Fast Single Depth Intra Mode Decision for Depth Map Coding in 3D-HEVC

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ABSTRACT

In 3D-HEVC, single depth intra mode has been applied and has been integrated into depth intra skip mode for efficient depth map coding. With single depth intra mode, one 2Nx2N prediction unit (PU) is predicted without high computational prediction process. In this paper, we propose a fast single depth intra mode decision method to address the problem of high computational complexity burden in depth intra mode decision of 3D-HEVC. To remove unnecessary computational complexity at the encoder, we early decide single depth intra mode for pruning quadtree in 3D-HEVC. This paper characterizes the statistics of smooth depth map signals for depth intra modes and analyzes distortion metrics of view synthesis optimization functionality as a decision criterion. With this proposed criterion, a single depth intra mode for intra coding has been detected and hierarchical CU/PU selection for intra coding can be stopped in 3D-HEVC. As a consequence, it utilizes the correlation between hierarchical block-based video coding and coding unit (CU)/PU mode decision for depth map coding so that a large number of recursive rate-distortion cost calculations can be skipped. We demonstrate the effectiveness of our approach experimentally. The simulation results show that the proposed scheme can achieve approximately 25.6% encoding time saving with 0.07% video PSNR/total bitrate gain and 0.18% synthesized view PSNR/total bitrate loss under all intra configuration.

Index Terms— Video coding, visual communications, 3D video codec, depth map coding, fast mode decision, statistical analysis, intra prediction

1. INTRODUCTION

Recently, depth image-based rendering (DIBR) have been noted for representing 3D video contents such as high resolution 3D videos and the multi-views plus depth (MVD) format [1]. One of this technique's characteristics is that it enables us to enjoy the arbitrary view angle of the scene such as virtual synthesized views in the 3D extension of High Efficiency Video Coding (3D-HEVC). In order to maximize benefits of this positive by-product, accurate depth map coding in 3D-HEVC is the key component so that some efficient depth map coding tools have been introduced, such as view synthesis optimization (VSO) [2], segment-wise DC (SDC) with depth lookup table (DLT) [3], and single depth intra mode [4]. These coding tools aim at increasing coding efficiency for a depth map component in 3D-HEVC and assume that depth maps consist of a large amount of smooth object areas bounded by sharp boundaries.

The current 3D-HEVC estimates the flat areas with single depth intra mode and preserves sharp edges with depth modeling mode (DMM) and SDC with DLT. Most of fast depth intra mode prediction techniques are associated with sharp edge prediction based on DMM and SDC since DMM and SDC require a lot of computational complexity for prediction. However, they do not utilize the dominant areas (e.g. smooth regions) of depth maps. As a result, these perspectives result in limited computational reduction even though all these methods decrease the computational complexity with negligible quality degradation.

In order to prevail high resolution 3D videos, a low complexity encoder in 3D-HEVC is needed while choosing the optimal depth intra mode. When we take single depth intra mode as a special mode for low complexity into consideration, it is obvious to contribute the reduction of computational complexity in depth intra coding.

To achieve this goal and maintain high quality of depth map coding, we propose finding a simple and computationally efficient criterion for detecting smooth regions of depth maps. In the literature, there is no previous works for early flat depth region decision for depth map coding.

The rest of this paper is organized as follows. Section 2 describes related works. We illustrate and analyze observation regarding single depth intra mode of 3D-HEVC in Section 3. In Section 4, we introduce the proposed algorithm. Experimental results are shown in Section 5. Finally, we conclude this paper in Section 6.

2. RELATED WORKS

In the 3D-HEVC, there are two categories of novel depth map coding tools for efficient depth intra coding. The first coding tools target at increasing the accuracy of depth map prediction by preserving sharp edges in such a way that it avoids visual artifacts such as ringing artifact. When it comes to sharp edge prediction, DMM and SDC with DLT are proposed. These techniques increase the complexity by estimating edge patterns, residual prediction of recursive transform unit (TU) prediction, and rate-distortion optimization (RDO) calculation for prediction unit (PU) decision. In particular, one of bottlenecks in depth map coding is SDC due to DC offset prediction at the encoder to represent residual depth maps.

To reduce encoding time of depth map coding in 3D-HEVC, fast algorithms for predicting edges have been proposed. These fast edge-based approaches decrease the number of pattern searches of DMM while maintaining accurate edges in depth maps. In the sequel, several fast methods aim at preserving accurate depth map edges since depth map represents geometry information between camera and objects for a view synthesis process. Chun-Su Park proposed a fast intra mode decision by utilizing edges in Hadamard transform domain. He utilized the characterization of Hadamard transform coefficients in order to detect DMM candidates for depth

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intra modes [5]. Xin Zhao et al. proposed a fast DMM prediction method by utilizing inter-component correlation. They exploited the inter-component correlation between the current depth mode and texture mode to reduce additional unnecessary computation [6]. Zhouye Gu et al. proposed a fast DMM selection method using most probable mode (MPM) for sharp edge regions in depth maps. They checked the variance in order to distinguish between DMM and other intra mode [7].

The drawback of above methods however is that these methods do not utilize smooth regions of depth maps and still require the huge amount of computational complexity for hierarchical block-based depth coding in the current 3D-HEVC.

The second depth map coding tool is to estimate the flat areas with single depth intra mode without quantization and transform for achieving high coding efficiency. Unlike edge-based fast methods, there is no speedup regarding smooth depth maps although flat areas generally dominate depth maps. As a consequence, the current fast mode decision methods in 3D-HEVC are restricted to edge-based fast intra mode decision so that the depth intra mode decision method fails to address the high computational complexity problem.

3. SINGLE DEPTH INTRA MODE

Recently, single depth intra mode in 3D-HEVC has been proposed and has been finally integrated into depth intra skip mode [8]. Since a lot of segments in depth map belong to smooth areas, single depth intra mode is frequently chosen as the best depth intra mode. Table 1 shows the percentage of single depth intra mode under the all intra configuration. Around 60% of the depth intra modes belong to these cases in Table 1. In general, single depth intra mode prefers large block sizes since depth maps consists of a large amount of homogeneous regions.

For prediction, single depth intra mode utilizes the observation that reconstructed pixel values of neighboring blocks are similar to the original pixel values of the current smooth area. In single depth intra mode, two neighboring samples are applied on the prediction values, the sample of the smallest rate-distortion (RD) cost is selected, and the selected one is applied for the current PU [4].

Regarding the computational complexity of single depth intra mode, in order to calculate the distortion, none of transform and quantization for residual signals is evaluated. In addition, there is no transmission and compensation of the prediction error.

Figure 1 and 2 draw an example of single depth intra mode regions at high bit rate. As one can see in Figure 1 and 2, large smooth areas inside objects belong to single depth intra mode.

3.1. Observation and analysis

In general, in order to decide a coding unit (CU) quadtree level or the PU, coding performance has been measured by computing the total bitrate and its distortion. For the distortion part, objective quality measurement of the mode decision is relied on a quantitative method, such as the sum of squared error (SSE) or the sum of absolute difference (SAD). Here, the cost J is

Table 1. The ratio of single depth intra mode (Anchor HTM 12.0, all intra configuration, and 200 frames)

Block Size	QP25	QP30	QP35	QP40
64×64	59.33%	56.91%	61.38%	69.03%
32×32	51.03%	56.46%	60.11%	62.80%
16×16	55.96%	57.32%	59.51%	63.59%
8×8	45.81%	50.83%	54.21%	61.31%

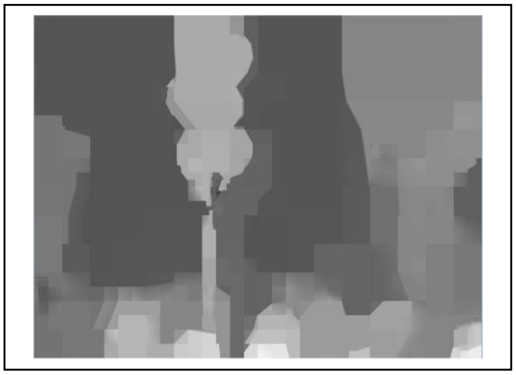

Fig. 1. The reconstructed depth map of Balloons sequence at QP 25.

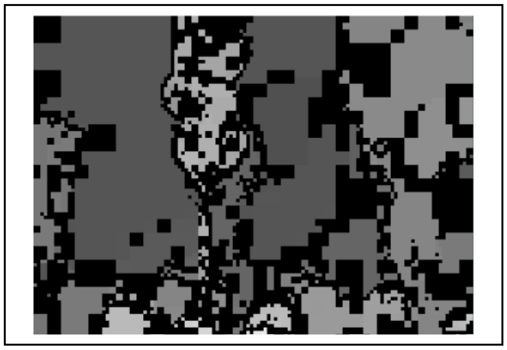

Fig. 2. The single depth intra mode areas of reconstructed depth map in gray color and other depth intra modes shown in black color on Figure 1.

$$J = D + \lambda \cdot R \,, \tag{1}$$

where λ is the Lagrange multiplier, D denotes the distortion part of the RD cost, and R represents the rate part of the RD cost.

To present the motivation of this paper, let us take account of a special case where the distortion part of RD costs fluctuates along with CU quadtree levels in depth map intra coding of 3D-HEVC. Furthermore, the rate part of single depth intra mode is almost zero and is negligible since only two neighboring candidates are available. As a consequence, the distortion part of RD cost contributes mostly for the optimal mode decision of the current PU. That is, we can assume the monotonicity constraint of the distortion part of RD cost in Equation (2) in terms of the CU quadtree level. In other words, the distortion part is

$$D_i > \sum_{j=1}^{k} D_{i+1,k} \quad , \tag{2}$$

where i denotes the CU quadtree level and k represents the number of PU modes on ith CU level such as 1, 2 or 4. When it comes to the optimal tree, we should focus on entropy of the distortion for PU. If we assume that the prediction error follows Laplacian distribution, the entropy of distortion part on the optimal CU quadtree is

$$\log(2 * \delta_i) > \max(\log(2 * \delta_{i+1})) \quad , \tag{3}$$

where δ is the squared root of variance scaled by 2. Thus, variance of input depth maps plays an important role in single depth intra mode.

It is important to note that the distribution of input depth maps for single depth intra mode is the same as that of prediction error due to only one predicted value of single depth intra mode on PU. That is, if there exist edges on the current depth map block, the prediction error of single depth intra mode should not be optimal because of decreased variance of sub units. Figure 3 illustrates an example of tree representation regarding variance of depth maps. Owing to large variance, the single depth intra mode in Figure 3 (A) should not be optimal compared to Figure 3 (B).

From this point of view, in order to find the optimal distortion of single depth intra mode, we need to check whether the variance of the original depth map is smooth or not. To decide smooth area, we use the monotonicity property in Equation (3) for input depth maps as well. That is, when the variance of the original data at CU depth *n* is smaller than or equal to that at CU depth *n*+1, the depth map is flat and it is a candidate for single depth intra mode. Table 2 shows the percentage of homogeneous regions in original depth maps with single depth intra mode and it justifies the assumption since large PUs contain flat regions at high bit rate.

Table 3 however demonstrates the rate of the incorrect single depth intra mode detection. If single depth intra mode is chosen at both the upper CU and the current CU, it is assumed to be an incorrect single depth intra mode detection. Single depth intra mode is not accurate at small PUs in Table 3. 74.30% 16x16 PUs are smooth in Table 2 and 73.08% 16x16 PUs are incorrect in Table 3 as well. It reflects that variance information on PU is not enough for CU/PU decision so that we exploit another metrics in Section 3.2.

3.2. Distortion metrics for depth intra coding

Depth maps on object areas are prone to contain one depth value. In addition, we should consider that the quality of virtual synthesized views is jointly determined by texture and depth map quality.

To address these characteristics, depth map coding tools take account of additional domain or residual distribution which is uniform and independent from quantization parameters. Based on this assumption, we use a distortion criterion that approximately minimizes the distortion part of RD costs as follows:

$$\sum_{(x,y)\in B} D(x,y) = \sum_{(x,y)\in B} D_{depth}(x,y) + \sum_{(x,y)\in B} D_{synth}(x,y) \quad , \qquad (4)$$

where *B* denotes the current PU, *x* and *y* depict the current pixel position within PU, D_{depth} presents the distortion function for depth maps, and D_{synth} is the distortion estimation for synthesized views. The form of D_{depth} is

$$D_{depth}(B) = a \cdot SSE(x,y) = a \cdot (f(x,y) - \hat{f}(x,y))^2 \quad , \qquad (5)$$

where *a* is a weight for depth distortion such as ½ in 3D-HEVC, *SSE* is a sum of squared distortion functions for depth distortion, *f*(*x*, *y*) presents the original depth map, and $\hat{f}(x,y)$ depicts the reconstructed depth map. Here, $\hat{f}(x,y)$ for single depth intra mode is the same as the reconstructed pixel value on neighboring blocks.

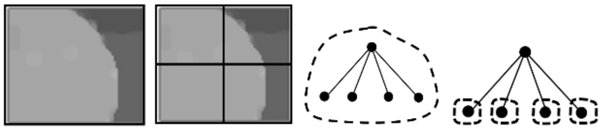
(A) (B) (C) (D)

Fig. 3. CU level determination and the tree representing their hierarchy: (a) a CU on level *n*; (b) four sub CUs on level *n*+1; (c) a tree node (dotted line) corresponding to a CU on level *n*; (4) four nodes (dotted line) regarding each CU on level *n*+1.

Table 2. The percentage of smooth depth maps with single depth intra mode (Anchor HTM12.0, all intra configuration, and 24 frames)

Block Size	QP25	QP30	QP35	QP40
64×64	69.07%	48.20%	37.84%	30.00%
32×32	70.00%	53.71%	44.88%	39.46%
16×16	74.30%	63.28%	58.28%	55.28%

Table 3. The prediction ratio of incorrect single depth intra mode (Anchor HTM12.0, all intra configuration, and 24 frames)

Block Size	QP25	QP30	QP35	QP40
32×32	44.6%	49.26%	60.43%	72.03%
16×16	73.08%	83.83%	91.04%	95.66%

Table 4. The percentage of zeroed *VSDE* with single depth intra mode (Anchor HTM12.0, all intra configuration, and 24 frames)

Block Size	QP25	QP30	QP35	QP40
64×64	97.34%	90.38%	81.55%	66.79%
32×32	93.01%	82.34%	72.59%	63.11%
16×16	88.48%	78.61%	71.85%	65.64%

The following D_{synth} denotes the *VSDE* oriented distortion part.

$$D_{synth}(x,y) = b \cdot VSDE(x,y) \quad , \qquad (6)$$

where *b* depicts a weight for *VSDE* such as ½ in 3D-HEVC, and *VSDE* represents a view synthesis distortion estimation function.

$$VSDE(x,y) = c^2 \cdot (f(x,y) - \hat{f}(x,y))^2 \quad , \qquad (7)$$

where *c* represents a coefficient of *VSDE* regarding corresponding color texture information and disparity approximation in [9-13]. As one can see, there is a relationship between SSE and *VSDE*. From Equations (5) to (7), we can rewrite Equation (4) as follows:

$$\sum_{(x,y)\in B} D(x,y) = \sum_{(x,y)\in B} (a + b \cdot c^2) \cdot (f(x,y) - \hat{f}(x,y))^2$$
$$\propto \sum_{(x,y)\in B} (c^2) \cdot (f(x,y) - \hat{f}(x,y))^2 = VSDE(x,y) \, , \qquad (8)$$

where *c* is large compared to *a* and *b*. For example, high texture areas on associated texture video are taken into consideration under flat depth map areas. That is, it is observed that *VSDE* becomes the main distortion criterion for single depth intra mode decision.

We use this observation to relate the statistical characteristics of the distortion parts of the RD cost for single depth intra mode. In the sequel, we minimize the variance for the distortion part of the RD cost by assuming that *VSDE* not only shows the hidden distortion for synthesized views but also represents the criterion for single depth intra mode. Table 4 shows the percentage of the zeroed *VSDE* when single depth intra mode is chosen. As one can see, they are correlated.

4. PROPOSED FAST SINGLE DEPTH INTRA MODE DECISION VIA TREE PRUNING

This paper proposes a novel fast single depth intra mode for CU/PU determination criterion by simply taking account of the variance of input depth map and model-based view synthesis distortion estimation. In particular, it is coupled with pruning tree. That is, the variance of depth map and the mean of *VSDE* completely characterize the efficiency of single depth intra mode. The following is the proof of the assumption.

4.1. Graphical model

We note that the optimal tree pruning problem has the same solution as the CU determination when we take the distortion metrics as the cost of the current CU in Equation (3) into account. To achieve the efficient solution for CU quadtree level detection, we construct a weighted graph $G = (V, E)$ where the nodes V consist of CUs. The edges E are the links between the current CU and sub CUs. The number of CUs and depth are denoted by n and d, respectively. The weights $W_1 = (w(v) : v \in V)$ are assigned to vertices according to *VSDE*, and the weights $W_2 = (w(e) : e \in E)$ are assigned to edges according to the difference between the variance of the current CU and those of sub CUs. We optimize the combination of W_1 and W_2.

Let us take an example. In Figure 3, the union of four nodes for CUs on level $d+1$ is a node for a CU on level d. In other words, there are four sub sets. That is, $G = G_1 \cup G_2 \cup G_3 \cup G_4$ and each CU corresponds to a node on a tree. Each cost of the sub nodes is equal to the variance given its *VSDE*. The cost of edge between the current CU and the lower CU is the difference of variance $Var(v_d) - Var(v_{d+1}) > 0$, where Var is a function for a variance of CUs, $\forall v_d \in G$ and $\forall v_{d+1} \in G_i$. As a consequence, the optimal solution prunes down sub trees for omitting TU/PU prediction.

4.2. Selecting the optimal tree pruning

In order to predict the computational complexity of smooth depth maps on the current CU quadtree level, we seek to minimize the prediction errors on the current CU level by using the following equation.

$$minD_{level}(B) = Var(B) + \lambda_{Dlevel} \cdot Mean(B) \quad , \qquad (9)$$

where *Mean* is a function for average *VSDE*, λ_{Dlevel} is larger than or equal to zero. In particular, λ_{Dlevel} is the Lagrangian multiplier for the tradeoff between mean of *VSDE* and variance among the CU quadtree levels. Here, we set it as a constant 1.

Since however *VSDE* is related to disparity values and has the smallest distortion under the condition that the disparity is less than 1, we simplify *VSDE* in Equation (9) with one in order to guarantee the high coding efficiency.

$$min\ D_{depth} = min\ (Var(v)) \quad , \qquad (10)$$

where the current CU $B' = (V', E')$, $\forall v \in V'$.

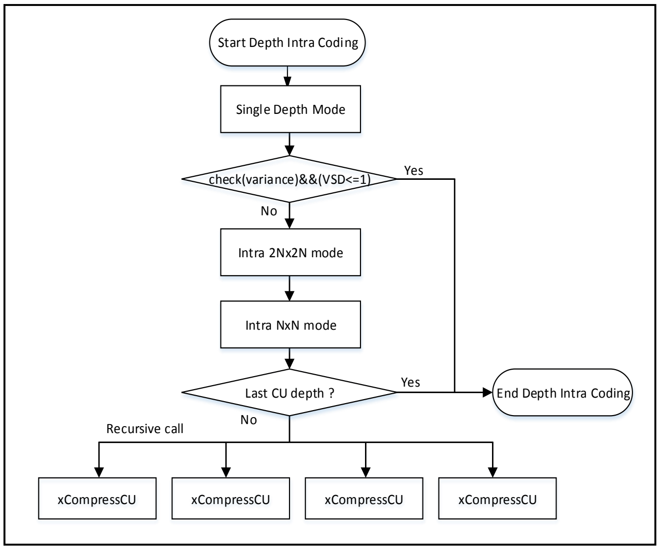

Fig. 4. Flowchart of the proposed fast single depth intra mode decision.

From Equation (10), we should optimize the pruning CU tree of the distortion with the adaptive Lagrange multiplier and the following condition should be met for the optimal CU depth level.

$$Var(B_{depth}) > Var(B_{depth+1}) \; . \qquad (11)$$

As one can see, Equation (11) is identical to Equation (3). Therefore, the CU/PU determination on proposed process is summarized as follows for each possible quadtree level d of the CU:

$$\text{Decision} = \begin{cases} 1, Var(v,d) \le Var(v,d+1)\ \&\&\ VSDE(v) <= 1 \\ \qquad\quad 0, otherwise \end{cases} . \qquad (12)$$

Finally, we conclude that we can successfully predict depth intra mode as single depth intra mode by checking the variance and model-based view synthesis distortion estimation. In order to utilize Equation (12), the proposed flowchart is depicted in Figure 4. If the proposed condition is met, the rest of intra mode prediction processes at the current and higher CU depths are skipped.

4.3. Computational complexity consideration

The additional computational complexity of the proposed criterion depends on the number of CU nodes and depth levels on the tree. Assume that the number of pixels on each vertex and the quadtree depth are denoted by n and d, it takes $O(n*d)$ since it only checks the variance of the input depth maps and the mean of *VSDE*.

5. EXPERIMENTAL RESULTS

The proposed method was implemented on the 3D-HEVC reference software version 12.0 (HTM 12) [14]. We compared the result of anchor HTM 12 with that of HTM 12 applying the proposed method. To evaluate the proposed method, we referred 3-view test case as the context of a Joint Collaborative Team on 3D Video coding development (JCT-3V). We conducted experiments on the eight test sequences listed in Table 5. These test sequences chosen by JCT-3V have been encoded using configuration with quantization parameters (QP) 25, 30, 35, 40 for texture and QP 34, 39, 42, 45 for depth maps. The experimental condition has been shown in Table 6. It is aligned with the all intra configuration test conditions and it is recommended by the JCT-3V [15]. The test platform was Intel® CPU 3 GHz with 12 cores, 24 GB RAM, with Windows 7 Professional 64-bit operating system.

In Table 7, it demonstrates that the proposed fast single depth intra mode is dependent on CU depth level and QP setting. It works well with large block size (64x64) at high bitrate (e.g. QP 25). In the current 3D-HEVC, single depth intra mode refers neighboring block samples as a prediction value. Thus, accurate neighboring PU at low QP increases the accuracy of the current PU of single depth intra mode. In other words, prediction for single depth intra mode at high QP is less accurate so that the percentage of single depth intra mode is reduced at high QP.

Table 8 shows the result of HTM 12 applying the proposed method with that of anchor HTM 12. In Table 8, two performance comparisons are considered using the Bjontegarrd delta rate [16]: video (texture and depth map) PSNR and synthesized video PSNR. The video PSNR/total bitrate is associated with the average PSNR (Peak Signal to Noise Ratio) of total bitrate regarding three input views and the synth PSNR/total bitrate is related to average PSNR and total bitrate for six synthesized views. The proposed method works only for depth map coding so that it is associated with depth map characteristics. PoznanHall and Kendo sequences save a lot of time compared to other test sequences since both sequences represent the indoor depth maps. In this case, these videos contain more redundant depth maps areas with flat regions. In particular, PoznanHall is of high resolution and the time saving is 45%.

When it comes to depth map generation method for analyzing results in Table 8, we can classify two classes: depth maps of computer-synthesized texture videos and depth map of natural texture videos. Depth maps of computer-synthesized texture videos (GhostTownFly, UndoDancer, and Shark sequences) possess more accurate depth maps so that the time saving of these sequences are higher than that of other sequences.

6. CONCLUSION

In this paper, we propose an optimal pruning tree based fast single depth intra mode decision for depth intra coding in 3D-HEVC. The aim is to take account of the properties of new depth intra coding tools and the distribution of depth map signals. As a consequence, by analyzing the distortion metrics, our proposed method is applied to hierarchical coding unit selection for intra coding. Moreover, low complexity encoding process for depth intra coding has been considered. Simulation results show that the proposed scheme can achieve approximately 25.6% encoding time saving with 0.07% video PSNR/total bitrate gain and 0.18% synth PSNR/total bitrate loss under all intra configuration.

Table 5. Test sequences

Title	Frame rate	Resolution	# of frames
Balloons	30	1024×768	300
Kendo	30	1024×768	300
Newspapercc	30	1024×768	300
GhostTownFly	25	1920×1088	250
PoznanHall	25	1920×1088	200
PoznanStreet	25	1920×1088	250
Shark	30	1920×1088	300
UndoDancer	25	1920×1088	250

Table 6. Experimental condition

UseEstimatedVSD	On
VSO	On
Single depth intra mode	On
QP (texture)	25, 30, 35, 40
QP (depth)	34, 39, 42, 45
DLT	On
TU max size	5
TU min size	2
RateControl	Off
RDOQ	On
WVSO	1
VSOWeight	10
DWeight	1
Comparison	HTM 12.0 and Proposed method

Table 7. The percentage of single depth intra mode increase with the proposed method (all intra configuration, 200 frames)

Block Size	QP25	QP30	QP35	QP40
64×64	61.20%	14.61%	4.56%	1.37%
32×32	3.96%	0.01%	0.39%	-3.61%
16×16	-1.93%	1.02%	2.06%	-3.95%
8×8	-5.81%	-4.00%	-0.20%	-2.08%

Table 8. Coding results with the proposed method under all intra configuration

	Video PSNR / total bitrate	Synth PSNR / total bitrate	Encoding time	Decoding time
Balloons	-0.02%	0.05%	80.00%	103.38%
Kendo	-0.02%	0.12%	77.37%	106.35%
Newspapercc	-0.05%	0.10%	88.89%	97.21%
GhostTownFly	-0.04%	0.10%	79.26%	99.64%
PoznanHall	-0.10%	0.40%	54.66%	101.77%
PoznanStreet	-0.17%	0.28%	82.13%	98.13%
UndoDancer	-0.06%	0.27%	63.89%	96.19%
Shark	-0.07%	0.13%	68.73%	100.12%
Average	-0.07%	0.18%	74.37%	100.35%

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