# A NEW SOURCE MODEL AND ACCURATE RATE CONTROL ALGORITHM WITH QP AND ROUNDING OFFSET ADAPTATION

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

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

**ABSTRACT**

Rate control plays an important role in regulating the encoding bit rate to meet the bandwidth and storage requirement. Most existing works regulate the bit rate by adjusting the quantization step size. We propose to incorporate a new dimension: the quantization rounding offset into a rate control algorithm. Based on our previous work of multi-pass fine rate control, in this work, we present a unified *one-pass* rate control algorithm that jointly adjusts the quantization step size and the rounding offset for high bit rate accuracy. Unlike the quantization step size that has a limited number of choices, the rounding offset is a continuously adjustable variable that allows the rate control algorithm to reach any precision in principle. Our extensive experimental results show that the proposed algorithm greatly improves the rate control accuracy at almost no extra computational complexity.

***Index Terms*—** Video coding, rate control, quantization, rounding offset

## 1. INTRODUCTION

There has been a large amount of research activities on rate control for video coding. One common approach is to develop a rate-distortion model and then select the best quantization step size $q$ (represented by the parameter $QP$) based on the target bit rate [1, 2, 3, 4], denoted as $QP$-only rate control. These algorithms attempt to accurately characterize the relationship between the bit rate $R$ and $QP$, assuming other quantization parameters such as the rounding offset and quantization matrix are constant. With a limited number of $QP$s 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 inconsistence 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 [5], $W$ is quantized as $Z = \left\lfloor \frac{|W|}{q} + s \right\rfloor \cdot sgn(W)$, 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 $sgn(\cdot)$ returns the sign of the input signal. If a quantization matrix is used, $W$ is scaled with the corresponding matrix element before quantization. At the decoder, the quantization level $Z$ is reconstructed to $W'$ by inverse quantization: $W' = q \cdot Z$, where $s$ is not involved. Therefore the rounding offset has the advantage of regulating the quantization process without the need to transmit additional parameters to the decoder. In our previous work of [6], a multi-pass rate control scheme with adaptive rounding offset has been presented. It achieves high bit rate accuracy and better visual quality by incorporating the rounding offset into the rate model.

In this paper, we propose a unified rate control framework that jointly adjusts both $QP$ and $s$ in a *single* pass. Unlike $QP$ that has a limited number of choices, $s$ 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 experiments that $\ln(R)$ is related to $s$ in a linear fashion at a given $QP$. Our proposed algorithm adaptively adjusts $s$ in addition to $QP$ based on the linear $R(s|QP)$ model. Simulations with numerous video sequences show that our algorithm provides much higher bit rate accuracy than $QP$-only algorithms. Compared with our previous multi-pass design in [6], the single-pass approach greatly reduces the computational complexity while attaining similar rate control performance. Moreover, this method can be applied to improve any $QP$-only rate control algorithm, and it can also be easily implemented on MB-level to achieve even higher control accuracy.

The paper is organized as follows. In Section 2, we briefly review the source model of our previous work before presenting the novel frame-level rate control algorithm that adjusts $QP$ and $s$ simultaneously. In Section 3, we present our experimental results and performance comparison with a H.264 video encoder. Section 4 concludes the paper and discusses future research directions.

## 2. FINE RATE CONTROL WITH ADAPTIVE ROUNDING OFFSET

### 2.1. Refined source model

In our recent work of [6], a multi-pass rate control scheme with adaptive rounding offset was proposed based on a linear source model between $\ln(R)$ and $s$. In this paper, we investigate coefficient bits $R_c$ and header bits $R_h$ separately. We find that $R_h$ is almost constant over different $s$, and there is a linear relationship between $\ln(R_c)$ and $s$. We plot $\ln(R_c)$ vs. $s$ for four different frames in Fig. 1. The frames are INTRA encoded with $QP = \{20, 21, 25, 29\}$ and $s = 0.28 \sim 0.45$. We observe from Fig. 1 that $\ln(R_c)$ is approximately a straight line although the sample images vary significantly from each other. Extensive simulations with other sequences have been performed (both INTRA and INTER coding) and their rate curves share the same pattern. Mathematically, the linear relationship between $\ln(R_c)$ and $s$ is described as:

$$\ln(R_c(QP, s)) = k_s \times s + f(QP). \qquad (1)$$

Therefore, with the encoding bit rate $R_c$ given the $QP$ and an initial $s$, the rounding offset can be updated to

$$s^T = \frac{1}{k_s} \ln \frac{R^T}{R_c} + s \qquad (2)$$

to approach the target bit rate $R^T$ with the same $QP$. In the multi-pass design, the values of $R_c$ and $s$ are from the previous encoding passes. Then, with Eq. (2), we can estimate $s^T$ without knowing the exact form of $f(QP)$ in Eq. (1). So the rounding offset adjustment can be applied to any $QP$-only rate control algorithms with their respective $R$-$QP$ models.

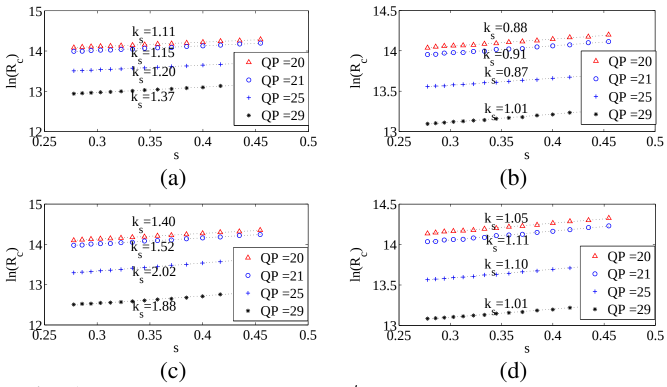



**Fig. 1**. $\ln(R_c)$ vs. $s$ for (a) the $1^{st}$ frame of "erin brockovich"; (b) the $1438^{th}$ frame of "man in restaurant"; (c) the $1^{st}$ frame of "pouring liquids"; and (d) the $1130^{th}$ frame of "royal wedding clip4". The resolution is $1920 \times 1080$.

It was shown in [6] that the multi-pass designs greatly improved the bit rate accuracy, however at a high computational complexity that is not desirable for a real-time application. This motivates us to seek a simplified rate control algorithm that achieves similar performance. In the following, we discuss the issues involved in simplification before presenting our novel one-pass rate control scheme.

### 2.2. One-pass design

In a multi-pass scheme, $R_c$ is obtained from a previous encoding pass that operates at a rounding offset $s$, which will be deployed as the base for calculating $s^T$ using Eq. (2). Therefore, one challenge in designing the one-pass rate control algorithm is to obtain an accurate estimate of $R_c$ at an initial $s$ without actually encoding the frame.

Another challenge is the variation of model parameters with $s$. A common assumption in rate control is that the model parameters should be similar between consecutive frames. For example, in the $\rho$-domain rate control, the source model parameters $\theta$ is shown to be independent of $QP$ when $s$ is fixed, so $\theta$ from previous frames is used for $QP$ selection of the current frame. Since $\theta$ varies with different $s$ [4], changing the $s$ for one frame may affect both $QP$ selection and $s$ adjustment for the following frames. To address this issue, in the multi-pass scheme of [6], $QP$ is determined in the first pass at a given $s$, and only $s$ is adjusted in later passes while $QP$ is fixed. In a single-pass design, both $QP$ and $s$ are to be adjusted simultaneously and we need to consider the impact of model parameter variation on $QP$ and $s$ adjustment.

We address the above mentioned issues in the following subsections and present a unified single-pass framework that jointly adjusts $QP$ and $s$. In the discussion, we will use the $\rho$-domain algorithm as an example of $QP$-only rate control algorithms.

#### *2.2.1. Rate estimate*

We initialize the rounding offset $s$ to a default value of $s_d$, and use it during preprocessing to build the $\rho$-$QP$ table [4] (denoted by "$\rho$-($QP$, $s_d$) table"). Suppose an initial $QP_n$ is selected to encode the $n^{th}$ frame. We need to estimate the encoding bit rate at $QP_n$ and $s_d$ before updating $s^T$ using Eq. (2). According to the linear source model in the $\rho$-domain rate control, a reasonable estimate of the bit rate $R_n(QP_n, s_d)$ is

$$\tilde{R}_n(QP_n, s_d) \;\; = \;\; \tilde{\theta}(QP_n, s_d) \cdot [1 - \rho(QP_n, s_d)], \quad (3)$$

where $\rho(QP_n, s_d)$ can be obtained by looking up the $\rho$-($QP$, $s_d$) table and $\tilde{\theta}(QP_n, s_d)$ is the estimated $\theta(QP_n, s_d)$ for the current frame. In general, $\tilde{\theta}(QP_n, s_d)$ can be set as $\theta$ of the previously encoded frames of the same picture type. To achieve the target rate $R^T$, $s_n^T$ is updated based on Eq. (2), where $s = s_d$ and $R_c = \tilde{R}_n(QP_n, s_d)$.

Due to the small dynamic range of linearity between $\ln(R_c)$ and $s$ as shown in Fig. 1, we may need to increase or decrease $QP_n$ until $s_n^T$ is within $(s_L, s_U)$. 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 [7]. Therefore the restriction of $s$ is also desirable for smooth visual quality without introducing visible film grain strength variation. During the iterative process of searching for the optimal $QP_n$, the estimation $\tilde{R}_n(QP_n, s_d)$ is updated with Eq. (3) before computing the new $s_n^T$.

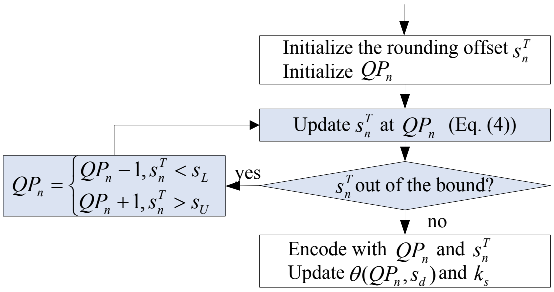



**Fig. 2**. The block diagram of the proposed one-pass rate control algorithm.

### 2.2.2. *Model update*

In order to address the issue of parameter variation, after the actual encoding with the selected $QP_n$ and $s_n^T$, the obtained rate $R_n(QP_n, s_n^T)$ should be converted to $R_n(QP_n, s_d)$ by

$$\begin{aligned} R_n(QP_n, s_d) &= R_n(QP_n, s_n^T) \cdot e^{k_s \cdot (s_d - s_n^T)} \\ &= R_n(QP_n, s_n^T) \cdot \frac{\tilde{R}_n(QP_n, s_d)}{R^T}, \end{aligned} \quad (4)$$

where $k_s$ is the model parameter in Eq. (1). It is then used to update the source model parameter, which is

$$\theta(QP_n, s_d) = \frac{R_n(QP_n, s_d)}{1 - \rho(QP_n, s_d)} \quad (5)$$

in the case of $\rho$-domain rate control.

As to the value of slope $k_s$, a typical value $k_s = 1.0$ is used for the first frame. The slope is updated using the linear regression between $\left\{ \ln \frac{R_j(QP_j, s_j^T)}{\tilde{R}_j(QP_j, s_d)} \right\}$ and $\left\{ s_j^T - s_d \right\}$ for $j = 1, \ldots, n$ after encoding the $n^{th}$ frame.

### 2.2.3. *Algorithm summary*

Fig. 2 depicts the block diagram of the proposed one-pass rate control algorithm, which proceeds by the following steps:

**Step 1** Set $n = 1$. Initialize $k_s$ and $s_d$. Encode the $1^{st}$ frame using $s_1^T = s_d$ at $QP_1$ that is determined by the $\rho$-domain rate control algorithm.

**Step 2** Set $n = n + 1$. Encode the $n^{th}$ frame with the following steps:

**Step 2.1** Preprocess the frame and build the $\rho$-($QP$, $s_d$) table. Initialize $QP_n$.

**Step 2.2** Compute $\tilde{R}_n(QP_n, s_d)$ using Eq. (3). Compute $s_n^T$ at $QP_n$ based on Eq. (2). If $s_n^T > s_U$, $QP_n = QP_n - 1$; if $s_n^T < s_L$, $QP_n = QP_n + 1$. Repeat this process for a maximum of $M$ times until $s_L \leq s_n^T \leq s_U$.

**Step 2.3** Encode the $n^{th}$ frame at $QP_n$ and $s_n^T$ to obtain the encoded bit rate $R_n(QP_n, s_n^T)$. Compute $R_n(QP_n, s_d)$ using Eq. (4). Calculate $\theta(QP_n, s_d)$ with Eq. (5). Update $k_s$ using linear regression.

**Step 3** Loop step 2 until all the frames are encoded.

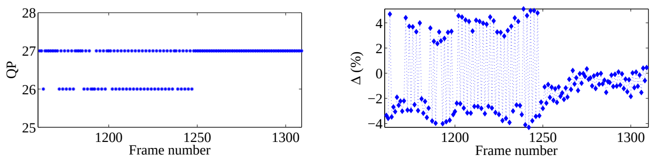
In the above algorithm, only step 2.2, $R_n(QP_n, s_d)$ computation and $k_s$ update in step 2.3 are the extra computation compared to the $\rho$-domain rate control.

## 3. EXPERIMENTAL RESULTS

We implemented the proposed one-pass fine rate control algorithm in a H.264 encoder and tested its performance with numerous video sequences. In our simulations, we encoded all frames as INTRA frames with $s_d = \frac{1}{3.0}$. We chose the $\rho$-domain rate control given its high accuracy as an example of $QP$-only algorithms. In our one-pass rate control, the $QP$ of each frame is initialized with that of the previous frame and the rounding offset $s$ is restricted to be within [0.23, 0.45]. The maximum times of iteration in step 2.2 is set as $M = 3$. To measure rate control performance, we define for the $m^{th}$ frame the relative control error as

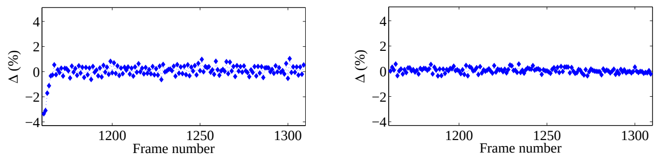
$$\Delta_m = \frac{B_m - B_m^T}{B_m^T} \times 100\%, \quad (6)$$

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




(a) (b)

**Fig. 3**. Encoding for frame 1161 - 1309 in "royal wedding clip4" sequence in "1pass": (a) $QP$ and (b) relative control error.




(a) (b)

**Fig. 4**. Relative control error for frame 1161 - 1309 in "royal wedding clip4" sequence: (a) "1pass new" and (b) "3pass".

In Fig. 3 and 4, we plot the results for the $1161^{st}$ to $1309^{th}$ 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 $QP$-only rate control are shown in Fig. 3(a). 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. The optimized $QP_n$ by the one-pass rate control is 27 for all frames.

In addition to the $QP$-only rate control, we also compare our proposed scheme with the best performing (three-pass) design in [6] in terms of bit rate accuracy. We calculate $\Delta$ for the $QP$-only rate control, the proposed one-pass design, and the three-pass design (denoted as "1pass", "1pass new", and

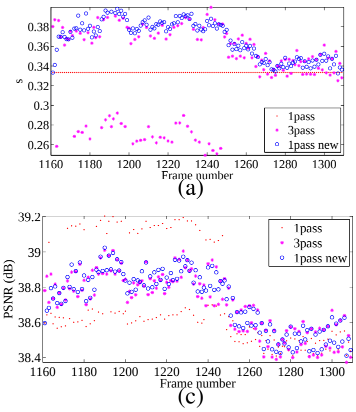



**Fig. 5**. (a) $s$ and (b) PSNR for each frame in different passes (frame 1161 - 1309 in "royal wedding clip4").

"3pass") in Fig. 3(b) and Fig. 4. We can see in Fig. 3(b) that the control error can be as large as 4% in "1pass" due to the limited choices of $QP$. The control error is significantly reduced to around 0.4% in "1pass new" and almost invisible in "3pass" (about 0.2%). Therefore, the proposed one-pass design achieves similarly high accuracy as the three-pass rate control scheme with almost the same computational complexity of the $QP$-only rate control.

The detailed comparison of the rounding offset $s_n^T$ and achieved PSNR is shown in Fig. 5. The range of $s$ is between 0.25 and 0.4 for all three schemes, where the linear relationship between $\ln(R_c)$ and $s$ is valid. In "3pass", the rounding offset vibrates up and down with different $QP$s of each frame, while it is constantly around 0.38 in "1pass new" as the $QP$ is stable at 27. Fig. 5(b) compares the PSNR of each frame in different schemes. We can see that in "1pass new" and "3pass", 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 $\overline{\Delta} = \sum_{m=1}^{N} |\Delta_m|/N$ are listed in Table 1. We can see that "1pass new" has roughly the same average PSNR as "1pass" (-0.05 dB $\sim$ +0.01 dB), but 1.56% $\sim$ 6.16% less average control error. The advantage of the proposed designs is more pronounced for high motion sequence (frame 1006 - 1160 of "royal wedding clip4" sequence), when the control error of the $QP$-only rate control becomes more severe.

## 4. DISCUSSION

In this paper, we have presented a unified framework that jointly adjusts $QP$ and $s$ in one pass for frame-level rate control. We refine the source model of [6] by removing the effect of header bits and address the issues of bit rate estimation and model parameter update. Compared to the existing rate control algorithms that only change $QP$, our scheme greatly improves the bit rate accuracy with even better visual quality at almost no extra computational complexity.

**Table 1**. Performance comparison among "1pass", "3pass", and "1pass new".

| Video | royal wedding clip4 | royal wedding clip4 | royal wedding 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 |
| $\overline{\Delta}$ (%) | | | | | |
| 1Pass | 6.86 | 2.39 | 2.93 | 2.63 | 4.97 |
| 3Pass | 0.47 | 0.16 | 0.17 | 0.40 | 0.44 |
| 1Pass new | 0.70 | 0.34 | 0.43 | 1.07 | 1.53 |
| PSNR (dB) | | | | | |
| 1Pass | 43.15 | 38.70 | 39.92 | 34.31 | 36.91 |
| 3Pass | 43.08 | 38.71 | 39.85 | 34.20 | 36.78 |
| 1Pass new | 43.10 | 38.72 | 39.87 | 34.30 | 36.89 |

Although both the linear source model and the experimental results are only presented for INTRA frames, we have observed that similar linear relationship between $\ln(R_C)$ and $s$ also holds for INTER frames. In our ongoing work, the multi-pass rate control algorithms have proved to significantly improve the control accuracy of INTER frames. We expect the proposed one-pass scheme to be effective for INTER frames as well and it is one of our future works to verify that. Another important step is to provide theoretical justifications for the linear rate model between $\ln(R_c)$ and $s$.

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