203992

149	B	29.59	21704	1225696
150	B	29.74	10000	1235696

For I pictures ....
total motion vector bits = 0
total luminance bits = 5697720
total chrominance bits = 785790
total misc. overhead bits = 70050

For B pictures ....
total motion vector bits = 1150888
total luminance bits = 1802183
total chrominance bits = 127603
total misc. overhead bits = 656390

For P pictures ....
total motion vector bits = 312402
total luminance bits = 8161497
total chrominance bits = 741791
total misc. overhead bits = 256182

GRAND TOTAL BIT COUNT = 19762496

**** FILE = GARDEN9.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	37.89	760216	760216
1	P	35.39	392704	1152920
2	B	35.55	196248	1349168
3	B	35.27	187744	1536912
4	P	35.17	473048	2009960
5	B	34.56	168624	2178584
6	B	34.45	174120	2352704
7	P	36.25	533168	2885872
8	B	35.45	193544	3079416
9	B	35.26	171280	3250696
10	I	37.62	824088	824088
11	B	33.71	178920	1003008
12	B	33.91	198064	1201072
13	P	34.19	411768	1612840
14	B	34.52	175656	1788496
15	B	34.22	175416	1963912
16	P	34.95	516400	2480312
17	B	32.80	163160	2643472
18	B	32.89	180552	2824024
19	P	33.84	447280	3271304
20	B	33.16	119200	3390504
21	B	32.88	123856	3514360
22	I	36.48	771136	771136
23	B	33.69	127328	898464
24	B	33.77	163816	1062280
25	P	36.15	493680	1555960
26	B	34.89	229088	1785048
27	B	35.11	181472	1966520
28	P	35.15	478208	2444728
29	B	34.59	154536	2599264
30	B	33.81	141256	2740520
31	P	34.83	462392	3202912
32	B	33.91	141368	3344280
33	B	33.68	165040	3509320
34	I	36.53	789176	789176
35	B	33.90	166816	955992
36	B	34.61	137176	1093168
37	P	34.93	475480	1568648
38	B	34.64	139472	1708120
39	B	34.41	159464	1867584
40	P	34.98	538072	2405656
41	B	34.55	149776	2555432
42	B	34.28	162296	2717728
43	P	34.72	511880	3229608
44	B	33.61	193568	3423176
45	B	33.48	198728	3621904

46	I	36.46	825560	825560
47	B	33.90	143232	968792
48	B	34.24	122032	1090824
49	P	35.80	543056	1633880
50	B	34.33	171512	1805392
51	B	33.55	144360	1949752
52	P	35.76	513544	2463296
53	B	31.22	144424	2607720
54	B	31.29	138904	2746624
55	P	32.96	369232	3115856
56	B	33.42	146976	3262832
57	B	33.31	148336	3411168
58	I	35.23	716168	716168
59	B	34.15	154304	870472
60	B	34.33	139224	1009696
61	P	34.70	515488	1525184
62	B	33.45	194848	1720032
63	B	33.76	205984	1926016
64	P	34.53	474208	2400224
65	B	34.36	144576	2544800
66	B	33.96	164256	2709056
67	P	35.60	512632	3221688
68	B	34.16	143328	3365016
69	B	34.26	140784	3505800
70	I	36.17	829760	829760
71	B	34.76	125912	955672
72	B	34.29	148008	1103680
73	P	34.29	464128	1567808
74	B	33.73	173112	1740920
75	B	33.29	152192	1893112
76	P	34.49	471664	2364776
77	B	33.44	139192	2503968
78	B	33.77	122296	2626264
79	P	35.68	504040	3130304
80	B	34.86	186048	3316352
81	B	34.92	193136	3509488
82	I	37.40	887304	887304
83	B	34.73	199208	1086512
84	B	35.11	198304	1284816
85	P	34.77	444904	1729720
86	B	34.90	128424	1858144
87	B	34.45	134712	1992856
88	P	34.56	426800	2419656
89	B	34.40	129408	2549064
90	B	34.28	131568	2680632
91	P	34.49	488360	3168992
92	B	34.21	131176	3300168
93	B	33.46	130288	3430456
94	I	36.49	837504	837504
95	B	34.36	136488	973992
96	B	34.17	173400	1147392

97	P	34.59	505688	1653080
98	B	33.47	214232	1867312
99	B	33.24	211304	2078616
100	P	33.69	471928	2550544
101	B	31.97	185560	2736104
102	B	32.05	186320	2922424
103	P	31.97	395296	3317720
104	B	31.57	183696	3501416
105	B	31.33	214592	3716008
106	I	33.55	669640	669640
107	B	31.17	193504	863144
108	B	31.22	167432	1030576
109	P	32.60	418800	1449376
110	B	31.92	140608	1589984
111	B	31.73	145200	1735184
112	P	32.77	466888	2202072
113	B	31.61	194888	2396960
114	B	31.63	159528	2556488
115	P	32.77	455840	3012328
116	B	31.83	160336	3172664
117	B	32.06	186184	3358848
118	I	35.00	773896	773896
119	B	34.73	244272	1018168
120	B	34.03	165632	1183800
121	P	34.66	546152	1729952
122	B	33.26	153536	1883488
123	B	33.43	151896	2035384
124	P	34.38	469600	2504984
125	B	34.01	151248	2656232
126	B	33.86	155632	2811864
127	P	33.39	472336	3284200
128	B	32.45	152328	3436528
129	B	32.23	144384	3580912
130	I	34.71	771016	771016
131	B	33.41	129896	900912
132	B	33.91	134520	1035432
133	P	35.37	572976	1608408
134	B	34.45	192992	1801400
135	B	34.48	181760	1983160
136	P	35.27	461736	2444896
137	B	34.55	162848	2607744
138	B	34.57	150600	2758344
139	P	35.31	490280	3248624
140	B	34.50	168296	3416920
141	B	34.32	186472	3603392
142	I	35.87	863328	863328
143	B	35.16	143504	1006832
144	B	34.85	136128	1142960
145	P	34.02	500520	1643480
146	B	33.19	148432	1791912
147	B	33.08	147416	1939328
148	P	34.97	480744	2420072

149	B	34.64	146368	2566440
150	B	35.03	25392	2591832

For I pictures ....
total motion vector bits = 0
total luminance bits = 8770239
total chrominance bits = 1486024
total misc. overhead bits = 62529

For B pictures ....
total motion vector bits = 1128323
total luminance bits = 13296391
total chrominance bits = 971413
total misc. overhead bits = 718345

For P pictures ....
total motion vector bits = 313035
total luminance bits = 15884984
total chrominance bits = 1751730
total misc. overhead bits = 221171

GRAND TOTAL BIT COUNT = 44604184

**** FILE = MOBILE4.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	28.75	560856	560856
1	P	26.78	210552	771408
2	B	26.03	43184	814592
3	B	25.65	42920	857512
4	P	25.91	194376	1051888
5	B	25.64	50216	1102104
6	B	25.34	50384	1152488
7	P	26.27	224224	1376712
8	B	25.36	52952	1429664
9	B	25.40	52056	1481720
10	I	26.90	446144	446144
11	B	25.96	42296	488440
12	B	26.10	41392	529832
13	P	27.93	256312	786144
14	B	26.95	63472	849616
15	B	26.89	64064	913680
16	P	27.85	186848	1100528
17	B	27.19	41880	1142408
18	B	27.16	42392	1184800
19	P	27.79	201512	1386312
20	B	27.14	40936	1427248
21	B	27.08	41200	1468448
22	I	30.19	644072	644072
23	B	28.62	40832	684904
24	B	28.39	44816	729720
25	P	29.71	237896	967616
26	B	29.09	38808	1006424
27	B	28.88	39608	1046032
28	P	29.46	233560	1279592
29	B	28.72	40552	1320144
30	B	28.81	39680	1359824
31	P	29.64	205320	1565144
32	B	27.93	56504	1621648
33	B	28.01	51120	1672768
34	I	29.72	623328	623328
35	B	28.00	43104	666432
36	B	28.21	41920	708352
37	P	28.84	187408	895760
38	B	27.73	49600	945360
39	B	27.57	53400	998760
40	P	27.78	164824	1163584
41	B	27.62	35176	1198760
42	B	27.59	38944	1237704
43	P	27.64	182424	1420128
44	B	27.17	37272	1457400
45	B	27.15	35848	1493248

46	I	29.11	571920	571920
47	B	27.59	41040	612960
48	B	27.59	39592	652552
49	P	28.48	202552	855104
50	B	27.84	43488	898592
51	B	27.63	52856	951448
52	P	28.34	205696	1157144
53	B	27.33	58744	1215888
54	B	27.27	56680	1272568
55	P	27.84	209768	1482336
56	B	27.13	60000	1542336
57	B	26.98	50680	1593016
58	I	28.67	550128	550128
59	B	27.54	37256	587384
60	B	27.39	38160	625544
61	P	27.57	203104	828648
62	B	27.31	35800	864448
63	B	27.22	33816	898264
64	P	27.22	234808	1133072
65	B	26.97	37488	1170560
66	B	26.77	36560	1207120
67	P	27.23	234672	1441792
68	B	26.63	43064	1484856
69	B	26.42	45824	1530680
70	I	28.56	545232	545232
71	B	27.17	44296	589528
72	B	27.14	45584	635112
73	P	27.27	223040	858152
74	B	26.74	45952	904104
75	B	26.64	48312	952416
76	P	27.33	212112	1164528
77	B	26.32	51888	1216416
78	B	26.24	50736	1267152
79	P	27.90	185224	1452376
80	B	26.86	51616	1503992
81	B	26.86	45568	1549560
82	I	29.65	618088	618088
83	B	27.74	51128	669216
84	B	27.62	50712	719928
85	P	28.72	164512	884440
86	B	27.65	51680	936120
87	B	27.67	53200	989320
88	P	28.72	188232	1177552
89	B	27.55	56160	1233712
90	B	27.29	54424	1288136
91	P	27.86	172920	1461056
92	B	27.01	48664	1509720
93	B	26.97	48144	1557864
94	I	28.96	563184	563184
95	B	27.70	47920	611104
96	B	27.80	43224	654328

97	P	28.78	209320	863648
98	B	28.19	48256	911904
99	B	28.16	47952	959856
100	P	28.26	215232	1175088
101	B	28.08	38048	1213136
102	B	27.86	34944	1248080
103	P	28.18	217008	1465088
104	B	27.98	37120	1502208
105	B	27.74	41472	1543680
106	I	29.00	555848	555848
107	B	27.70	42112	597960
108	B	28.04	41168	639128
109	P	29.00	217984	857112
110	B	27.82	52520	909632
111	B	27.88	52672	962304
112	P	28.98	211768	1174072
113	B	27.94	57680	1231752
114	B	27.66	50528	1282280
115	P	29.11	192528	1474808
116	B	28.11	50376	1525184
117	B	27.85	56928	1582112
118	I	29.60	606088	606088
119	B	28.79	35072	641160
120	B	28.85	35816	676976
121	P	29.53	206400	883376
122	B	28.32	55464	938840
123	B	28.60	53096	991936
124	P	29.16	164488	1156424
125	B	28.01	49048	1205472
126	B	28.35	44752	1250224
127	P	29.23	159352	1409576
128	B	28.21	44320	1453896
129	B	28.33	43552	1497448
130	I	30.43	637688	637688
131	B	29.46	45104	682792
132	B	28.79	49248	732040
133	P	30.22	196904	928944
134	B	29.53	44352	973296
135	B	29.29	42968	1016264
136	P	29.97	185152	1201416
137	B	29.38	43952	1245368
138	B	29.40	43872	1289240
139	P	29.24	165712	1454952
140	B	28.98	36104	1491056
141	B	28.73	39272	1530328
142	I	30.69	705896	705896
143	B	29.70	37944	743840
144	B	29.28	40856	784696
145	P	30.13	208200	992896
146	B	29.54	43392	1036288
147	B	29.64	43320	1079608
148	P	28.99	169408	1249016

149	B	28.10	39848	1288864
150	B	28.99	11680	1300544

For I pictures ....
total motion vector bits = 0
total luminance bits = 6302990
total chrominance bits = 1230860
total misc. overhead bits = 94622

For B pictures ....
total motion vector bits = 815123
total luminance bits = 2825184
total chrominance bits = 194888
total misc. overhead bits = 696397

For P pictures ....
total motion vector bits = 197006
total luminance bits = 6283192
total chrominance bits = 813606
total misc. overhead bits = 347548

GRAND TOTAL BIT COUNT = 19801416

**** FILE = MOBILE9.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	32.87	760640	760640
1	P	31.04	410520	1171160
2	B	30.19	188112	1359272
3	B	29.98	191528	1550800
4	P	30.97	432264	1983064
5	B	30.05	187080	2170144
6	B	29.91	190648	2360792
7	P	31.19	422160	2782952
8	B	29.96	185376	2968328
9	B	29.93	186920	3155248
10	I	32.38	748152	748152
11	B	30.44	166120	914272
12	B	30.71	177232	1091504
13	P	33.69	497144	1588648
14	B	32.03	219120	1807768
15	B	31.97	226960	2034728
16	P	32.91	371400	2406128
17	B	32.20	174528	2580656
18	B	32.16	167944	2748600
19	P	32.81	399600	3148200
20	B	32.07	174104	3322304
21	B	32.06	173592	3495896
22	I	35.14	952320	952320
23	B	33.15	171936	1124256
24	B	33.07	188552	1312808
25	P	33.64	397456	1710264
26	B	33.29	155400	1865664
27	B	33.06	164872	2030536
28	P	33.87	417216	2447752
29	B	32.88	161680	2609432
30	B	32.85	151616	2761048
31	P	35.17	498032	3259080
32	B	32.13	184920	3444000
33	B	32.20	177088	3621088
34	I	35.17	952792	952792
35	B	32.96	229424	1182216
36	B	33.05	221408	1403624
37	P	33.22	322712	1726336
38	B	32.21	197648	1923984
39	B	32.14	206960	2130944
40	P	32.51	363112	2494056
41	B	31.68	123888	2617944
42	B	31.87	138304	2756248
43	P	32.86	396264	3152512
44	B	32.13	167728	3320240
45	B	32.05	175448	3495688

46	I	34.29	864120	864120
47	B	32.28	185920	1050040
48	B	32.27	180440	1230480
49	P	33.09	370528	1601008
50	B	32.48	170584	1771592
51	B	32.39	192112	1963704
52	P	32.92	367040	2330744
53	B	32.21	218976	2549720
54	B	32.18	209488	2759208
55	P	32.21	392360	3151568
56	B	31.20	176136	3327704
57	B	31.28	166152	3493856
58	I	33.29	779808	779808
59	B	32.18	186992	966800
60	B	32.04	197368	1164168
61	P	32.86	450968	1615136
62	B	32.07	191176	1806312
63	B	32.05	181016	1987328
64	P	32.81	480568	2467896
65	B	32.05	189216	2657112
66	B	31.91	184504	2841616
67	P	32.78	476816	3318432
68	B	31.93	207416	3525848
69	B	31.01	165616	3691464
70	I	33.19	780184	780184
71	B	31.32	158808	938992
72	B	31.50	168080	1107072
73	P	31.82	410280	1517352
74	B	30.94	173448	1690800
75	B	30.85	176144	1866944
76	P	31.76	377184	2244128
77	B	30.77	185824	2429952
78	B	30.66	185952	2615904
79	P	32.25	354168	2970072
80	B	31.06	163576	3133648
81	B	31.71	199464	3333112
82	I	34.28	862688	862688
83	B	32.24	189512	1052200
84	B	32.14	206272	1258472
85	P	33.94	414848	1673320
86	B	32.93	255576	1928896
87	B	32.89	250992	2179888
88	P	33.00	332184	2512072
89	B	32.12	207304	2719376
90	B	31.98	204880	2924256
91	P	32.38	364888	3289144
92	B	31.13	174320	3463464
93	B	31.14	168960	3632424
94	I	33.18	781712	781712
95	B	31.70	140168	921880
96	B	32.23	179080	1100960

97	P	33.78	460256	1561216
98	B	33.11	184376	1745592
99	B	33.11	175168	1920760
100	P	33.88	471352	2392112
101	B	33.33	164824	2556936
102	B	33.19	160144	2717080
103	P	33.97	475048	3192128
104	B	33.29	152176	3344304
105	B	33.32	164072	3508376
106	I	35.26	961352	961352
107	B	32.51	172472	1133824
108	B	32.60	168728	1302552
109	P	34.11	425896	1728448
110	B	32.92	213488	1941936
111	B	32.91	213024	2154960
112	P	33.03	340544	2495504
113	B	32.31	180560	2676064
114	B	32.13	191432	2867496
115	P	32.98	318376	3185872
116	B	32.31	168056	3353928
117	B	32.09	193592	3547520
118	I	34.30	850544	850544
119	B	33.42	178768	1029312
120	B	33.47	169296	1198608
121	P	34.06	371264	1569872
122	B	32.99	232592	1802464
123	B	33.18	209176	2011640
124	P	33.31	313584	2325224
125	B	32.42	188480	2513704
126	B	32.62	161008	2674712
127	P	34.08	369808	3044520
128	B	32.84	146160	3190680
129	B	33.00	163112	3353792
130	I	34.96	930120	930120
131	B	33.71	170736	1100856
132	B	33.31	203144	1304000
133	P	34.21	340104	1644104
134	B	33.87	180568	1824672
135	B	33.72	192072	2016744
136	P	34.76	362392	2379136
137	B	33.81	187720	2566856
138	B	33.83	173720	2740576
139	P	34.16	382432	3123008
140	B	33.77	161784	3284792
141	B	33.56	175904	3460696
142	I	36.11	1001368	1001368
143	B	34.25	149808	1151176
144	B	33.97	178696	1329872
145	P	34.91	402104	1731976
146	B	34.14	154984	1886960
147	B	34.19	149424	2036384
148	P	34.75	453584	2489968

149	B	33.48	224768	2714736
150	B	34.75	42888	2757624

```
For I pictures ....
   total motion vector bits = 0
   total luminance bits = 9302807
   total chrominance bits = 1841605
   total misc. overhead bits = 81388

For B pictures ....
   total motion vector bits = 813334
   total luminance bits = 15344079
   total chrominance bits = 1109422
   total misc. overhead bits = 847693

For P pictures ....
   total motion vector bits = 196913
   total luminance bits = 13096124
   total chrominance bits = 1619312
   total misc. overhead bits = 294107

GRAND TOTAL BIT COUNT = 44546784
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**** FILE = POPPLE9.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	39.47	851064	851064
1	P	37.29	432048	1283112
2	B	35.47	213024	1496136
3	B	35.43	213216	1709352
4	P	36.37	383832	2093184
5	B	35.41	221824	2315008
6	B	35.38	217344	2532352
7	P	36.39	402432	2934784
8	B	35.35	221888	3156672
9	B	35.38	220296	3376968
10	I	37.55	615528	615528
11	B	35.45	209816	825344
12	B	35.02	195200	1020544
13	P	36.40	384352	1404896
14	B	35.41	217384	1622280
15	B	35.34	215896	1838176
16	P	36.30	387248	2225424
17	B	35.38	215736	2441160
18	B	35.34	211816	2652976
19	P	36.25	388752	3041728
20	B	34.84	194552	3236280
21	B	34.76	193392	3429672
22	I	37.50	624360	624360
23	B	34.90	194976	819336
24	B	34.92	188560	1007896
25	P	36.36	384320	1392216
26	B	34.95	196648	1588864
27	B	34.87	190720	1779584
28	P	36.37	394736	2174320
29	B	34.88	190064	2364384
30	B	34.89	188496	2552880
31	P	37.31	446576	2999456
32	B	36.02	245104	3244560
33	B	35.98	239408	3483968
34	I	38.44	676032	676032
35	B	36.10	237600	913632
36	B	36.10	240944	1154576
37	P	36.50	382536	1537112
38	B	35.50	211720	1748832
39	B	35.50	219792	1968624
40	P	36.47	389392	2358016
41	B	35.49	214320	2572336
42	B	35.44	219744	2792080
43	P	36.47	396448	3188528
44	B	35.39	214592	3403120
45	B	35.38	215696	3618816

46	I	36.97	464648	464648
47	B	35.50	204808	669456
48	B	35.49	203280	872736
49	P	37.41	429880	1302616
50	B	36.14	232624	1535240
51	B	36.11	234184	1769424
52	P	37.33	436136	2205560
53	B	36.08	236016	2441576
54	B	36.06	234816	2676392
55	P	36.44	382776	3059168
56	B	35.48	213496	3272664
57	B	34.96	193168	3465832
58	I	37.64	625328	625328
59	B	35.46	204768	830096
60	B	35.53	206128	1036224
61	P	36.46	396304	1432528
62	B	35.46	213152	1645680
63	B	35.43	211728	1857408
64	P	36.48	412264	2269672
65	B	35.37	226424	2496096
66	B	35.37	233832	2729928
67	P	36.02	324608	3054536
68	B	35.33	221632	3276168
69	B	35.36	223312	3499480
70	I	37.69	609288	609288
71	B	35.45	228680	837968
72	B	35.47	228720	1066688
73	P	36.54	405328	1472016
74	B	35.44	256656	1728672
75	B	35.47	263008	1991680
76	P	36.14	329432	2321112
77	B	34.72	196816	2517928
78	B	34.74	189632	2707560
79	P	36.57	400840	3108400
80	B	35.53	246016	3354416
81	B	35.50	240664	3595080
82	I	37.78	576720	576720
83	B	35.61	232320	809040
84	B	35.68	226888	1035928
85	P	37.44	416880	1452808
86	B	35.87	222616	1675424
87	B	35.89	216528	1891952
88	P	37.39	424032	2315984
89	B	35.95	211752	2527736
90	B	35.89	216568	2744304
91	P	37.43	430824	3175128
92	B	35.94	222032	3397160
93	B	35.97	231984	3629144
94	I	37.95	553768	553768
95	B	35.98	227128	780896
96	B	35.99	235440	1016336

97	P	35.77	313984	1330320
98	B	35.37	182688	1513008
99	B	35.28	189224	1702232
100	P	35.59	344448	2046680
101	B	35.03	204976	2251656
102	B	34.98	220064	2471720
103	P	34.76	356848	2828568
104	B	34.54	218264	3046832
105	B	34.34	239128	3285960
106	I	35.83	516272	516272
107	B	33.90	237432	753704
108	B	33.80	249328	1003032
109	P	34.01	343768	1346800
110	B	33.88	266056	1612856
111	B	33.13	252304	1865160
112	P	33.41	344776	2209936
113	B	33.00	256160	2466096
114	B	32.47	262752	2728848
115	P	33.54	358592	3087440
116	B	32.74	265176	3352616
117	B	32.25	261488	3614104
118	I	34.72	508656	508656
119	B	32.80	265248	773904
120	B	32.24	241048	1014952
121	P	33.61	320936	1335888
122	B	32.61	249712	1585600
123	B	32.36	258512	1844112
124	P	33.49	326608	2170720
125	B	32.67	239536	2410256
126	B	32.50	253840	2664096
127	P	33.05	335360	2999456
128	B	32.51	253984	3253440
129	B	31.94	240368	3493808
130	I	34.26	553504	553504
131	B	31.85	241128	794632
132	B	31.54	245400	1040032
133	P	32.75	329992	1370024
134	B	31.84	261400	1631424
135	B	31.44	255280	1886704
136	P	32.50	332808	2219512
137	B	31.54	243944	2463456
138	B	31.10	241080	2704536
139	P	32.80	337576	3042112
140	B	31.51	242896	3285008
141	B	31.18	241544	3526552
142	I	33.78	531648	531648
143	B	31.46	245608	777256
144	B	31.48	254544	1031800
145	P	32.44	334688	1366488
146	B	31.40	252680	1619168
147	B	31.00	242032	1861200
148	P	32.12	386784	2247984

149	B	31.04	217368	2465352
150	B	32.12	10248	2475600

For I pictures ....
total motion vector bits = 0
total luminance bits = 6050935
total chrominance bits = 1584343
total misc. overhead bits = 71538

For B pictures ....
total motion vector bits = 3338761
total luminance bits = 13723310
total chrominance bits = 4647090
total misc. overhead bits = 749863

For P pictures ....
total motion vector bits = 694735
total luminance bits = 10616436
total chrominance bits = 2770002
total misc. overhead bits = 247971

GRAND TOTAL BIT COUNT = 44494984

**** FILE = TENNIS4.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	28.39	563568	563568
1	P	27.44	201568	765136
2	B	27.25	38176	803312
3	B	27.26	39368	842680
4	P	26.50	248304	1090984
5	B	26.83	23800	1114784
6	B	26.02	27376	1142160
7	P	25.60	250496	1392656
8	B	25.58	26504	1419160
9	B	25.26	29032	1448192
10	I	27.55	507592	507592
11	B	25.18	34824	542416
12	B	25.87	26696	569112
13	P	26.29	276896	846008
14	B	25.95	33472	879480
15	B	25.97	33672	913152
16	P	26.14	248880	1162032
17	B	25.62	28768	1190800
18	B	25.46	29424	1220224
19	P	26.27	237440	1457664
20	B	25.65	29992	1487656
21	B	25.68	30320	1517976
22	I	29.53	559016	559016
23	B	25.02	43616	602632
24	B	24.34	58848	661480
25	P	27.49	163944	825424
26	B	25.57	45216	870640
27	B	26.44	43336	913976
28	P	29.14	226632	1140608
29	B	27.40	48760	1189368
30	B	27.59	44792	1234160
31	P	30.54	234048	1468208
32	B	28.61	44376	1512584
33	B	29.06	46128	1558712
34	I	33.49	447920	447920
35	B	30.18	55344	503264
36	B	30.94	48896	552160
37	P	33.41	240224	792384
38	B	31.72	53176	845560
39	B	31.99	56552	902112
40	P	34.20	250832	1152944
41	B	32.64	59560	1212504
42	B	32.76	56680	1269184
43	P	34.18	234784	1503968
44	B	32.94	53920	1557888
45	B	32.97	58408	1616296

46	I	35.75	386856	386856
47	B	33.29	58568	445424
48	B	33.53	56928	502352
49	P	34.86	245704	748056
50	B	33.75	67992	816048
51	B	33.58	71544	887592
52	P	34.35	217920	1105512
53	B	33.23	57984	1163496
54	B	33.28	57576	1221072
55	P	34.25	215544	1436616
56	B	33.23	56120	1492736
57	B	33.30	54408	1547144
58	I	34.75	350352	350352
59	B	33.10	47800	398152
60	B	33.36	55200	453352
61	P	34.27	221968	675320
62	B	33.43	53864	729184
63	B	33.36	51128	780312
64	P	34.19	233432	1013744
65	B	33.32	55152	1068896
66	B	33.17	54784	1123680
67	P	30.40	240664	1364344
68	B	30.04	30176	1394520
69	B	30.42	47016	1441536
70	I	34.32	430896	430896
71	B	33.67	97760	528656
72	B	33.73	96568	625224
73	P	35.22	212904	838128
74	B	34.38	81176	919304
75	B	34.37	74112	993416
76	P	35.17	174816	1168232
77	B	34.42	69456	1237688
78	B	34.48	67264	1304952
79	P	35.12	162456	1467408
80	B	34.57	63512	1530920
81	B	34.52	66704	1597624
82	I	37.52	611880	611880
83	B	35.77	81080	692960
84	B	35.80	77008	769968
85	P	36.39	179800	949768
86	B	35.54	71800	1021568
87	B	35.48	72288	1093856
88	P	35.85	144824	1238680
89	B	35.40	69248	1307928
90	B	35.42	67120	1375048
91	P	35.71	141656	1516704
92	B	35.18	57592	1574296
93	B	35.18	58504	1632800
94	I	36.59	559184	559184
95	B	35.53	46368	605552
96	B	35.46	47248	652800

97	P	26.99	179192	831992
98	B	26.86	59408	891400
99	B	27.39	67208	958608
100	P	28.57	143392	1102000
101	B	28.87	63456	1165456
102	B	28.80	55664	1221120
103	P	31.34	262544	1483664
104	B	30.44	28800	1512464
105	B	30.59	27216	1539680
106	I	33.11	490488	490488
107	B	32.29	22312	512800
108	B	32.27	21280	534080
109	P	34.79	257848	791928
110	B	34.00	77776	869704
111	B	33.91	64816	934520
112	P	33.99	197136	1131656
113	B	34.11	62952	1194608
114	B	33.74	65184	1259792
115	P	33.89	200968	1460760
116	B	33.81	66688	1527448
117	B	33.28	40232	1567680
118	I	36.36	648640	648640
119	B	34.08	28920	677560
120	B	33.95	27776	705336
121	P	32.92	167576	872912
122	B	33.00	31104	904016
123	B	32.84	33048	937064
124	P	32.87	188472	1125536
125	B	30.54	44168	1169704
126	B	31.86	33208	1202912
127	P	32.92	191536	1394448
128	B	30.38	54520	1448968
129	B	31.22	45728	1494696
130	I	34.09	572312	572312
131	B	32.25	41896	614208
132	B	32.22	38264	652472
133	P	33.48	208296	860768
134	B	32.47	47280	908048
135	B	31.58	65712	973760
136	P	33.58	212640	1186400
137	B	31.42	63056	1249456
138	B	32.25	50080	1299536
139	P	33.32	224928	1524464
140	B	32.47	47008	1571472
141	B	31.45	57392	1628864
142	I	34.08	584344	584344
143	B	30.84	48784	633128
144	B	31.13	43720	676848
145	P	32.66	190648	867496
146	B	31.16	44656	912152
147	B	30.55	49944	962096
148	P	31.78	185240	1147336

149	B	30.11	38720	1186056
150	B	31.78	9424	1195480

For I pictures ....
total motion vector bits = 0
total luminance bits = 6033847
total chrominance bits = 605255
total misc. overhead bits = 73946

For B pictures ....
total motion vector bits = 1179809
total luminance bits = 2878105
total chrominance bits = 277133
total misc. overhead bits = 722433

For P pictures ....
total motion vector bits = 279295
total luminance bits = 6824579
total chrominance bits = 640092
total misc. overhead bits = 272186

GRAND TOTAL BIT COUNT = 19786680

**** FILE = TENNIS9.stat ****

Index	Type	YSNR(dB)	Frame bits	Cumu. bits
0	I	33.87	792256	792256
1	P	31.97	384592	1176848
2	B	31.82	189072	1365920
3	B	31.82	196736	1562656
4	P	31.22	446824	2009480
5	B	31.59	166432	2175912
6	B	31.08	215480	2391392
7	P	30.31	462792	2854184
8	B	29.39	125416	2979600
9	B	29.40	176680	3156280
10	I	32.24	696272	696272
11	B	29.16	157688	853960
12	B	30.20	173768	1027728
13	P	31.29	502744	1530472
14	B	30.32	216688	1747160
15	B	30.53	211928	1959088
16	P	31.17	469704	2428792
17	B	29.89	148200	2576992
18	B	29.87	175456	2752448
19	P	31.23	434224	3186672
20	B	30.19	177848	3364520
21	B	30.20	175032	3539552
22	I	34.20	768504	768504
23	B	29.85	244600	1013104
24	B	28.62	260992	1274096
25	P	30.52	316984	1591080
26	B	28.19	148984	1740064
27	B	29.81	181424	1921488
28	P	32.76	400784	2322272
29	B	30.73	177752	2500024
30	B	30.92	180800	2680824
31	P	34.16	418592	3099416
32	B	31.87	170312	3269728
33	B	32.40	171456	3441184
34	I	36.70	588216	588216
35	B	33.35	181256	769472
36	B	34.59	226144	995616
37	P	36.96	453632	1449248
38	B	34.92	207040	1656288
39	B	35.56	225768	1882056
40	P	37.33	445440	2327496
41	B	35.87	211768	2539264
42	B	36.13	245272	2784536
43	P	37.64	460512	3245048
44	B	36.41	245368	3490416
45	B	36.48	250128	3740544

46	I	38.49	592232	592232
47	B	35.89	166816	759048
48	B	36.27	178008	937056
49	P	37.41	415536	1352592
50	B	36.55	218792	1571384
51	B	36.53	227400	1798784
52	P	37.46	418824	2217608
53	B	36.16	209696	2427304
54	B	36.28	211912	2639216
55	P	37.47	416824	3056040
56	B	36.26	210672	3266712
57	B	36.70	227760	3494472
58	I	37.85	585064	585064
59	B	36.27	209064	794128
60	B	36.34	216416	1010544
61	P	37.04	404160	1414704
62	B	36.40	216376	1631080
63	B	36.38	214776	1845856
64	P	37.02	418848	2264704
65	B	36.29	225400	2490104
66	B	36.00	175608	2665712
67	P	34.13	406008	3071720
68	B	33.86	129096	3200816
69	B	34.56	154680	3355496
70	I	38.20	696592	696592
71	B	37.20	228696	925288
72	B	37.23	229776	1155064
73	P	37.80	403480	1558544
74	B	36.71	179536	1738080
75	B	36.66	176208	1914288
76	P	38.89	454624	2368912
77	B	36.85	181152	2550064
78	B	36.93	175040	2725104
79	P	39.17	466032	3191136
80	B	37.43	189752	3380888
81	B	37.39	192720	3573608
82	I	40.12	921288	921288
83	B	37.69	188448	1109736
84	B	37.67	183544	1293280
85	P	39.11	440656	1733936
86	B	37.47	192488	1926424
87	B	37.46	195472	2121896
88	P	39.08	428504	2550400
89	B	37.48	188184	2738584
90	B	37.53	184280	2922864
91	P	39.06	424680	3347544
92	B	37.48	186936	3534480
93	B	37.50	187072	3721552
94	I	40.06	928384	928384
95	B	37.75	174624	1103008
96	B	37.74	179736	1282744

97	P	32.60	389856	1672600
98	B	31.14	77416	1750016
99	B	32.92	135848	1885864
100	P	35.61	389008	2274872
101	B	34.88	163520	2438392
102	B	34.79	154600	2592992
103	P	37.04	448640	3041632
104	B	36.47	222720	3264352
105	B	36.34	222656	3487008
106	I	38.28	801424	801424
107	B	36.57	123320	924744
108	B	36.54	123896	1048640
109	P	38.18	429504	1478144
110	B	37.42	201904	1680048
111	B	37.35	203136	1883184
112	P	38.15	428096	2311280
113	B	37.44	201328	2512608
114	B	37.26	209432	2722040
115	P	37.25	366608	3088648
116	B	37.21	211624	3300272
117	B	37.09	225640	3525912
118	I	38.55	831360	831360
119	B	37.11	197152	1028512
120	B	37.02	195624	1224136
121	P	37.23	391608	1615744
122	B	35.63	145248	1760992
123	B	35.78	141320	1902312
124	P	36.36	370296	2272608
125	B	35.83	232096	2504704
126	B	35.47	150608	2655312
127	P	36.39	382920	3038232
128	B	35.21	210416	3248648
129	B	35.25	176808	3425456
130	I	36.78	775016	775016
131	B	35.61	151536	926552
132	B	35.37	153456	1080008
133	P	36.36	373912	1453920
134	B	35.37	157168	1611088
135	B	35.28	202656	1813744
136	P	36.37	375432	2189176
137	B	35.66	256480	2445656
138	B	35.68	225448	2671104
139	P	36.24	386880	3057984
140	B	36.37	244520	3302504
141	B	35.24	181344	3483848
142	I	37.65	839328	839328
143	B	35.34	191824	1031152
144	B	34.73	161272	1192424
145	P	36.32	375752	1568176
146	B	34.69	162512	1730688
147	B	34.59	180784	1911472
148	P	36.27	393776	2305248

149	B	-	34.65	180024	2485272
150	B	-	36.28	9328	2494600

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For I pictures ....
   total motion vector bits = 0
   total luminance bits = 8941863
   total chrominance bits = 801939
   total misc. overhead bits = 72134

For B pictures ....
   total motion vector bits = 1178389
   total luminance bits = 15870203
   total chrominance bits = 971806
   total misc. overhead bits = 805890

For P pictures ....
   total motion vector bits = 282098
   total luminance bits = 14280388
   total chrominance bits = 968654
   total misc. overhead bits = 266148

GRAND TOTAL BIT COUNT = 44439512
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