

# A Novel Fine Rate Control Algorithm with Adaptive Rounding Offset

Yali Liu\*, Xiaoan Lu, Cristina Gomila, and Qian Xu

\*University of California, Davis, Electrical and Computer Engineering, Davis, CA 95616, USA  
Thomson Corporate Research, Princeton, NJ 08540, USA

**Abstract**— The rate control algorithm is of essential importance to a video encoder. It enables the encoded bitstream to meet the bandwidth and storage requirement while maintaining good video quality. Most existing works adjust the quantization step size to achieve the required bit rate accuracy. This paper introduces a new dimension: the quantization rounding offset into a frame-level fine rate control algorithm. Specifically, we propose a novel fine rate control algorithm based on a linear model between the bit rate and the rounding offset. Unlike the quantization step size that has a limited number of choices, the quantization rounding offset is a continuously adjustable variable which allows the rate control algorithm to reach any precision in principle. Extensive experiment results show that the proposed algorithm greatly improves the bit rate accuracy and provides better visual quality by fine tuning of the rounding offset in addition to the quantization step size.

## I. INTRODUCTION

A successful video encoder aims at providing the best possible quality given the bit budget. Accurate rate control plays a very important role in achieving this goal. A good rate control algorithm (1) smartly allocates the available bits to the video data in such a way that the quality is optimal; and (2) provides a mechanism to encode the video data at approximately the number of allocated bits. This paper proposes an algorithm that regulates the encoder on a frame level to obtain the number of bits that is very close to the allocated one, assuming the bit allocation scheme is already given.

There has been a large body of research works on bit rate regulation. One common approach is to model the relationship between the bit rate  $R$  and the quantization step size  $q$  (represented by the parameter  $QP$ ), then select the best step size based on the target bit rate [1]–[3]. The bit rate  $R$  is calculated based on a power function in [1] and a polynomial formulation in [2]. In [3], the authors employ the empirical entropy of quantized coefficients to model  $R(QP)$ . In a  $\rho$ -domain rate control algorithm [4], [5],  $R(\rho)$  and  $QP(\rho)$  models are applied for more accurate rate control, where  $\rho$  is the percentage of zero coefficients.

The above models [1]–[5] all attempt to find the best relationship between  $R$  and  $QP$ , assuming other quantization parameters such as rounding offset and quantization matrix are constant. With a limited number of  $QPs$  to choose from, existing rate control algorithms usually resort to macroblock-level (MB-level)  $QP$  adjustment to obtain high accuracy.

However, the  $QP$  variation among different MBs may cause quality inconsistency under some circumstances.

In recent video coding standards, the *rounding offset*  $s$ , together with the quantization step size  $q$ , are used to quantize the transformed coefficient  $W$ . For example, in H.264/AVC encoding,  $W$  is quantized as:

$$Z = \left\lfloor \frac{|W|}{q} + s \right\rfloor \cdot \text{sgn}(W), \quad (1)$$

where  $Z$  is the quantization level of  $W$ . The function  $\lfloor \cdot \rfloor$  rounds a value to the nearest integer that is less than or equal to its argument, and  $\text{sgn}(\cdot)$  returns the sign of the input signal. If a quantization matrix is also used,  $W$  is scaled with the corresponding matrix element before quantization.

In this paper, we propose to incorporate *the rounding offset* into the rate model and present a fine rate control algorithm with high bit rate accuracy. Unlike  $QP$  which has a limited number of choices, the rounding offset  $s$  is a continuously adjustable variable and it enables the rate control algorithm to reach any precision in principle. More importantly, it is observed from our extensive simulations that  $\ln(R)$  is related to  $s$  in a linear fashion at a given  $QP$ . Our proposed algorithm adaptively adjusts the rounding offset based on the linear  $R(QP, s)$  model. Simulations with numerous video sequences show that, by adaptively adjusting  $s$ , our algorithm provides higher bit rate accuracy than existing ones that only change  $QP$ . To the best of our knowledge, this work represents the first step towards applying the rounding offset to rate control in video coding. In addition, this scheme can also be easily implemented on MB-level to achieve even higher control accuracy.

The paper is organized as follows. In Section II, we discuss the linear  $R(QP, s)$  model and propose a novel frame-level rate control algorithm that adjusts both  $QP$  and  $s$ . In Section III, we implement our technique in a H.264 video encoder and present our experimental results and performance comparison. Section IV concludes the paper and points to future research directions.

## II. FINE RATE CONTROL WITH ADAPTIVE ROUNDING OFFSET

### A. Linear Relationship Between $\ln(R)$ and $s$

We have performed extensive simulations to discover the effect of the rounding offset  $s$  on the bit rate  $R$ . As an

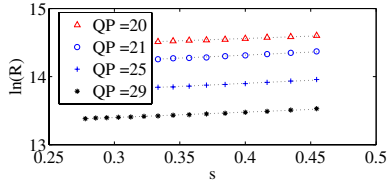


Fig. 1. Relationship between  $\ln(R)$  and  $s$  for the 1130<sup>th</sup> frame of “royal wedding clip4” sequence.

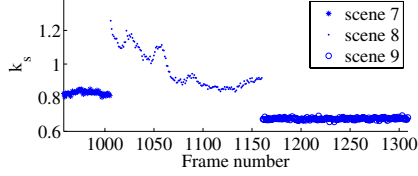


Fig. 2. The estimated  $k_s$  for frame 958 - 1309 in “royal wedding clip4” sequence.

example, the plot of  $\ln(R)$  v.s.  $s$  for the 1130<sup>th</sup> frame of a HD (1920×1080) sequence “royal wedding clip4” is shown in Fig. 1. This frame is encoded as an INTRA frame with  $QP = \{20, 21, 25, 29\}$  and  $s = 0.28 \sim 0.45$ . It is observed that, with a fixed rounding offset  $s$ , we can only obtain a limited set of  $R$  with discrete values of  $QP$ . However, with proper manipulation of  $s$ , any intermediate number of bits can also be achieved since  $s$  is a continuous variable. This motivates us to include the rounding offset  $s$  in the rate control algorithm to further improve the bit rate accuracy. A closer look at Fig. 1 reveals that there is a linear relationship between  $\ln(R)$  and  $s$  within a certain range, which can be described mathematically as:

$$\ln(R(QP, s)) = k_s \times s + f(QP), \quad (2)$$

where  $k_s$  is a constant and  $f(QP)$  is a function of  $QP$ . To illustrate how the parameter  $k_s$  changes across different frames, we plot in Fig. 2 the estimated  $k_s$  for frame 958 - 1309 in “royal wedding clip4” sequence, where scene cuts occur at frame 1006 and 1161. There is large motion at the beginning of scene 8 and the video content changes dramatically over these frames. As a result,  $k_s$  varies a lot at the beginning of scene 8. When the content becomes more stationary, such as the frames in scene 7 and 9, and the latter part of scene 8,  $k_s$  becomes much smoother.

In the following, we propose a novel frame-level rate control algorithm that adaptively adjusts the rounding offset based on the relationship described in Eq. (2).

### B. Three-pass Design

As we have seen above, the rounding offset  $s$ , in addition to the  $QP$ , should be adopted in rate control for better accuracy. Since we aim to show the prominent effect of rounding offset on the bit rate in this work, any regular rate control algorithm that uses a constant rounding offset  $s$  and only changes  $QP$  can be used to encode the video at first to obtain a set of optimized  $QP$ . We need to emphasize here there is no constraint to any specific rate control scheme as the rounding offset adjustment is, in principle, independent of the  $QP$  adjustment for rate control. With the resulting bit rate  $R$  from

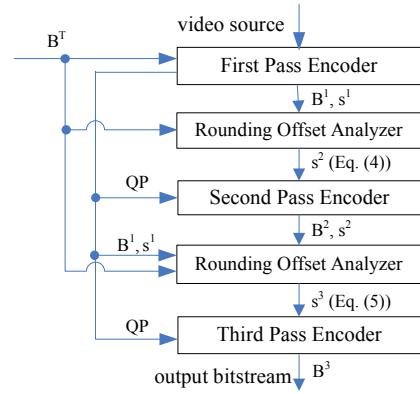


Fig. 3. A three-pass video encoder that utilizes both  $QP$  and  $s$  in rate control.

encoding with the optimized  $QP$  and an initial  $s$ , we can update the rounding offset with

$$s_T = \frac{1}{k_s} \ln \frac{R_T}{R} + s \quad (3)$$

to approach the target bit rate  $R_T$  with the same  $QP$ . Since the only parameter in Eq. (3) is  $k_s$ , the key problem is then how to obtain a good estimate of  $k_s$ , hence an accurate  $s$ .

A straightforward approach is to perform multi-pass encoding. Fig. 3 illustrates how  $s$  is updated by the rate control algorithm in a three-pass video encoder. Note that no more pass is necessary to get a more accurate estimate for  $k_s$  due to the linear nature of our rate model in Eq. (2). The three-pass encoding process is applied for coding of each scene, as  $k_s$  is a content-dependent parameter and we need to estimate it on a scene basis. For video sequence with more than one scene, the coding of each scene is carried out separately. For illustration purpose, we assume there is only one scene to be encoded in the following description. Suppose the target bit rate for the scene is  $R^T$ , and a certain rate allocation scheme determines the target number of bits for the  $m^{\text{th}}$  frame as  $B_m^T$ ,  $m = 0, \dots, N - 1$ , where  $N$  is the total number of frames in the scene. The work flow of the three-pass encoder is as follows:

**First Pass:** During the first encoding pass, the encoder encodes the  $m^{\text{th}}$  picture with  $QP_m$  (obtained with a regular rate control algorithm) and initial rounding offset  $s_m^1$ ,  $m = 0, \dots, N - 1$ . The same set of  $\{QP_m\}$ ,  $m = 0, \dots, N - 1$  will be used in the latter passes. Since there are only limited choices of  $QP_m$ , the obtained number of bits of the  $m^{\text{th}}$  frame,  $B_m^1$ , will fluctuate around the target number of bits,  $B_m^T$ .

**Second Pass:** To reduce the mismatch between  $B_m^1$  and  $B_m^T$ , the analyzer keeps the same  $QP_m$  but updates  $s$  to

$$s_m^2 = \frac{1}{k_s^1} \ln \frac{B_m^T}{B_m^1} + s_m^1, m = 0, \dots, N - 1, \quad (4)$$

where  $k_s^1$  is initialized to 1, an average value for typical sequences.  $QP_m$  and  $s_m^2$  are used for the  $m^{\text{th}}$  frame in the second-pass encoding, with resulting number of bits  $B_m^2$ .

**Third Pass:** Usually,  $B_m^2$  is closer to  $B_m^T$  than  $B_m^1$ . But now that we have the rate and offset information for all the frames from the previous two passes, we can get a more precise

estimate of  $k_s$  to further reduce the gap between the target and resulting number of bits. Specifically, before the third encoding pass,  $k_s$  is updated to  $k_s^2$  using the linear regression between  $\left\{ \ln \frac{B_m^2}{B_m^1} \right\}$  and  $\{s_m^2 - s_m^1\}$  for  $m = 0, \dots, N-1$ , and the new rounding offset for each frame is computed as:

$$s_m^3 = \frac{1}{k_s^2} \ln \frac{B_m^T}{B_m^2} + s_m^2, m = 0, \dots, N-1. \quad (5)$$

$QP_m$  and  $s_m^3$  are then used for the third-pass encoding, resulting number of bits  $B_m^3$  which is very close to  $B_m^T$ .

### C. Two-pass Design

The three-pass design achieves a very accurate estimate of the rate model and provides fine rate control by regulating the rounding offset at the cost of two more encoding passes. Considering that the model parameter  $k_s$  is almost a constant within the same scene, we can simplify the three-pass design to a two-pass design to reduce the computational cost. Instead of updating  $k_s$  after finishing the second encoding pass for all frames, it can be updated adaptively after each frame based on all the previously encoded frames. The simplified two-pass algorithm proceeds by the following steps:

**First Pass:** The same as in the three-pass design.

**Second Pass: Initialization.** Set  $m = 0$  and  $k_s^1 = 1$ . The rounding offset of the  $m^{\text{th}}$  frame is calculated as

$$s_m^2 = \frac{1}{k_s^1} \ln \frac{B_m^T}{B_m^1} + s_m^1, m = 0 \quad (6)$$

and the  $m^{\text{th}}$  frame is encoded with  $B_m^2$  bits.

**Step 2.1: Update  $k_s$ .** The model parameter is updated to  $k_s^2$  using the linear regression between  $\left\{ \ln \frac{B_j^2}{B_j^1} \right\}$  and  $\{s_j^2 - s_j^1\}$  for  $j = 0, \dots, m$ .

**Step 2.2: Determine the rounding offset  $s$ .** Set  $m = m + 1$ . The new rounding offset for the  $m^{\text{th}}$  frame is computed as:

$$s_m^2 = \frac{1}{k_s^2} \ln \frac{B_m^T}{B_m^1} + s_m^1 \quad (7)$$

and the  $m^{\text{th}}$  frame is encoded with  $B_m^2$  bits.

**Step 2.3: Loop.** Repeat step 2.1 and step 2.2 until all the frames are encoded.

## III. EXPERIMENTAL RESULTS

We implemented our proposed fine rate control algorithm (both the three-pass and two-pass designs) in a H.264 encoder and tested its performance with numerous video sequences. In our simulations, we encode all frames as INTRA frames. We use a frame-level rate control algorithm that only changes  $QP$  in the first encoding pass, denoted as  $QP$ -only rate control. In particular, we choose the  $\rho$ -domain rate control given its high accuracy. To measure rate control performance, we define for the  $m^{\text{th}}$  frame the relative control error as

$$\Delta_m = \frac{B_m - B_m^T}{B_m^T} \times 100\%, \quad (8)$$

where  $B_m$  and  $B_m^T$  are the actual and target number of bits of the  $m^{\text{th}}$  frame.

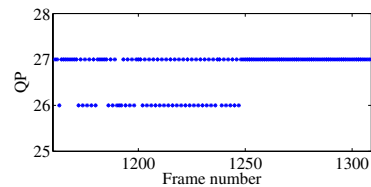


Fig. 4.  $QP$  for frame 1161 - 1309 in “royal wedding clip4” sequence in “pass1”.

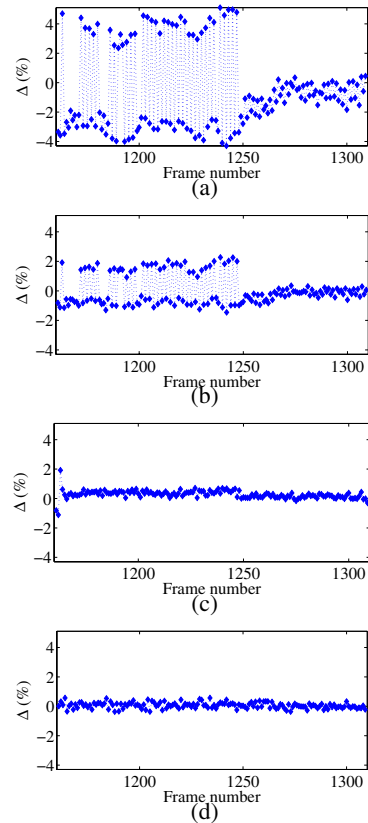


Fig. 5. Performance of the multi-pass rate control algorithm (frame 1161 - 1309 in “royal wedding clip4” sequence): relative rate control error for each frame from (a) “pass1”; (b) “pass2”; (c) “pass2 adaptive”; and (d) “pass3”.

In Fig. 4, 5 and 6, we plot the results for the 1161<sup>st</sup> to 1309<sup>th</sup> frame (a complete scene segment) of the HD sequence “royal wedding clip4”. The target bit rate is 30 Mbps. The set of  $QP$  determined by the first pass using  $QP$ -only rate control are shown in Fig. 4. We can see that the  $QP$  of each frame switches between 26 and 27, attempting to meet the target number of bits for each frame. These are the values of  $QP$  that will also be used in our multi-pass designs.

We calculate  $\Delta$  for all the passes in the three-pass design (denoted as “pass1”, “pass2”, and “pass3”) and the last pass in the two-pass design (denoted as “pass2 adaptive”) in Fig. 5(a)~(d). Note that pass1 corresponds to the case when  $QP$ -only rate control is used. We can see in Fig. 5(a) that the control error can be as large as 4% in pass1 due to the limited choices of  $QP$ . The control error is significantly reduced to around 2% in pass2 and almost invisible in pass2 adaptive (below 0.7%) and pass3 (below 0.5%). Therefore, compared with the frame-level  $QP$ -only rate control, the proposed

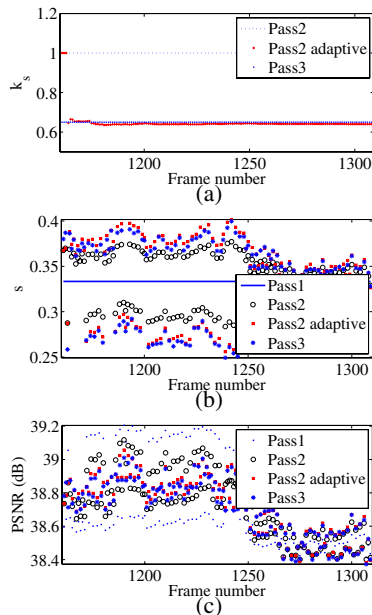


Fig. 6. (a)  $k_s$ ; (b)  $s$ ; and (c) PSNR for each frame in different passes (frame 1161 - 1309 in “royal wedding clip4” sequence).

designs perform much better by integrating the rounding offset in the rate control.

The detailed comparison of the model parameter  $k_s$  used by the two-pass and three-pass designs is displayed in Fig. 6(a). The estimated  $k_s$  by pass2 adaptive is very close to that of pass2 for the first few frames, but soon converges to the  $k_s$  of pass3, which is 0.65. This is because in pass2 adaptive,  $k_s = 1$  at the beginning (the same as in pass2), but a more and more precise estimate of  $k_s$  is obtained with more frames being encoded, until the whole sequence is completed. Actually, this is also verified by the performance of “pass2 adaptive” in Fig. 5(c), where the relative control error of pass2 adaptive is around 2% for the first 3 frames, but drops down to around 0.5% immediately.

Similar phenomena is also observed for  $s$  in Fig. 6(b). The range of  $s$  is between 0.25 and 0.4, where the linear relationship between  $\ln(R)$  and  $s$  is valid. Besides, it is known that the modification of the rounding offset is directly associated with the intensity of the remaining film grain in the reconstructed video [6]. With  $s$  limited in a fairly small region, we can ensure smooth visual quality without introducing visible film grain strength variation. Fig. 6(c) compares the PSNR of each frame in different passes. We can see that in “pass2 adaptive” and “pass3”, the PSNR curve is much smoother, which is more pleasant to human visual system.

For more tested sequences, the average PSNR and the average control error  $\bar{\Delta} = \sum_{m=1}^N |\Delta_m|/N$  are listed in Table I. We can see that pass2 adaptive and pass3 have roughly the same average PSNR as pass1 (-0.13 dB  $\sim$  +0.02 dB), but 2.23%  $\sim$  6.39% less average control error. In general, the proposed schemes achieve higher rate control accuracy than the  $QP$ -only rate control with at most 1% average error. The advantage of the proposed designs is more pronounced for high motion sequence (frame 1006 - 1160 of “royal wedding

TABLE I  
PERFORMANCE COMPARISON AMONG “PASS1”, “PASS2”, “PASS2  
ADAPTIVE” AND “PASS3”.

Video	royal wed- ding clip4	royal wed- ding clip4	royal wed- ding clip3	stefan	foreman
frame #	1006-1160	1161-1309	1130-1269	0-299	0-299
resolution	HD	HD	HD	CIF	CIF
$R^T$ (kbps)	30000	30000	30000	3000	2000
$\bar{\Delta}$ (%)					
Pass1	6.86	2.39	2.93	2.63	4.97
Pass2	1.37	0.81	0.85	1.49	1.57
Pass2Ada	0.96	0.31	0.31	0.64	0.77
Pass3	0.47	0.16	0.17	0.40	0.44
PSNR (dB)					
Pass1	43.15	38.70	39.92	34.31	36.91
Pass2	43.13	38.72	39.87	34.28	36.85
Pass2Ada	43.11	38.72	39.85	34.23	36.81
Pass3	43.08	38.71	39.85	34.20	36.78

clip4” sequence), when the control error of the  $QP$ -only rate control becomes more severe.

#### IV. CONCLUSION AND DISCUSSION

In this paper, we present a linear source model between  $\ln(R)$  and  $s$ , based on which we propose a novel frame-level fine rate control algorithm with adaptive rounding offset. This represents the first work known so far that utilizes the rounding offset for efficient rate control. Extensive simulation results show that the algorithm can greatly increase the bit rate accuracy while maintaining or improving the video quality.

Although the experimental results are encouraging, a lot more needs to be done. First, in this work, we constrain ourselves to INTRA frame coding. The source model and the rate control algorithms can be easily extended to INTER frames, which will make it more applicable in real practice. Second, currently, the proposed source model requires two or more passes to refine the estimation of  $k_s$  before computing the new rounding offset. To develop a fast fine rate control system, we need to integrate the rounding offset adjustment with the  $QP$  regulation in a single pass based on a unified source model between  $R$ ,  $QP$ , and  $s$ . Last, the linear model between  $\ln(R)$  and  $s$  proposed in Section II is based on the observation of extensive experiment results. Rigorous theoretical analysis is still needed to substantiate this linear relationship.

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