ADAPTIVE RATE CONTROL FOR HIGH EFFICIENCY VIDEO CODING

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ABSTRACT

A frame level adaptive rate control scheme for the emerging High Efficiency Video Coding (HEVC) standard is proposed in this paper, where both rate model and distortion model are provided. For rate modeling, a new rate model is proposed based on the weighted complexity estimation of multiple previously encoded frames. For distortion modeling, the distortion is modeled as an exponential function of the sum of absolute transformed difference (SATD) and the quantization parameter of the current frame. Moreover, a quality smoothing method based on the distortion model is proposed to reduce quality fluctuation. The proposed rate control algorithm is implemented into HM5.0. Experimental results show that the bitrate derivation of the proposed rate control algorithm is within 1%. And the coding gain over the rate control scheme proposed in JCTVC-H0213 is up to 0.64dB for LB HE & LB LC, 0.33dB, 0.31dB, 0.42dB, 0.44dB for LP HE, LP LC, RA HE and RA LC respectively. The proposed rate control scheme is further combined with the proposed quality smoothing method to generate smoother coding quality.

Index Terms— rate control, video coding, HEVC

1. INTRODUCTION

Rate control plays an important role in video coding technologies. None of the existing video coding standards can be practically applied without rate control. Because the underflow or overflow of client buffer may occur due to the mismatching of the source bit rate and the available channel bandwidth when delivering the compressed bitstreams. Therefore, video coding standards usually recommend their own rate control schemes, such as TM5 for MPEG-2, TMN8 for H.263 and VM8 for MPEG-4.

However, these rate control algorithms are designed for their corresponding coding standards specifically, which may be not efficient for the upcoming video coding standard, High Efficiency Video Coding (HEVC). For example, the first rate control scheme for HEVC proposed in JCTVC-H0213 is a transplant of H.264/AVC rate control algorithm, which doesn't work well for HEVC. Its performance is worse than the HM anchor, the average loss is up to -0.62dB. This is because HEVC has adopted many new coding tools, which should be considered in the rate distortion modeling.

HEVC aims to improve the coding efficiency compared with H.264/AVC High Profile and to reduce the bitrate by 50% with comparable quality, allowing an increase of computational complexity [1]. Compared with the previous coding standards such as H.264/AVC, many new tools are adopted into HEVC to improve the coding performance. Coding unit (CU), prediction unit (PU) and transform unit (TU) are three new concepts defined in HEVC. CU, the basic coding unit similar to macroblock in H.264/AVC, can have various sizes and allows recursive quad-tree splitting. Each CU may contain one or more PUs, or multiple TUs for transforming. Besides, two new in-loop filters are employed in HEVC, i.e. Sample Adaptive Offset (SAO) and Adaptive Loop Filter (ALF).

In this paper, new rate model and distortion model are proposed for HEVC respectively. For the rate modeling, complexities of previously encoded frames are taken into account to decide an appropriate quantization parameter (*QP*) value for the current frame. For Distortion modeling, distortion is modeled as an exponential function of the sum of absolute transformed difference (*SATD*) and *QP* of the current frame. In addition, a PSNR estimation method is proposed based on the proposed distortion model. According to the rate and distortion analysis, a frame level adaptive rate control algorithm is proposed. And a quality smoothing method is designed based on the proposed PSNR estimation method to reduce the coding quality fluctuation. The proposed rate control scheme shows much better performance than that of JCTVC-H0213. The bitrate derivation is within 1%, while the maximum average coding gain over the scheme in JCTVC-H0213 is up to 0.64dB for Low Delay (LD) configuration. When combined with the proposed quality smoothing method, the proposed rate control algorithm can generate smoother coding quality without quality dropping. The proposed rate control scheme is also proposed to HEVC as a proposal.

The rest of this paper is organized as follows. Section 2 describes the proposed rate and distortion models. And a frame level adaptive rate control scheme w/o quality smoothing is presented in Section 3. The experimental results are provided in Section 4. Finally, Section 5 concludes this paper.

2. RATE AND DISTORTION MODELS

2.1. Rate model

In the previous video coding standards, rate and distortion models have been widely studied in both *q*-domain and *ρ*-domain. In the *q*-domain, rate is modeled as a function of the quantization step size and the complexity of the residual signal. Studies show that quadratic models can achieve more accurate rate control and provide better performance than linear models with relatively high computational complexity. In the *ρ*-domain, where ρ is the percentage of zero DCT coefficients, the rate is modeled as a linear function of (1-ρ) [3], and a histogram of DCT coefficient is used to find the relationship between *ρ* and the quantization step size.

Considering the characteristics of HEVC, we propose an improved linear R-D model for quantization parameter determination. In the proposed model, SATD is used as complexity estimation of the residual signal and its performance is better than MAD [5]. The proposed rate model is shown as:

$$R = \alpha \times X / QP \tag{1}$$

where α is the model parameter. R is the coding rate. X is the complexity estimation for the current picture. QP is the quantization parameter. X is computed as:

$$X = \left(\sum_{i=0}^{n} (w_i \times SATD_i) / \sum_{i=0}^{n-1} (w_i \times SATD_i) \right)^{1-\lambda} \times R_{n-1} \times QP_{n-1} \tag{2}$$

where n is the current frame number. $QP_{n\text{-}1}$ is the quantization parameter of the $(n\text{-}1)^{th}$ frame. $R_{n\text{-}1}$ is the actual bits of the $(n\text{-}1)^{th}$ frame. λ is a constant, the recommended value is 0.6. w_i is the weight of $SATD$ values of previously encoded frames. w_i is defined as:

$$w_i = 0.5^{n-i} / \sum_{i=0}^{n} 0.5^{n-i} \tag{3}$$

Actually, (1) is developed from the implicit rate model used in the popular x264 codec. The difference between the proposed model and TM5 is that the complexities of several previously encoded frames are taken into account, which provides efficient information to smooth the coding quality.

Fig. 1 shows the performance of the proposed rate model. The test sequence is encoded with a fixed QP. Obviously, the mismatch of generated bits and estimated bits per frame is relatively small.

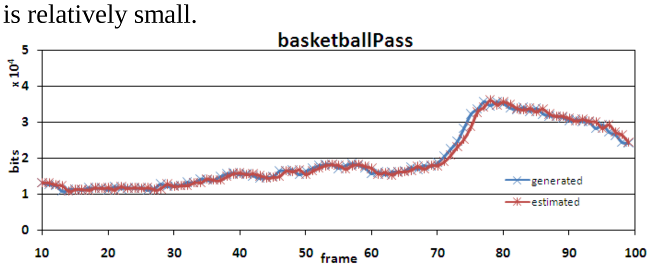

Fig. 1: The relationship between the generated bits and the estimated bits per frame when QP is set to 32.

According to (1), given the target rate for the n^{th} picture, the quantization parameter QP_n for the n^{th} picture can be calculated as:

$$QP_n = \alpha \times X / T_n \tag{4}$$

where T_n is the target bits of the n^{th} frame. Equation (4) will be used for quantization parameter determination in the proposed rate control algorithm detailed in Section 3.

2.2. Distortion model

The distortion of a coded frame is closely related with the quantization error that is decided by QP. Distortion is usually defined as a function of the error between the input and output of the quantizer [6]. Generally, distortion can be modeled as an exponential function of the source bits [7]. Given the rate model in equation (1), we consider the relationship between the distortion and $SATD$. Based on the experiments, the relationships between the frame distortion and $SATD \times QP^{\gamma}$ for different frame types are shown in Fig. 2 (a), (c) and (e), where γ is a constant. The distortion is measured in Sum of Squared Error (SSE).

Obviously, there is a strong exponential relationship between the frame distortion and $SATD \times QP^{\gamma}$. Therefore, the distortion of a coded frame can be modeled as:

$$D = \alpha \times (SATD \times QP^{\gamma})^{\beta} \tag{5}$$

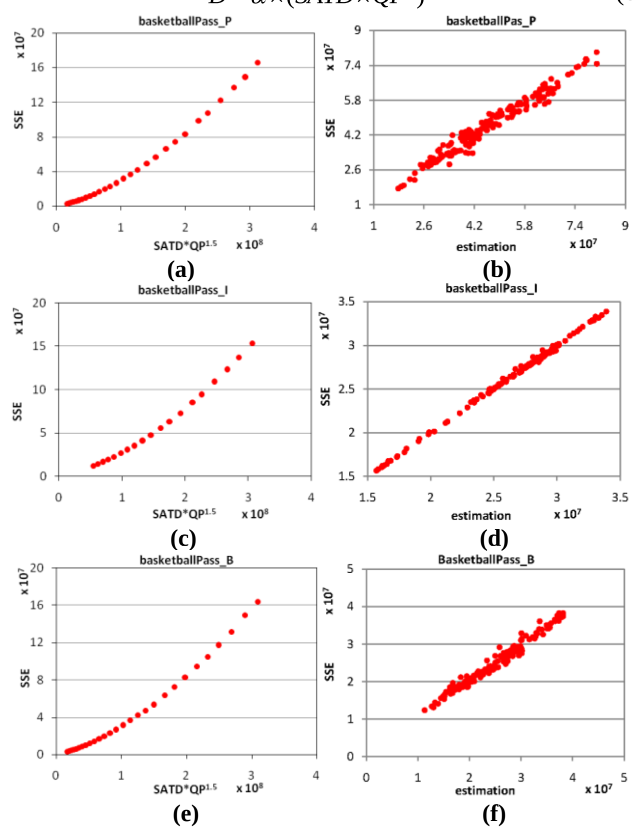

Fig. 2: (a), (c) and (e) show the relationship between *SSE* and *SATD*QP*$^{1.5}$. (b), (d) and (f) show the relationship between the actual distortion and the estimated distortion.

where α and β are model parameters, which can be estimated with least square method. And the value of γ is recommended 1.5 according to the experimental results.

To verify the accuracy of the proposed distortion model, the relationship of the estimated distortion and the actual distortion of frames are plotted in Fig. 2 (b), (d) and (f), where it can be seen that the distortion model works well.

Rate control schemes usually bring quality fluctuation while achieving the target bit rate. To reduce that, a PSNR based quality smoothing method is proposed. PSNR is a commonly used objective quality measurement, defined as:

$$PSNR = 10 \times \log \frac{255^2}{MSE} \tag{6}$$

As *MSE* is the average of *SSE*, a *PSNR-QP* model can be derived from equation (5) and (6) as:

$$PSNR = \alpha_1 + \beta_1 \times \log(SATD \times QP^{\gamma}) \tag{7}$$

where α_1 and β_1 are model parameters. Based on the experimental results, as shown in Fig. 3, we get a simpler formulation for PSNR estimation:

$$PSNR \approx \alpha_2 \times (\log SATD - QP) + \beta_2 \tag{8}$$

where α_2 and β_2 are model parameters, and α_2 is positive. The proposed PSNR estimation method indicates that PSNR of a coded frame is related with both the picture content and *QP*.

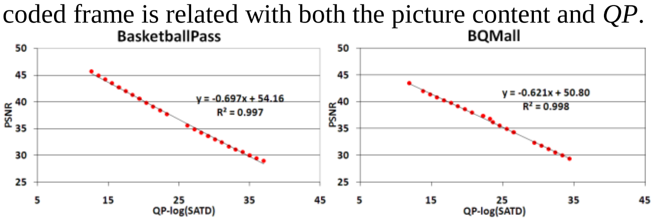

Fig. 3: The relationship between *PSNR* and *(logSATD-QP)*.

3. ADAPTIVE RATE CONTROL ALGORITHM

Based on the rate distortion models presented in Section 2, we propose a frame level adaptive rate control algorithm for HEVC. Considering the difference between Low Delay (LD) and Random Access (RA) settings, the proposed rate control algorithm is designed for LD and RA dedicatedly. For LD setting, a Video Buffer Verifier (VBV) operation model is established. And adaptive bit allocation is performed considering the current VBV buffer status. Then the *QP* for the current frame can be derived with the proposed rate model, and the *QP* value is clipped to comply with the VBV buffer to avoid overflow or underflow. For RA setting, a GOP level *QP* adjustment strategy is designed to make the generated bitrate approach the target requirement. Moreover, a quality smoothing scheme is developed based on the proposed PSNR estimation method. The proposed rate control algorithms are shown as follows.

3.1. Rate control algorithm for LD coding

***Step* 1:** Initialize the VBV buffer fullness as $B_0=M*0.9$, where *M* is the buffer size. Let *B* denote the current buffer fullness and set $B=B_0$.

***Step* 2:** Perform bit allocation for the current frame with the following equation:

$$T = BR / Fr - \Delta \tag{9}$$

where *T* is the target bits, *BR* is the target bitrate and *Fr* is the frame rate. Δ is defined as follows:

$$\Delta = \begin{cases} W / Fr, & W > Z \times BR / Fr \\ W - Z \times BR / Fr, & others \end{cases} \tag{10}$$

where *W* is the difference between the current and the initial VBV buffer fullness and equals to B-B_0. *Z* is set to 0.1 by default.

***Step* 3:** Estimate the frame complexity *SATD* by doing rough motion estimation over LCUs, which can be merged with motion estimation of CUs in the future without increasing complexity. And Experimental results show that this pre-analysis slightly effects the overall encoding time. For example, the encoding time increased 1.13%, 0.51% for *BasketballPass* and *BQSqure* under LB HE configuration respectively.

***Step* 4:** Calculate the quantization parameter with the rate model proposed in section 2. As for the first frame of the sequence, a constant value C defined as equation (11) is used to substitute $R_{n-1} \times QP_{n-1}$, which is not available yet:

$$C = 0.01 \times (7 \times 10^5)^{0.6} \times \sqrt{((H+15)/16) \times ((W+15)/16)} \tag{11}$$

***Step* 5:** Check if the calculated *QP* in *Step* 3 complies with the VBV buffer constraints. If not, clip *QP* to avoid buffer overflow or underflow. The detail steps are shown as:

i. If the current buffer fullness *B* is less than the half of the buffer size *M*, it means the former encoded frame has consumed too much bits. Therefore, the *QP* value of the current frame is increased as follows:

$$QP' = QP / (2 * B / M) \tag{12}$$

where *2*B/M* is clipped between 0.5 and 1.

ii. Predict the bits to be used by the current frame with QP' and *SATD* of the frame, defined as:

$$b_{\text{pred}} = (\alpha_3 * SATD + \beta_3) / QP' \tag{13}$$

where b_{pred} is the predicted bit count. α_3, β_3 are constants, which are updated with the final *QP* and the actual bits after the frame is coded.

iii. If b_{pred} is bigger than *B*0.5*, then the *QP* value should be increased as the following:

$$QP'/ = B / (b_{pred} * 2) \tag{14}$$

iv. Otherwise, if b_{pred} is smaller than *BR/Fr*0.5*, then the *QP* value should be decreased as the following:

$$QP'* = b_{pred} * 2 / (BR / Fr) \tag{15}$$

***Step* 6:** Implement adaptive frame level QP adjustment by regulating the *QP* for the current frame based on the difference between the generated bits and the target bits so far.

$$QP' = \begin{cases} QP_{prev}, & d / BR + 1 < \varepsilon_1 \ \&\& \ QP > QP_{prev} \\ QP_{prev}, & d / BR + 1 > \varepsilon_2 \ \&\& \ QP < QP_{prev} \\ QP, & others \end{cases} \tag{16}$$

where $\varepsilon_1, \varepsilon_2$ are constants, ε_1 is between 0~1. ε_2 is bigger than 1. d is the difference between the generated and the target bits so far. QP_{prev} is the QP of the latest reference frame.

***Step* 7:** For quality smoothness, *QP* derived from *Step* 6 is clipped into a limited range of the QP value of the closest encoded frame of the same type.

$$|QP - QP_{prev}| < \delta \tag{17}$$

δ is 2 or 4 in the experiments according to the bit rate fluctuation .

***Step* 8:** The *QP* value is further clipped between the minimum and maximum *QP* value allowed. The range is set to (10, 46) in the experiments.

***Step* 9:** Update the VBV buffer fullness after the frame is encoded using the following equation:

$$B = B + BR/F - bits \tag{18}$$

***Step* 10:** Go to *Step* 2 to continue coding the next frame until the sequence is finished.

3.2. Rate control algorithm for RA coding

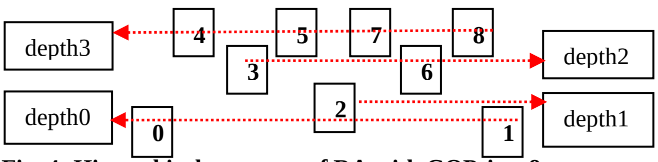

Fig. 4: Hierarchical structure of RA with GOPsize=8

***Step* 1:** Perform average bit allocation for the current frame, shown as:

$$T = BR/Fr \tag{19}$$

***Step* 2:** Same as *Step* 3 of the LD setting.

***Step* 3:** As shown in Fig. 4, for the referenced frames (frames in depth 0, 1 and 2), *QP* determination is the same as *Step* 4 of LD setting. And *QP* of the unreferenced B frames (frames in depth 3) is derived with a linear interpolation method as:

$$QP = \frac{QP_1 \times d_1 + QP_2 \times d_2}{d_1 + d_2} + offset \tag{20}$$

where QP_1 and QP_2 are the quantization parameters of the two nearest reference frames respectively. *offset* is a constant set to 1.4. And $d_1 = |POC - POC_{ref1}|$, $d_2 = |POC - POC_{ref2}|$, where POC is the picture order count for display order.

***Step* 4:** Perform GOP level adaptive QP adjustment for I frames according to the coding status of the previous GOP.

$$QP' = \begin{cases} (QP_{avg\_prev} + QP)/2 + \Delta, & d > \varepsilon \\ (QP_{avg\_prev} + QP)/2 - 2*\Delta, & d < -\varepsilon \\ (QP_{avg\_prev} + QP)/2 - \Delta, & others \end{cases} \tag{21}$$

where R_{prev}, T_{prev} are the generated and target bits of the previous GOP respectively. QP_{avg_prev} is the average QP of the previous GOP. d equals to $(R_{prev}\text{-}T_{prev})/\ T_{prev}$ and ε is a constant. This step is skipped for the first GOP.

***Step* 5:** Implement adaptive frame level QP adjustment by regulating the quantization parameter for the current frame based on the difference between the generated bits and the target bits so far. And quantization parameter of B-frames should not be less than its reference frames.

$$QP_i' = \begin{cases} QP_{i-1}, & d/BR + 1 < \varepsilon_1 \ \&\&\ QP_i > QP_{i-1} \\ QP_{i-1}, & d/BR + 1 > \varepsilon_2 \ \&\&\ QP_i < QP_{i-1} \\ QP_i, & others \end{cases} \tag{22}$$

where $\varepsilon_1, \varepsilon_2$ are constants. ε_1 is between 0~1 and ε_2 is bigger than 1. d is the difference between target bits and generated bits of encoded frames. *depth_i* is the depth of the current picture.

***Step* 6:** For quality smoothness, *QP* derived from *Step* 5 is clipped with the QP value of the closest frame in the lower depth. As for frames in depth 0, the previously encoded frame in depth 0 is used as the boundary for QP clipping.

$$\begin{cases} |QP_i - QP_{prev\_i-1}| < \delta, i > 0 \\ |QP_i - QP_{prev\_i}| < \delta, \quad i = 0 \end{cases} \tag{23}$$

δ is 1 or 2 used in the experiments according to the bit rate fluctuation .

***Step* 7:** Same as *Step* 8 of the LD setting.

***Step* 8:** Go to *Step* 1 to continue coding the next frame, until the sequence is finished.

3.3. Rate control algorithm with quality smoothing

Better smoothness of video coding quality is necessary for application. However, the rate control scheme usually causes quality fluctuation while achieving the target bitrate. Even with the same *QP* value, picture quality differs for different picture content and coding methods. To reduce the quality fluctuation, a quality smoothing method is proposed.

Given the target rate and the complexity estimation of the current picture, the *QP* value can be derived with the proposed rate control algorithm. Therefore, an estimation of the PSNR value of the current frame can be derived as:

$$PSNR\_est = \alpha_2 \times (\log SATD - QP) + \beta_2 \tag{24}$$

Let *PSNR_avg* be the average PSNR of the previously coded frames. For quality smoothing, *PSNR_avg* can be seen as the target PSNR value for the current frame, and *PSNR_est* should be in a small range of *PSNR_avg*. Consequently, a constraint on PSNR to regulate *QP* for smoother coding quality is designed as:

$$QP' = \begin{cases} QP, & |PSNR\_avg - PSNR\_est| \le \Delta \\ \log SATD - (PSNR\_avg \pm \varepsilon - \beta_2)/\alpha_2, & others \end{cases} \tag{25}$$

where ε, Δ are constants, and $\varepsilon < \Delta$. Therefore, the following steps are combined with the above rate control algorithms for quality smoothing.

Step* 1*: Derive the quantization parameter using the above LD and RA rate control algorithms.

Step* 2*: Estimate the PSNR of the current frame under the derived *QP* with equation (24).

Step* 3*: Calculate the average PSNR of the previously encoded frames.

***Step* 4:** Regulate the *QP* value with the estimated and average PSNR value by equation (25),.

***Step* 5:** Calculate the difference between the target bits and the generated bits, and regulate the quantization parameter as a compromise between the rate control accuracy and PSNR smoothness, shown as:

$$QP' = \begin{cases} QP+\Delta, & d>\eta \\ QP-\Delta, & d<-\eta \\ QP, & others \end{cases} \quad (26)$$

where η is a constant between 0~1 and $d=(T'-T)/T$. T, T' are the target and generated bits respectively.

***Step* 6:** Update the model parameters of equation (24) with least square method after the frame is coded.

***Step* 7:** Go to *Step* 1 to continue coding the next frame, until the sequence is finished.

4. EXPERIMENTAL RESULTS

To verify the performance of the proposed algorithms, the proposed rate control scheme has been implemented into HEVC test model HM5.0. The test sequences in Class A~E are detailed in [9]. Firstly, the experimental results of the proposed adaptive rate control algorithm are presented and compared with that of JCTVC-H0213 and the HM5.0 anchor respectively. Then, the results of the proposed rate control algorithm combined with quality smoothing are demonstrated. The details are shown as follows.

4.1. Results of the proposed rate control algorithm

Table. 1 and Table. 2 illustrate the coding performance of the proposed rate control scheme compared with that in JCTVC-H0213. Obviously, the proposed algorithm is better than that in JCTVC-H0213.The coding gain can be up to 0.64dB for LB. Table. 3 and Table. 4 show that the control accuracy of the proposed rate control algorithm is within 1% and the R-D performance is comparable with HM5.0. R-D curves of typical test sequences are shown in Fig. 5.

Table. 1: rate control performance with HE vs H0213

HE	vs H213					
	Low delay		**Low delay P**		**Random Access**	
	BD-PSNR	BD-RATE	BD-PSNR	BD-RATE	BD-PSNR	BD-RATE
ClassA					0.29	-7.68
ClassB	0.81	-28.95	0.39	-15.27	0.38	-15.31
ClassC	0.56	-13.73	0.31	-7.76	0.46	-10.78
ClassD	0.57	-13.63	0.37	-9.59	0.50	-11.42
ClassE	0.58	-16.36	0.21	-6.76		
Avg	0.64	-18.95	0.33	-10.37	0.42	-12.05

Table. 2: rate control performance with LC vs H0213

LC	vs H213					
	Low delay		Low delay P		Random Access	
	BD-PSNR	BD-RATE	BD-PSNR	BD-RATE	BD-PSNR	BD-RATE
ClassA					0.38	-9.59
ClassB	0.83	-28.99	0.42	-16.30	0.43	-17.34
ClassC	0.58	-14.27	0.18	-4.64	0.47	-11.27
ClassD	0.52	-12.95	0.37	-9.60	0.46	-10.77
ClassE	0.56	-15.52	0.20	-6.11		
Avg	0.64	-18.78	0.31	-9.80	0.44	-12.93

Table. 3: rate control performance with HE vs HM5.0

HE	vs HM5.0								
	Low delay			Low delay P			Random Access		
	accuracy	BD-	BD-	accuracy	BD-	BD-	accurac	BD-	BD-
ClassA							0.98%	-0.23	6.20
ClassB	0.32%	-0.09	-3.40	0.25%	-0.09	-3.03	1.40%	-0.07	1.64
ClassC	0.27%	0.00	0.01	0.27%	0.00	-0.02	0.59%	0.11	-2.74
ClassD	0.49%	-0.05	-1.27	0.43%	-0.04	-1.17	0.71%	0.10	-2.58
ClassE	0.38%	-0.01	-0.79	0.33%	-0.04	-1.43			
Avg	0.36%	-0.04	-1.53	0.32%	-0.05	-1.51	0.83%	0.00	-0.04

Table. 4: rate control performance with LC vs HM5.0

LC	vs HM5.0								
	Low delay			Low delay P			Random Access		
	accuracy	BD-	BD-	accuracy	BD-	BD-	accurac	BD-	BD-
ClassA							1.06%	-0.17	4.73
ClassB	0.29%	-0.10	-3.91	0.28%	-0.10	-3.73	1.39%	-0.04	0.35
ClassC	0.32%	-0.03	-0.77	0.30%	-0.02	-0.62	0.51%	0.12	-2.86
ClassD	0.49%	-0.05	-1.41	0.44%	-0.05	-1.65	0.81%	0.09	-2.39
ClassE	0.28%	-0.02	-0.79	0.36%	-0.03	-1.91			
Avg	0.34%	-0.06	-1.92	0.34%	-0.06	-2.09	0.95%	0.02	-0.65

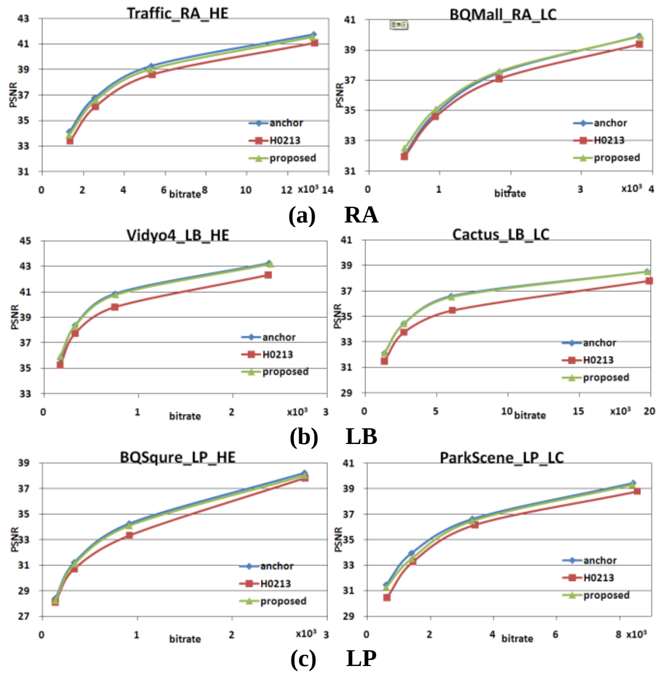

Fig. 5: The rate distortion curve of typical test sequences with different resolution and frame rate. (a) RA, (b) LB, (c) LP

4.2. Results of the proposed rate control algorithm with quality smoothing

Fig. 6 shows the PSNR curves of the proposed rate control scheme w/o quality smoothing. It can be seen that the coding quality of the proposed rate control scheme is relatively smooth. That's because the complexities of previously encoded frames are taken into account in the proposed rate model. Thus, the resulted QP value of the current frame is appropriate for both accuracy and quality smoothness. Table. 5 shows the average PSNR and variance of PSNR of typical test sequences. Apparently, when combined with the proposed quality smoothing (QS) method, the coding quality of the proposed rate control scheme is smoother with comparable average PSNR.

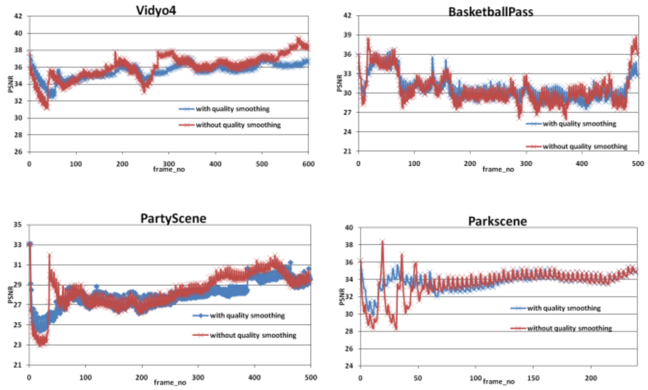

Fig. 6: The PSNR curve of the proposed rate control scheme w/o quality smoothing of typical test sequences with different resolution and frame rate.

Table. 5: Average PSNR and variance of PSNR of typical test sequences with different resolution and frame rate.

seq	Proposed RC		Proposed RC with QS	
	Avg_PSNR	Variance	Avg_PSNR	Variance
Kimono	36.99	3.82	37.00	2.07
ParkScene	31.43	1.98	31.69	0.67
BQMall	31.81	6.87	32.01	4.70
PartyScene	31.06	4.08	30.76	2.17
BasketballPass	30.94	6.13	30.95	4.12
RaceHorses	28.82	4.09	28.94	2.08
Vidyo3	35.43	2.59	35.23	1.19

5. CONCLUSION

This paper proposes a frame level adaptive rate control scheme for HEVC standard. An improved linear rate model is developed considering the complexities of multiple previously encoded frames. Meanwhile, a distortion model is established based on the analysis of the relationship between the distortion and $SATD \times QP^{\gamma}$. It is shown by experimental results the proposed rate control algorithm is better than that of JCTVC-H0213 with coding gain up to 0.64dB. The control accuracy is within 1% and the coding performance is comparable with that of HM5.0. Moreover, combined the rate and distortion model, a rate control scheme with quality smoothing is developed. Experimental results show that the proposed rate control scheme can generate smoother coding quality when combined with the proposed quality smoothing method.

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