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Local curve fitting based Lagrange multiplier selection for I_d-slice in multi-view video coding*

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Abstract: The rate and distortion of I_d-slice do not fit the globally linear relationship on a logarithmic scale. Lagrange multiplier selection methods based on the globally linear approximate relationship are neither efficient nor optimal for multi-view video coding (MVC). To improve the coding efficiency of MVC, a local curve fitting based Lagrange multiplier selection method is proposed in this paper, where Lagrange multipliers are selected according to the local slopes of the approximate curves. Experimental results showed that the proposed method improves the coding efficiency. Up to 2.5 dB gain was achieved at low bitrates.

Key words: I_d-slice, Lagrange multiplier, Local curve fitting, Multi-view video coding (MVC)
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INTRODUCTION

Multi-view video coding (MVC) has a wide range of applications in entertainment, manufacturing, telemedicine, remote operations, 3D visual communications, virtual reality, etc. (Smolic and Kauff, 2005; Chen *et al.*, 2006). For transmission and storage of multi-view video data, compression is important as the required bandwidth increases linearly with the number of camera channels when traditional coding techniques are used. Smolic and Kauff (2005) presented an MVC system, in which new slice types such as I_d-, P_d- and B_d-slice were introduced for auxiliary views. These new slice types exploit the redundancy among views.

Rate-distortion optimization (RDO) is an important and widely used technique in video compression (Sullivan and Wiegand, 1998) and transcoding (Xie *et al.*, 2003). Significant coding gain can be achieved by using the best coding mode, selected using the Lagrange multiplier method based on RDO (Wiegand *et al.*, 1996). How to find an appropriate Lagrange multiplier is one of the key problems in RDO. A number of Lagrange multiplier selection methods have been proposed (Sullivan and Wiegand, 1998; Wiegand and Girod, 2001; Flierl and Girod, 2003; Carlsson *et al.*, 2004). However, a Lagrange multiplier selection method specific for I_d-slice has not been reported. Lagrange multipliers were calculated based on a globally approximate relationship between rate and distortion (Sullivan and Wiegand, 1998; Wiegand and Girod, 2001; Flierl and Girod, 2003), but the R-$\log_2 D$ curve of I_d-slice does not fit the globally approximate relationship. The method proposed by Carlsson *et al.*(2004) was valid only for non-reference slices and was not efficient for a reference frame, such as the I_d-slice.

The objective of this paper is to propose an optimal Lagrange multiplier selection method for I_d-slice. In this method, Lagrange multipliers are selected before coding according to the local slopes of the approximate curves. The proposed method improves coding efficiency without increasing coding complexity.

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CHARACTERISTICS OF I_d-SLICE

Multi-view video contains a large amount of inter-view statistical dependencies, since all cameras capture the same scene from different viewpoints. Significant coding efficiency can be achieved by exploiting the redundancy among views. Disparity compensation is a common method to exploit the redundancy (Li and He, 2003). New slice types, such as I_d-, P_d-, and B_d-slice, were introduced for auxiliary views (Yang *et al.*, 2006). Frames are predicted not only from temporally neighboring frames but also from corresponding frames in adjacent views. ISO/MPEG and ITU/VCEG have been developing a dedicated MVC specification (Vetro *et al*., 2008a; 2008b). It is an extension of H.264/AVC (ISO/IEC 14496-10, 2005).

Compared with I-slice, there are more macroblock modes in I_d-slice, such as InterView_16×16, InterView_16×8, InterView_8×16 and InterView_8×8. This poses great challenges for mode selection. The objective of video coding is to minimize the distortion of the coded sequence at a given target rate, which can be formulated as

$$\min D(R), \text{ subject to } R<R_C, \tag{1}$$

where D, R, and R_C denote the sum of squared differences (SSD) in distortion between the reconstructed frames and the original frames, bitrate, and target bitrate, respectively.

The optimization task in Eq.(1) can be elegantly solved using Lagrange optimization where a distortion term is weighted against a rate term. The Lagrange formulation of the minimization problem is given by

$$\min J, \text{ where } J=D+\lambda R. \tag{2}$$

The optimal mode is the one that minimizes the Lagrange cost function J. λ is a non-negative real number referred to as the Lagrange multiplier. The Lagrange multiplier imposes the rate constraint in Eq.(1) and its value directly controls the rate-distortion trade-off. Small values of λ correspond to low distortion and high bitrates, while large values of λ correspond to high distortion and low bitrates (Sullivan and Wiegand, 1998).

In rate-distortion theories, mode selection can be optimized when the Lagrange multiplier is the negative slope of the R-D curve (Sullivan and Wiegand, 1998), which yields

$$\lambda = -\frac{\partial D(R)}{\partial R}. \tag{3}$$

The rate-distortion function in high rate is often approximated as (Jayant and Noll, 1994)

$$R(D) = a\log_2(b/D), \tag{4}$$

where a and b are constants that depend on the source probability distribution function.

For the distortion-to-quantizer relation, it is assumed that at sufficiently high rates, the source probability distribution can be approximated as uniform within each quantization interval (Gish and Pierce, 1968), which yields

$$D = \frac{QP_{\text{H.263}}^2}{3} = \frac{2^{(QP_{\text{H.264}}-12)/3}}{3}, \tag{5}$$

where $QP_{\text{H.263}}$ and $QP_{\text{H.264}}$ denote quantization parameter (QP) in H.263 and H.264/AVC, respectively (ITU-T Recommendation H.263, 1995; ISO/IEC 14496-10, 2005).

Plugging Eqs.(4) and (5) into Eq.(3), gives

$$\lambda = -\frac{\partial D(R)}{\partial R} = c\cdot QP_{\text{H.263}}^2 = c\cdot 2^{(QP_{\text{H.264}}-12)/3}. \tag{6}$$

In the traditional methods (Sullivan and Wiegand, 1998; Wiegand and Girod, 2001; Flierl and Girod, 2003), the Lagrange multiplier was selected using Eq.(6), based on the globally approximate relationships in Eqs.(4) and (5). These methods were adopted in video coding reference software, such as MVC reference software JMVM (Vetro *et al*., 2008a).

According to the R-D theory (Hang and Chen, 1997), if the input source is Gaussian signal, the R-D function can be formulated by Eq.(4). The R-D theory describes the performance limit of the loss data compression and answers the following fundamental question: what is the minimum number of bits needed in compressing the source data at a given distortion level? The proofs of achievability depend on arbitrarily long block lengths. Real encoding systems are limited to rather small block sizes in the interest of both computational complexity and encoder delay. Because of these limitations, real encoding systems cannot reach the rate-distortion limit (Gormish and Gill, 1993). So the actual *R*-*D* relationship for I_d-slice is different from the approximate relationship in Eq.(4). As shown in Fig.1, the R-$\log_2 D$ curves of I_d-slice are not linear, especially at low bitrates and high bitrates. The globally approximate relationship in Eq.(4) is no longer appropriate for I_d-slice. So the traditional Lagrange multiplier selection methods were not optimal.

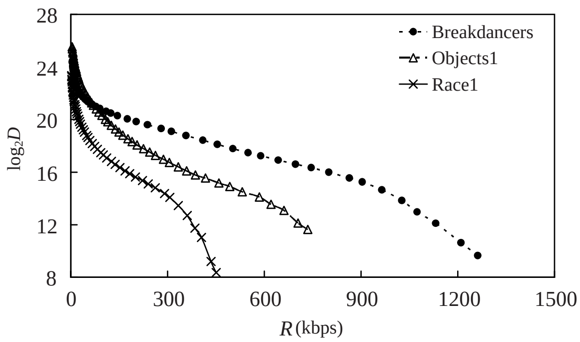

Fig.1 R-$\log_2 D$ curves of I_d-slice for different sequences

In I_d-slice, the Lagrange multiplier is used to choose a suitable mode to encode the disparity vector and disparity prediction residual data. The residual data is modeled as Gaussian noise with zero mean in the traditional Lagrange multiplier selection methods. However, due to various lighting conditions (spotlights, shadows, etc.) between viewpoints and dissimilar radiometric characteristics of different cameras, significant illumination and color inconsistencies often exist in multi-view video sequences. These inconsistencies affect the exploitation of inter-view statistical dependencies, and cause the residual data in I_d-slice to have a non-zero-mean distribution (Chen *et al*, 2006; Smolic *et al.*, 2007). In such cases, the traditional Lagrange multiplier selection methods formulated in Eq.(6) are no longer optimal, as proved by Li and Tourapis (2008).

PROPOSED LAGRANGE MULTIPLIER SELECTION METHOD

Lagrange multipliers can be selected according to the *R*-*D* curve's slope (Sullivan and Wiegand, 1998), as shown in Fig.2. It is convenient to solve this problem on logarithmic scale, because the local R-$\log_2 D$ curves are approximately linear (Fig.1) and it is much easier to fit a linear function than a non-linear function. Instead of all of the 52 QPs' points, only local points are used to fit the local curve for two reasons. First, the R-$\log_2 D$ curve is not globally linear, and therefore fitting a line to all of the points causes a large fitting error. Second, the slopes at only some points are relevant and the slopes can be calculated according to the local curves, so it is unnecessary to obtain the global curve.

Local points $\{(R_i, \log_2 D_i), q-N \le i \le q+N\}$ are selected to calculate the slope at point *A*, where q denotes the *QP* value of point *A*, i is the *QP* value of a local point, R_i and D_i are bitrate and distortion of the local point, respectively, and N determines the number of local points (Fig.3). In our experiments N was set to

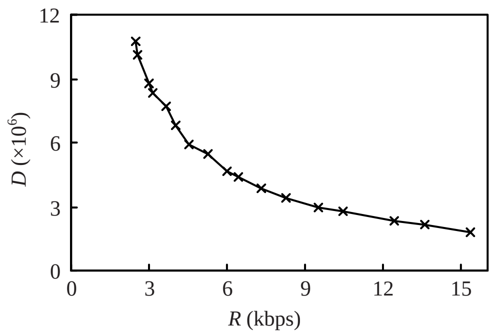

Fig.2 *R*-*D* curve with *QP*s greater than 35 on Race1

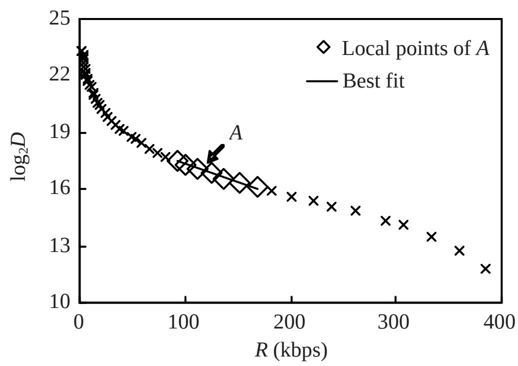

Fig.3 Local points selected to calculate the slope at point *A*

3. The number of selected local points is $2N+1$. For QP less than N, the set of local points is $\{(R_i, \log_2 D_i), 0\le i\le q+N)\}$; for QP greater than $51-N$, the set of local points is $\{(R_i, \log_2 D_i), q-N\le i\le 51)\}$.

Fitting a line to the local points by the least-square technique, the local curve is formulated as

$$R(D)=a_q\log_2 D+b_q, \tag{7}$$

where a_q and b_q parameterize the local approximation curve around point A.

Combining Eq.(7) with Eq.(3), we obtain

$$\lambda_{\mathrm{I_d}}(q)=-\left.\frac{\partial D(R)}{\partial R}\right|_{R=R_q}=-\frac{\ln 2\cdot D_q}{a_q}, \tag{8}$$

where $\lambda_{\mathrm{I_d}}(q)$ is the calculated Lagrange multiplier.

Using Eq.(8), $\lambda_{\mathrm{I_d}}(q)$ ($q\in\{0, 1, ..., 51\}$) can be calculated for each sequence. To make sure that $\lambda_{\mathrm{I_d}}$ performs well on all kinds of sequences, we set the new Lagrange multiplier as

$$\lambda_N(q)=\frac{1}{S}\sum_{s\in T}(\lambda_{\mathrm{I_d}}(q))_s, \tag{9}$$

where $\lambda_N(q)$ ($q\in\{0, 1, ..., 51\}$) denotes the new Lagrange multiplier selected for $\mathrm{I_d}$-slice by the proposed method, T is the training sequences set, and S is the number of training sequences. λ_N is pre-calculated before coding. Setting the Lagrange multiplier as λ_N for $\mathrm{I_d}$-slice does not increase the computational complexity of coding.

Let λ_P be the present Lagrange multiplier in JMVM8.8 (Vetro *et al*., 2008a), which adopts the traditional Lagrange multiplier selection method (Wiegand and Girod, 2001). PD is the percentage difference between λ_N and λ_P, which is defined as follows:

$$PD=\frac{\lambda_N(q)-\lambda_P(q)}{\lambda_P(q)}\times 100\%. \tag{10}$$

Table 1 lists λ_P, λ_N and PD for different QPs. The average PD is much more than 50%. For low bitrates and high bitrates, PD is up to 122.77% and 163.80% respectively, because the R-$\log_2 D$ curves of $\mathrm{I_d}$-slice are not linear. Especially at low and high bitrates, the globally approximate relationships in Eq.(4) are no longer appropriate and the Lagrange multiplier selection method using Eq.(6) is not optimal for $\mathrm{I_d}$-slice.

Table 1 Values of λ_P, λ_N and PD for QPs ranging from 0 to 51

QP	λ_P	λ_N	PD (%)	QP	λ_P	λ_N	PD (%)
0	0.0531	0.0705	32.7	26	21.589	40.846	89.2
1	0.0669	0.0868	29.8	27	27.200	49.585	82.3
2	0.0843	0.1560	85.1	28	34.270	66.895	95.2
3	0.1063	0.2117	99.2	29	43.177	86.268	99.8
4	0.1339	0.2718	103.0	30	54.400	111.52	105.0
5	0.1687	0.3355	98.9	31	68.540	145.30	112.0
6	0.2125	0.4271	101.0	32	86.355	174.43	102.0
7	0.2677	0.4337	62.0	33	108.80	238.27	119.0
8	0.3373	0.6011	78.2	34	137.08	315.28	130.0
9	0.4250	0.6549	54.1	35	172.71	417.96	142.0
10	0.5355	0.7631	42.5	36	217.60	546.18	151.0
11	0.6746	0.9222	36.7	37	274.16	655.24	139.0
12	0.8500	1.1917	40.2	38	345.42	884.28	156.0
13	1.0709	1.5100	41.0	39	435.20	1122.8	158.0
14	1.3493	1.8634	38.1	40	548.32	1436.6	162.0
15	1.7000	2.3239	36.7	41	690.84	1816.9	163.0
16	2.1419	2.8530	33.2	42	870.40	2228.2	156.0
17	2.6986	3.5595	31.9	43	1096.6	2774.4	153.0
18	3.4000	4.3656	28.4	44	1381.7	3399.0	146.0
19	4.2837	5.3760	25.5	45	1740.8	4265.0	145.0
20	5.3972	7.8044	44.6	46	2193.3	5527.1	152.0
21	6.8000	10.112	48.7	47	2763.3	6880.6	149.0
22	8.5675	13.674	59.6	48	3481.6	8286.2	138.0
23	10.794	18.177	68.4	49	4386.5	9474.8	116.0
24	13.600	23.596	73.5	50	5526.7	11164	102.0
25	17.135	31.237	82.3	51	6963.2	12603	81.2

EXPERIMENTAL RESULTS

Twelve test sequences with different camera mounting types and picture sizes were used for evaluation. Breakdancers and Ballet, provided by Microsoft Research (Zitnick *et al*., 2004), were in 1024×768 size at 15 frames/s. Ballroom, Exit, and Vassar, provided by Mitsubishi, were in 640×480 size at 30 frames/s. Race1, Objects1, Flamenco1 and Golf1, provided by KDDI, were in 320×240 size at 30 frames/s. Aquarium, X_MAS and Rena, provided by Tanimoto Lab, were in 640×480 size at 30 frames/s. Five sequences were used as training sequences to calculate λ_N: Objects1, Flamenco1, Golf1, Aquarium, and Breakdancers. Performances were tested using all 12 sequences. We compared the proposed method with the traditional method in JMVM8.0 using the following steps [here the traditional method means the Lagrange multiplier selection method in JMVM8.0 (Wiegand and Girod, 2001)]:

For each sequence, we chose the two middle views. The left view was encoded independently as the main view with H.264/AVC standard. The right view was compressed as the auxiliary view using both motion compensation and disparity compensation. Various block-size motion predictions and quarter-sample-accurate motion compensation technologies of H.264/AVC were also applied in disparity compensation along inter-view prediction. The MVC used the group of picture (GOP) structure shown in Fig.4. In the experiment, the encoding parameters were set as in Table 2.

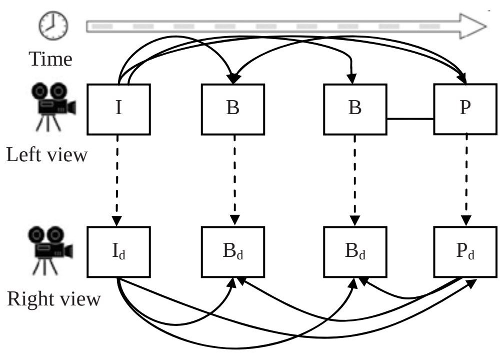

Fig.4 Group of picture (GOP) structure of the MVC

Table 2 Encoding parameters

Parameter	Value
RD optimization	On
Entropy coding method	CABAC
Loop filter	On
Motion search range	±32
Disparity search range (vertical)	±8
Disparity search range (horizontal)	±64
Period of I-frames	5

PSNR gains of the proposed Lagrange multipliers for I_d-slice on various sequences are shown in Table 3. The average *PSNR* gains of 10 *QP*s were calculated using Bjontegaard's method (Bjontegaard, 2001). The positive values mean that the proposed method outperforms the traditional Lagrange multiplier selection method in JMVM8.0.

The coding gains were significant at low bitrates and high bitrates. For example, the average coding gain was 2.317 dB for *QP* ranging from 40 to 51 on the sequence Race1, and 0.532 dB for *QP* ranging from 0 to 9 on the sequence Aquarium. Coding gains were achieved for each of the sequences. The average gain for all of the test sequences was 0.456 dB. The RD performances on test sequences are shown in Figs.5~7. Up to 2.5 dB gain was achieved on Race1 at the low bitrate of 100 kbps.

Table 3 *PSNR* gains of the proposed method

Sequence	*PSNR* gains (dB)					
	QP=0~9	10~19	20~29	30~39	40~51	0~51
Aquarium	0.532	0.038	0.031	0.349	0.832	0.356
Ballet	0.325	0.042	0.045	0.586	0.799	0.360
Ballroom	0.387	0.039	0.052	0.637	2.103	0.644
Breakdancers	0.397	0.039	0.023	0.434	1.207	0.420
Exit	0.322	0.025	0.037	0.410	1.055	0.370
Flamenco1	0.460	0.022	0.068	0.702	1.293	0.509
Golf1	0.061	0.031	0.089	0.296	0.954	0.286
Objects1	0.395	0.019	0.016	0.031	0.158	0.124
Race1	0.397	0.062	0.202	1.102	2.317	0.816
Rena	0.382	0.050	0.312	1.200	1.259	0.641
Vassar	0.431	0.050	0.097	0.905	1.585	0.614
X_MAS	0.052	0.046	0.178	0.610	0.756	0.328
Average	0.345	0.039	0.096	0.605	1.193	0.456

PSNR curves over the auxiliary view's first 60 frames on the sequence Race1 are shown in Fig.8. All of the auxiliary view's frames are coded as I_d-slice here. The average bitrate for the traditional method was 192 kbps, and the average bitrate for the proposed method was 185 kbps. The proposed method can achieve higher PSNR for all of the frames even at a slightly lower bitrate.

To further verify that the particular choice of λ provides good results in rate-distortion performance, the encoder was run with various Lagrange multipliers $\lambda\in\{\lambda_N(p), \lambda_P(p), 0.3\lambda_N(p), 0.5\lambda_N(p), 2\lambda_N(p), 3\lambda_N(p)\}$. For each multiplier, the sequence Breakdancers was encoded with *QP* from 0 to 51. The resulting rate-distortion points are depicted in Fig.9, where '+' indicates the rate-distortion point obtained when setting $\lambda=\lambda_N$, and '·' indicates the rate-distortion point obtained when setting $\lambda\in\{\lambda_P(p), 0.3\lambda_N(p), 0.5\lambda_N(p), 2\lambda_N(p), 3\lambda_N(p)\}$. The rate-distortion points obtained when setting $\lambda=\lambda_N$ are connected by a line. All the diamonds are below the line, confirming that setting $\lambda=\lambda_N$ gave the best results. Similar results could be obtained for other sequences.

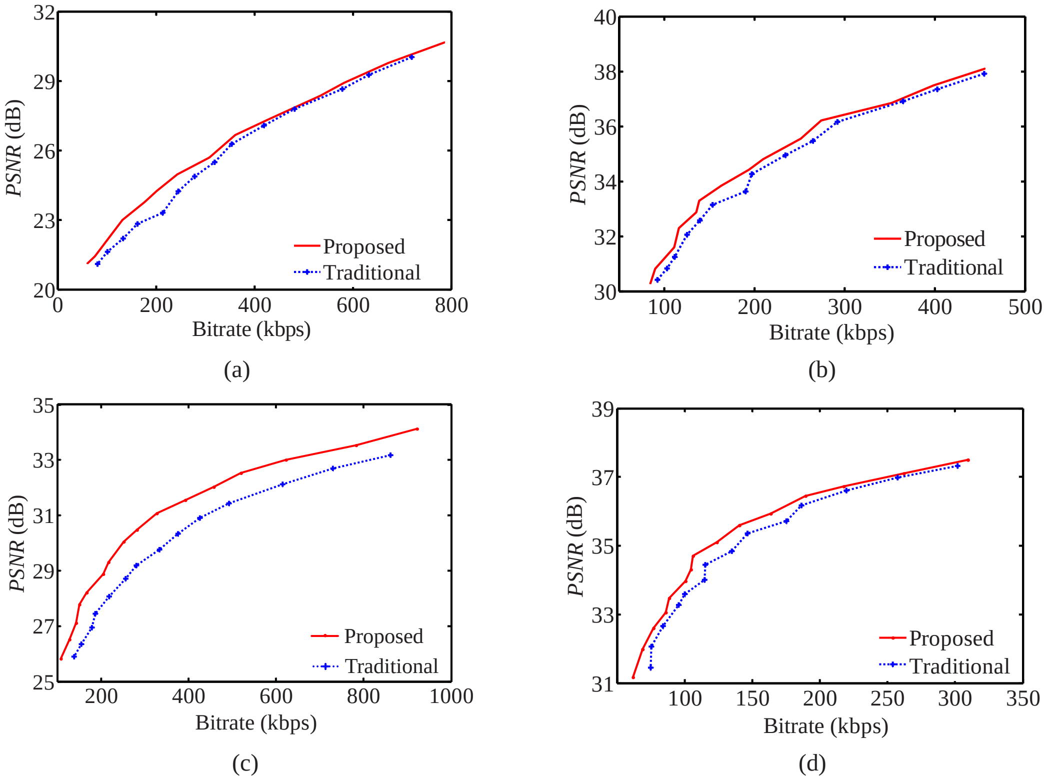

Fig.5 RD performances on test sequences Aquarium (a), Ballet (b), Ballroom (c), and Breakdancers (d)

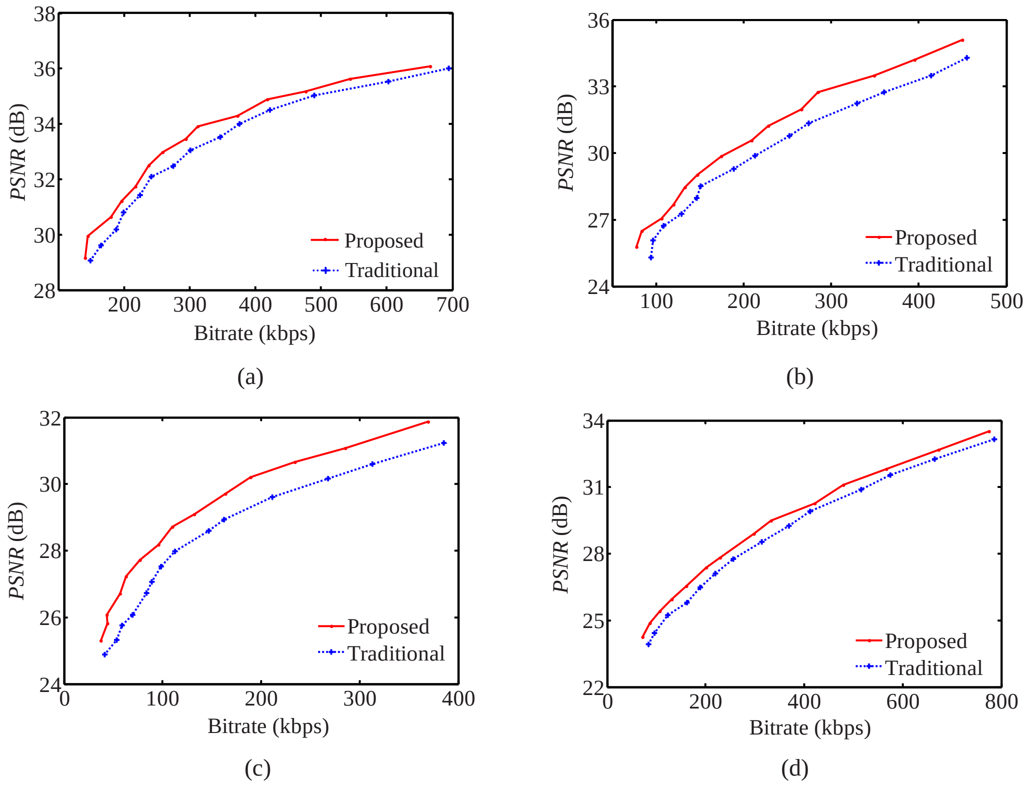

Fig.6 RD performances on test sequences Exit (a), Flamenco1 (b), Golf1 (c), and Objects1 (d)

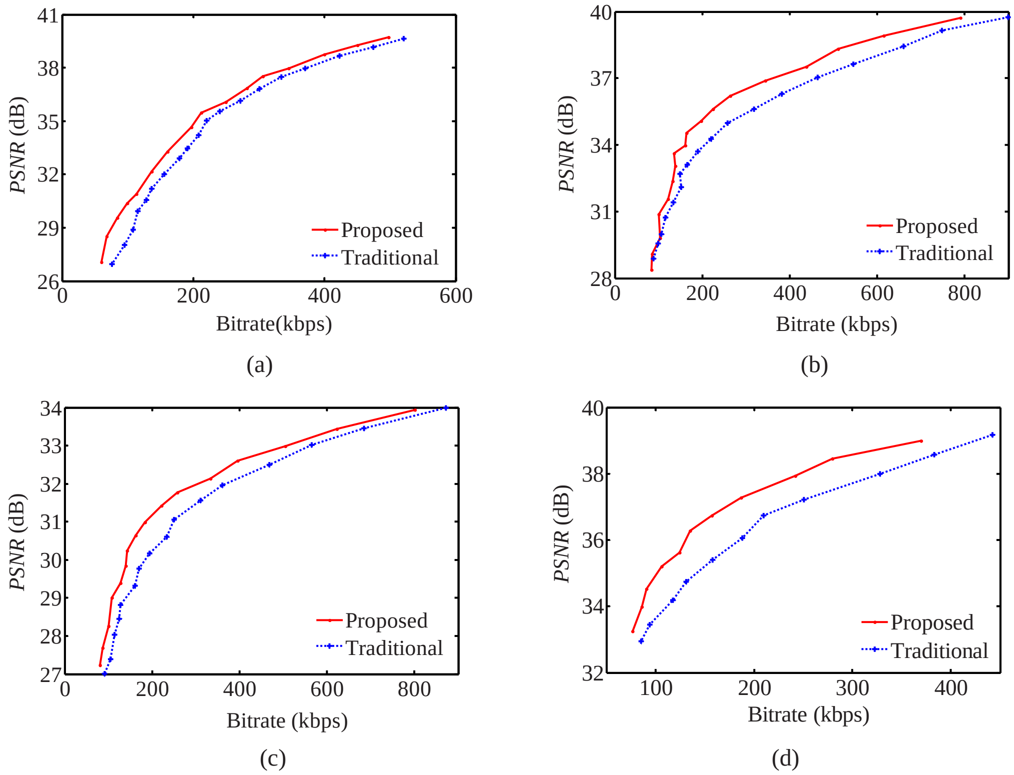

Fig.7 RD performances on test sequences Race1 (a), Rena (b), Vassar (c), and X_MAS (d)

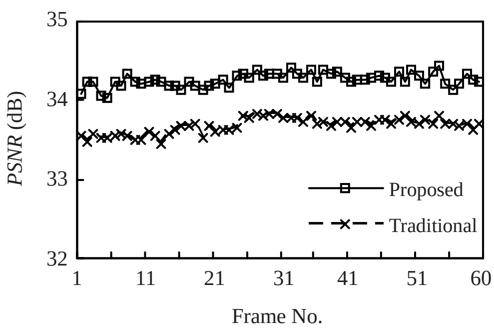

Fig.8 *PSNR* curves for the auxiliary view's frames 1~60 on Race1

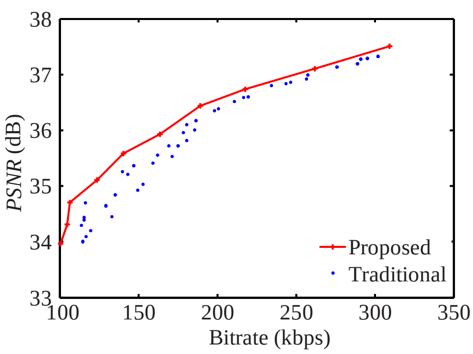

Fig.9 *PSNR* vs bitrate of I_d-slice on Breakdancers

CONCLUSION

A local curve fitting based Lagrange multiplier selection method is proposed for I_d-slice in MVC. The new fitting method can approximate the R-$\log_2 D$ curve more accurately and lead to a higher coding efficiency. Experimental results confirmed its efficiency. Coding gains were achieved for all the test sequences, especially at low and high bitrates. Up to 2.5 dB gain was achieved at low bitrates. The average improvement for the sequences was about 0.46 dB. The Lagrange multipliers are pre-calculated before coding. So replacing the original Lagrange multipliers with the Lagrange multipliers selected by the proposed method does not increase the computational complexity of coding.

In the future, the proposed method will be extended to Lagrange multiplier selection for P_d- and B_d-slice. The relationships among Lagrange multipliers for I-, P-, B-, I_d-, P_d-, and B_d-slice will be studied.

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