A Rate Control Algorithm for Video-based Point Cloud Compression

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Abstract—Video-based point cloud compression (V-PCC) has been an emerging compression technology that projects the 3D point cloud into a 2D plane and uses high efficiency video coding (HEVC) to encode the projected 2D videos (geometry video and color video). In this work, we propose a rate control algorithm for the all-intra (AI) configuration of V-PCC. Specifically, based on the quality-dependency existing in the projected videos, we develop an optimization formulation to allocate target bits between the geometry video and the color video. Furthermore, we design a two-pass method for HEVC to adapt to the new characteristics of projected videos, which significantly improves the accuracy of rate control. Experimental results demonstrate that our algorithm outperforms V-PCC without rate control in R-D performance with just 0.43% bitrate error.

Index Terms—V-PCC, rate control, optimal bit allocation, two-pass, quality-dependency

I. INTRODUCTION

A point cloud is a three-dimensional (3D) data representation that has attracted extensive attention for describing the spatial structure and properties of 3D objects. Each point in point clouds contains rich 3D coordinate information (x, y, z) and optional characteristics such as color [1]. In recent years, point clouds have been widely employed in various immersive media applications [2]. However, thousands of points represent a 3D object, which is a problem for hardware storage and network transmission, prompting the development of the high efficiency point cloud compression (PCC).

The Moving Picture Expert Group (MPEG) develops two distinct compression technologies: geometry-based PCC (G-PCC) and video-based PCC (V-PCC) [3]. Different from G-PCC, which compresses the point cloud in its original domain, V-PCC projects the position and color attributes of the 3D point cloud into different 2D patches [4]. The projected 2D patches are then placed in different 2D images with the size of W × H, which make up 2D videos (geometry video, color video) [5]. In this case, we can make full use of mature 2D video compression frameworks such as HEVC [6] to compress the projected 2D videos.

Due to the limited bandwidth in actual transmission, rate control (RC) is an indispensable part of a compression framework [7]–[9]. Nonetheless, the RC algorithm is under-explored for V-PCC. To the best of our knowledge, there are few studies on V-PCC rate control. In [10], the authors calculate the QPs of the geometry and color videos by solving a bit allocation problem. To provide more precise rate control, Liu et al. [11] take advantage of the rate-distortion (R-D) characteristics of seven regions to calculate the QP for each region. The adjustment of QP in the work above is still rough. To this end, [12] employs the rate control mechanism in HEVC to refine QP adjustment, in which each frame in the geometry and color videos can be assigned a different QP.

Nevertheless, in [12], the quality-dependency between the geometry and color videos is not considered in the bit allocation. The following are the primary contributions of this work: (1) We are the first to propose an efficient RC algorithm for AI configuration of V-PCC and validate its good performance on V-PCC test model (TMC2-10.0) [13]. Note that TMC2-10.0 is associated with HEVC reference software (SCM8.8) [14]. (2) An optimal bit allocation formulation is proposed by establishing a quality-dependency model and R-D models. (3) A two-pass rate control algorithm for HEVC is designed to improve the accuracy of rate control. Different from other two-pass schemes [15], [16], our scheme not only improves the accuracy of the model parameters but also guides the bit allocation of the group-of-pictures (GOP).

The rest of this paper is structured as follows. Section II introduces the proposed novel rate control framework for V-PCC, including an optimal bit allocation algorithm and a two-pass rate control method for HEVC. The experimental results are presented in Section III. Finally, Section IV concludes the paper.

II. PROPOSED RATE CONTROL ALGORITHM FOR V-PCC

In V-PCC, the point cloud generates occupancy map (OCC), geometry video (GV), color video (CV), and auxiliary patch information (PATCH) through several techniques such as path and packing. The OCC is encoded with a lossless video.
encoder, and the PATCH also selects lossless encoding. Accordingly, the consumed bits of the compressed OCC and PATCH are constant. It means that the proposed bit allocation algorithm only works on GV and CV. The two-pass-based RC method is then adopted to adjust GV and CV bits to the allocated target bits. The proposed method is described in full below.

A. Optimal Bit Allocation Algorithm

**Rate-Distortion (R-D) models for geometry and color videos:** Several symbols are used for simplicity, whose exact meaning can be found in Table I. Refer to [17] for the detailed calculation process of distortion metrics \( D_G \) and \( D_C \). \( D_G \) represents D1 in [17], and \( D_C \) represents the point-to-point distortion in the Y component. In this paper, \( D_G \) and \( D_C \) are converted to PSNR values. The larger the \( D_G \) and \( D_C \) values, the smaller the point cloud coding distortion. Seven point clouds of three classes under different \( QP_G \) settings \((8, 12, \ldots, 40, 44)\) are encoded to derive the \( R_G - D_G \) model. Because the \( QP_G \) affects \( D_C \) and \( R_C \), when investigating the relationship between \( R_C \) and \( D_C \), we set \( QP_G \) to \((14, 18, \ldots, 46, 50)\) with a fixed \( QP_G \) \((24)\). The results for four point clouds are presented in Fig. 1. For the curve fitting, the following proposed R-D models are used,

\[
D_G = a_g \cdot R_G^{-1} + b_g, \quad (1)
\]

\[
D_C = a_c \cdot R_C^{-1} + b_c, \quad (2)
\]

where \( a_g, b_g, a_c, b_c \) represent the parameters of the models. Besides, \( a_g \) is a negative number. On the contrary, \( a_c \) is a positive number. \( \partial D_G / \partial R_G \) and \( \partial D_C / \partial R_C \) are derived as,

\[
\frac{\partial D_G}{\partial R_G} = \theta_g \cdot R_G^{-2}, \quad (3)
\]

\[
\frac{\partial D_C}{\partial R_C} = \theta_c \cdot R_C^{-0.9}, \quad (4)
\]

where \( \theta_g \) is equal to \(-a_g\) and \( \theta_c \) is equal to \(0.1 \cdot a_c\). Both \( \theta_g \) and \( \theta_c \) are greater than 0. It is worth noting that equations (3) and (4) will be used in the optimal bit allocation. The R-squared \( R^2 \) correlation coefficient is chosen to measure the accuracy of the proposed R-D models. Closer \( R^2 \) to 1 demonstrates higher model accuracy. As shown in Fig. 1, most of the \( R^2 \) results are close to 0.98, which implies sufficiently high accuracy of the R-D models.

**Quality-dependency modeling:** The point cloud is reconstructed from the geometry video, which contains location information. Following reconstructed point clouds, V-PCC recolors each point in point clouds. Thus, the quality of the compressed geometry video has a significant impact on the quality of the color video. We fix the \( QP_G \) to 22, 26, 30, 34 with various \( QP_C \) in the range of 12-36 (the change step is 4) to encode seven different point clouds. From Fig. 2, an approximated linear relationship between \( D_C \) and \( D_G \) for the same \( QP_C \) can be found,

\[
D_C = \kappa \cdot D_G + b, \quad (5)
\]

where \( \kappa \) is a linear coefficient ranging between [0.1, 0.5]. Based on numerous experiments, \( \kappa \) is set to 0.3 in this paper.

\[
\frac{\partial D_C}{\partial D_G} = \kappa. \quad (6)
\]

Moreover, the \( R^2 \) results of four point clouds are presented in Fig. 2, which confirms the accuracy of (5).

**Optimal bit allocation algorithm:** Unlike the 2D compression task, V-PCC has more than one distortion metric, including \( D_G \) and \( D_C \). It is necessary to integrate the two metrics to define the overall distortion. In the common test conditions (CTC) [17] of V-PCC, \( QP_G \) is about five smaller than \( QP_C \), which means the quality of geometry is far more important than that of color. For this reason, the overall distortion of the point cloud \( D_{\text{total}} \) can be expressed as:

\[
D_{\text{total}} = w \cdot D_G + D_C, \quad (7)
\]

where \( w \) is the weight of the geometry video. In this paper, \( w \) is set to 25. We set \( w \) to 20, 25 and 30, respectively. Experimental results show that when \( w=25 \), the R-D performance is
excellent. Under the limitation of target bits $R_{\text{tar}}$, the optimal bit allocation seeks to minimize the total distortion of the point cloud, which can be derived by:

$$\min \left\{ -(w \cdot D_G + D_C) \right\} \quad \text{s.t.} \quad R_G + R_C \leq R_{\text{tar}}. \quad (8)$$

Note that $D_C$ and $D_G$ are PSNR values, which means that the larger the value of $D_C$ and $D_G$, the smaller the point cloud distortion. Next, we can introduce the Lagrangian multipliers method to solve the constrained optimization problem:

$$\min \left\{ -(w \cdot D_G + D_C) + \lambda (R_G + R_C - R_{\text{tar}}) \right\}, \quad (9)$$

where $\lambda$ is the Lagrangian multiplier for the optimization problem. Taking the derivative of (9) for $R_G$ and $R_C$, respectively, we get the following expression:

$$-w \frac{\partial D_G}{\partial R_G} - \frac{\partial D_C}{\partial R_G} + \lambda = 0, \quad (10)$$

$$-w \frac{\partial D_G}{\partial R_C} - \frac{\partial D_C}{\partial R_C} + \lambda = 0. \quad (11)$$

Convert Equations (10) and (11) to (12) and (13), respectively,

$$-w \frac{\partial D_G}{\partial R_C} - \frac{\partial D_C}{\partial R_G} + \lambda = 0, \quad (12)$$

$$-w \frac{\partial D_G}{\partial R_G} - \frac{\partial D_C}{\partial R_C} + \lambda = 0, \quad (13)$$

where $\frac{\partial D_C}{\partial D_G}$ represents the influence of the geometry on color, which is discussed in (6). Combining (3), (6) and (12), we can get:

$$R_G = \left( \frac{(w + \kappa) \cdot \theta_g}{\lambda} \right)^{\frac{1}{\psi}}. \quad (14)$$

Similarly, $\frac{\partial D_G}{\partial R_C}$ represents the influence of the color on geometry which is equal to 0. Combining (4) and (13), we have:

$$R_C = \left( \frac{\theta_c}{\lambda} \right)^{\frac{1}{\psi}}. \quad (15)$$

Combining (8), (14) and (15), the optimization problem will be formulated as:

$$\sqrt{(w + \kappa) \cdot \theta_g} \left( \frac{\theta_c}{\lambda} \right)^{\frac{1}{\psi}} \leq R_{\text{tar}}. \quad (16)$$

The analytical solution of (16) is still difficult to obtain. Note that $\theta_g$ and $\theta_c$ are fixed by the average value of seven point clouds and greater than zero, which indicates that (14) and (15) are monotonic functions of $\lambda$. According to the

### Algorithm 1: Iterative Solution Search for $\lambda$

**Input:**
- $\lambda_{\text{comp}} = \lambda_{\text{init}}$
- $R_{\text{tar}}$

**Output:**
- The best Lagrange multiplier $\lambda_{\text{comp}}$

1: $\lambda_{\text{comp}} = \lambda_{\text{init}}$
2: for Iter in [1, Itermax]
3: 
4: Calculate the consumed bits $R(\lambda_{\text{comp}})$
5: if $R(\lambda_{\text{comp}}) > R_{\text{tar}}$
6: 
7: 
8: $\lambda_{\text{max}} = \lambda_{\text{comp}}$
9: $\lambda_{\text{comp}} = (\lambda_{\text{comp}} + \lambda_{\text{min}}) / 2$
10: return $\lambda_{\text{comp}}$

According to the proposed optimal bit allocation algorithm, we test the original RC algorithm [7] of HEVC reference software (SCM8.8) [14] in V-PCC. The experimental results in Table II suggest the poor performance of the original RC algorithm. Two main reasons for the poor performance are found by analyzing experimental data.

1) Due to the lack of previous knowledge, the initialization parameters of the R-$\lambda$ model cannot be very accurate.

2) In the generation process of 2D videos, each patch is projected into two images: a near image and a far image, which solves the problem of multiple points projected to the same point [1]. In view of this characteristic, HEVC adopts the IP coding structure shown in Fig. 3 to encode the projected videos. Since the IP coding structure is quite different from the traditional ones, including All-Intra (AI), Random Access (RA), and Low Delay (LD), the existing RC algorithm in SCM8.8 can not sufficiently adapt to this new structure.

To address these shortcomings, a two-pass rate control algorithm is designed, which not only improves the accuracy of the initialization parameters of the model but also guides the bit allocation of IP structure well.
POC 0 1 2 3 nn-1 n-2 n-3

R to the closest I-frame. For instance, if the QP corresponding to the R is 28, 89.28% of the GOP bits are allocated to the I-frame. As shown in Table III, we collect four different QPs for each point cloud. The number of encoding frames is 32. After that, the obtained bitrates are designated as the target bitrates for our proposed RC algorithm. The bitrate error and R-D performance after comparison are given in Table IV.

### Table III

| Point Cloud | 44 | 36 | 28 | 20 | 12 |
|-------------|----|----|----|----|----|
| Loot        | 97.45% | 95.70% | 90.49% | 82.23% | 72.29% |
| Redandblack | 96.97% | 92.26% | 89.45% | 81.89% | 69.39% |
| Soldier     | 98.27% | 95.22% | 90.29% | 82.81% | 71.49% |
| Queen       | 98.52% | 91.65% | 87.39% | 79.79% | 68.03% |
| Longdress   | 97.30% | 93.08% | 88.93% | 82.43% | 71.40% |
| Basketball  | 98.81% | 93.00% | 89.56% | 82.68% | 73.65% |
| Dancer      | 97.45% | 93.52% | 88.87% | 83.37% | 73.81% |
| **Average** | 97.82% | 93.49% | 89.28% | 82.17% | 71.44% |

Table III: Proportion of I-frame Consumed Bits in a GOP with Different QPs for Geometry Video

Fig. 3. IPP.IP coding structure for geometry video and color video.

#### Make the model initialization parameters more accurate:
In our two-pass RC method, we employ the R-Q model instead of the R-λ model, which can be represented as:

\[ R = a \cdot QP^b, \]  

where \( a \) and \( b \) denote parameters of the model. We convert equation (17) to the logarithm domain,

\[ \ln R = \ln a + b \cdot \ln QP. \]  

Before the actual encoding, four different QPs are used to pre-encode the first frame of the geometry and color videos. Later, the consumed bits \( R \) are recorded, and four different pairs of \( (R_i, QP_i; i = 1, 2, 3, 4) \) can be used to approximate the linear relationship parameters \( (a, b) \) by applying the least squares method. Eventually, the accurate initialization of R-Q model parameters \( (a, b) \) can be achieved.

#### Guide bit allocation:
As shown in Table III, an I-frame and a P-frame form an IP GOP. As shown in Table III, we collect the ratio of bits consumed by I-frame in a GOP under different encoding QPs of various sequences. The proportion of I-frame consumed bits is more than 70% and this proportion is related to the encoding QP. Therefore, \( R_i \) \( (i = 1, 2, 3, 4) \) obtained in pre-encoding can guide the bit allocation in each IP GOP. By comparing the target bits of each GOP with \( R_i \) \( (i = 1, 2, 3, 4) \), the closest \( R_i \) can be found. The larger the QP corresponding to the closest \( R_i \), the more bits are allocated for the I-frame in the IP GOP. For instance, if the QP corresponding to the closest \( R_i \) is 28, 89.28% of the GOP bits are allocated to the I-frame.

### III. Experimental Results

To confirm the good performance of the proposed RC method, we implement it on TMC2-10.0 [13] and the corresponding SCM8.8 [14]. The anchor is the V-PCC without rate control, called the Fixed-QP method. Seven point clouds are encoded following the CTC [17] of V-PCC and using AI configuration. The number of encoding frames is 32. After that, the obtained bitrates are designated as the target bitrates for our proposed RC algorithm. The bitrate error and R-D performance after comparison are given in Table IV.

#### A. Bitrate Error
As shown in Table IV, the average bitrate error for all point clouds is 0.43%, which means our RC algorithm achieves accurate rate control. Moreover, the highest bitrate error is only 0.58%.

#### B. R-D Performance
Bjøntegaard delta (BD)-rate [19] is used to measure the R-D performance of our RC algorithm. The R-D performance is analyzed from the perspectives of geometry, color and geometry+color (overall). Based on (7), the overall R-D performance is computed by \( D_{total} \) and total rate. More bits are allocated to the geometry video in our bit allocation algorithm because it can produce a more significant R-D performance gain. As shown in Table IV, our algorithm achieves 8.2% and 5.2% Geom.BD-TotalRate gains on average in D1 and D2 with only 1.9% Color.BD-TotalRate loss on average in the Y component. Ultimately, the proposed algorithm achieves 7.48% Overall.BD-TotalRate gain on average.

### IV. Conclusion

An efficient rate control algorithm for V-PCC under AI configuration is presented in this paper. In particular, an optimal bit allocation formulation considering quality-dependency is proposed. Meanwhile, an iterative solution search approach is introduced to solve the formulation. In addition, a two-pass strategy for HEVC is developed to improve the accuracy of rate control. Based on the above methods, compared with the Fixed-QP method in V-PCC, the proposed RC algorithm achieves 7.48% Overall.BD-TotalRate gain on average with only 0.43% bitrate error.
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