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Fast Mode Decision Algorithm Using Mode Classification for H.264

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Abstract

H.264 is a new international video coding standard that can achieve considerably higher coding efficiency than previous standards. This comes at the cost of the number of increased macroblock modes and the complex mode decision procedure using the rate-distortion optimization, which makes real-time encoding difficult. In this paper, we propose a fast mode decision algorithm using mode classification for H.264. Simulation results show that the proposed algorithm can reduce the encoding time by 29.65% on average and the rate-distortion computation complexity by 89.12%, without considerable PSNR degradation and bitrate increment.

Keywords: H.264, rate-distortion optimization, selective mode decision, fast mode decision.

1. Introduction

H.264 is the latest international video coding standard and it can achieve considerably higher coding efficiency versus previous standards [1]. This is accomplished by an enhanced exploitation of the spatiotemporal correlation, such as various macroblock modes, variable block sizes for motion compensation, multiple reference frames, quarter-pixel motion accuracy, and various predictive direction modes for intra prediction. H.264 also enhances coding efficiency by several new features, such as context adaptive entropy coder and in-loop de-blocking filtering [2].

The macroblock mode among several coding parameters is important and complex since other coding parameters depend on the macroblock mode. For example, variable block sizes and multiple reference frames are only related to inter macroblock modes, and predictive direction modes are related only to intra macroblock modes.

H.264 supports seven macroblock modes. In order to exploit the temporal correlation of the video sequence, H.264 allows five inter macroblock modes: SKIP, 16x16, 16x8, 8x16, and P8x8. P8x8 also allows four sub-inter modes: 8x8, 8x4, 4x8, and 4x4 for each 8x8 block. In order to determine the macroblock mode, we need to perform motion estimation with various block sizes over multiple reference frames. In this paper, we define two different classes: Class8 and Class16. Figure 1 shows inter macroblock modes of H.264 and two classes while Class16 includes 16x16, 16x8 and 8x16, and Class8 contains all sub-inter modes.

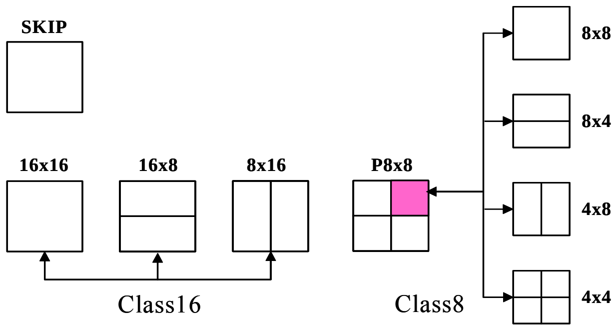


Fig. 1. Inter modes and classes

In order to use a spatial correlation of the video sequence, we have two intra macroblock modes: intra4x4 and intra16x16. The intra macroblock mode supports various predictive direction modes. The prediction unit of the intra4x4 mode is the block of 4x4 pixels. The intra4x4 mode allows nine predictive direction modes between 4x4 block and available boundary pixels of the neighboring macroblocks (upper or/and left) for the current macroblock. Hence, the intra4x4 mode requires 16 direction mode decisions. The prediction unit of the intra16x16 is the macroblock. The intra16x16 mode employs four predictive direction modes.

H.264 also supports predictive direction modes for the prediction of the chrominance components. In inter macroblock modes, prediction of the chrominance components is performed by motion vectors and reference frames of the luminance component. However, in intra macroblock modes, the prediction of the chrominance components is independently performed with the luminance component. Prediction of the chrominance components is based on the 8x8 block with four predictive direction modes which are similar to the intra16x16, except the numbering the predictive direction mode.

During the encoding process, the best mode decision for each macroblock is the ultimate goal for high coding efficiency. In order to determine the best macroblock mode, H.264 examines all possible macroblock modes and coding parameters in terms of the rate-distortion optimization (RDO) [3-4]. RDO requires high complexity because it should calculate the rate and the distortion for each macrobock mode with the Lagrangian cost function.

In this paper, we propose to classify all possible macroblock modes of H.264 into four groups considering the frequency and computational complexity of each macroblock. These four different groups are applied to RDO instead of each macroblock mode of H.264. Hence, we can determine the best macroblock mode quickly, and reduce the encoding complexity by eliminating unnecessary coding parameters and macroblock modes.

This paper is organized as follows. In Section 2, we describe the macroblock mode decision of H.264. In Section 3, we explain a fast algorithm for the macroblock mode decision using mode classification. In Section 4, experimental results for various sequences are provided. Finally, draws conclusion in Section 5.

2. Macroblock Mode Decision for H.264

One problem in the non-normative part of the codingvideo standard is the operational control of the source encoder. This problem is compounded because typical video sequences contain widely varying content and motion; hence, we need to determine different coding parameters or the macroblock modes with varying rate-distortion efficiency for different parts of the image [3]. The operational control of H.264 is performed by RDO based on the unconstrained Lagrangian cost function [4].

$$\begin{aligned}\mathbf{I}^* &= \arg\min_{\mathbf{I}} J(\mathbf{S},\mathbf{I} \mid \lambda) \\ &= \arg\min_{\mathbf{I}} \left[D(\mathbf{S}\cdot\mathbf{I} \mid \lambda) + \lambda \cdot R(\mathbf{S}\cdot\mathbf{I} \mid \lambda) \right]\end{aligned} \tag{1}$$

From Eq. (1), the main goal of the coder control is to determine **I*** that is the optimal set of coding parameters for a set of the source sample **S**. This formulation is simplified with an assumption of additive distortion and rate, and therefore it can be solved by independently selecting the coding parameter $I_k^* \in \mathbf{I}$ for each $S_k \in \mathbf{S}$.

$$\begin{aligned}I_k^* &= \arg\min_{I_k} J(S_k, I_k \mid \lambda) \\ &= \arg\min_{I_k} \left[D(S_k, I_k \mid \lambda) + \lambda \cdot R(S_k, I_k \mid \lambda) \right]\end{aligned} \tag{2}$$

where λ is the Lagrangian multiplier.

H.264 employs two different Lagrangian cost functions according to the distortion measure. However, the distortion is measured at a high computational complexity of motion estimation in inter modes. Hence, H.264 splits the motion estimation procedure from the mode decision procedure of the macroblock with a much simpler Lagrangian cost function [5]. With the different distortion measure, the Lagrangian multiplier is also changed [6]. If the distortion measure is the sum of the squared difference (SSD), the Lagrangain multiplier is

$$\lambda_{\text{mode}} = 0.85 \times 2^{Q/3} \tag{3}$$

If the distortion measure is the sum of absolute difference (SAD), the Lagrangian multiplier is

$$\lambda_{\text{motion}} = \sqrt{0.85 \times 2^{Q/3}} = \sqrt{\lambda_{\text{mode}}} \tag{4}$$

where Q is a quantization parameter.

With the two Lagrangian cost functions, H.264 determines the best mode of coding parameters and the macroblock mode. Before performing the mode decision of the macroblock, H.264 first determines motion vectors and reference frames for all inter modes. Since P8x8 is some combination of sub-inter modes, H.264 has to find the best combination of sub-inter modes and the rate-distortion cost (RDcost). In motion estimation, the motion vector (*mv*) and the reference frame (*ref*) are selected by minimizing the cost, which is the simple Lagrangian cost function based on SAD and calculated by

$$\begin{aligned} & mv^*, ref^* \\ &= \arg\min_{mv\in MV,\, ref\in REF} J_{\text{motion}}(S_k, C_k, (mv, ref) \mid \lambda_{\text{motion}}) \\ &= \arg\min_{mv\in MV,\, ref\in REF} \begin{bmatrix} SAD(S_k, C_k, (mv, ref) \mid \lambda_{\text{motion}}) \\ + \lambda_{\text{motion}} \cdot R((mv, ref) \mid \lambda_{\text{motion}}) \end{bmatrix}\end{aligned} \tag{5}$$

where the rate term of the Lagrangian cost function is the number of bits for the motion vector and the reference frame, which do not consider residual image. The distortion is SAD between the original and reconstructed signals with motion estimation.

$$\begin{aligned} & SAD(S_k, C_k, (mv, ref) \mid \lambda_{\text{motion}}) \\ &= \sum_{(x,y)\in A} \left| S_k(x,y,t) - C_k(x - m_x, y - m_y, t - m_t) \right| \end{aligned} \tag{6}$$

where A is a variable block. m_x and m_y are motion vectors, and m_t indicates the reference frame.

The best combination of P8x8, the best predictive direction mode, and the best macroblock mode are determined by

$$\begin{aligned} m^* &= \arg\min_{m\in\mathbf{M}} J_{\text{mode}}(S_k, C_k, m \mid \lambda_{\text{mode}}) \\ &= \arg\min_{m\in\mathbf{M}} \begin{bmatrix} SSD(S_k, C_k, m \mid \lambda_{\text{mode}}) \\ + \lambda_{\text{mode}} \cdot R(S_k, C_k, m) \mid \lambda_{\text{mode}}) \end{bmatrix}\end{aligned} \tag{7}$$

where m is the macroblock mode, predictive direction mode, or sub-inter mode. The rate is the number of bits consumed by encoding a block related to m. The distortion is SSD between the original and reconstructed signals where the reconstructed signal is obtained by the forward and inverse procedure of transform and quantization.

$$SSD(S_k, C_k, m) = \sum_{(x,y)\in A} \left| S_k(x,y,t) - C_k(x,y,t) \right|^2 \tag{8}$$

The best combination of P8x8 and the predictive direction mode decision for intra modes are based on Eq. (7) without considering RDcost of the chrominance components. However, the macroblock mode decision is based on Eq. (7), considering

RDcost of the chrominance components. In inter modes, the chrominance components are reconstructed by motion vectors and reference frames for the luminance component. RDcost of the chrominance components is also calculated by Eq. (7) and summed up with RDcost of the luminance component for obtaining RDcost of the inter mode.

In intra modes, the predictive direction mode of the chrominance components is determined by Eq. (7). RDcost of the chrominance components for the best predictive direction mode is summed up with RDcost of the luminance component for obtaining RDcost of the intra mode. In the mode decision procedure, H.264 examines RDcost of seven macroblock modes and compares RDcost of seven macroblock modes.

As described above, RDcost of the macroblock mode is obtained by calculating RDcost of coding parameters related to each macroblock mode, and the best macroblock mode is determined by the minimum RDcost. Although the mode decision procedure as H.264 can obtain good coding efficiency in terms of RDO, the complexity of the encoder is considerably increased by performing RDO for all macroblock modes.

3. Fast Macroblock Mode Decision

Although H.264 applies all the macroblock modes to the rate-distortion optimization procedure based on the Lagrangian cost function, the occurrence probability and computational complexity of each macroblock mode are not uniform and different according to the characteristics of the image sequence and the frame type.

As a simple example, the first frame (as the I frame) does not need to perform the motion estimation procedure; it does not consider inter modes. However, H.264 includes all the inter modes in the rate-distortion optimization procedure; it increases computational complexity and encoding delay. Hence, in the first frame, we only consider intra modes. However, subsequent frames as P frames have to investigate all possible macroblock modes during the rate-distortion optimization procedure; therefore, we only consider the P frame from now on.

Table 1 shows the frequency of each macroblock mode (M) to be the best macroblock mode from the second frame to the 100-th frame in both MOBILE and SILENT sequences on various quantization parameters (QP). In Table 1, the value of 0 indicates SKIP. The value of 1, 2, and 3 indicate Class16 modes in the order. The value of 8 indicates P8x8. The value of 9 and 10 indicate intra4x4 and intra16x16, respectively. From Table 1, we can identify that the frequency of each macroblock mode depends on the image sequence and quantization parameters, and the frequency of each macroblock mode is not uniform.

Table 1. Frequency of coding modes

MOBILE Sequence					SILENT Sequence				
M	Qp				M	Qp			
	28	32	36	40		28	32	36	40
0	379	923	1960	3802	0	6320	6924	7603	8297
1	2354	3007	3941	4055	1	1183	1208	1073	825
2	1456	1648	1310	745	2	485	409	322	194
3	1399	1548	1353	737	3	607	532	414	282
8	4210	2671	1233	401	8	1103	628	268	78
9	0	0	0	0	9	92	73	63	36
10	3	4	4	1	10	11	27	58	89

Considering the above characteristics and computational complexity, we classify the macroblock modes into four groups: SKIP, Class16, P8x8, and the intra modes. In order to determine the best macroblock mode, we first examine selectively three groups: SKIP, Class16, and P8x8, which belong to the inter mode. After we determine the best inter mode in three groups, we examine the intra mode to refine the best inter mode. In order to selectively apply three groups in RDO, we define the base mode, as shown in Fig. 2. The base mode is the simplest combination of P8x8 mode: the sub-inter mode of each 8x8 block is 8x8 mode. The base mode performs the motion estimation over each 8x8 block.

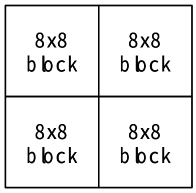


Fig. 2. Base mode

3.1 Fast SKIP Mode Decision

The SKIP mode refers to the 16x16 mode where no motion and residual information is encoded. So, no motion search is required and it has the lowest complexity. Because of its importance, we differentiate it from other macroblock modes. In order to determine whether the best mode is SKIP or not, we propose to use comparison between RDcost of SKIP and RDcost of the base mode.

$$J_{mode}(Base \mid \lambda_{mode}) > J_{mode}(SKIP \mid \lambda_{mode}) \qquad (9)$$

RDcost of SKIP is calculated by Eq. (8) between the current macroblock to be encoded and the macroblock of the same position in the previous frame. RDcost of the base mode is calculated by Eq. (7). If Eq. (9) is satisfied, we determine SKIP into the best mode without considering other macroblock modes and coding parameters which are not related to the

SKIP mode. Otherwise, we progress the inter macroblock mode decision.

In the inter mode, as the motion estimation is performed from SKIP to the base mode, the distortion is decreased and the rate is increased. Specially, if the motion estimation is more efficient than SKIP as the inverse case of Eq. (9), the distortion reduction over the rate increment is much larger. Although motion estimation is efficient, there is a tradeoff between the distortion and the rate in terms of RDO; therefore, we should consider Class16 modes.

However, in the inverse case, we can see that the motion estimation operation of the base mode only requires the rate for motion vectors and reference frame indices without considerable reduction of the distortion for SKIP. Since the base mode includes Class16 in terms of the accuracy for motion estimation, the motion estimation operation of Class16 modes also has similar characteristics as the base mode of Eq. (9). Hence, if Eq. (9) is satisfied, we determine the current macroblock mode into SKIP without considering Class16 modes.

3.2 Inter Macroblock Mode Decision

The P8x8 mode is more complex than Class16 since the P8x8 mode performs motion estimation with a smaller block size than Class16. Complexity of P8x8 is easily induced by the motion estimation procedure.

Let B be the number of partitioned blocks in the macroblock, R the number of reference frames, and W the search range of motion estimation. In general, complexity of motion estimation is expressed by $B \times R \times (2W+1)^2$. R and W are the same in P8x8 and Class16, but B is different. On average, the value of B in Class16 is 1.67: the minimum value is one for 16x16, and the maximum value is two for 16x8 or 8x16.

However, the average of B in P8x8 is nine when we consider all combinations of sub-inter modes for the P8x8 macroblock mode. The total combination of sub-inter modes for the P8x8 mode is 256. Hence, complexity of motion estimation for P8x8 is about five times than Class16 modes. Also, complexity of RDcost calculation has the same property as complexity of motion estimation.

From Table 1, we note that P8x8 occurs less frequently than Class16. However, P8x8 has more complexity than Class16. Therefore, it is not efficient to perform motion estimation unconditionally and mode decision for P8x8. In this paper, we differentiate P8x8 from other inter modes. The criterion for this differentiation is RDcost of the base mode, already calculated in the fast SKIP mode decision. In terms of P8x8, the base mode has the simplest block division and the largest block size in the combination of sub-inter modes. However, the base mode has more complex block divisions than the macroblock modes of Class16. Hence, we think that the base mode is an intermediate macroblock mode between Class16 and P8x8.

If Eq. (9) is not satisfied in the fast SKIP mode decision, we first examine motion vectors and reference frames for Class16. After we determine the best macroblock mode (*Best16*) among Class16 and SKIP modes, we compare its RDcost value with that of the base mode.

$$J_{\text{mode}}(Best16 \mid \lambda_{\text{mode}}) > J_{\text{mode}}(Base \mid \lambda_{\text{mode}}) \qquad (10)$$

If Eq. (10) is satisfied, it indicates that the macroblock has more complex motion than Class16 modes; thus, we need to examine the P8x8 mode. Otherwise, *Best16* is the best inter mode; so, we do not perform motion estimation and mode decision for P8x8. With this strategy, we can save motion estimation and macroblock mode decision operations for P8x8; consequently, we can reduce coding delay and computational complexity.

3.3 Intra Macroblock Mode Decision

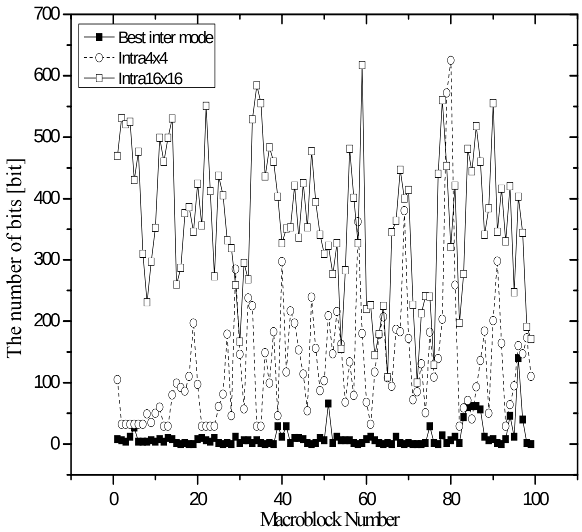
In order to achieve high coding efficiency, H.264 uses spatial correlation by employing several predictive direction modes. Since the predictive direction in the intra macroblock mode is determined by Eq. (7), it requires high computational complexity.

For the intra macroblock mode, several algorithms have been proposed to make a quick decision on the predictive direction mode [7]. Since the frequency of the intra macroblock mode is very low, those algorithms do not provide efficient reduction in coding complexity.

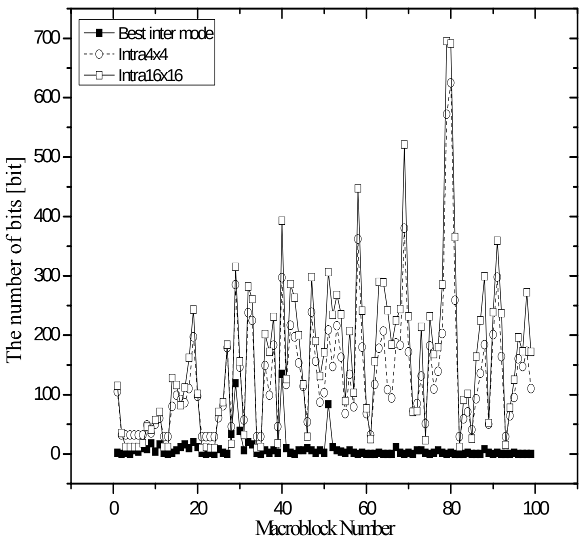
When an image sequence has high spatial correlation, it causes remarkable decrement of coding efficiency to omit all intra macroblock modes in the Lagrangian optimization procedure. Hence, we should consider the intra macroblock mode in the mode decision process.

The intra macroblock mode is very important for high coding efficiency. However, it causes much coding complexity to consider the intra macroblock mode in each macroblock mode decision process. Considering the low frequency of the intra macroblock mode, we propose a quick mode decision method between the intra macroblock mode and the inter macroblock mode. In order to minimize additional computational requirements, we use previously mentioned intermediate results and rate-distortion characteristics. In the proposed method, we use the rate and distortion for the best inter macroblock mode.

In Fig. 3, we show the generated rate between the best inter macroblock mode and the intra macroblock mode for each frame of MOBILE and CONTAINER sequences. We verify the rate of the intra macroblock mode requires a higher value than that of the best inter macroblock mode.



(a) MOBILE Sequence



(b) CONTAINER Sequence

Fig. 3. Comparison of coding bits

When we consider the Lagrangian cost function written by D = J-λR in the rate-distortion curve, the best macroblock mode is determined by the operating point having the minimum RDcost value. We already know the operating point (R, D) for the best inter macroblock mode. All values of (R, D) that lie on the curve of the Lagrangian cost function passing the operating point for the best inter macroblock mode have the same RDcost value.

In order for the intra macroblock mode to be the best macroblock mode, the operating point for the intra macroblock mode should be below the curve of the Lagrangian cost function for the best inter macroblock mode. In Fig. 3, since the rate of the intra macroblock is larger than that of the best inter macroblock mode, the distortion value of the intra macroblock mode should be smaller than that of the best inter macroblock mode. Hence, when its condition is satisfied, we only investigate the intra macroblock mode.

In order to calculate the distortion of the intra macroblock mode, we use the available boundary pixels between the current macroblock to be encoded and the already encoded upper or/and left macroblock, as shown in Fig. 4.

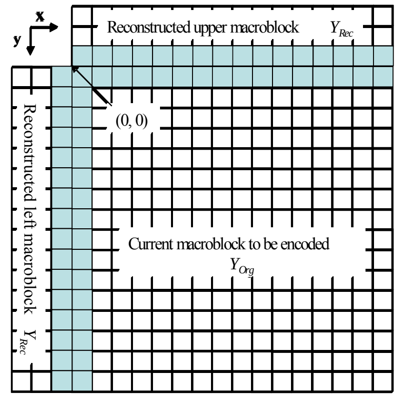


Fig. 4. Boundary pixels

We approximate the distortion of the intra macroblock mode with the mean squared boundary error (*MSBE*), calculated by Eq. (11) [8-9].

$$MSBE = \frac{w_{up}}{16}\cdot\sum_{i=0}^{15}\left[Y_{Org}(x+i,y)-Y_{\mathrm{Rec}}(x+i,y-1)\right]^2 + \frac{w_{left}}{16}\cdot\sum_{i=0}^{15}\left[Y_{Org}(x,y+i)-Y_{\mathrm{Rec}}(x-1,y+i)\right]^2 \quad (11)$$

where w_{up} and w_{left} are zero or one. Zero indicates that neighboring macroblocks are not available. One indicates the reverse case. Y_{Org} and Y_{Rec} indicate the original signal to be encoded and the already reconstructed signal, respectively. If w_{up} and w_{left} are zero, we do not consider the intra macroblock mode. The best macroblock mode is determined by the best inter macroblock mode.

After the decision of *MSBE*, we calculate the mean of SSD for the best inter macroblock mode (*MSSD*), and compare *MSBE* with *MSSD*. If $MSBE < MSSD$ is satisfied, it indicates that the RDcost value of the intra macroblock mode can be smaller than that of the best inter macroblock mode. Hence, we examine the intra macroblock mode and refine the best inter macroblock mode. Otherwise, we omit the intra macroblock mode. Figure 5 illustrates main functional blocks of the proposed fast macroblock mode decision algorithm.

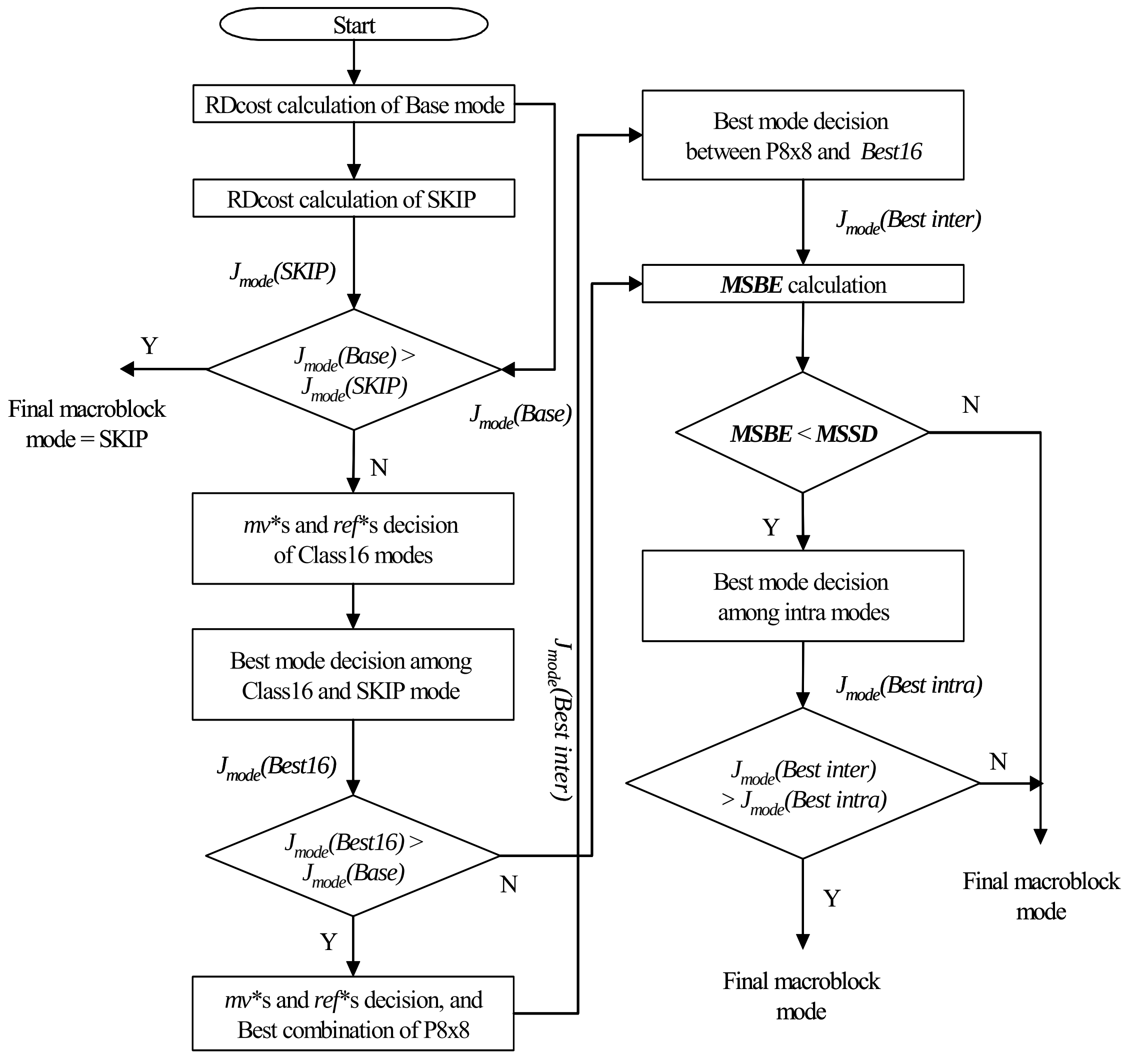


Fig. 5. Flowchart for the fast mode decision algorithm

4. Experiment Results

The proposed algorithm is implemented into JM6.1. We have tested six video sequences of different characteristics, and each of them has 100 frames of the QCIF format. Four reference frames are enabled with the maximum search range of ± 32, and the maximum resolution of the motion vector is 1/4 pixel.

CAVLC is adopted as the entropy coding method, and the Hadamard transform is also used to transform the DC coefficients of the intra16x16 mode. The frame rate is 30 fps, and the frame coding structure is IPPP baseline profile. In order to obtain the rate-distortion curve and compare coding efficiency between two methods, we have conducted our experiment for four quantization parameters: QP =28, 32, 36, and 40 [10].

For performance comparison, we employ the encoding time (*T*) which is the total time to encode the test sequence and the rate-distortion computational complexity (*N*).

$$\Delta N = \frac{\#N[H.264] - \#N[proposed]}{\#N[H.264]} \times 100[\%]$$

$$\Delta T = \frac{T[H.264] - T[proposed]}{T[H.264]} \times 100[\%] \quad (12)$$

It is very difficult to measure performance with only the encoding time. Hence, we employ the rate-distortion computational complexity. In order to calculate the rate-distortion cost at the encoder using RDO, we should perform the encoding operation: forward and inverse integer transform, quantization, and entropy coding. To calculate each rate-distortion cost, we should perform the 4x4 integer transform at the encoder.

Hence, we employ the 4x4 integer transform as the basic unit for measuring the rate-distortion computational complexity, which is the total number of the 4x4 integer transforms to encode the test sequence. The performance comparison between the proposed algorithm and H.264 is calculated by Eq. (12).

Figure 6 shows the rate-distortion (RD) curve between H.264 and the proposed algorithm. Figure 6 is obtained by examining the bitrate and PSNR for four quantization parameters in each image sequence. Comparison of PSNR and bitrate between two RD curves is achieved by Ref. [11]. In Table 2, we compare the coding efficiency and complexity between the proposed algorithm and H.264.

Table 2. Coding efficiency vs. complexity

Sequence	Δ BR [%]	Δ PSNR [dB]	Δ N [%]	Δ T [%]
MOBILE	-0.092	-0.003	85.6	30.24
SILENT	1.353	-0.068	92.4	32.52
FOREAMAN	-2.599	-0.142	85.1	27.41
CONTAINER	2.983	-0.163	94.4	31.51
NEWS	-2.099	0.122	90.4	28.50
COASTGUARD	-2.428	0.078	86.8	27.70
Average	-0.480	-0.029	89.12	29.65

5. Conclusions

In this paper, we classify macroblock modes of H.264 into four different groups considering the frequency and computational complexity of each macroblock mode. We apply the rate-distortion optimization procedure to the four groups selectively. In the inter macroblock mode, we differentiate SKIP and P8x8 from other macroblock modes with the defined base mode, and then consider the intra macroblock mode conditionally to refine the best inter macroblock mode in terms of the rate-distortion characteristics. By computer simulations, we have verified that the proposed method provides lower PSNR value and less bitrate than H.264 by 0.029 and 0.480, respectively. The average encoding time and rate-distortion computational complexity of the proposed algorithm are also reduced by 29.65%, and 89.12%, respectively.

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7. References

[1] ITU-T Rec. H.264 | ISO/IEC 14496-10 AVC, “Draft ITU-T Recommendation and Final Draft International Standard of Joint Video Specification”, JVT Doc. G050, March 2003.

[2] T. Wiegand, G. J. Sullivan, G. Bjontegaard, and A. Luthra, “Overview of the H.264/AVC Video Coding Standard,” *IEEE Trans. Circuit and System for Video Technology,* vol. 13, no. 7, pp. 560-576, July 2003.

[3] T. Wiegand, M. Lightstone, T. G. Campbell, and S. K. Mitra, “Efficient Mode Selection for Block-Based Motion Compensated Video Coding”, *Proc. Int. Conf. on Image Processing*, October 1995, pp. 23-26.

[4] T. Wiegand, H. Schwarz, A. Joch, F. Kossentini and G. J. Sullivan, “Rate-Constrained Coder Control and Comparison of Video Coding Standards”, *IEEE Trans. Circuit and System for Video Technology,* vol. 13, no. 7, pp. 688-703, July 2003.

[5] G. Sullivan and T. Wiegand, “Rate-distortion optimization for video compression”, *IEEE Signal Processing Magazine*, vol. 15, pp. 74-90, November 1998.

[6] T. Wiegand and B. Girod, “Lagrange Multiplier Selection in Hybrid Video Coder Control”, *Proc. Int. Conf. on Image Processing,* October 2003, pp. 542-545.

[7] F. Pan, X. Lin, S. Rahardja, K. P. Lim, Z. G. Li, G. N. Feng, D. J. Wu, and S. Wu, “Fast Mode Decision Algorithm for JVT Intra Prediction”, JVT Doc. G013, March 2003.

[8] Y. Wang, Q. F. Zhu and L. Shaw, “Maximally Smooth Image Recovery in Transform Coding”, *IEEE Tansactions on Communication*, vol. 41, no. 10, pp. 1544-1551, October 1993.

[9] Q. F. Zhu, Y. Wang and L. Shaw, “Coding and Cell-Loss Recovery in DCT-Based Packet Video”, *IEEE Trans. Circuit and System for Video Technology*, vol. 3, no. 3, pp. 248-258, June 1993.

[10] G. Sullivan and G. Bjontegaard, “Recommended Simulation Common Conditions for H.26L Coding Efficiency Experiments on Low-Resolution Progressive-scan Source Material”, ITU-T Q.6/16, Doc. VCEG-N81, September 2001.

[11] G. Bjontegaard, “Calculation of Average PSNR Difference between RD-curve”, ITU-T Q.6/16, Doc. VCEG-M33, April 2001.

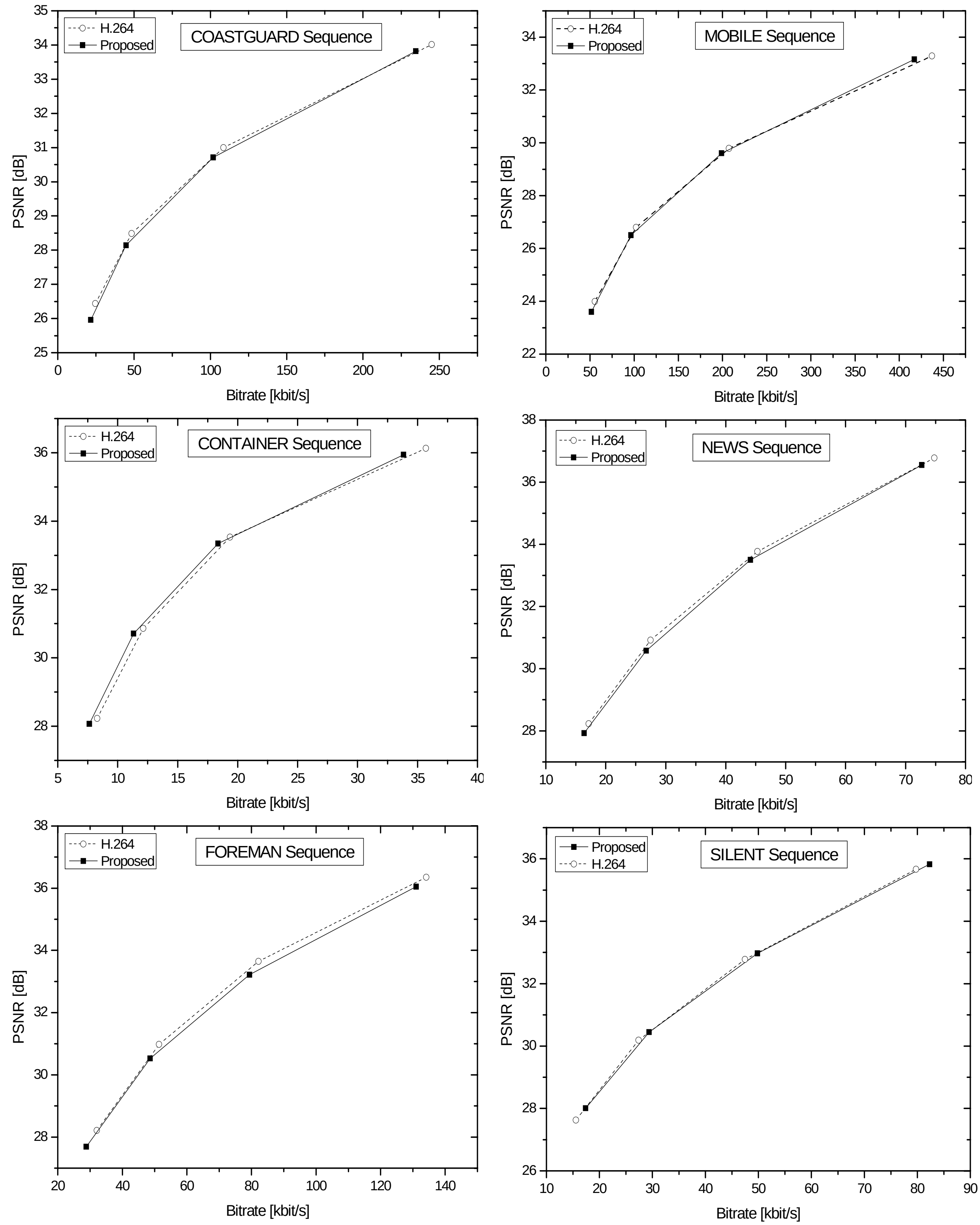

Fig. 6. Comparison of rate-distortion curve