Two-Pass Rate Control for UHDTV Delivery with HEVC

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***Abstract*—Rate control has been regarded as an indispensable video coding tool for virtually any application involving video transmission. With the advent of many flexible tools introduced in the current state-of-the-art High Efficiency Video Coding (HEVC) standard, previous Rate-Distortion (RD) models used for rate control become insufficiently accurate. To overcome this issue, a new RD model has been recently proposed based on a robust correspondence between the rate and Lagrange multiplier λ. However, existing methods based on this model tend to perform sub-optimally after the scene change. In this paper, a two-pass rate control method is proposed, targeting Ultra High Definition Television (UHDTV) applications. In the first pass, a fast encoder with a reduced set of coding tools is used to obtain the data used for rate allocation and model parameter initialisation utilised during the second pass. Multiple encoding steps required to derive this information are avoided with the proposed variable quantisation parameter framework. Experimental evaluation showed that the proposed two-pass rate control method achieves on average 4.4% BD-rate loss, compared with variable bit-rate encoding. That significantly outperforms the state-of-the-art HEVC rate control method with an average BD-rate loss of 8.8%.**

***Index Terms*—Two-pass rate control, UHD video, HEVC**

I. Introduction

The new Ultra High Definition Television (UHDTV) format is expected to deliver a greater impact and more immersion than the current High Definition Television (HDTV). Among other parameters specified in the ITU Recommendation BT.2020 [1], two spatial resolutions of 3840×2160 and 7680×4320 luma samples per frame are standardised. Temporal resolutions for UHDTV can go up to 120 frames per second (fps) with progressive scanning only. It also allows 10- and 12-bit colour depth with wider colourimetry system. Such enormous volume of data associated with UHDTV signals calls for the improved compression efficiency when delivering UHDTV services. To answer these needs, the H.265/High Efficiency Video Coding (HEVC) standard [2] was developed as a result of a joint partnership between the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG). HEVC is the state-of-the-art video compression standard which can provide the same perceived video quality as its predecessor H.264/Advanced Video Coding (AVC) [3] for up to 60% bit-rate reduction when encoding UHDTV content [4].

Besides improving compression efficiency, a distribution of the available bit-budget which minimises the impact of coding artefacts is almost equally important. A rate control method aims to distribute the available bit-budget so that the visual quality of a sequence is optimised. It is usually divided into two main steps. In the first one, bits are allocated to each level of the encoding process, e.g. Structure Of Pictures (SOP), frame, or Coding Unit (CU) in HEVC. In the second step, the allocated rate is fitted into a Rate-Distortion (RD) model to derive the encoding parameters to be used when encoding a given part of the sequence. Depending on the application, rate control can be performed in single- or multi-pass manner. Single-pass rate control is usually employed in applications with real time or very low latency requirements. When using single-pass methods, the available rate is allocated and the encoding is tuned based on some *a priori* knowledge on the sequence statistics or data collected over previously encoded frames. Conversely, multi-pass rate control is usually employed in near real-time applications, where additional computational complexity can be tolerated. In multi-pass rate control methods, a given video segment is encoded multiple times with the results of one step used in the subsequent ones.

In this paper, a two-pass rate control method for streaming of UHDTV content encoded with HEVC is proposed. In the first pass, the algorithm performs a pre-encoding analysis with a low complexity encoder. To limit the number of coding points tested to derive the RD model parameters, a novel framework is proposed, which allows multiple quantisation steps within a frame. The information obtained is then used during the actual compression in the second pass. The proposed rate control method achieves improved performance compared to existing approaches, particularly after a scene change.

The remainder of this paper is organised as follows. Section II provides an overview of the state-of-the-art rate control methods with the emphasis on the methods developed in the context of HEVC standard. The proposed two-pass rate control is described in Section III, while its experimental evaluation is presented in Section IV. Finally, Section V concludes the paper.

II. Related Work

This section provides an overview of previous rate control methods. The existing RD models used for rate control are reviewed first, followed by multi-pass rate control methods. Finally, the rate control method used in HEVC reference software (HM) [5] is described.

A. RD Models Used for Rate Control

Rate control is one of the fundamental tools in any practical video codec application. Early attempts in modeling the relationship between coding rate and Quantisation Parameter (QP) date back to the MPEG-2 Video [6] and MPEG-4 Part 2 (Visual) [7] standards. The reference implementation of the AVC standard uses a rate control method based on a quadratic Rate-Quantisation (R-Q) relationship [8], with the assumption of Laplacian distribution of the residual information [9]. Based on the quadratic R-Q model, Choi *et al.* proposed a rate control method [10] used in early versions of HM [5]. However, due to the flexible quadtree partitioning used in HEVC, the R-Q model is not sufficiently accurate to quantify the relationship between rate and quantisation step.

Another group of rate control methods tries to build a relationship between the rate and the percentage (ρ) of coefficients which are quantised to zero [11]. A quadratic ρ-domain rate model was proposed by Wang *et al.* [12] and used in a hierarchical bit-allocation scheme for rate control in an HEVC codec. Rate control algorithms based on the ρ-domain relationship work well in fixed transform size coding schemes. Nonetheless, in video coding standards such as HEVC, which specify variable sizes for transform blocks, the relationship between ρ and rate is not sufficiently accurate.

The relation between Lagrange multiplier λ and coding rate was firstly analysed by Li *et al.* [13]. The proposed hyperbolic R-λ model shows higher correlation when compared with the aforementioned RD models. The R-λ model is utilised in the rate control method used in HM, where the bit-budget is allocated at three different levels of granularity. This rate control method was further improved for intra frames [14] using the Sum of Absolute Transformed Differences (SATD) as a complexity measure. Finally, Wang and Ngan [15] proposed a method which uses the distortion of collocated Coding Tree Units (CTUs) in the previous frame for a different bit-allocation algorithm in λ-domain.

B. Multi-Pass Rate Control Methods

Despite parallel architectures are becoming prevalent, not many multi-pass rate control methods have been proposed in the literature. In the x264 software [16], five different rate control modes are specified. Apart from a two-pass approach, where the target number of bits is predicted based on the frame complexity from full encoding in the first pass, one-pass approaches with fast complexity estimation scheme are also available. In this case, a fast Motion Estimation (ME) algorithm is performed over a half-resolution version of the frame and SATD of the residuals is used as a complexity measure.

In the context of HEVC, Wen *et al.* [17] proposed a rate control method based on R-λ model with pre-encoding. In the pre-encoding step, the video sequence is encoded using only 16×16 CUs. The coding rate for the CUs of size 64×64 is then estimated using the rate associated with 16×16 CUs. R-λ model parameters, as well as weights for CU bit-allocation, are computed using the data from pre-encoding. A mechanism for handling cases when the scene change leads to the existing model parameters becoming obsolete is also proposed. Another two-pass rate control method for HEVC was proposed by Wang *et al.* [18]. Coding statistics collected during the first pass using a constant QP are used in the second pass for SOP level bit-allocation. Then, Laplacian-based rate and perceptual distortion models are established to adaptively derive λ and dynamically allocate bits. A multi-pass rate control method [19] was proposed based on the SATD of the residuals and pre-encoding. Pre-encoding is performed multiple times using different QP values and a limited set of depths and PU modes to obtain rate, distortion, and SATD data which is fitted into the SATD-RD model using the least squares method. Estimated data is then used to set the parameters used in rate control. It should be noted that latter two methods may be of limited use in practical applications with low latency requirements, due to the computationally costly pre-encoding steps.

C. Rate Control in the HEVC Reference Implementation

The existing rate control method used in HM is based on the recently proposed R-λ model [13]. It was shown that there exists a robust relation between the rate R (in bits per pixel) and the Lagrange multiplier λ which can be expressed with a hyperbolic function:

$$R = a \cdot \lambda^b, \tag{1}$$

where parameters a and b are related to the video source. Due to its enhanced accuracy and robustness, the rate control method based on the R-λ model defined in (1) has been included in the HM since Version 9.0. The algorithm can be divided in two parts: bit-allocation and actual encoding using the R-λ model. Bit-allocation is performed at three different levels, namely SOP, frame, and CTU level. When allocating bits at a frame level, the frame weights are assigned according to its position in the SOP. Throughout this paper, the encoding denoted as Variable Bit-Rate (VBR) will correspond to encoding each frame with a QP value determined by its position in the SOP. At CTU level, the weights to allocate the available bit-budget are calculated dynamically using the prediction error from a collocated CTU in the previously coded frames of the same temporal layer.

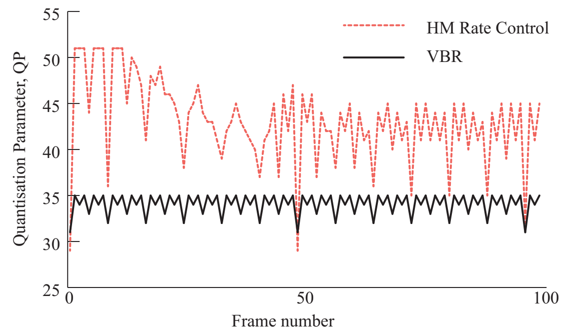

Fig. 1. QP values for the first 100 frames of the *Somersault* test sequence which correspond to the rate obtained with QP value 31 for VBR. QP values associated with VBR encoding are denoted with black, while QP values used by the rate control in HM are depicted with a red dotted line.

Once the target rate is determined, it is straightforward to compute λ using the inverse of relation (1):

$$\lambda = \alpha \cdot R^{\beta}, \tag{2}$$

with α and β being the model parameters. However, the main issue is how to determine the parameters α and β, which are generally content dependent. Furthermore, in case of random access SOP structure, different temporal layers may have different model parameters, and hence multiple sets of parameters have to be used within the sequence. In the existing approach, the corresponding α and β are continuously updated after encoding one CTU or one frame. Ultimately, the QP value is determined as:

$$QP = c_1 \cdot \ln(\lambda) + c_2, \tag{3}$$

where c_1 and c_2 are set to 4.2005 and 13.7122, respectively. Finally, for consistent video quality, both λ and QP are bounded to a range centred around the values from previously encoded frames and CTUs.

III. Proposed Rate Control Method

When encoding a sequence with the existing rate control method in HM, sub-optimal performance was observed, especially after a scene change. This results in high QP values used after the shot change, as shown in Figure 1. In our previous study on rate control in HEVC [20], an analysis was carried out which proved that the encoding efficiency can be improved with the new frame-level rate allocation obtained from pre-encoding and model parameter initialisation after fitting the data from pre-encoding.

Based on these findings, a two-pass rate control method with pre-analysis is proposed here. A computationally light encoder which allows variable QP values within a frame is used during the pre-analysis step. The information collected during the pre-encoding step is used to bypass the existing frame level bit-allocation and parameter initialisation. A fast HEVC encoder implementation based on HM Version 12.0 denoted as *HM-fast* and described in [21] has been used as a basis for the implementation of the proposed method.

A. Bit-Rate Profile Analyser for Pre-Encoding Step

During pre-encoding, a rate control method encodes a given video segment (e.g. one SOP or one intra period) and uses the coding rate to derive the number of bits spent in each frame. Having this information would allow the rate allocation stage to distribute the bit-budget accordingly, where the higher the rate spent on a frame, the more bits allocated to it. This pre-encoding step is performed in VBR mode and, ideally, the encoder should test all possible coding modes that would be tested during the actual encoding to obtain a bit-rate profile which is as accurate as possible. However, by doing so, the introduced complexity can be prohibitive, even for applications without real time constraints and running on parallel computing architectures. One may be also tempted to re-use the coding modes derived during pre-encoding for actual compression to speed up the whole process. However, given that those modes where derived for a fixed quantisation step, i.e. a fixed Lagrange multiplier, they may be sub-optimal when a different QP is selected by the rate control method. Therefore, the coding modes used during pre-encoding can be only partially re-used and the aforementioned claim on computational complexity needs to be carefully addressed.

In the proposed rate control method, a simplified version of *HM-fast* is used. To derive this simplified encoder, the workload associated with *HM-fast* was profiled to identify the most demanding parts in terms of computational complexity. Figure 2 (a) shows the percentage of encoding time spent on testing different CU depths for all sequences belonging to the test material. It can be seen that the most encoding time is spent while testing CUs at depth 0. Hence, testing of depth 0 may be considered as the most important among all the available depths. Figure 2 (b) shows the distribution of prediction tasks for CUs at depth 0 for all sequences belonging to the test set. It can be seen that fractional precision ME is the most time consuming inter prediction module. That is followed by integer precision ME and bi-prediction. However, it should be noted that some tasks, such as integer precision ME, are critical and cannot be removed without greatly affecting the encoding process.

From this profiling, a configuration for the simplified encoder has been defined and hereafter denoted *SE*. In *SE*, the size for each CU is set to 64×64, fractional precision (i.e. half- and quarter-pel) and bi-directional motion estimation are disabled. The overall encoding time is reduced almost 4 times for considerable drop in coding efficiency. However, as stated above, the ultimate goal of the pre-encoding stage is to derive the profile on how the coding rate is spent in relative terms. To measure how accurate the profile derived by *SE* is, the Pearson correlation coefficient was measured on a frame basis between the coding rate spent by *HM-fast* and *SE*. Table I shows these correlation coefficients for different SOP layers.

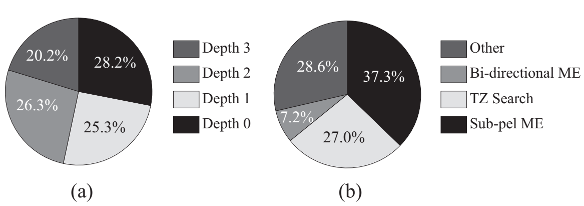

Fig. 2. *HM-fast* encoder profiling: (a) percentage of encoding time spent on each CU depth and (b) percentage of time spent in each module for depth 0.

TABLE I
PEARSON'S CORRELATION ON CODING RATES OF HM-FAST AND SE WITH ASSOCIATED MODEL PARAMETERS FOR DIFFERENT TEMPORAL LAYERS.

SOP temporal layer	P	k	l
Intra	0.9841	0.3986	1.0576
0	0.9578	1.1785	0.9722
1	0.9559	0.8126	0.9822
2	0.9670	1.2695	0.9421
3	0.9604	1.8709	0.9011

As may be noted, the correlation coefficient is fairly high for all temporal layers. This confirms the validity of using the rate obtained from *SE* to estimate the actual rate in unconstrained VBR mode.

Even though good correlation values are obtained for *SE*, the rate spent by *SE* (R_{SE}) is on a different scale with respect to the one spent by *HM-fast* (R_{orig}). The reason for this resides in the limited number of coding modes tested by the simplified encoder. To correct the rate values obtained by *SE*, the hyperbolic model was used:

$$R_{orig} = k \cdot R_{SE}^{l}, \tag{4}$$

where k and l are model parameters. It should be noted that different parameter values were used for frames at different temporal layers as shown in Table I. These parameters were derived by performing the least squares fitting on frame data from the test material. The weights for R_{orig} within one intra period are then calculated and used for SOP and frame level bit-allocation. However, in order to initialise the α and β parameters for the R-λ model (2) used to derive the QP for each coding block, some additional pre-encoding steps would be required to fit the R-λ curve resulting in increased computational complexity. The next subsection will describe how the proposed rate control method addresses this issue by performing bit-rate profile and model parameters estimation in one pre-encoding step.

B. Pre-Encoding with Variable QP Within Frame

As demonstrated in our previous work [20], initialising the R-λ model parameters on a per sequence and QP basis leads to improved coding performance of the rate control method. However, in practical applications, it is not feasible to encode a sequence with multiple different QP values in order to fit the R-λ model. This section describes the proposed Variable QP (VQP) framework designed to reduce the computational complexity associated with the pre-encoding phase in rate control.

The main idea of VQP is to encode different CTUs in a frame with different QP values. After the encoding is completed, the coding rate R can be measured over the group of CTUs sharing the same QP value. Over the same group, the value for λ is computed using the inverse of (3). By collecting the pairs (R, λ) for all tested QP values, the curve defined in (2) can be fitted so that parameters α and β can be obtained. After the parameters α and β are available, the actual encoding can be performed. It should be noted that the described VQP is not an additional step performed during pre-encoding but it is a framework applied during the bit-rate profile analysis described in Section III-A. Therefore, no additional processing is required.

Apart from using the VQP to derive the right R-λ model parameters, it can also be used for the decision on the initial QP value for the first intra frame and the pre-encoding stage. In fact, once the R-λ model for the video segment under analysis is available, the target rate value is used to derive the associated λ and QP value using (2) and (3), respectively. The QP value derived is then used during the bit-rate profile analysis as well as for the first intra frame.

The main assumption behind the proposed VQP method, is that CTUs sharing the same QP value are representative of the overall

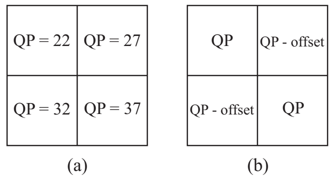

Fig. 3. Variable QP pattern used within a frame for (a) intra frames, (b) inter frames. Each square represents one CTU.

statistics associated with the content. To guarantee this, appropriate sampling of the available coding units should be performed. In this paper, two sampling patterns are defined for intra- and inter-coded frames as depicted in Figure 3, where each square represents one CTU. Given that the sampling pattern is regular, each QP value will have associated CTUs coming from different image areas. By considering all tested QP values, the derived points on the R-λ model would allow for a more accurate fitting rather than if the points were derived from CTU referring to particular image areas. For intra-coded frames, the four values in Figure 3 (a) are the same as suggested in [22], while in Figure 3 (b) the offset value is set equal to 2. The reason for using two different patterns in intra and inter frames is because the former is used to derive the initial QP, so a wider R-λ curve is needed, while the latter allows statistics to be collected while not interfering significantly with motion estimation and compensation operated by SE.

C. Overall Two-Pass Rate Control Algorithm

The overall proposed two-pass rate control method is summarised in the pseudo code of Algorithm 1. As stated above, there are two main processing steps involved: pre-encoding with the proposed VQP and encoding with the results gathered from the first step. The pre-encoding stage introduces a delay which can be minimised using multi-threading with one thread dedicated to pre-encoding so that only one intra period delay (i.e. roughly 1 second) is introduced.

Algorithm 1 Processing for the proposed rate control algorithm.

Require: Target bit-rate $\bar{R}$

1: Encode the first frame of the video sequence with the VQP pattern in Figure 3 (a)
2: Collect the coding rate R_{QP} and compute the associated λ for each QP value tested in the VQP pattern
3: Fit the $R-\lambda$ curve and set the average rate for the first intra picture $\bar{R}_I$ to $\bar{R}/F \times 6$, where F is the frame rate of a sequence
4: Derive the initial QP, QP_{ini} using (2) and (3), and $\bar{R}_I$
5: **for all** intra periods in the sequence **do**
6: Encode the current intra period IP with the simplified encoder *SE1*, encode the intra frame with fixed QP_{ini} and encode the remaining inter frames with the VQP pattern in Figure 3 (b), where QP is determined based on SOP temporal layer of a frame
7: Collect the coding rate R_I for the first intra frame
8: Set $r_2 = \frac{R_{IP}}{R_I}$ as the ratio between the number of bits obtained for the intra period and intra frame
9: Adjust the rate for the intra frame as $R_I \leftarrow R_I \times r_2$ and recompute QP_{ini} using the $R-\lambda$ curve derived in Step 3
10: For each frame in IP adjust the allocated bit-budget according to the bit-rate profile derived from the simplified encoder
11: Derive parameters α and β for the model in (2) from the data associated with the tested QP values in the VQP pattern in Figure 3 (b)
12: Run actual encoding using the data for rate control derived in the previous steps
13: **end for**

IV. Experimental Results

The experimental evaluation of the proposed two-pass rate control method is presented in this section. All the results presented here were obtained using the implementation based on the *HM-fast* codec [21] run in VBR mode as an anchor. The *HM-fast* encoder was developed as a fast HEVC optimisation specifically tailored for encoding of UHDTV content. The target rate values fed as input to the proposed rate control algorithm will be therefore the ones associated with *HM-fast* run in VBR mode. The test set used in this paper is composed of 16 sequences with 8 bits per component, 4:2:0 chroma format, 3840×2160 spatial resolution and frame rate of 50 and 60 fps. The name of these sequences, along with the type of content portrayed are listed in Table II. Each sequence is coded with four QP values. They have been determined by visually inspecting the test set compressed with QP ranging from 22 to 45, to determine a good coverage of different visual quality levels: from very good (i.e. coding artifacts unnoticeable) to fairly poor (i.e. coding artifacts visible and annoying). All the sequences have been encoded according to the JCT-VC Common Test Conditions (CTC) [22] using the aforementioned QP values and the Random Access Main (RA-Main) configuration, as this is representative of the encoding settings used in broadcasting services. All the tests were run on a Linux cluster of Intel Xeon X3450 machines with 2.67 GHz clock frequency and 8 GB of RAM.

Compression efficiency and rate inaccuracy are used as performance metrics. For compression efficiency, the metric used is the Bjøntegaard Delta-rate (BD-rate) [23] computed between the anchor data and the sequences compressed according to the described experiments. In this context, negative BD-rate values correspond to compression efficiency gains. Given the use of 4:2:0 chroma format, only the BD-rate for the luminance component is considered. The rate inaccuracy is measured as an absolute percentage deviation from the target rate. Lower values correspond to higher rate accuracy.

Table III shows the experimental results for the proposed two-pass rate control method. When compared to the VBR encoding mode, the proposed rate control method (*SE RC with param. init.*) achieves an average BD-rate coding penalty of 4.4% with 0.3% rate inaccuracy for 10 second sequences. This compares favourably with the state-of-the-art HEVC rate control (*HM RC*) method which provides on average 8.8% BD-rate losses with 0.3% rate inaccuracy. Note that the rate control method where only the SOP and frame level bit-allocation are replaced with rate prediction obtained from pre-encoding with SE (*SE RC*) also outperforms the state-of-the-art HEVC rate control by obtaining 5.5% BD-rate losses with 0.3% rate inaccuracy. It

TABLE II
Test material description.

Sequence name	Fps	Type	Sequence name	Fps	Type
ParkAndBuildings	50	outdoor	TableCar	50	objects
NingyoPompoms	50	objects	TapeBlackRed	60	sport
ShowDrummer1	60	drama	Hurdles	50	sport
Sedof	60	outdoor	LongJump	50	sport
Petitbato	60	outdoor	Discus	50	sport
Manege	60	outdoor	Somersault	50	sport
ParkDancers	50	outdoor	Boxing	50	sport
CandleSmoke	50	drama	Netball	50	sport

TABLE III
BD-RATES (BD-R) AND RATE INACCURACY (I) RESULTS.

Sequence	*HM RC*		*SE RC*		*SE RC with param. init.*	
	BD-R [%]	I [%]	BD-R [%]	I [%]	BD-R [%]	I [%]
ParkAndBuildings	4.2	1.3	6.8	0.3	4.6	0.4
NingyoPompoms	6.5	0.0	4.1	0.0	5.1	0.0
ShowDrummer1	23.4	0.0	11.4	0.1	9.5	0.1
Sedof	3.9	0.0	7.7	0.2	5.8	0.2
Petitbato	8.8	0.1	−0.4	0.0	−1.2	0.1
Manege	1.4	0.0	11.0	0.0	9.2	0.0
ParkDancers	5.0	1.1	2.5	1.3	2.4	1.7
CandleSmoke	16.2	0.0	8.4	0.5	6.9	0.4
TableCar	8.2	1.8	1.9	1.1	−0.1	1.4
TapeBlackRed	13.6	0.2	4.7	0.5	4.2	0.3
Hurdles	8.9	0.1	8.6	0.0	9.0	0.0
LongJump	5.0	0.0	5.2	0.0	3.8	0.0
Discus	4.1	0.0	2.1	0.0	1.5	0.0
Somersault	21.9	0.0	8.8	0.0	4.4	0.0
Boxing	6.5	0.0	2.7	0.0	3.2	0.0
Netball	4.1	0.0	2.2	0.0	2.1	0.0
Average	8.8	0.3	5.5	0.3	4.4	0.3

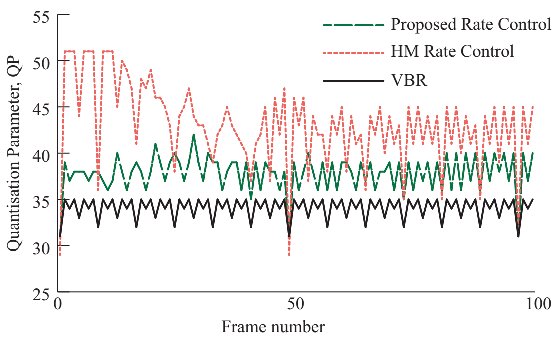

Fig. 4. QP values for the first 100 frames of the *Somersault* test sequence which correspond to the rate obtained with QP value 31 for VBR.

should be noted that the proposed methods achieve considerably lower encoding efficiency losses, while at the same time preserving the very high accuracy. Also, the second pass of the proposed method does not increase the overall computational complexity.

The proposed method also performs considerably better when compared to the existing methods at the beginning of a sequence. Figure 4 shows the comparison of QP values used at the beginning of the sequence between the existing and the proposed rate control method. It can be seen that QP values used by the proposed method are considerably lower, and generally correlate more with QP values from the VBR encoding mode.

V. CONCLUSIONS

Rate control in video coding aims to optimise the bit distribution to achieve the highest possible video quality for a given bandwidth constraint. However, in many practical applications with frequent scene changes, the existing rate control methods for HEVC perform sub-optimally, resulting in degraded visual quality after a scene change. A two-pass rate control method is proposed in this paper where a simplified encoder is used in the pre-encoding stage to obtain the bit-rate profile for each intra period. A variable QP framework is proposed to avoid encoding a sequence multiple times for tuning the model parameters. When compared with variable bit-rate encoding mode, the proposed two-pass rate control method achieves on average lower compression losses, 4.4% BD-rate losses compared to 8.8% BD-rate losses for the state-of-the-art HEVC rate control method.

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