BUFFER-CONSTRAINED R-D MODEL-BASED RATE CONTROL FOR H.264/AVC

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1. ABSTRACT

Most existing R-D model based rate control schemes are not applicable in H.264/AVC due to the unique features of H.264/AVC, for example, the QP-dependent rate distortion optimization (RDO); the large amount of bits (header bits) used for encoding the header information (except DCT coefficients) of an macroblock (MB); the huge number of zero-coefficient MBs. In this paper, we present a R-D model based rate control scheme for H.264/AVC. A pre-analysis is conducted for R-D estimation. A rate model is developed to separately estimate the coefficient bits and the header bits. A frame-level bit allocation scheme is proposed to allocate the bits to individual frames. In comparison with JM6.1e, our scheme not only evidently improves the PSNR of decoded video (an average 0.54dB PSNR gain is achieved for 7 sequences tested) but also meets the target bit rates accurately (within 2%).

2. INTRODUCTION

The hybrid DCT-based motion-compensated video coding algorithm intrinsically produces a variable bit rate. Rate control is usually used to, firstly, stabilize the video quality by appropriately allocating the bits to individual MBs and frames; secondly, control the output bit rate to ensure that output buffer is not overflowed and to meet the target bit rate.

The rate control in a DCT-based video encoder performs bit allocation by selecting the quantization parameter (QP) for MBs based on certain available knowledge of the MBs/frames. Usually, this type of knowledge is referred to as *source information*. Due to the QP-dependent RDO process where the best prediction mode is selected for the MB, obtaining an accurate source information is usually difficult in H.264/AVC. This imposes a difficulty for rate control in H.264/AVC. In Section 3, other difficulties of rate control in H.264/AVC will be further investigated.

Although many studies concerning rate control have been conducted for MPEG-2, H.263, MPEG-4 [1, 2, 3], the proper method [4, 5] for rate control in H.264/AVC has not been fully explored. In this paper, we present a R-D model based rate control scheme targeting at buffer-constrained CBR coding for H.264/AVC. The rest of the paper is organized as follows. The aforementioned difficulties for rate control in H.264/AVC are investigated in Section 3. The proposed R-D model is presented in Section 4, while the overall rate control process is described in Section 5. Experimental results and related discussion are given in Section 6. Finally, Section 7 concludes this paper.

3. DIFFICULTIES OF RATE CONTROL IN H.264/AVC

In H.264/AVC, a total of 7 prediction modes, i.e., SKIP, INTER16x16, INTER16x8, INTER8x16, P8x8, INTRA4x4 and INTRA16x16, can be used for one MB in a P frame. In the case of P8x8, each of the 8x8 sub-MBs can be further partitioned into blocks of 8x8, 8x4, 4x8, or 4x4 luminance samples. The mode decision is made using RDO technique. The best mode is selected by minimizing the following Lagrangian function (R-D cost) [6]:

$$J_{Mode} = D(Mode|QP) + \lambda R(Mode|QP) \quad (1)$$

where $Mode$ is one of the 7 prediction modes; QP is the quantization parameter; $D(Mode|QP)$ is the distortion, which is measured as the sum of the squared differences between the reconstructed and the original MBs; $R(Mode|QP)$ is the rate after entropy coding including both the header bits and coefficient bits; λ is the Lagrange multiplier, which is computed as $\lambda = 0.85 \times 2^{(QP-12)/3}$.

Clearly, to compute λ for RDO, QP should be first provided by the rate control, which is usually based on the motion compensated residual information. However, such residual information is only available after performing the RDO. This is a typical chicken and egg dilemma [7].

Table 1 shows the bit statistics for QCIF sequences *news* and *foreman* encoded at different QPs using JM6.1e [8]. From the table, we see the header bits are comparable to (or even more than) the coefficient bits; the header bits vary greatly with video contents and QPs (therefore bit rates). To do a good rate estimation, a special look at the header bits is necessary.

Table 1. Percentage Of Header Bits (POHB) for *news* and *foreman* encoded at different QPs by JM6.1e

QP	POHB for *news*	POHB for *foreman*
24	28.0%	32.4%
32	40.6%	49.6%
40	52.1%	65.4%

Table 2. Percentage Of Zero-coefficient MBs (POZM) for *news* and *foreman* encoded at different QPs by JM6.1e

QP	POZM for *news*	POZM for *foreman*
24	59.1%	23.0%
32	76.1%	60.6%
40	87.6%	78.8%

In H.264/AVC, many MBs are quantized to zero due to the good prediction capability offered by the 7 prediction modes. Table 3 shows the percentages of the zero-coefficient MBs for *news* and *foreman* encoded at different QPs using JM6.1e. From the table, we see the percentage of zero-coefficient MBs is quite high. To estimate the rate of a MB using the typical quadric model, it will be useful if we can separate these zero-coefficient MBs.

4. RATE AND DISTORTION ESTIMATION

In this section, we describe our R-D estimation that estimates the rate and distortion for a MB based on the variance of motion compensated residues and the QP.

4.1. Pre-analysis

To break the chicken and egg problem so as to obtain the necessary source information for R-D estimation, all MBs in current frame are pre-analyzed before the encoding. In our implementation, INTER16x16 is used to do pre-analysis before RDO. After pre-analysis, the signal measurements, such as variances of the motion compensated errors, R-D costs of individual MBs, etc., are obtained. They are then used for determining the QPs and frame targets.

4.2. Rate estimation

As pointed out in in Section 3, both header bits and coefficients bits may dominate the output bitstream. In this section, the header bits and the coefficients bits used for a MB are separately considered in our rate estimation.

4.2.1. *Coefficient bits estimation*

The quadric model proposed in [2] is used for coefficient bits estimation. Let F_i denote the bits required for encoding the DCT coefficients of ith MB; σ_i^2 denote the variance of the motion-compensated residues obtained in the RDO; Q_i denote the quantization step size; F_i can be estimated by the following formula:

$$F_i = AK\frac{\sigma_i^2}{Q_i^2} \quad (2)$$

where, A is the number of the pixels in an MB; K could be set to $e/ln2$ if the DCT coefficients were Laplacian distributed and independent. However, since this assumption is simply an approximate to the actual statistics, it is better to set the value of K adaptively during the encoding.

Note Eq. (2) is based on the variance of the residues obtained using the prediction mode selected by the RDO, which may be different from the variance obtained using INTER16x16 in pre-analysis. Such discrepancy usually leads to a better performance of our scheme for low-motion or simple video sequence as can be seen in Section 6. The variance obtained by pre-analysis is always used for our R-D estimation.

As discussed in Section 3, many MBs are quantized to zero in H.264/AVC. For these zero MBs, Eq. (2) is obviously not applicable since the K in the equation is unlikely to be zero. To improve the rate estimation accuracy, in our algorithm, these zero MBs are separated by considering the MB's local scene activities.

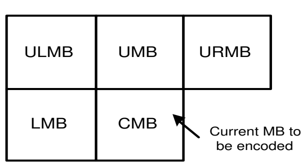

Fig. 1. Separate the zero-coefficient MB based on the coding results of up to four neighboring MBs denoted as ULMB, UMB, URMB and LMB respectively

As shown in Fig. 1, whether current MB will produce zero coefficient bits (flagged by $ZCOF$) is predicted according to the coding results of up to four neighboring MBs. The more number of the neighboring MBs with zero coefficient, the higher the possibility that current MB will produce zero coefficient bits. In the encoding process, we count the number of neighboring MBs (num) who produce zero coefficient bits. Then, the variance of current MB (σ^2) is compared to its neighbors'. Once we find that σ^2 is smaller than certain times of the variances of its neighboring MBs, we set $ZCOF$ to "1". We refer to this algorithm as *Separation Algorithm*.

4.2.2. *Header bits estimation*

Based on our extensive experiments with different video sequences and different bit rates, we find that H_i is approximately linear to $log(\sigma_i^2)^2$ when $H_i > 10$, i.e.,

$$H_i = C \times [log(\sigma_i^2)]^2 \qquad when \;\; H_i > 10 \quad (3)$$

where, H_i is the header bits of a MB; σ_i^2 is the variance of the motion-compensated residues obtained in the pre-analysis phase; C is a constant that models the relation between H_i and $log(\sigma_i^2)^2$. Fig. 2 shows the $C-H$ curve when *news* is encoded at 27Kbps using our rate control scheme. From the figure, we see C varies little along H axis and thus Eq. (3) is good for header bits estimation.

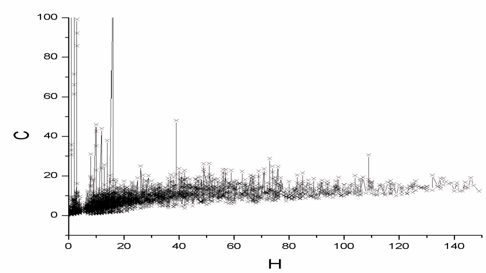

Fig. 2. The $C-H$ curve for *news* encoded at 27Kbps using our rate control scheme

The cases with $H_i < 11$ correspond mostly to the situation when INTER16x16 is selected by the RDO as the best prediction mode. In our algorithm, the separation of these small-header-bits MBs is as follows: 1) During the encoding of previous frame, record σ^2 and H of the MBs whose H is smaller than 11; 2) After encoding previous frame, compute the averages of all recorded σ^2 and H, which are referred to as σ_{Htrd}^2 and H_{trd} respectively; 3) During the encoding of current frame, once we find $\sigma^2 \leq \sigma_{Htrd}^2$ for an MB, we deem that this MB will produce small header bits and H is directly estimated by H_{trd}. Thus, the header bits can be estimated using following formula:

$$H_i = \begin{cases} H_{trd}, & \sigma_i^2 \leq \sigma_{trd}^2 \\ C \times [log(\sigma_i^2)]^2, & else \end{cases} \quad (4)$$

Eq. (4) can be rewritten as:

$$H_i = C \times com_i \quad (5)$$

with

$$com_i = \begin{cases} H_{trd}/C, & \sigma_i^2 \leq \sigma_{trd}^2 \\ (log(\sigma_i^2))^2, & else \end{cases} \quad (6)$$

Note above formula for header bits estimation is derived using a statistical method, it may not work well for every individual MB. Anyway, since the computation of the QP by our scheme needs only an estimate of the total number of header bits required for a number of MBs, the proposed method fits our needs well. Furthermore, frame by frame and MB by MB adaptive updating of C makes the proposed header bits estimation more robust.

4.3. Distortion estimation

In our design, the following typical distortion model [2] is used to measure the distortion of the encoded MBs:

$$D = \frac{1}{N}\sum_{i=1}^{N} \alpha_i^2 \frac{Q_i^2}{12} \quad (7)$$

where N is the number of MBs in a frame; α_i is the distortion weight of ith MB, which is adopted to control the QP changes across MBs. In our desgin, α_i is selected using following formula:

$$\alpha_i = \begin{cases} \sigma_i^{\frac{3}{4}}, & \frac{B}{AN} \le 0.05 \\ \sigma_i^{\frac{1}{2}}, & \frac{B}{AN} \le 0.2 \\ \sigma_i^{\frac{1}{4}}, & \frac{B}{AN} \le 0.5 \\ 1.0, & else \end{cases} \quad (8)$$

where B is the bit budget for the frame to be encoded. Like in other video standards, the QPs are differentially encoded in H.264/AVC. Frequent QP change may consume too many bits. Using Eq. (8), by appropriately setting the α_i according to the bit rate (B/AN), frequent QP change will be allowed at high bit rates and will be restricted at low bit rates.

5. THE RATE CONTROL SCHEME

Fig. 3 shows the processes of our rate control scheme, which mainly comprises of three major steps, i.e., the pre-analysis, the frame-layer bit allocation and the MB-layer rate control.

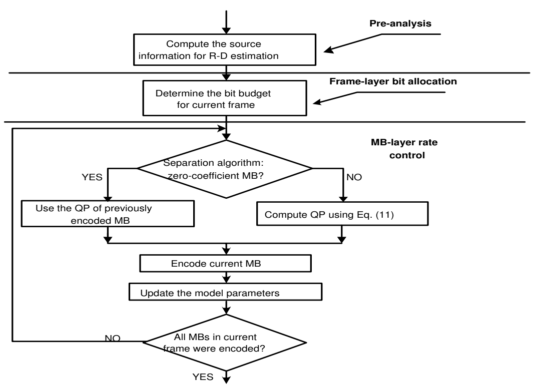

Fig. 3. Implementation steps of our rate control scheme

5.1. Pre-analysis

As discussed in Section 4, pre-analysis phase is where we compute the source information for R-D estimation before the RDO.

5.2. Frame-layer bit allocation

Our frame-layer bit allocation scheme can be divided into two steps. Firstly, determine the frame target for the best video quality without considering the buffer constraints using the following formula:

$$B_1 = [1 + (\hat{P} - P_n)/2] \times \frac{\mathbf{J}_{cur} - \mathbf{J}_{prev,0}}{\widehat{\mathbf{J}} - \mathbf{J}_{prev,0}} \times \frac{R}{f} \quad (9)$$

where, R is the available channel bandwidth; f is the frame rate; $\mathbf{J}_{cur}$ is the R-D cost of current frame, which is defined as the sum of the R-D cost of all the MBs in current frame; $\widehat{\mathbf{J}}$ is the average R-D cost of all the encoded frames and current frame; $\mathbf{J}_{prev,0}$ is the sum of the R-D cost of all the zero-coefficient MBs in previous frame; P_n is the average PSNR of the previous n frames, which is computed using a sliding window algorithm; $\hat{P}$ is the average PSNR of all the encoded frames. Using Eq. (9), more bits will be allocated to the frames whose activity (measured by $\mathbf{J}_{cur}$) is high and the predicted PSNR (measured by P_n) is low, and vice versa.

Secondly, the frame target obtained above is further adjusted according to the buffer state: 1) given the B_1 obtained by Eq. (9), we estimate the actual number of bits (B_2) that may be generated after encoding current frame (according to the bits statistics for previous frames); 2) if the buffer level is predicted to increase ($B_2 > R/f$) after encoding current fame and the current observed buffer fullness L is above a certain level B_{inc}, or if the buffer level is predicted to decrease ($B_2 < R/f$) and the buffer fullness is below a certain level B_{dec}, B_1 is then further adjusted to avoid the possible buffer overflow or underflow; 3) in the implementation, any possible buffer level increase ($B_2 - R/f$) above B_{inc} and any buffer level decrease ($R/f - B_2$) below B_{dec} are restricted according to the buffer occupancy. The higher the buffer fullness, the stronger the buffer level increase will be restricted, and the lower the buffer fullness, the stronger the buffer level decrease will be restricted. We do not include the details of this algorithm in this paper due to space stringency.

5.3. MB-layer rate control

The Lagrangian optimization is applied to the proposed R-D model in Section 4, and the optimized quantization step sizes $Q_1^*, Q_2^*, \cdots Q_N^*$ for the MBs are determined to minimize the following rate-constrained $cost$:

$$cost = \frac{1}{N}\sum_{i=1}^{N} \alpha_i^2 \frac{Q_i^2}{12} + \lambda[\sum_{i=1}^{N}(AK\frac{\sigma_i^2}{Q_i^2} + C \times com_i) - B] \quad (10)$$

where B is the frame target; λ is the Lagrangian multiplier. Based on the observation that we are minimizing a convex, differentiable function on a convex set, Lagrangian optimization is the ideal tool. By setting partial derivatives of $Q_1, Q_2, \cdots Q_N$ and λ to zero, we have $N+1$ equations with $N+1$ independent variables. Solving the $N+1$ equations, we obtain:

$$Q_i^* = \sqrt{\frac{AK}{B - C\sum_{i=1}^{N} com_i}\frac{\sigma_i}{\alpha_i}\sum_{i=1}^{N}\alpha_i\sigma_i} \quad (11)$$

Thus, the optimized quantization step sizes that minimize the distortion of the frame subject to frame target can be computed.

As discussed in Section 4.2.1, an *Separation Algorithm* is developed to separate the zero-coefficient MBs from others. As shown in Fig. 3, the separation algorithm is applied before encoding the MB. Once the MB is predicted to produce zero coefficient bits, the QP of the previously encoded MB is used as the QP for current MB. Otherwise, Eq. (11) is used to compute the QP. Misusing of the quadric model to the zero-coefficient MBs is therefore avoided.

6. RESULTS AND DISCUSSIONS

In this section, we implement our rate control (ORC) scheme in a H.264/AVC reference encoder version JM6.1e. The performance of the proposed scheme is evaluated in comparison with the original encoder JM6.1e, in which the fixed-QP (FQP) rate control is used. In the experiments, the video sequence is first encoded using FQP to determine the target bit rate, according to which the video sequence is then encoded using our scheme. The PSNR and the bit rate for the two schemes are thereafter compared.

Table 3. Test sequences

Test Sequence	Size	Frame Rate	QP range	Frames Encoded	Frame Type
news	QCIF	10	24-44	100	IPPP
container	QCIF	10	24-44	100	IPPP
silent	QCIF	15	24-44	150	IPPP
foreman	QCIF	30	24-44	100	IPPP
paris	CIF	15	24-44	150	IPPP
mobile	CIF	30	24-44	300	IPPP
tempete	CIF	30	24-44	240	IPPP

Table 3 lists the video sequences used in this paper. The test conditions under witch our experiments are conducted are as follows: MV resolution = 1/4 pel, RDO = OFF, search range = 32 and reference frames = 1.

Each of the seven sequences is encoded at 6 different bit rates with a QP ranged from 24 to 44. Due to the space stringency, as shown in Table 4, we only present the results when the sequences are encoded at a QP equal to 32 for FQP (for ORC, the QP for the first I frame is 28). In the table, R is the overall bit rate; OFW denotes the occurrence of buffer overflows; GAIN denotes the PSNR gain achieved by ORC over the FQP; R_{DIFF} denotes the *bit rate in-accuracy*, which is computed as $(R_{ORC} - R_{FQP})/R_{FQP} \times 100\%$, where R_{ORC} is the bit rate achieved by ORC and R_{FQP} is the bit rate achieved by FQP.

Table 4. Results achieved by two schemes

sequence	scheme	PSNR (dB)	R (b/s)	OFW	GAIN (dB)	R_{DIFF} (%)
news	FQP	33.50	27,586			
	ORC	34.51	27,158	0	1.01	-1.55
container	FQP	33.14	13,841			
	ORC	33.86	13,867	0	0.72	0.19
silent	FQP	32.77	34,558			
	ORC	33.76	34,271	0	0.99	-0.83
foreman	FQP	33.17	55,544			
	ORC	33.28	55,758	0	0.11	0.39
paris	FQP	32.34	182,965			
	ORC	33.39	180,298	0	1.05	-1.46
tempete	FQP	31.38	616,914			
	ORC	31.39	610,268	0	0.01	-1.08
mobile	FQP	30.22	850,171			
	ORC	30.41	845,756	0	0.19	-0.52

As observed from the table, our scheme is able to significantly improve the PSNR at most cases. For the seven sequences encoded at six bit rates, our scheme achieves an average of 0.54dB PSNR gain over the FQP scheme.

Our buffer control assumes that the bits for first I frame are, in some way, transmitted to the terminal without pushing them into the encoder buffer. Thus, when compute the target bit rate for the P frames, the bits for first I frame need to be deducted from the overall bit budget. In our experiments, the encoder buffer size is set to five times the average P frame size. Upon completion of encoding a frame, all the bits are pushed into the buffer instantaneously. The bits in buffer are drained to the channel at a constant bit rate unless buffer is empty.

Table 4 also shows the number of the buffer overflows (OFW) occurred in the experiments. As we see, no single buffer overflow is observed. Our rate control scheme is able to control the bit rate to meet the target bit rate accurately. The maximum bit-rate in-accuracy is less than 2%.

Fig. 4 shows the PSNR, number of bits of each frame for *forman* encoded using two rate control schemes. The buffer level at any time interval using our scheme is shown as well. From the figure, we see the PSNR of most video frames achieved by our scheme is higher than that by FQP. We also note the PSNR fluctuation of our scheme is greater than the original. This is reasonable considering the strict buffer constraints in our scheme.

7. CONCLUSION

In this paper, we present a R-D model-based rate control scheme for H.264/AVC targeting at buffer-constrained CBR video coding. As shown by our extensive experimental results, the proposed rate control scheme significantly improves the video quality and nicely meets the buffer constraints. The average PSNR gain is 0.54dB and the maximum bit rate in-accuracy is less than 2% for 7 sequences encoded at 6 bit rates. The features of our rate control scheme include: 1) the pre-processing algorithm provides us with an relatively accurate source information for R-D estimation. 2) the separation algorithm effectively separates the zero-coefficient MBs from others and avoids the misusing of the quadric model. 3) the proposed header bits model is effective for header bits estimation. 4) adaptive updating of the

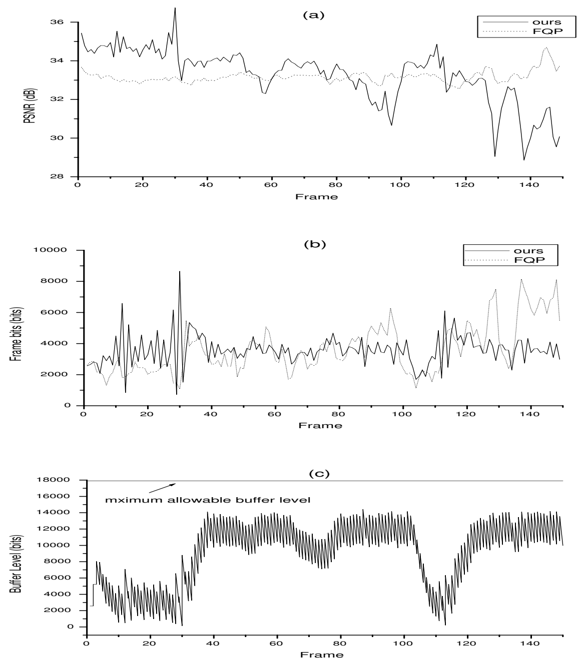

Fig. 4. (a)&(b): comparison of the PSNR, frame bits of each frame when *foreman* is encoded at 55Kbps using our rate control scheme and FQP scheme; (c): buffer level at each frame interval when *foreman* is encoded at 55Kbps using our rate control scheme.

various parameters makes our scheme well adaptive to the contents of the video sequence. 5) the frame-layer bit allocation scheme is able to appropriately allocate the bits to individual frames based on the frame activity and buffer state.

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