LAPLACE DISTRIBUTION BASED CTU LEVEL RATE CONTROL FOR HEVC

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ABSTRACT

This paper proposes a coding tree unit (CTU) level rate control for HEVC based on the Laplace distribution modeling of the transformed residuals. Firstly, we give a study on the relationship model among the optimal quantization step, the Laplace parameter and the Lagrange multiplier. Based on the relationship model, the quantization parameter for each CTU can be dynamically adjusted according to the distribution of the transformed residual. Secondly, a CTU level rate control scheme is proposed to achieve accurate rate control as well as high coding performance. Experimental results show that the proposed rate control scheme achieves better coding performance than the state-of-the-art rate control schemes for HEVC in terms of both objective and subjective quality.

***Index Terms*—**Rate control, HEVC, Laplace distribution

1. INTRODUCTION

Rate control plays a key role in video coding applications, especially in real time applications such as video conference. The primary goal of rate control algorithm is to avoid client buffer overflow or underflow when delivering a compressed bitstream under a limited available bandwidth. Nevertheless, rate control is also an important tool for optimizing the coding performance of the encoder. Consequently, each exiting video coding standard recommends its own rate control scheme based on its distinct properties. For example, MPEG-2 recommends to use TM5 [1] rate control algorithm, and H.263 adopts TMN8 [2] algorithm, and the rate control algorithm specified in [3] is used in H.264/AVC.

The High Efficiency Video Coding (HEVC) standard is the state-of-the-art video coding standard, which is developed by the Joint Collaborative Team on Video Coding (JCT-VC), jointly founded by ISO/IEC MPEG and ITU VCEG working group. Compared to H.264/AVC, HEVC can achieve 50% or even more bits saving with comparable visual quality. Compared to the previous video coding standards, HEVC still adopts the traditional hybrid video coding framework. But many new coding tools have been added to HEVC for high efficiency coding, such as Advanced Motion Vector Prediction (AMVP), merge mode etc.

Recently, rate control for HEVC is emerging as a hot research topic since it is very important for real applications. In JCTVC-H0213 [5], a rate control scheme similar to the H.264/AVC rate control algorithm is proposed for HEVC. However, it causes significant performance loss. In JCTVC-K0103 [6], the authors propose a R-λ model based rate control algorithm. Although it achieves higher coding performance compared to JCTVC-H0213, there are still several problems unresolved. For instance, the Lagrange multiplier λ is scaled for different picture depths in HEVC, while the rate control in JCTVC-K0103 violates the scheme. Besides, it shows great performance loss in chroma components. Therefore, rate control with better coding performance for HEVC is highly desired.

In this paper, we propose a Laplace distribution based CTU level rate control scheme for HEVC. Firstly, based on the Laplace distribution of transformed residuals, the relationship among the optimal quantization step, the Laplace parameter and the Lagrange multiplier is modeled. Based on the relationship model, the quantization parameter for each CTU can be dynamically adjusted according to the distribution of the transformed residual. Then an adaptive rate control scheme is proposed with CTU level quantization parameter decision. The experimental results show that the proposed rate control scheme can achieve accurate rate control as well as good coding performance.

The rest of the paper is organized as follows. Section 2 describes the Laplace distribution property of HEVC as well as the CTU level QP determination process. Section 3 details the proposed rate control scheme with Laplace distribution based optimization. Experimental results and analysis are presented in Section 4. And Section 5 concludes the paper.

2. LAPLACE DISTRIBUTION BASED OPTIMIZATION

2.1 Laplace distribution analysis of HEVC

The distribution modeling of the transform residuals is widely studied in the rate distortion modeling of video coding, and there are three well known distributions which are usually used for the distribution modeling of the transformed residuals in the literature, namely, Laplace distribution, generalized Gaussian distribution (GGD) and Cauchy distribution. Cauchy distribution shows higher accuracy than Laplace distribution and GGD in case of heavy tails of transformed residuals [9]. However, it's hard to be applied since the mean and variance of Cauchy distribution are not defined. Laplace distribution is a special case of GGD. Though GGD has higher accuracy than the Laplace distribution, it has an additional control parameter to be determined. As [10] indicates that the predictability of control parameters is even more important than the accuracy of the models. Therefore, Laplace distribution is selected in this work to model the transformed residuals because it's a good trade-off between fitting accuracy and computational complexity.

Consequently, the transformed residual of the source signal in video coding is assumed to obey a zero-mean Laplace distribution, which is shown as:

$$f(x)=\frac{\Lambda}{2}e^{-\Lambda|x|} \qquad (1)$$
$$\Lambda=\sqrt{2}/\sigma$$

where σ is the standard derivation of transformed residuals and Λ is the Laplace distribution parameter. The statistics of transformed residuals of several pictures from sequence "*BQMall"*, which are encoded with the same QP value by HEVC encoder, are shown in Fig.2. It's observed that Fig. 2 (a) shows a more centralized curve than others, which is attributed to the reason that, pictures are divided into different depths for hierarchical coding in HEVC. Fig.1 shows an example of the depth setting under low delay configuration. There are three kinds of picture depths. And the Lagrange multiplier of higher depth pictures is magnified 2~4 times compared with that of depth 0. Therefore, even encoded with the same QP value, pictures in depth 0 can achieve better coding performance than other frames, that is to say, the residuals of frames in depth 0 are smaller and the distribution of the residuals is more concentrated to zero, as can be seen from Fig. 2.

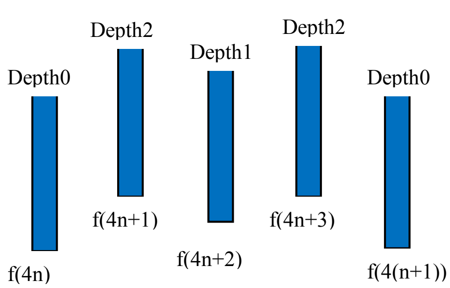

Fig. 1: An example of depth setting of the LD configuration. *f(n)* represents the POC number of a frame.

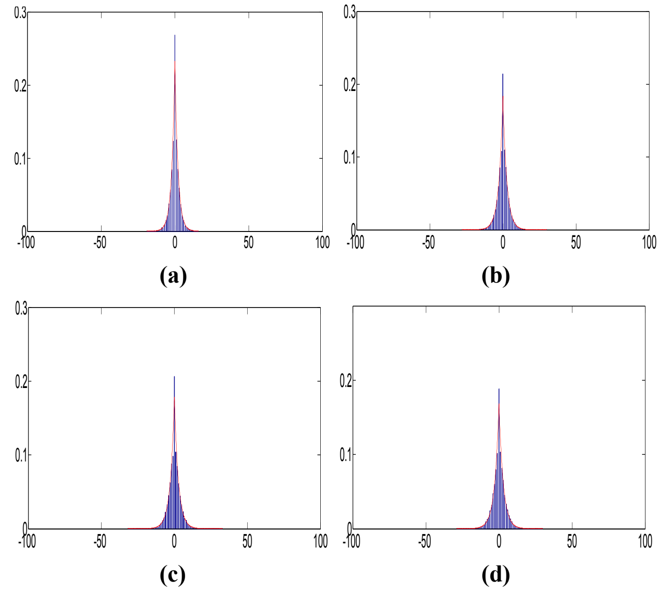

Fig. 2: The distribution of transformed residuals at LCU level of pictures at different depths. (a) depth 0; (b), (d) both are from depth 1 but based on different frames ; (c) depth 2.

2.2 QP determination at CTU level

According to [11], the rate of the source signal can be modeled as the entropy of the signal, shown as:

$$R=-P_0\log P_0-2\sum_{n=1}^{\infty}P_n\log P_n \qquad (2)$$

where P_0 and P_n are the probabilities of the transformed residuals quantized to the dead zone and the *n-th* quantization level, respectively, modeled as:

$$P_0=\int_{-(Q-rQ)}^{Q-rQ}f(x)dx \qquad (3)$$

$$P_n=\int_{nQ-rQ}^{(n+1)Q-rQ}f(x)dx \qquad (4)$$

where r is the rounding offset. And the distortion in form of MSE is modeled as:

$$D=\int_{-(Q-rQ)}^{Q-rQ}x^2f(x)dx+2\sum_{n=1}^{\infty}\int_{nQ-rQ}^{(n+1)Q-rQ}(x-nQ)^2f(x)dx \qquad (5)$$

Despite the basic requirement to meet the target bitrate, the rate distortion performance is a key consideration in rate control problems. The aim is to minimize the perceived distortion D with the number of used bits R subject to a constraint target value R_c. This converts to an unconstrained optimization problem shown as:

$$\min\{J\}\ \text{ where }\ J=D+\lambda\times R \qquad (6)$$

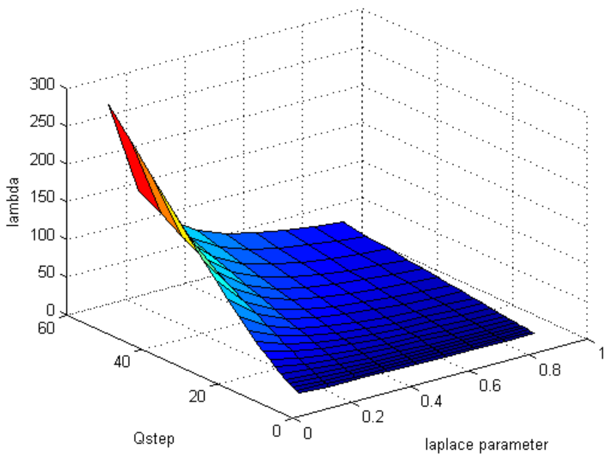

Fig. 3: The relationship between the optimal λ and (Λ, Q).

where J is the so called rate distortion cost, and λ is the Lagrange multiplier which determines the trade-off between the rate and the distortion. From equation (6), λ can be derived as:

$$\lambda = -dD / dR \tag{7}$$

By substituting (2) and (5) into (7), the optimal Lagrange multiplier λ can be modeled as a function of the quantization step and the Laplace distribution parameter:

$$\lambda = f'(\Lambda, Q) \tag{8}$$

The relationship between the optimal Lagrange multiplier λ and (Λ, Q) is shown in Fig.3. With the relationship model, given a specific λ value, for CTUs which has different Laplace distributions properties, the quantization step can be derived as:

$$Q = g(\Lambda, \lambda) \tag{9}$$

3. PROPOSED CTU LEVEL RATE CONTROL SCHEME

A linear rate model which takes into account the complexity of previously encoded frames for HEVC is employed and verified to be effective in [8] [13], it is calculated as follows:

$$\begin{aligned} R &= \alpha \times X / Q \\ X &= \left(\sum_{i=0}^{n} (w_i \times SATD_i) / \sum_{i=0}^{n-1} (w_i \times SATD_i) \right)^{\theta} \times R_{n-1} \times Q_{n-1} \end{aligned} \tag{10}$$

where Q_{n-1} is the quantization scale of the $(n\text{-}1)th$ frame. R_{n-1} is the actual bits. θ is a constant, and w_i is the weight of Sum of Absolute Transformed Difference (SATD) of previously encoded frames. In [8], a frame level rate control algorithm based on the above rate model is proposed. In this paper, the rate control algorithm is further developed and incorporated with the CTU level optimal QP determination process to achieve accurate rate control as well as better coding performance.

In HEVC, a picture is split into multiple CTUs, and the encoder processes the CTUs in Z order. And within each CTU, it may split into smaller blocks using quadtree structure as actual coding units (CU). Prediction units (PU) and transform units (TU) can be even smaller than the size of CU, and TU may be larger than PU. In the Picture Parameter Set (PPS), a syntax element is used to specify the minimum CU size for a delta QP, which is CTU as default in HM. Namely, the minimum unit which can be coded with a separate quantization parameter is CTU. Due to the hierarchical coding structure, the Lagrange multiplier λ is calculated differently for frames of different depths. For each frame, CTUs usually have different Laplace distribution properties. Therefore, the quantization step for a CTU can be determined with the specified Laplace parameter and the frame level λ. The aim is to give each CTU a more appropriate quantization step with the basic idea that allocating fewer bits to aeries which can tolerate more distortion.

On the one hand, larger Laplace parameter Λ means smaller but more centralized energy, which means the area is more sensitive to quantization and smaller quantization step shall be used. On the other hand, smaller Λ means the energy is decentralized, and a small change of quantization parameter can hardly effects the overall distortion. This conclusion has been explained by the experiments in [12], where intense reconstruction levels are set for residuals distributed near the central axis, while it becomes looser when getting far away from the centralized area. And from section 4, our experimental results also verify its effectiveness.

Based on the above analysis, the QP value for the *i-th* CTU can be derived as:

$$\begin{aligned} QP_i &= 2QP_{frame} - t(Q_i)) \\ Q_i &= g(\Lambda_i, \lambda) \end{aligned} \tag{11}$$

where QP_{frame} is the frame level quantization parameter, Λ_i is the Laplace parameter of the *i-th* CTU of the frame, and t is a function mapping the quantization step to a corresponding quantization parameter.

Except for the CTU level QP determination process, the proposed rate control scheme takes HRD (Hypothetical Reference Decoder) into consideration. Before encoding a frame, during the bit allocation process, the number of target bits Tb for the frame is clipped to satisfy the HRD constraints, shown as:

$$Tb = \mathrm{MIN}(UB, \mathrm{MAX}(BR / Fr, LB) \tag{12}$$

where UB and LB are the upper and lower boundary of HRD requirements. BR is the target bitrate and Fr is the sequence frame rate. UB and LB are initialized at each IDR frame and updated with the actual coding bits after the encoding of a frame. The initialization process is performed as:

$$UB = (T - R) + W * \alpha$$
$$LB = (T - R) + BR / Fr \tag{13}$$

The update process is performed as follows:

$$UB \mathrel{+}= BR / Fr - b$$
$$LB \mathrel{+}= BR / Fr - b \tag{14}$$

where b is number of the actual coding bits of the currently encoded frame. T and R are the target and actual numbers of bits of the overall encoded frames of the sequence, respectively. α is a constant, set to 0.8, and W is the virtual buffer size.

With the allocated target bits and the rate control method in [10], a frame level quantization parameter QP_{frame} can be derived, so as the Lagrange multiplier value λ. For the *i-th* CTU, reserve the non-zero transformed coefficients and calculate the related zero mean Laplace distribution parameter Λ_i. Then the quantization parameter QP_i for the *i-th* CTU can be derived with equation (11). Usually, the QP value for adjacent CTUs shouldn't change sharply. Therefore, QP_i is further adjusted with the following method:

$$| QP_i - QP_{i-1} | < \delta$$
$$| QP_i - QP_{frame} | < \delta \tag{15}$$

QP_{i-1} is the quantization parameter of the (i-1) *th* CTU. δ is a constant set to 2. Finally, the quantization value should be within the range of 0~51.

4. EXPERIMENTAL RESULTS

To verify the performance of the proposed rate control scheme, the proposed CTU level rate control algorithm detailed in Section 3 is implemented in HM10.0. Test sequences from class A~E as specified in [14] are tested. The target bitrates are set as the HM10.0 default hierarchical QP setting without rate control. In the development of HEVC, two rate control algorithms are adopted sequently, which are JCTVC-H0213 and JCTVC-K0103. First of all, we give an overall comparison of the rate distortion performance between the proposed rate control scheme and JCTVC-H0213. As shown in Table. 1, the proposed rate control scheme shows great coding gain against JCTVC-H0213. Besides, the bitrate error of JCTVC-H0213 rate control is larger, 2.63%, 2.21% and 2.2% for RA, LB and LP on average. On the contrary, the bitrate error of the proposed rate control for all test sequences is mostly within 1%, as shown in Table. 2. The bitrate error is calculated as:

$$bitrate\ error = \frac{| AR - BR |}{BR} \times 100\% \tag{16}$$

where AR and BR are the actual and target coding bitrate.

Table. 1: Overall performance gain of the proposed rate control against that of JCTVC-H0213

	RA		LB		LP	
	BD-RATE	Δ PSNR (dB)	BD-RATE	Δ PSNR (dB)	BD-RATE	Δ PSNR (dB)
Class A	-31.60%	1.45				
Class B	-38.37%	1.10	-25.37%	0.80	-23.62%	0.72
Class C	-43.35%	2.01	-17.14%	0.67	-19.78%	0.70
Class D	-32.76%	1.41	-13.83%	0.46	-14.42%	0.47
Class E			-32.10%	0.87	-31.83%	0.78
All	-37.30%	1.47	-21.69%	0.70	-21.90%	0.67

Table. 2: Bitrate error of the proposed rate control and that of JCTVC-H0213

bitrate error	RA		LB		LP	
	H0213	proposed	H0213	proposed	H0213	proposed
Class A	3.34%	0.57%				
Class B	2.29%	0.80%	2.12%	0.60%	2.16%	0.59%
Class C	2.59%	0.37%	2.56%	0.76%	2.62%	0.69%
Class D	2.73%	0.41%	2.24%	0.71%	2.25%	0.69%
Class E			1.84%	0.71%	1.84%	0.62%
All	2.63%	0.55%	2.21%	0.69%	2.24%	0.64%

Table. 3: Coding performance of typical sequences compared with the JCTVC-K0103 (LB)

	Low delay							
	JCTVC-K0103				proposed			
	target bitrate	actual bitrate	PSNR (dB)	bitrate error	actual bitrate	PSNR (dB)	bitrate error	BD-RATE
Kimono	5201.60	5201.60	41.42	0.00%	5208.79	41.57	0.14%	-6.9%
	2401.41	2401.52	39.35	0.00%	2396.65	39.55	-0.20%	
	1150.93	1151.20	36.75	0.02%	1158.76	37.02	0.68%	
	563.30	563.11	34.25	-0.03%	557.84	34.57	-0.97%	
BasketballDrive	19835.96	19832.97	39.29	-0.02%	19960.69	39.30	0.63%	-5.9%
	6750.86	6751.16	37.34	0.00%	6798.20	37.50	0.70%	
	3111.43	3111.75	35.35	0.01%	3132.96	35.57	0.69%	
	1584.97	1585.10	33.24	0.01%	1593.26	33.47	0.52%	
PartyScene	8054.41	8047.30	38.29	-0.09%	8115.83	38.42	0.76%	-5.3%
	3447.50	3447.53	34.53	0.00%	3470.76	34.65	0.67%	
	1504.47	1504.60	30.99	0.01%	1515.41	31.35	0.73%	
	643.56	643.83	27.72	0.04%	647.26	28.24	0.57%	
RaceHorses	5702.67	5624.14	39.74	-1.38%	5686.34	39.89	-0.29%	-4.2%
	2263.50	2254.58	36.12	-0.39%	2279.12	36.32	0.69%	
	996.33	995.98	32.87	-0.04%	1002.33	33.05	0.60%	
	456.74	456.14	29.81	-0.13%	459.94	30.19	0.70%	
BQSquare	2225.07	2225.62	38.33	0.02%	2243.94	38.28	0.85%	-5.3%
	772.31	772.88	34.25	0.07%	778.44	34.29	0.79%	
	308.50	309.19	30.89	0.22%	310.32	31.28	0.59%	
	126.63	127.12	27.53	0.39%	127.36	28.31	0.58%	
BasketballPass	1722.44	1703.55	40.95	-1.10%	1728.44	41.15	0.35%	-3.6%
	856.41	852.21	37.04	-0.49%	860.46	37.29	0.47%	
	415.70	415.73	33.54	0.01%	417.74	33.74	0.49%	
	209.21	209.32	30.57	0.05%	210.06	30.75	0.40%	
FourPeople	2225.79	2225.81	42.40	0.00%	2243.66	42.43	0.80%	-13.9%
	866.01	866.22	39.95	0.02%	863.82	40.38	-0.25%	
	422.86	422.94	37.11	0.02%	420.95	37.87	-0.45%	
	219.98	220.02	34.12	0.02%	221.22	34.90	0.56%	
KristenAndSara	1968.08	1968.45	43.16	0.02%	1984.31	43.21	0.82%	-13.1%
	697.61	698.46	40.80	0.12%	703.32	41.23	0.82%	
	315.65	316.04	38.16	0.12%	319.05	38.75	1.08%	
	161.56	161.73	35.44	0.11%	162.84	36.15	0.79%	
Average				**-0.07%**			**0.48%**	**-7.3%**

Secondly, the coding performance of the proposed rate control scheme is compared with the state-of-the-art rate control for HEVC, namely, the rate control scheme described in JCTVC-K0103. Table. 3 and Table. 5 show the bitrate error as well as the detailed coding results of typical test sequences of various resolution and frame rate. By employing the results of JCTVC-K0103 rate control as the anchor, the coding performance gain of the proposed CTU level rate control scheme is up to 4.7% and 13.9% in random access and low delay B configuration, respectively. As for low delay P configuration, the performance gain is up to 12.5%. Besides, Fig. 4 gives some rate distortion curves of typical test sequences. Besides, to verify the effectiveness of the CTU level rate control, the coding performance of the proposed algorithm is compared the frame level rate control scheme proposed in [8]. It can be seen from Table. 4 that the proposed CTU level rate control scheme achieves 5.0% and 2.4% performance gain on average for LD and RA configuration, respectively.

Table. 4: Coding performance gain against the frame level rate control in [8]

	BD-RATE	
	LD	RA
Class A		0.7%
Class B	-8.7%	-2.7%
Class C	-3.7%	-2.6%
Class D	-3.3%	-3.4%
Class E	-2.8%	
Overall	-5.0%	-2.4%

Moreover, we also observed the reconstructed sequences to compare the subjective quality of the proposed rate control algorithm with that of JCTVC-H0213 and JCTVC-K0103. The experimental results show that with the proposed CTU level rate control algorithm, the HM10.0 encoder can give a better reconstruction compared to the other two rate control schemes in terms of subjective quality. As can be seen from Fig. 5 (a), (c) and (e), with the proposed algorithm, the number on the clock, the girl's face as well as her clothes are better reconstructed than the other two. Fig. 5 (b), (d) and (f) also verifies that the proposed rate control scheme can help to achieve better subjective coding quality, the man's face is better coded, besides, details like the texture of the man's suit and the dots on the tie are better preserved as well.

5. CONCLUSION

This paper proposes a Laplace distribution based CTU level rate control scheme for HEVC. The novelty of this scheme lies in that we modeled the optimal quantization step as a function of the Laplace distribution parameter of transformed residuals and the Lagrange multiplier. And the model is employed to adjust the quantization parameter at CTU level. When employed in CTU level rate control algorithm, experimental results show that the proposed rate control scheme can achieve accurate rate control. And the coding performance is better than the state-of-the-art rate control schemes, in terms of both objective and subjective measurements.

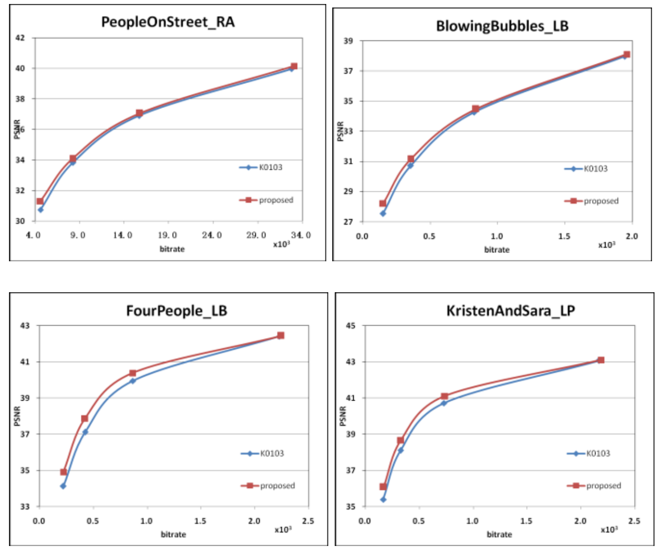

Fig. 4: The rate distortion curves of the coding results of the proposed algorithm, and JCTVC-K0103 rate control.

Table. 4: Coding performance of typical sequences compared with the JCTVC-K0103 (RA)

	Random Access							
	JCTVC-K0103				proposed			
	target bitrate	actual bitrate	PSNR (dB)	bitrate error	actual bitrate	PSNR (dB)	bitrate error	BD-RATE
PeopleOnStreet	32762.28	32773.79	39.96	0.04%	33048.65	40.15	0.87%	-4.7%
	15693.50	15704.06	36.91	0.07%	15752.02	37.06	0.37%	
	8242.08	8249.94	33.83	0.10%	8247.30	34.09	0.06%	
	4621.33	4625.59	30.74	0.09%	4604.16	31.31	-0.37%	
Kimono	4782.25	4785.64	41.42	0.07%	4754.73	41.44	-0.58%	0.2%
	2185.16	2187.09	39.55	0.09%	2165.18	39.49	-0.91%	
	1068.65	1069.65	37.24	0.09%	1068.12	37.21	-0.05%	
	542.68	543.06	34.87	0.07%	530.30	34.87	-2.28%	
BasketballDrive	17365.74	17370.54	39.07	0.03%	17472.69	39.13	0.62%	-3.8%
	6014.45	6016.22	37.36	0.03%	6026.74	37.44	0.20%	
	2807.15	2807.81	35.49	0.02%	2805.64	35.59	-0.05%	
	1474.12	1474.44	33.50	0.02%	1471.33	33.62	-0.19%	
PartyScene	6836.94	6838.21	38.19	0.02%	6857.21	38.09	0.30%	-0.9%
	3111.85	3112.55	34.58	0.02%	3115.89	34.60	0.13%	
	1465.12	1466.59	31.44	0.10%	1468.93	31.49	0.26%	
	691.61	691.68	28.42	0.01%	694.59	28.71	0.43%	
RaceHorses	4793.23	4783.27	38.94	-0.21%	4780.29	39.09	-0.27%	-4.4%
	2027.26	2028.42	35.80	0.06%	2025.27	35.88	-0.10%	
	945.83	946.20	32.79	0.04%	946.04	33.00	0.02%	
	463.02	463.20	29.92	0.04%	462.52	30.32	-0.11%	
BasketballPass	1506.20	1496.17	40.56	-0.67%	1504.90	40.64	-0.09%	-0.6%
	753.52	754.16	36.89	0.09%	753.39	36.92	-0.02%	
	371.55	371.83	33.55	0.07%	370.88	33.54	-0.18%	
	193.35	193.47	30.67	0.06%	192.46	30.72	-0.46%	
BlowingBubbles	1649.38	1649.16	38.04	-0.01%	1658.41	38.08	0.55%	-2.7%
	754.75	758.25	34.58	0.46%	759.02	34.75	0.57%	
	352.72	356.13	31.51	0.97%	355.73	31.61	0.85%	
	163.38	166.52	28.61	1.92%	165.18	28.65	1.10%	
Average				**0.13%**			**0.02%**	**-2.4%**

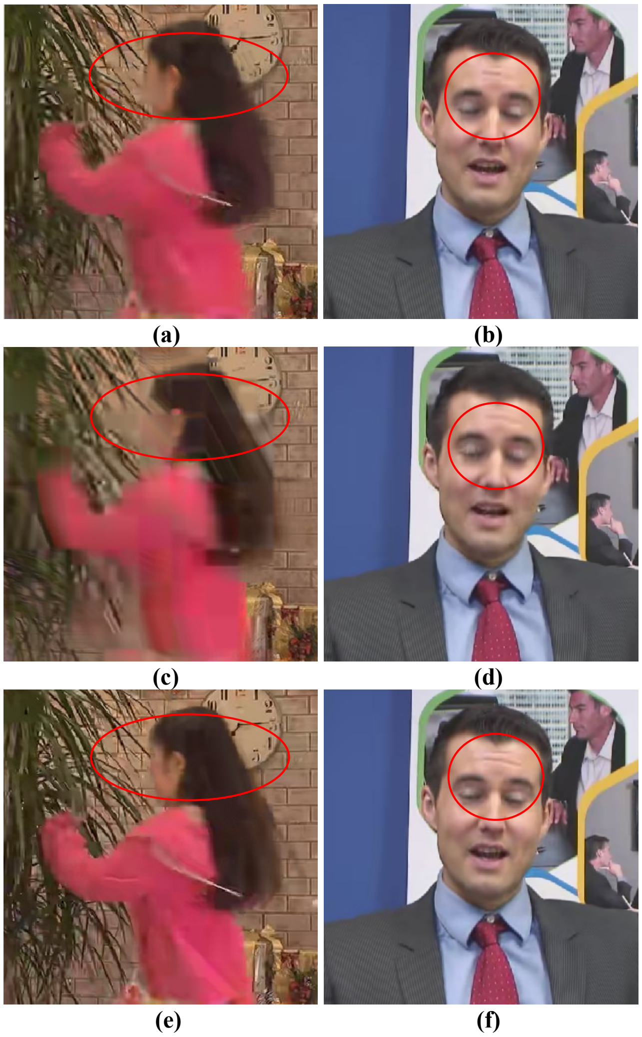

Fig. 5: Subjective quality comparisons. (a) and (b) are from the reconstruction results of JCTVC-H0213, (c) and (d) are results of JCTVC-K0103 rate control, (e) and (f) are results of the proposed rate control algorithm, respectively.

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