A RATE CONTROL ALGORITHM FOR HEVC WITH HIERARCHICAL GOP STRUCTURES

Sergio Sanz-Rodríguez, Thomas Schierl

Multimedia Communications, Fraunhofer HHI, Berlin, Germany.

ABSTRACT

In this paper a buffer-constrained *rate control* (RC) algorithm for High Efficiency Video Coding (HEVC) with hierarchical group of pictures structures is proposed. Specifically, a *quantization parameter* (QP) cascading approach, which the QP value is increased from one temporal layer to the next, is employed to achieve high coding efficiency while maintaining the buffer fullness at secure levels. When compared to the current state-of-the-art RC algorithm, the experimental results show that our proposal achieves a slightly better rate-distortion performance and a remarkably better buffer control with an acceptable increase in computational complexity.

***Index Terms*—** High Efficiency Video Coding (HEVC), hierarchical video coding, rate control, quantization parameter cascading.

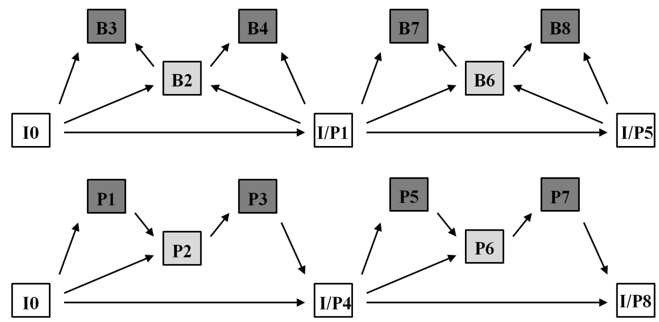

Fig. 1. Hierarchical IB...BP (top) and hierarchical IP...PP (bottom).

1. INTRODUCTION

Hierarchical coding patterns have been adopted by the High Efficiency Video Coding (HEVC) standard as they have been shown to improve compression efficiency compared to classical coding patterns [1, 2]. Particularly, in hierarchical coding the pictures inside a *group of pictures* (GOP) are split up into temporal levels, with the length of the GOP as the distance between two pictures belonging to the lowest temporal level, which are *key* (K) pictures. These pictures can be either I-coded (to allow random access points) or P-coded by referring to pictures belonging to the same temporal level, whereas the remaining pictures are P or B-coded from references belonging to lower temporal levels as illustrated in Fig. 1 for two well-known GOP structures: hierarchical IB...BP and hierarchical IP...PP. Additionally, as already stated in [3], in hierarchical IP...PP a picture can be referred to the most recent encoded picture to also allow for a short-distance reference and, thus, improve the motion-compensated prediction especially in high motion video sequences.

For providing high coding efficiency in hierarchical GOP structures, several non-normative temporal level dependent *quantization parameter* (QP) setting strategies have been proposed in the literature: Within the H.264/Advanced Video Coding (AVC) and Scalable Video Coding (SVC) frameworks, some simple *QP cascading* (QPC) algorithms were proved to be reasonably robust for a wide range of tested video sequences, but not as efficient as that proposed in [2] describing a content-dependent approach for QP selection. In HEVC, a simple QPC method has been adopted by the Joint Collaborative Team on Video Coding (JCTVC) as default QP setting in the HEVC test model (HM) reference software [4], but in [5] those QP values are further recomputed for the sake of *rate-distortion* (R-D) performance. Naturally, the objective behind these QPC methods is to increase the QP value from one temporal level to the next in order to provide high-fidelity reference pictures for efficient motion-compensated prediction and, even if they may result in large quality fluctuations, the subjective quality is not adversely affected [1].

Nevertheless, in a video transmission application these QP setting methods becomes impractical in most cases, since they do not guarantee the constraints imposed by the *hypothetical reference decoder* (HRD) [6], which is virtually connected to the output of the video encoder, for bit stream conformance[1]. In order to provide deliverable bit streams, a *rate control* (RC) algorithm must be embedded into the encoder. The objective of the RC algorithm is the regulation of some encoder parameters (typically the QP) affecting the bit rate so that the average bit rate of compressed video meets a specific target bit rate without exceeding the HRD constraints, while minimizing the distortion of reconstructed video. For this purpose, a target bit budget is allocated to a video segment and, subsequently, a suitable QP value is derived from *rate-quantization* (R-Q) modeling.

The RC problem for hierarchical GOP structures has been studied extensively in H.264/AVC and SVC (the reader can be referred to [7] and [8] for details), but only a few RC algorithms have been proposed for the HEVC standard, of which those described in [9] and [10] are highlighted. Specifically, the algorithm proposed by Li *et al* in [10], in which a novel R-*Lagrange multiplier* (λ) model for bit rate regulation is presented, has been adopted by the JCTVC as the new reference RC algorithm in [4]. Nevertheless, although a noticable better R-D performance is achieved in comparison with its predecessor [9], the HRD constraints are not taken into account for a proper transmission and decoding of compressed video.

In this paper we propose an RC algorithm for hierarchical HEVC with HRD constraints. In particular, the proposed rate controller focuses on ensuring QPC for coding efficiency maximization, as long as the buffer occupancy is not close to underflow or overflow.

The rest of this paper is organized as follows. In Section 2 a brief description of the state-of-the-art RC algorithm in [10] is provided. In Section 3 the proposed RC algorithm is described in detail. In Section 4 the method we use for λ computation is given. In Section 5 both experimental results are reported and discussed, to end up with some conclusions and future work in Section 6.

[1]A bit stream complying with the HRD constraints entails that both the encoder buffer, which is required to transmit at the specified target bit rate, and the decoder buffer, which performs the opposite buffering process for a subsequent decoding and play out, will not incur in underflow and overflow.

2. REFERENCE RATE CONTROL ALGORITHM [10]

Assuming that the bit rate is more sensitive to λ than QP, Li *et al* [10] propose an R-λ model for rate-controlled HEVC. Specifically, the well-known Cauchy-density-based R-D function for transform coefficient modeling [11] is deployed to estimate, from the bit budget targeted to a video segment, the required λ value for R-D optimization [12], and then a simple λ-QP mapping function [5] is employed for final QP computation.

Owing to its excellent coding performance under bit rate constraints, this algorithm actually constitutes the current state of the art in RC for HEVC and, therefore, a benchmark for comparison purposes. Nevertheless, it also deserves some critical comments concerning the frame bit allocation method, QP estimation and HRD consideration that will be discussed in detail in Section 5.

3. PROPOSED RATE CONTROL ALGORITHM

In the following subsections we describe the proposed rate controller, which operates on three layers: *intra period* (IP) *layer*, *picture layer*, and *coding tree block* (CTB) *layer*. However, for the sake of conciseness, some expressions commonly used in RC will not be included, but the reader is referred to [13] to find them.

3.1. Intra Period Layer

IP is defined in hierarchical video coding as the distance between two consecutive I pictures and it can be composed of either one or several GOPs. If we assume that the j picture within an IP is to be encoded, in this layer the amount of target bits for the remaining pictures in the IP, Br_j, is computed.

3.2. Picture Layer

In this layer a QP value, QP_j, for the current picture is estimated. For this purpose, the following four stages are conducted: *bit allocation*, *QP estimation*, *QP-cascading-based clipping*, *buffer underflow and overflow prevention*, and *parameter updating*. These stages are described in the sequel.

3.2.1. Bit Allocation

The target frame bit budget is computed in this stage as:

$$T_j = \begin{cases} \widehat{T}_j, & \text{if I picture} \\ (1-\beta)\widetilde{T}_j + \beta\widehat{T}_j, & \text{otherwise,} \end{cases} \tag{1}$$

The term $\widehat{T}_j$ stands for a hierarchy-based bit allocation that aims to properly distribute Br_j among the rest of pictures in the IP, i.e.,

$$\widehat{T}_j = \frac{\widetilde{X}_{I/l,j}}{\widetilde{X}_{I,j} Nr_{I,j} + \sum_{u=0}^{N_L-1} \widetilde{X}_{u,j} Nr_{u,j}} \left(Br_j - \widetilde{Hr}_j\right) + \widetilde{h}_{I/l,j}, \tag{2}$$

where $\widetilde{X}_{I/u,j}$ denotes a prediction of the coding complexity, in terms of product of texture bits (i.e., the bits used to encode the transform coefficients) and quantization step, for the current intra picture/inter picture at temporal level u. This complexity measurement is updated by means of exponential average with a forgetting factor set to 0.5 in our experiments. $Nr_{I/u,j}$ is the number of remaining intra pictures/inter pictures at level u in the IP. N_L denotes the number of temporal levels. $\widetilde{h}_{I/l,j}$ is a prediction of the header bits for the current intra picture/inter picture at level l, which is also updated by means of exponential average with a forgetting factor fixed to 0.5 in our experiments. And $\widetilde{Hr}_j$ represents a prediction of the header bits for the remaining pictures in the IP.

The term $\widetilde{T}_j$ watches over the buffer status by measuring the difference between the current fullness, V_j, and a prediction of the fullness after encoding the picture, $\widetilde{V}_{j+1}$, i.e.,

$$\widetilde{T}_i(j) = \frac{R_T}{f} + \delta\big(\widetilde{V}_{j+1} - V_j\big), \tag{3}$$

being R_T the target bit rate, f the frame rate, and δ a convergence factor that is set to 0.5 in our experiments to provide a good trade-off between QP fluctuation and target buffer level adaptation. Since this term for frame bit budget calculation is very useful for those applications requiring a tight buffer control, the factor that weights both bit allocation methods, β, is set to 0.75 for *low delay* (LD) coding and 1 for *random access* (RA) coding in our experiments.

Finally, in order to satisfy the HRD constraints, T_j is upper and lower bounded.

3.2.2. QP Estimation

The QP value is estimated by means of the Cauchy-density-based R-Q function stated in [11], i.e.,

$$R = aQ^{-\alpha}, \tag{4}$$

where R is the bit rate in terms of target texture bits, $T_j - \widetilde{h}_{I/l,j}$, Q is the quantization step value associated with QP_j, and $\{a, \alpha\}$ are the model parameters whose values depend on the hierarchy level (due to the R-D differences between temporal levels) and, besides, on the picture type for the lowest temporal level (see Subsection 3.2.5).

3.2.3. QP-Cascading-Based Clipping

Generally, when using analytical R-Q modeling for rate-controlled video coding, the estimated QP value is restricted in a small range in order to ensure quality consistency. Particularly, in this paper we propose a novel QPC-based clipping method that also attempts to maximize the coding efficiency.

For *non-K pictures* ($l > 0$), the QP value derived from Eq. (4) is bounded as follows:

$$QP_j = \min\left[QP_{REF,l>0} + 2, \max\left[QP_{REF,l>0} - 2, QP_j\right]\right], \tag{5}$$

being $QP_{REF,l>0}$ a reference QP at level l that is computed by means of the following expresion that is based on the default QP setting in [4]:

$$QP_{REF,l>0} = QP_K + l + (K\ pic = I\text{–}type?1:0), \tag{6}$$

where QP_K is the QP value used to encode the last K picture. It is worth noticing that Eq. (6) might be replaced by another QPC-based approach to be proved more efficent in terms of R-D performance. Afterwards, QP_j is bounded with respect to $QP_{LST,l' \neq l}$, the QP value used to encode the last picture belonging to a temporal level l' different to the current one l, specifically:

$$QP_j = \begin{cases} \max\left[QP_{LST,l' \neq l}, QP_j\right], & \text{if } l' < l \\ \min\left[QP_{LST,l' \neq l}, QP_j\right], & \text{if } l' > l. \end{cases} \tag{7}$$

For *K pictures*, the estimated QP value is limited as follows:

$$QP_j = \min\big[QP_{LST,l' \neq l} + \Delta + 2, \cdots \tag{8}$$

$$\max\big[QP_{LST,l' \neq l} + \Delta - 2, QP_j\big]\big], \tag{9}$$

where Δ is a target QP range for the GOP that is computed as the difference between the actual QP_j (from Eq. (7)) and $QP_{REF,l=L-1}$ (from Eq. (6)) if QP_K was set to QP_j.

3.2.4. *Buffer Underflow and Overflow Prevention*

In order to reduce the underflow and overflow risk in the encoder buffer, QP_j can be modified as follows:

$$QP_j = \begin{cases} QP_j - 1, & \text{if } V_j \leq 2\times\frac{R_T}{f} \\ QP_j + 4, & \text{if } V_j \geq 0.8\times BS, \end{cases} \tag{10}$$

where BS denotes the buffer size. Finally, QP_j is bounded by the maximum and minimum values allowed in HEVC.

3.2.5. *Parameter Updating*

Once the current picture at level l has been encoded, the model parameters for that level, a_l and α_l (the subindex l is included to specify the hierarchy level dependence), are updated. On the one hand, the updating expression for a_l obeys:

$$a_{l,j+J} = \begin{cases} t_j Q_j^{\alpha_l}, & \text{if I picture} \\ (1-\theta)a_{l,j} + \theta t_j Q_j^{\alpha_l}, & \text{otherwise,} \end{cases} \tag{11}$$

where J is, depending on which case, the distance between two consecutive I pictures or between two consecutive pictures belonging to the same temporal level, t_j is the amount of consumed texture bits, and θ is a forgetting factor that is set to 0.5 in our experiments.

On the other hand, α_l is recalculated, for RA coding, every IP and, for LD coding, every 8 GOPs by means of the following linear model:

$$\alpha_l = \begin{cases} 1.1, & \text{if I picture} \\ c_1 - c_2 \frac{t_j}{N_{PXL}}, & \text{otherwise,} \end{cases} \tag{12}$$

where c_1 and c_2 are the model parameters, which have been obtained empirically (see Table 1), and N_{PXL} is the number of luminance (Y) and crominance (U and V) pixels in the picture.

3.3. Coding Tree Block Layer

A finer adjustment to the frame target bits can be achieved if the QP value is regulated on a CTB basis. For the first CTB in the jth picture, the QP value is that obtained at picture layer. Otherwise, the amount of target texture bits for the kth CTB, $T_{j,k}$, is computed first:

$$T_{j,k} = \frac{a_{l,k}}{\sum_{v=k}^{N_B} a_{l,v}} \left(Br_{j,k} - \widetilde{Hr}_{j,k} \right), \tag{13}$$

where $a_{l,k}$ is the R-Q model parameter corresponding to the current CTB, which can also be seen as a coding complexity measurement, N_B is the number of CTBs in the picture, and, finally, $Br_{j,k}$ and $\widetilde{Hr}_{j,k}$ stand for the amount of target total bits and a prediction of the header bits for the remaining CTBs in the picture, respectively.

Then, the corresponding QP value, $QP_{j,k}$, is estimated by means of Eq. (4), where specific parameter values, $a_{l,k}$ and $\alpha_{l,k}$, are used for each CTB. Thus, a particular temporal level has model parameters operating at picture layer and, besides, a set of N_B model parameters operating at CTB layer.

Next, for the sake of quality consistency within the picture, $QP_{j,k}$ is bounded ± 1 unit with respect to $QP_{j,k-1}$ and ± 4 units with respect to QP_j.

Finally, after encoding the kth CTB, $a_{l,k}$ is updated as in Eq. (11) from co-located CTBs at the same temporal level, and $\alpha_{l,k}$ as in Eq. (12). If the encoded CTB is the last one, the average QP for whole picture is also calculated for the RC process at picture layer.

It is also worth noticing that for K pictures CTB layer is disabled (i.e., Q_j is used to encode all CTBs) in order to keep the distortion as low as possible and, hence, provide more efficient motion-compensated predictions for non-K pictures.

Table 1. Parameter values for the linear model in Eq. (12).

	LD		RA	
Layer	$\mathbf{c_1}$	$\mathbf{c_2}$	$\mathbf{c_1}$	$\mathbf{c_2}$
0	1.54	0.22	1.39	0.10
1	2.32	0.23	2.10	0.43
2	2.46	0.57	2.37	0.69
3	-	-	3.05	0.34

4. λ COMPUTATION

The Lagrange formulation [12] plays a paramount role in the R-D optimization process aimed at finding the best prediction mode and motion vector for a coding unit. The relative importance between D and R is weighted by λ that is obtained in the HM reference software [4] by the following widely-accepted empirical function:

$$\lambda = \begin{cases} \Phi \times 2^{\frac{QP-12}{3}}, & \text{if K picture} \\ \max\left[2, \min\left[4, \frac{QP-12}{6}\right]\right] \times \Phi \times 2^{\frac{QP-12}{3}}, & \text{otherwise,} \end{cases} \tag{14}$$

where Φ is a QP factor that depends on the temporal level and picture type. In particular, Eq. (14) is designed to attach more importance to D as the temporal level decreases (to improve the quality in those pictures used as references). Furthermore, given that λ is derived from QP, it should be recalculated whenever the QP value is modified in some way. So, unlike the RC scheme in [10], Eq. (14) is the method we employ for λ computation at both picture and CTB layers, which is the result of many observations and experiences.

5. EXPERIMENTS AND RESULTS

5.1. Experimental Setup

The proposed RC algorithm was implemented on the HM reference software version HM-9.0-dev [4] that already includes our benchmark for performance evaluation: the RC algorithm described in [10]. In order to guarantee fair comparisons, CTB layer was enabled in both schemes, hierarchical bit allocation was enabled in [10] and, since in [10] there is no buffering mechanism itself, the buffer size for the proposed rate controller was set to $1s$, which is large enough to properly bear the variable output bit rate of the video encoder.

Following the recommendations specified in [14], the set of test video sequences, encoder configurations and target bit rates were selected. In particular, the set of target bit rates was obtained from previous codings using the default hierarchical QP setting in [4] with the following four base QP values: 22, 27, 32 and 37.

5.2. Results and Discussion

The average *Bjøntegard difference* (BD)-rate measurement, which compares two R-D curves by means of a single number, was used to assess both RC schemes from the R-D performance point of view. Table 2 reports the BD-rate results for two specific encoder configurations: RA Main and LD Main. As can be observed, the proposed RC algorithm generally achieved a sligthly better R-D performance (a negative percentage means that the tested algorithm outperforms the reference one) for each sequence class. One reason for these R-D differences might be related to the frame bit allocation algorithm: while a set of prefixed weighting factors is employed in [10] for bit budget distribution among temporal levels, changes in video complexity can be followed in the proposed bit allocation approach by means of a continuous updating of the coding complexities $\widetilde{X}_{I/l,j}$.

Table 2. BD-rate performance of the proposed RC algorithm compared to the reference RC algorithm in [10].

Sequence Class	RA Main			LD Main		
	Y	U	V	Y	U	V
A	-1.3%	-2.0%	-1.2%	-	-	-
B	-0.7%	-3.9%	-0.7%	-5.7%	-2.6%	-1.2%
C	-3.3%	-8.6%	-7.4%	-2.4%	1.8%	1.9%
D	-4.3%	-6.2%	-4.7%	-4.5%	-5.2%	-5.4%
E	-	-	-	-8.4%	-4.6%	-4.4%
Overall	-2.3%	-5.1%	-3.3%	-5.1%	-2.5%	-2.1%
Enc. Time	100%			102%		

Table 3. Bit rate error (average/maximum) of the reference RC algorithm in [10] and the proposed RC algorithm, and number of underflows, #U, (average/maximum) of the proposed RC algorithm.

Encoder Configuration	Bit Rate Error [%]		#U [%]
	Reference	Proposed	Proposed
RA Main	0.28/3.17	0.20/2.33	1.45/11.00
RA HE10	0.29/3.05	0.18/0.78	1.44/9.67
LD Main	0.12/1.22	0.11/1.17	0.25/4.80
LD HE10	0.13/1.28	0.13/1.42	0.22/4.20
LD P Main	0.12/1.26	0.12/1.96	0.27/4.40
LD P HE10	0.13/1.39	0.11/1.25	0.23/5.20

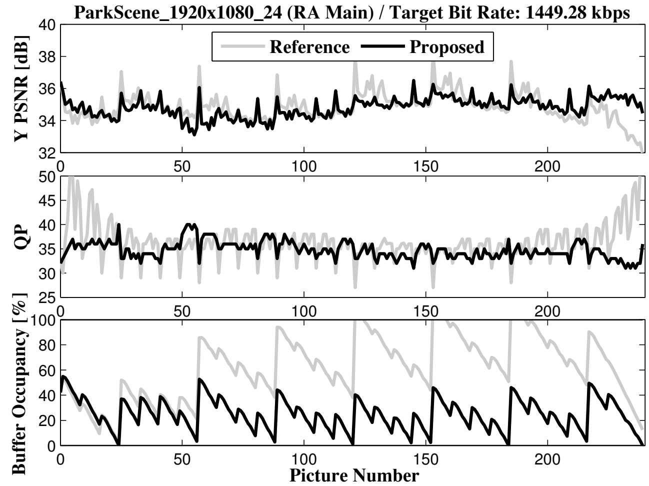

Fig. 2. Y PSNR, QP and buffer occupancy time evolutions for *ParkScene_1920x1080_24* (RA Main). Target bit rate: 1449.28 kbps.

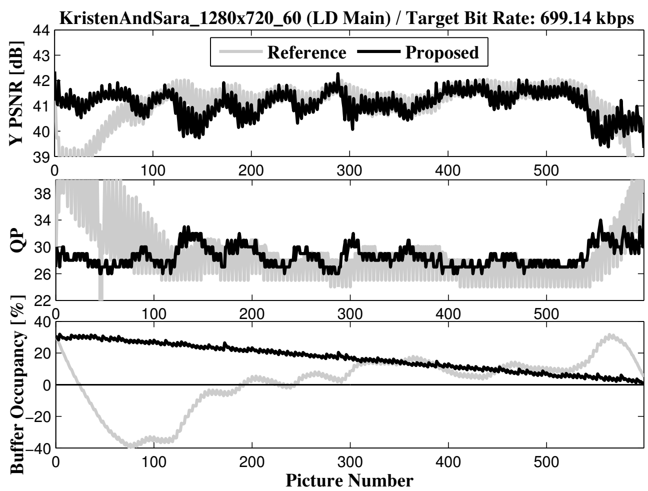

Fig. 3. Y PSNR, QP and buffer occupancy time evolutions for *KristenAndSara_1280x720_60* (LD Main). Target bit rate: 699.14 kbps.

Additionally, in order to discuss the results concerning the quality consistency, representative behaviors of the Y PSNR and QP time evolutions are shown in Figs. 2 and 3 for the test video sequences *ParkScene_1920x1080_24* (RA Main) and *KristenAndSara_1280x720_60* (LD Main), respectively. In comparison with the reference RC algorithm, our proposal was able to produce smoother QP time evolution, thus resulting in a better quality consistency, since stricter clipping conditions for QP assigment are imposed at both picture and CTB layers.

Regarding the encoder buffer behavior, on the one hand, the experimental results proved that in our proposal buffer overflow never happened and buffer underflow remained bellow an acceptable threshold (see Table 3 for details) taking into account that the target buffer level after encoding each IP was set to 0% of the buffer size. On the other hand, as shown in the buffer occupancy time evolution in Figs. 2 and 3 for the two sequences under study, the reference RC scheme is not prepared for applications that may require restricted buffer sizes, since the HRD constraints are not considered (and so, no numerical results are provided for lack of significance).

In terms of target bit rate adjustment, Table 3 shows that the proposed rate controller was able to reduce the average and maximum bit rate errors in most of the tested encoder configurations. Furthermore, since the reference RC algorithm pursues a long-term bit rate adaptation, the potential bit resource over-use or under-use may incur in QP increases or decreases especially at the end of the coding process in order to meet the target bit rate (see the QP time evolution in Figs. 2 and 3 from the pictures #220 and #550, respectively).

Finally, from the complexity perspective, the average coding time consumed by the video encoder with the proposed rate controller compared to that yielded with the reference RC approach is also reported in Table 2. The results indicate that our approach is up to 2% heavier computationally, but acceptable given the coding performance benefits achieved under HRD constraints. Nevertheless, it should be pointed out that these complexity results are just for guidance, since the HM reference software is not computationally optimized, thus affecting the comparisons, and the simulations were performed on a system with shared resources.

6. CONCLUSIONS AND FUTURE WORK

In this paper a buffer-constrained RC algorithm for real-time HEVC with hierarchical GOP structures has been proposed. On the one hand, the HRD constraints are considered in order to properly transmit and decode the compressed video. On the other hand, a novel QPC-based approach for QP assignment is employed in order to also provide high coding efficiency. When compared to the RC algorithm described in [10], our proposal achieves a slightly better R-D performance and a remarkably better buffer control at the expense of an acceptable increase in computational complexity.

In future work we plan to improve the performance of the RC algorithm by using other QP scaling strategies, such as those described in [3] and [5], for the proposed QPC-based clipping method.

7. REFERENCES

[1] H. Schwarz, D. Marpe, and T. Wiegand, "Analysis of hierarchical B pictures and MCTF," in *Multimedia and Expo, 2006 IEEE International Conference on*, july 2006, pp. 1929 –1932.

[2] Weixing Wan, Ying Chen, Ye-Kui Wang, M.M. Hannuksela, Houqiang Li, and M. Gabbouj, "Efficient hierarchical inter picture coding for H.264/AVC baseline profile," in *Picture Coding Symposium, 2009. PCS 2009*, may 2009, pp. 1 –4.

[3] K. Ugur, K.R. Andersson, and A. Fuldseth, "Description of video coding technology proposal by Tandberg, Nokia, Ericsson," *JCTVC-A119, 1th JCTVC Meeting*, Dresden, Germany, April 2010.

[4] HM-9.0-dev reference software, "https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/branches/HM-9.0-dev," .

[5] B. Li, D. Zhang, H. Li, and J. Xu, "QP determination by lambda value," *JCTVC-I0426, 9th JCTVC Meeting*, Geneva, Switzerland, April 2012.

[6] B. Bross, W.J. Han, J.R. Ohm, G.J. Sullivan, Y.K. Wang, and T. Wiegand, "High efficiency video coding (HEVC) text specification draft 10," *JCTVC-L1003, 12th JCTVC Meeting*, Geneva, Switzerland, Jan. 2013.

[7] Chan-Won Seo, Jung Won Kang, Jong-Ki Han, and T.Q. Nguyen, "Efficient bit allocation and rate control algorithms for hierarchical video coding," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 20, no. 9, pp. 1210 –1223, sept. 2010.

[8] S. Sanz-Rodríguez and F. Díaz-de María, "In-layer multibuffer framework for rate-controlled scalable video coding," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 22, no. 8, pp. 1199 –1212, Aug. 2012.

[9] H. Choi, J. Nam, J. Yoo, D. Sim, and I.V. Bajić, "Rate control based on unified RQ model for HEVC," *JCTVC-H0213, 8th JCTVC Meeting*, Sanz José, CA, USA, Oct. 2012.

[10] B. Li, H. Li, L. Li, and J. Zhang, "Rate control by R-lambda model for HEVC," *JCTVC-K0103, 11th JCTVC Meeting*, Shanghai, China, October 2012.

[11] N. Kamaci, Y. Altunbasak, and R.M. Mersereau, "Frame bit allocation for the H.264/AVC video coder via Cauchy-density-based rate and distortion models," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 15, no. 8, pp. 994–1006, 2005.

[12] G.J. Sullivan and T. Wiegand, "Rate-distortion optimization for video compression," *Signal Processing Magazine, IEEE*, vol. 15, no. 6, pp. 74–90, 1998.

[13] S. Sanz-Rodríguez, Ó. del Ama-Esteban, M. de Frutos-López, and F. Díaz-de María, "Cauchy-density-based basic unit layer rate controller for H.264/AVC," *Circuits and Systems for Video Technology, IEEE Transactions on*, vol. 20, no. 8, pp. 1139–1143, Aug. 2010.

[14] F. Bossen, "Common test conditions and software reference configurations," *JCTVC-J1100, 10th JCTVC Meeting*, Stockholm, Sweden, July 2012.