QP Selection Optimization for Intra-Frame Encoding Based on Constant Perceptual Quality

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SUMMARY In lossy image/video encoding, there is a compromise between the number of bits and the extent of distortion. Optimizing the allocation of bits to different sources, such as frames or blocks, can improve the encoding performance. In intra-frame encoding, due to the dependency among macro blocks (MBs) introduced by intra prediction, the optimization of bit allocation to the MBs usually has high complexity. So far, no practical optimal bit allocation methods for intra-frame encoding exist, and the commonly used method for intra-frame encoding is the fixed-QP method. We suggest that the QP selection inside an image's frame can be optimized by aiming at the constant perceptual quality (CPQ). We proposed an iteration-based bit allocation scheme for H.264/AVC intra-frame encoding, in which all the local areas (which is defined by a group of MBs (GOMBs) in this paper) in the frame are encoded to have approximately the same perceptual quality. The SSIM index is used to measure the perceptual quality of the GOMBs. The experimental results show that the encoding performance on intra-frames can be improved greatly by the proposed method compared with the fixed-QP method. Furthermore, we show that the optimization on the intra-frame can bring benefits to the whole sequence encoding, since a better reference frame can improve the encoding of the subsequent frames. The proposed method has acceptable encoding complexity for offline applications.

key words: bit allocation optimization, intra-frame encoding, constant quality, perceptual video coding

1. Introduction

The goal of lossy image/video encoding is to minimize the loss on the quality of the reconstructed image/video under the constraint of bit budget, or to use as few as possible bits to encode the image/video at a certain level of quality. Generally, the more bits that an encoder uses to encode a source (such as a block in an image, or a frames in a video), the less distortion on the source it brings to, which is known as the rate-distortion (R-D) property of the source [1]. However, the R-D property varies with the content contained in the sources. Thus, it is necessary for an encoder to determine how many bits should be allocated to each source in the coding object so that the overall encoding can achieve the best performance [2]. Generally, bit allocation is controlled by the quantization parameters (QP) used to encode the sources [3].

In modern hybrid video coding standards (e.g., H.264/AVC [4] or HEVC [5]), intra-frame plays an important role, where the encoding of all the other frames in a group of picture (GOP) depends on it directly or indirectly due to the inter prediction. The optimization on intra-frame encoding can not only improve the encoding performance on itself, but also benefit the encoding of the whole GOP, because a better reference frame can further improve the performance of inter prediction [6]. In this sense, optimizing the bit allocation inside intra-frames is valuable.

Most of the existing works optimize the bit allocation in rate control algorithms [7]–[10]. However, all of these methods only control the QP for blocks in inter-frames, and use fixed-QP to encode the intra-frames. In these methods, the object for optimization is to minimize the average distortion of the sources (MINAVE) [11], and it is usually assume that the sources are encoded independently. When sources are encoded independently, the MINAVE based optimal bit allocation can be solved easily by using the Lagrangian multiplier method [12]. However, when sources are dependent, the Lagrangian multiplier method is quite difficult to use, details about this have been discussed in [13]. The much more complicated dynamic programming (DP) method is usually used to solve the optimization problem when sources are encoded dependently [6], [11], [14], [15]. It has been proved that the computational complexity of DP method increases exponentially with the number of dependent sources [11].

Due to the intra prediction, the number of dependent sources in an intra-frame in H.264/AVC is equal to the number of macro blocks (MBs) in a slice [4], which makes it very time consuming to use the DP method in intra-frame encoding. In this sense, MINAVE-based bit allocation methods are difficult to be used in intra-frame encoding. The fixed-QP method is still the commonly used method to encode intra-frames for now.

Another drawback of the MINAVE criterion could be its incompatible with the human perception. Since the encoded video is to be shown to the human, the optimization of the bit allocation should improve the perceptual quality of the reconstructed frames. However, it was pointed out in [11] that MINAVE may result in sudden variation in quality, which is annoying. The study in [16] had shown that the human vision prefers to pay more attention to the signal which is distinctly different from the others. As a result, it is better to encode all the sources to have similar level of distortion, so that no individual source is extremely distorted to attract the viewer’s attention.

The MINMAX criterion aims to minimize the max-

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minimum distortion of the sources in bit allocation, and it generally leads to constant quality under a given bit constraint [17]. However, almost all the existing MINMAX-based methods [18]–[21] focus on minimizing the quality variation among frames, and none aims for constant quality inside a frame. This is understandable because the distortion/quality metrics that have been used in these works are usually the mean square error (MSE) or the peak signal to noise ratio (PSNR). It is well known that MSE/PSNR cannot represent the human visual perception [22]. Forcing the adjacent frames in a GOP to have similar MSE/PSNR is reasonable, because they contain almost the same scenes. But it is quite different for the blocks or local areas inside a frame, the contents of these sources can be very different even if they are adjacent to each other, and forcing them to have similar MSE/PSNR is meaningless.

In our opinion, the optimization of bit allocation in intra-frames should aim for constant perceptual quality (CPQ) among the sources inside the frame. Perceptual quality metrics are necessary to be used in this situation, and the great improvement of the research on image quality assessment (IQA) in the past decade creates opportunities for this purpose [23]. There are many works that use IQA metrics in video encoding and achieves promising results [10], [24]–[28]. Our previous works have shown the advantage of using IQA metrics in intra-frame constant quality encoding [29]–[31]. In this paper, we propose an CPQ-based method for the bit allocation of intra-frames in H.264/AVC. The proposed method encodes all the local areas in an intra-frame, which are named by group of MBs (GOMBs), to have similar perceptual quality. The purpose of constant perceptual quality among GOMBs is achieved by using an iteration-based encoding process, and the distortion/quality of GOMBs are measured by the widely Structural SIMilarity (SSIM) index [32]. The proposed method can be used to replace the standard intra-frame encoding in H.264/AVC with acceptable encoding complexity. It is useful for the applications that can be encoded offline, such as still image encoding, video storage and video streaming, etc.

The rest of this paper is organized as follows: the CPQ-based bit allocation method is introduced in Sect. 2; the experiments and results are shown in Sect. 3; more discussions about the proposed method are given in Sect. 4; and finally we draw the conclusions in Sect. 5.

2. Bit Allocation Based on Constant Perceptual Quality

In this section, we propose a bit allocation method for intra-frame encoding in H.264/AVC, which is called constant perceptual quality (CPQ). The idea is to encode the local areas in the intra-frame to similar perceptual quality under given bitrate constraint. We define the local area first, and then propose an iteration-based bit allocation method aiming for CPQ. The SSIM index is used to evaluate the quality of the local areas.

2.1 Group of Macro Blocks

To design the method for achieving constant perceptual quality inside a frame, we first define the concept of a local area. Since the basic encoding unit of H.264/AVC is an MB, We define a local area as a group of macro blocks (GOMB). An GOMB is a square area consists of several adjacent MBs. Let \( M_{B_i} \) be the \( j \)th MB of the \( i \)th row in a frame, we define the GOMB whose upper left is \( M_{B_i} \) as

\[
GOMB_{i,j} = \{ M_{B_{u,v}} \mid u = i, \ldots, i + N - 1,
\]

\[
v = j, \ldots, j + N - 1\}
\]

where, \( N \) is the size of GOMB. We set \( N \) to 4 in this paper. A legal GOMB should satisfy the following conditions: \( 1 \leq i \leq H_{MB} + 1 - N \) and \( 1 \leq j \leq W_{MB} + 1 - N \), where \( H_{MB} \) and \( W_{MB} \) are the frame height and width in MB, respectively. We denote the set of all the legal GOMBs as \( S_G \).

Figure 1 illustrates the definition of \( GOMB_{i,j} \) and shows the example of three other legal GOMBs, where the dashed boxes refer to the MBs.

2.2 CPQ-Based Bit Allocation

An iteration-based bit allocation method for intra-frame encoding is developed to pursue constant perceptual quality among GOMBs. The flowchart of the method is shown in Fig. 2. The idea is to find a proper target quality \( Q_T \) that when all the GOMBs in the intra-frame are encoded to \( Q_T \), the encoding results (total number of bits or frame quality)
meet the given constraint $T$. The encoding is called rate constrained when $T$ is the constraint on bit number for encoding the frame, and quality constrained when $T$ is the constraint on frame quality.

In this paper, we try to improve the perceptual quality of the reconstructed frames, and the object of constant perceptual quality is for this purpose. So, we use Multi-scale SSIM (MS-SSIM) index\cite{33} to measure the perceptual quality, which has been proved to have better correlation with human assessment.

2.2.1 Initial Encoding

In the initial encoding, the fixed-QP method is used to encode the frame, in which all the MBs are encoded by a fixed QP $QP_0$. Suppose the quality of $GOMB_{i,j}$ after the initial encoding is $Q_{G}^{(0)}(i,j)$, the initial target quality for the following CPQ encoding is calculated as

$$Q_T^{(0)} = \frac{\sum_{GOMB_{i,j}} Q_{G}^{(0)}(i,j)}{\text{numel}(S_G)},$$

(2)

where $\text{numel}(S)$ is a function to get the number of elements in set $S$. $QP_0$ should be carefully determined so that the result (bits or quality) of the initial encoding is as close to $T$ as possible. Given $T$, there exist a lot of R-Q (or D-Q) models that can be used to help determining the $QP_0$\cite{7,8,34}.

2.2.2 CPQ Encoding with Given $Q_T$

Given a target quality $Q_T$ for the GOMBs, the CPQ encoding is performed to pursue the constant perceptual quality. The process of CPQ encoding is shown in Algorithm 1.

In the algorithm, $\theta$ is the adjusting step of the QPs for the MBs in an GOMB. Function $\text{direct}(\cdot)$ is used to determine to which direction the QPs should be adjusted, which is defined as

$$\text{direct}(q, Q_T) = \begin{cases} 1 & q > Q_T + \Delta Q_T \\ -1 & q < Q_T - \Delta Q_T \\ 0 & \text{other} \end{cases}$$

(3)

Algorithm 1 CPQ Encoding

Require: $Q_T$, $Q_G$, $QP_B$
Ensure: $T_{act}$, $Q_G$, $QP_B$
1: $it \leftarrow 1, H_{QP_B} \leftarrow \{QP_B\}$
2: while do
3: $it \leftarrow it + 1$
4: $\forall (i,j) \in S_G, M_G(i,j) \leftarrow \theta \cdot \text{direct}(Q_G(i,j), Q_T)$
5: $\forall (u,v), \Delta Q_P(u,v) \leftarrow \text{round}\left(\frac{Q_{G}^{(0)}(i,j)}{\text{numel}(S_{G,u,v})}\right)$
6: $\forall (u,v), Q_{P_B}^{(1)}(u,v) \leftarrow \text{clip3}(Q_{P_B}(u,v) + \Delta Q_P(u,v), 0, 51)$
7: if $Q_{P_B}^{(1)} \in H_{QP_B}$ then
8: break
9: else
10: $QP_B \leftarrow Q_{P_B}^{(1)}$, $H_{QP_B} \leftarrow \{H_{QP_B}, QP_B\}$
11: end if
12: Encode the frame with $QP_B$, and get $T_{act}, Q_G$
13: end while

Where, $q$ states for the quality (SSIM) of an GOMB, and $\Delta Q_T$ is the threshold to terminate the CPQ encoding. Set $S_{u,v}$ contains the GOMBs that $MB_{u,v}$ belongs to, and it is defined as

$$S_{u,v} = \{GOMB_{i,j}|MB_{u,v} \in GOMB_{i,j}\}$$

(4)

Function $\text{round}(x)$ gets the nearest integer of $x$, and $\text{clip3}(x, a, b)$ clips $x$ into the range of $[a, b]$.

2.2.3 Searching for the Best $Q_T$

Generally, the result of the CPQ encoding (the number of frame bits and frame quality) changes monotonously with $Q_T$. Figure 3 shows the relation between $Q_T$ and the result of the first frame of “bus” encoded by the CPQ encoding. We can find that, the higher $Q_T$ the GOMBs are encoded to, the higher frame quality the encoding achieves, and the more bits the encoder spends on the frame. Based on the monotonicity discussed above, we propose an adaptive-step method to search for the best $Q_T$ to meet the target $T$, which is shown in Algorithm 2. In the algorithm, $S_{up}$ is a set of available $Q_T$ adjusting steps for the encoder, $B_{OT}$ is the boundary condition to terminate the searching of $Q_T$. Func-

![Fig. 3](image)

Algorithm 2 Adaptive-step Method

Require: $T$, $Q_T^{(0)}$, $Q_G^{(0)}$, $QP_B$, $S_{up}$, $B_{OT}$
Ensure: $Q_T$, $T_{act}$
1: $Q_T \leftarrow Q_T^{(0)}$, $Q_G \leftarrow Q_G^{(0)}$, $QP_B \leftarrow QP_B$
2: $H_{OT} \leftarrow \{\}$, $k \leftarrow 1$
3: $[T_{act}, Q_G, QP_B] \leftarrow \text{CPQ}(Q_T, Q_G, QP_B)$
4: while do
5: $sn \leftarrow \text{comp}(T_{act}, T, B_{OT})$
6: if $sn == 0$ then
7: break
8: end if
9: $Q_T^{(1)} \leftarrow Q_T + sn \cdot S_{up}(k)$
10: if $Q_T^{(1)} \in H_{OT}$ then
11: $k \leftarrow k + 1$
12: else
13: $Q_T \leftarrow Q_T^{(1)}$, $H_{OT} \leftarrow \{H_{OT}, Q_T\}$
14: $[T_{act}, Q_G, QP_B] \leftarrow \text{CPQ}(Q_T, Q_G, QP_B)$
15: end if
16: if $k > \text{numel}(S_{up})$ then
17: break
18: end if
19: end while
Table 1 Parameter setting for the CPQ-based method.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>2</td>
</tr>
<tr>
<td>$\Delta QT$</td>
<td>0.01</td>
</tr>
<tr>
<td>$S_{stp}$</td>
<td>[0.01, 0.005, 0.0025]</td>
</tr>
<tr>
<td>$B_{QT}$</td>
<td>Rate constrained: 0.02</td>
</tr>
<tr>
<td></td>
<td>Quality constrained: 0.0005</td>
</tr>
</tbody>
</table>

The rate distortion function $comp(T_{act}, T, B_{QT})$ is defined in different form depends on the type of constraint. In rate constraint encoding, it is defined as

$$comp(T_{act}, T, B_{QT}) = \begin{cases} 1 & T_{act} < T \cdot (1 - B_{QT}) \\ -1 & T_{act} > T \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

And in quality constraint encoding, it is defined as

$$comp(T_{act}, T, B_{QT}) = \begin{cases} 1 & T_{act} < T \\ -1 & T_{act} > T + B_{QT} \\ 0 & \text{other} \end{cases} \quad (6)$$

2.3 Parameters Setting

There are several encoding parameters in the CPQ-based method, and the parameters setting should give consideration to both the encoding performance and the encoding complexity. In this paper, the parameters are set empirically as it is shown in Table 1. We found that, smaller adjusting steps or more strict thresholds for terminating could not improve more on the encoding performance, but brings much more encoding complexity. More details about the parameter setting will be discussed in Sect. 4.

3. Experiments and Results

The proposed method is tested on JM18.6 [35], the reference software of H.264/AVC. Since there is barely no optimal bit allocation for intra-frame encoding, we compare the proposed method with the recommended fixed-QP method in JM18.6.

3.1 Rate Constrained Encoding

We first evaluate the performance of CPQ-based method in rate constrained intra-frame encoding, where the bits used by the CPQ-based method is constrained to be not more than that used by the fixed-QP method.

3.1.1 Rate-Distortion Performance

Figure 4 shows the R-D curves of the four intra-frames encoded by the CPQ-based method and the fixed-QP method, respectively. For each frame, it is first encoded by the fixed-QP method with QPs of 25, 30, and 35, respectively. And then the CPQ-based encoding is performed based on the results of the fixed-QP method. It is clear that the CPQ-based method can achieve better R-D performance than the fixed-QP method. We can also find that, the performance of the CPQ-based method varies with the frames. We will discuss more about this phenomenon in Sect. 4.

3.1.2 Subjective Quality

To illustrate the quality improvement by the CPQ-based method more clearly, we show more details of the encoded results of the 1st frame of “bus(CIF),” “container(CIF),” “paris(CIF)” and “parkjoy(720P)” respectively.

Fig. 4 The R-D curves of four frames which are encoded as intra-frames by the CPQ-based method and the fixed-QP method, respectively. From left to right and from top to bottom: the 1st frame of “bus(CIF),” “container(CIF),” “paris(CIF)” and “parkjoy(720P),” respectively.
Fig. 5  Comparing the subjective quality of the 1st frame of "bus". The QP used by the fixed-QP method is 30, and the number of bits used by the two methods are 108970 (fixed-QP) and 108882 (CPQ), respectively.

Fig. 6  Comparing the subjective quality of the 1st frame of "paris". The QP used by the fixed-QP method is 30, and the number of bits used by the two methods are 114924 (fixed-QP) and 111159 (CPQ), respectively.

bits) on this areas. The results illustrate that, the CPQ-based method can achieve better perceptual quality on intra-frames than the fixed-QP method while using the same number of bits.
3.1.3 Quality Variation

Figure 7 shows the quality (SSIM) of all the GOMBs of the 1st frames of “bus” and “pairs” encoded by the CPQ-based method and fixed-QP method, respectively. Where, the QP used by the fixed-QP method is 30. It is clear that the quality of GOMBs encoded by the fixed-QP method spreads in a wide range, while the CPQ-based method achieves almost constant quality.

In order to compare the quality variation of the results encoded by the two methods numerically, we use the standard deviation of the GOMBs’ quality to describe the extent of the quality variation in a frame. The quality variation achieved by the CPQ-based method and the fixed-QP method are noted as $\sigma_{cpq}$ and $\sigma_{fix}$, respectively. Then, the reduction on quality variation by the CPQ-based method is defined as

$$\Delta \sigma_{cpq} = \frac{\sigma_{cpq} - \sigma_{fix}}{\sigma_{fix}} \times 100\%.$$  (7)

The results are shown in Table 2. Thirteen frames from 9 different CIF sequences and 2 720P sequences are used in the test. The QPs used by the fixed-QP method are 25, 30 and 35, and the rate constrained CPQ encoding is setup correspondingly. We can find that the CPQ-based method can greatly reduce the quality variation among GOMBs (45% ~ 60% in average and up to nearly 80%) compared with the fixed-QP method.

3.2 Quality Constrained Encoding

In quality constrained encoding, the CPQ-based method is constrained to encode an intra-frame with quality not lower than that encoded by the fixed-QP method. The results are shown in Table 3, in which $R$ states for the number of bits used in the encoding, $Q$ is the quality of the reconstructed frame (measured by the MS-SSIM index). $\Delta R$ and $\Delta Q$ state for the percentage of bit saving and quality improvement by the CPQ-based method compared with the fixed-QP method, respectively. From Table 3 we can see that, the CPQ-based method uses much fewer bits on most of the frames than the fixed-QP method (4% ~ 9% in average and up to 24.22%), while maintaining the same or even higher frame quality.

We can also see that, as it is found in the rate constrained encoding, the performance of the CPQ-based method varies with different frame contents. Though the CPQ-based method saves bits in most of the conditions and has extremely better performance on several frames (see the data that bolded), it has lower performance on some frames (see the data that underlined).

3.3 Encoding Performance on Sequence

In prediction-based video coding, a better reference frame usually improves the encoding performance of the following frames [6], and thus can improve the encoding performance on the whole sequence. Since it has been proved that the CPQ-based method can achieve better intra-frames, we want to see how much improvement it can bring to the whole sequence encoding.

The baseline encoder of H.264/AVC without rate control [35] is used as the benchmark for the comparing, we call it SEQ-FIX because it encode all the frames in the sequence by the fixed-QP method. In the CPQ-based sequence encoding, only the intra-frames are encoded by the CPQ-based method, and the other frames are encoded by the fixed-QP method with QP the same with that used in SEQ-FIX, we
Table 3 Comparing the R-D performance on the intra-frames (the 1st frame of different sequences) in quality-constrained encoding.

<table>
<thead>
<tr>
<th>Sequences</th>
<th>QP = 25</th>
<th></th>
<th>QP = 30</th>
<th></th>
<th>QP = 35</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>fixed-QP</td>
<td>CPQ</td>
<td>fixed-QP</td>
<td>CPQ</td>
<td>fixed-QP</td>
<td>CPQ</td>
</tr>
<tr>
<td></td>
<td>$\Delta R$ (%)</td>
<td>$\Delta Q$</td>
<td>$\Delta R$ (%)</td>
<td>$\Delta Q$</td>
<td>$\Delta R$ (%)</td>
<td>$\Delta Q$</td>
</tr>
<tr>
<td>bus(CIF)</td>
<td>174869.0</td>
<td>0.9948</td>
<td>108970.0</td>
<td>0.9847</td>
<td>62775.0</td>
<td>0.9597</td>
</tr>
<tr>
<td>foreman(CIF)</td>
<td>87050.0</td>
<td>0.9918</td>
<td>49796.0</td>
<td>0.9828</td>
<td>29442.0</td>
<td>0.9706</td>
</tr>
<tr>
<td>container(CIF)</td>
<td>115645.0</td>
<td>0.9859</td>
<td>68364.0</td>
<td>0.9706</td>
<td>39598.0</td>
<td>0.9540</td>
</tr>
<tr>
<td>flower(CIF)</td>
<td>213278.0</td>
<td>0.9983</td>
<td>148217.0</td>
<td>0.9953</td>
<td>94914.0</td>
<td>0.9876</td>
</tr>
<tr>
<td>news(CIF)</td>
<td>91587.0</td>
<td>0.9943</td>
<td>59110.0</td>
<td>0.9885</td>
<td>37844.0</td>
<td>0.9791</td>
</tr>
<tr>
<td>pairs(CIF)</td>
<td>175108.0</td>
<td>0.9956</td>
<td>114924.0</td>
<td>0.9896</td>
<td>72153.0</td>
<td>0.9790</td>
</tr>
<tr>
<td>silent(CIF)</td>
<td>126724.0</td>
<td>0.9915</td>
<td>68996.0</td>
<td>0.9784</td>
<td>37403.0</td>
<td>0.9541</td>
</tr>
<tr>
<td>stefan(CIF)</td>
<td>175407.0</td>
<td>0.9962</td>
<td>114484.0</td>
<td>0.9928</td>
<td>75978.0</td>
<td>0.9855</td>
</tr>
<tr>
<td>tempete(CIF)</td>
<td>201078.0</td>
<td>0.9966</td>
<td>129495.0</td>
<td>0.9916</td>
<td>78003.0</td>
<td>0.9779</td>
</tr>
<tr>
<td>parkjoy(720P)</td>
<td>1312366.0</td>
<td>0.9905</td>
<td>806815.0</td>
<td>0.9804</td>
<td>458791.0</td>
<td>0.9608</td>
</tr>
<tr>
<td>mobcal(720P)</td>
<td>1749813.0</td>
<td>0.9919</td>
<td>1030794.0</td>
<td>0.9812</td>
<td>582448.0</td>
<td>0.9601</td>
</tr>
<tr>
<td>Average</td>
<td>−6.38</td>
<td>0.0003</td>
<td>−8.82</td>
<td>0.0002</td>
<td>−4.11</td>
<td>0.0002</td>
</tr>
</tbody>
</table>

Fig. 8 Frame bits and quality (MS-SSIM) of each frame in sequence “bus” and “paris”.

3.3.1 Encoding Performance on Each Frame

Figure 8 shows the results on each frame of the CIF sequences “bus” and “paris”, encoded by SEQ-CPQ and SEQ-FIX, respectively. Where the QP used by the SEQ-FIX and the initial QP for CPQ in SEQ-CPQ is 30. We can find that, though we only control the bit number that used on the intra-frame, the SEQ-CPQ encodes the other frames with almost the same number of bits to those used in SEQ-FIX. On the other hand, all the quality of frames are improved obviously by the SEQ-CPQ scheme than SEQ-FIX, though we only optimize the bit allocation on the intra-frames. The results show clearly the benefits that CPQ-based intra-frame encoding can bring to the whole sequence encoding.

3.3.2 R-D Performance

To compare the R-D performance of the two encoding schemes, we draw the R-D curves of their results in Fig. 9.
The QPs used by the SEQ-FIX scheme are 25, 30 and 35. We can see it clearly that the SEQ-CPQ scheme achieves better R-D performance than the SEQ-fixedQP scheme.

3.4 Encoding Complexity

From the algorithms we can see that, the CPQ-based method needs to encode a frame multi-times to find the final solution, this brings much complexity to the encoding. In this subsection, we show the encoding complexity of the proposed method.

3.4.1 Comparing with the DP Method

In Table 4, we count the encoding times of each intra-frame by the CPQ-based method. We can see that, the average encoding times of a frame is about 20 ∼ 40.

We can compare the proposed method with the DP method. It has been pointed out that the encoding complexity of DP method is $O(N \cdot |x|^M)$ [11], where $N$ is the number of encoding units, $|x|$ is the number of QPs can be used, and $M$ is the number of dependent encoding units. In intra-frame encoding, no single MB in a Slice is encoded independently, except the first one. In this case, $N$ and $M$ are both the number of MBs in a Slice. As a result, it needs $|x|^S$ times of Mb encoding for each Slice by the DP method, where $S$ is the number of MBs in a Slice, and needs about $|x|^S / S$ times of frame encoding for the DP method on each intra-frame.

In the proposed method, the deference between the maximum and minimum QP used for the MBs is about 15, this corresponds to that $|x| = 15$; the size of a Slice is set as a whole frame, in the CIF sequences this corresponds to that $S = 396$. We can find it clearly that, the DP method is too complicate to be used in intra-frame encoding, while the proposed method is a much better choice.

3.4.2 Encoding Complexity on the Whole Sequence

The results in Table 4 show that, the proposed method is still quite time consuming to encode a single frame. However, the total complexity for the whole sequence encoding is not so unacceptable. In sequence encoding, only the intra-frames are encoded multi-times, the other frames are encoded only once. In this sense, the whole complexity for sequence encoding is much lower, which is depends on the size of GOP.

Suppose the average encoding times needed by an intra-frame is $N_I$, the size of GOP is $G$, and then the average encoding times $N_s$ needed by a frame in the sequence can be estimated as

$$N_s = \frac{N_I + G - 1}{G}.$$  \hspace{1cm} (8)

Based the results in Table 4, when $G = 15$, the encoding complexity of SEQ-CPQ is about 2 ∼ 4 times of SEQ-FIX.

Further, since intra-frame encoding doesn’t need to do the motion estimation (ME), the encoding time of intra-frames are much lower than that of inter-frames, this can be seen clearly in Table 5. In this sense, the encoding complexity of the proposed method can be even lower.

4. Discussion

The experimental results have shown the advantage of the proposed CPQ-based bit allocation method. In this section, we discuss more about the method in two aspects, the parameters setting and the variational performance on different contents.

4.1 Parameter Setting

The parameters ($\theta$, $\Delta Q_T$, $S_{stp}$ and $B_{QT}$) in the CPQ-based method are used to control the iteration and the coding performance. Generally, the smaller adjusting steps and thresholds are, the better results will be found by the iteration, but the more times of iteration will be needed. We have given the empirically selected parameters for the method in Table 1, we call this set of parameters as SET-I. To compare, we chose a set of parameters for rate constrained encoding with much smaller adjusting steps and stricter thresholds, which is set as $\theta = 1$, $S_{stp} = [0.01, 0.005, 0.002, 0.001]$, $\Delta Q_T = 0.005$, $B_{QT} = [0.005, 0]$, and we call it SET-II.

Figure 10 shows the R-D curves of the results of the 1st

<table>
<thead>
<tr>
<th>Sequences</th>
<th>$QP = 25$</th>
<th>$QP = 30$</th>
<th>$QP = 35$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bus(CIF)</td>
<td>5</td>
<td>12</td>
<td>57</td>
</tr>
<tr>
<td>foreman(CIF)</td>
<td>23</td>
<td>23</td>
<td>38</td>
</tr>
<tr>
<td>container(CIF)</td>
<td>37</td>
<td>53</td>
<td>25</td>
</tr>
<tr>
<td>flower(CIF)</td>
<td>15</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>news(CIF)</td>
<td>6</td>
<td>30</td>
<td>48</td>
</tr>
<tr>
<td>pairs(CIF)</td>
<td>5</td>
<td>36</td>
<td>10</td>
</tr>
<tr>
<td>silent(CIF)</td>
<td>33</td>
<td>14</td>
<td>33</td>
</tr>
<tr>
<td>stefan(CIF)</td>
<td>23</td>
<td>18</td>
<td>37</td>
</tr>
<tr>
<td>tempete(CIF)</td>
<td>5</td>
<td>7</td>
<td>73</td>
</tr>
<tr>
<td>parkjoy(720P)</td>
<td>29</td>
<td>36</td>
<td>57</td>
</tr>
<tr>
<td>mobcal(720P)</td>
<td>26</td>
<td>26</td>
<td>46</td>
</tr>
<tr>
<td>Average</td>
<td>18.8</td>
<td>25.6</td>
<td>41.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sequences</th>
<th>I frame (ms)</th>
<th>P frame (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bus(CIF)</td>
<td>181</td>
<td>2712</td>
</tr>
<tr>
<td>foreman(CIF)</td>
<td>137</td>
<td>2800</td>
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<tr>
<td>container(CIF)</td>
<td>139</td>
<td>2786</td>
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<tr>
<td>flower(CIF)</td>
<td>164</td>
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<td>136</td>
<td>2797</td>
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<tr>
<td>pairs(CIF)</td>
<td>157</td>
<td>2783</td>
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<tr>
<td>silent(CIF)</td>
<td>143</td>
<td>2733</td>
</tr>
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<td>stefan(CIF)</td>
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<td>tempete(CIF)</td>
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<td>parkjoy(720P)</td>
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</tr>
<tr>
<td>mobcal(720P)</td>
<td>1147</td>
<td>25124</td>
</tr>
</tbody>
</table>
few of either the two kinds of areas, the proposed method structures, the CPQ-based method can play a role in improv-
frames which have both abundant textures and lots of strong can easily improve the perceptual quality. As a result, in the tion to the frame, but adding them to encode the Area-blue to be distorted. The reduction of bits from the hard use larger QPs on the areas with strong structures, which features, which are easily to be distorted by quantization, and prefers to allocate more bits to the areas with abundant tex-

can bring benefits to the whole sequence encoding. The method compared to the commonly used fixed-QP method encoding performance can be improved greatly by the proposed method compared to the commonly used fixed-QP method in intra-frame encoding. Further experiments show that the intra-frame encoding optimized by the CPQ-based method can bring benefits to the whole sequence encoding. The complexity of the proposed method is acceptable for offline video compression applications.

4.2 Performance Depends on the Contents

The results of the experiments have shown that the perfor-
mance of the CPQ-based method varies with the different contents and QPs, this phenomenon is caused by the intrin-
sic property of the CPQ-based method.

The results in Figs. 5 and 6 have shown that the bit allocation by the CPQ-based method relates strongly with the dif-
fierent areas that the frame contents. Survey the four different areas that compared in the figures, we can find that the contents in the Area-reds have much stronger structures than those in the Area-blues. This illustrates that the CPQ-based method prefers to allocate more bits to the areas with abundant textures, which are easily to be distorted by quantization, and use larger QPs on the areas with strong structures, which are hard to be distorted. The reduction of bits from the hard to be distorted Area-reds brings no more perceptual distortion to the frame, but adding them to encode the Area-blues can easily improve the perceptual quality. As a result, in the frames which have both abundant textures and lots of strong structures, the CPQ-based method can play a role in improving the encoding performance. But, when the frame has few of either the two kinds of areas, the proposed method could not work. This is why the proposed method has lower performance on scenes such as “foreman” “flower” and “silent”. Fortunately, most of the natural scenes contains both these two kinds of areas.

5. Conclusion

In this paper, we proposed a CPQ-based method for intra-
frame bit allocation, in which all the GOMBs, which are used to define the local areas in a frame, are encoded to have as similar a perceptual quality as possible under the given encoding constraint. The perceptual quality of the GOMBs is measured by the SSIM index. The results show that in most of the frames with different natural scenes, the encoding performance can be improved greatly by the proposed method. Further experiments show that the intra-frame encoding optimized by the CPQ-based method can bring benefits to the whole sequence encoding. The complexity of the proposed method is acceptable for offline video compression applications.

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