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Fast depth map mode decision based on depth–texture correlation and edge classification for 3D-HEVC ☆

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ABSTRACT

The 3D extension of High Efficiency Video Coding (3D-HEVC) has been adopted as the emerging 3D video coding standard to support the multi-view video plus depth map (MVD) compression. In the joint model of 3D-HEVC design, the exhaustive mode decision is required to be checked all the possible prediction modes and coding levels to find the one with least rate distortion cost in depth map coding. Furthermore, new coding tools (such as depth-modeling mode (DMM) and segment-wise depth coding (SDC)) are exploited for the characteristics of depth map to improve the coding efficiency. These achieve the highest possible coding efficiency to code depth map, but also bring a significant computational complexity which limits 3D-HEVC from real-time applications. In this paper, we propose a fast depth map mode decision algorithm for 3D-HEVC by jointly using the correlation of depth map-texture video and the edge information of depth map. Since the depth map and texture video represent the same scene at the same time instant (they have the same motion characteristics), it is not efficient to use all the prediction modes and coding levels in depth map coding. Therefore, we can skip some specific prediction modes and depth coding levels rarely used in corresponding texture video. Meanwhile, the depth map is mainly characterized by sharp object edges and large areas of nearly constant regions. By fully exploiting these characteristics, we can skip some prediction modes which are rarely used in homogeneity regions based on the edge classification. Experimental results show that the proposed algorithm achieves considerable encoding time saving while maintaining almost the same rate-distortion (RD) performance as the original 3D-HEVC encoder.

1. Introduction

Three-dimensional (3D) video has received more and more attention by the development of 3D content acquisition and display technologies in recent years. Multi-view video plus depth (MVD) is one of the most promising 3D video representations to support depth perception of 3D scenes [1,2]. In the MVD systems, a small number of captured texture video and its corresponding depth map are coded and the resulting bitstream packets are multiplexed into a 3D video bitstream [3,4]. After decoding texture video and depth map, much more intermediate virtual views suitable for displaying the 3D content on a free-viewpoint display can be synthesized using a depth-image-based-rendering (DIBR) technique [5]. Especially, the additional intermediate virtual view quality (rendered by the DIBR) highly depends on the coding result of depth map. Thus, high efficient depth map coding is most crucial to realize the 3D video practical applications.

As a result, efficient depth map coding has been recently investigated by Joint Collaborative Team on 3D Video Coding Extension Development (JCT-3V) established by international organization for standardization (ISO) MPEG and the international telecommunication union (ITU) VCEG, and 3D extension of high efficiency video coding (3D-HEVC) is developed for the effective compression of depth map data [6]. Different from the conventional texture video compression [7], it is key point to preserve the depth sharp object edges rather than the depth map visual quality. Based on this characteristic, 3D-HEVC introduces several new prediction modes and coding tools to preserve the sharp object edges in depth map coding, such as the Depth Modeling Mode (DMM) [8],

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segment-wise depth coding (SDC) [9], and motion parameter inheritance (MPI) [10]. Meanwhile, a computationally expensive exhaustive quadtree coding structure of HEVC is also used in 3D-HEVC depth map coding. Hence, the 3D-HEVC mode decision is required to be checked all combinations of conventional HEVC prediction modes [11–13] with the additional new tools to find the one with least rate distortion cost in depth map coding. These techniques achieve the highest possible coding efficiency but require a very high computational complexity, which limit 3D-HEVC from the practical applications. Therefore, fast algorithms, which can reduce the complexity of depth map coding without sacrificing rate distortion (RD) performance, are extremely necessary for 3D-HEVC real-time applications.

A number of fast algorithms [14–19] have been proposed to reduce the depth map computational complexity for previous video coding standards (such as H.264/AVC and its extension of multi-view video coding (MVC)), achieving significant time savings with acceptable video quality degradation. However, these fast algorithms are not directly applicable to the new standard 3D-HEVC, which high computational complexity is intrinsically related to the use of new prediction modes and coding tools in 3D-HEVC encoder. Recently, several studies on the reduction of depth map coding complexity have been reported for 3D-HEVC encoders in the literature. A fast depth map wedgelet partitioning scheme is presented in [20] based on adaptively utilizing the mode with minimal cost in rough mode decision of HEVC intra prediction. Fast depth mode decision algorithms are proposed in [21,22] to early terminate the unnecessary prediction modes with full RD cost calculation in 3D-HEVC. A fast mode decision algorithm based on simplified edge detector is proposed in [23] to reduce the complexity of the 3D-HEVC depth intra prediction. Fast depth mode decision algorithms are employed in [24,25] to selectively omit unnecessary DMM based on the pre-calculated RD costs of the HEVC intra modes and the edge classification. A fast depth intra mode decision is introduced in [26] to reduce the depth intra complexity in a smooth region. A fast algorithm is designed in [27] based on the early SKIP mode detection and the prediction size correlation based-mode decision to reduce 3D-HEVC encoding time for real-time applications. A flexible block partitioning is employed in [28] to efficiently represent the depth map smooth areas delimited by sharp edges. A fast depth map coding algorithm is proposed in [29] to reduce the computation complexity of the 3D-HEVC encoder by utilizing early Skip and early DIS scheme. A fast depth map quadtree structure determination scheme is designed in [30] to terminate the quadtree-based partition process of coding tree unit(CTU) as early as possible. A fast mode decision algorithm based on the grayscale similarity and inter-view correlation is proposed in [31] to reduce the complexity of depth map coding by skip unnecessary mode checking within the mode decision process. Two fast algorithms including the squared euclidean distance of variances (SEDV) and probability-based early depth intra mode decision (PBED) are presented in [32] to speeding up the most time-consuming intra mode processes in 3D-HEVC depth map coding. Effective early termination and intra mode decision algorithms are also developed in our previous work [33,34] to reduce the depth map coding complexity of 3D-HEVC encoders. The aforementioned algorithms are well developed for depth map coding achieving significant time savings in 3D-HEVC. However, most of these fast algorithms have not adequately exploited the correlation of depth map and texture video. Additionally, the characteristics of the depth map are not fully studied. This situation results in a limited time saving. Furthermore, most of the previous fast depth map algorithms are not designed for the recent 3D-HEVC test model HTM-16.0 [4]. There is still some room for further reduce mode decision complexity of the 3D-HEVC depth map coding.

To further relieve the computation complexity of depth map mode decision, this paper proposes a fast depth map mode decision algorithm for 3D-HEVC encoders based on the depth–texture correlation and edge classification. The main idea of the proposed algorithm is that the correlation of depth map–texture video and the edge information of depth map are used to analyze the current depth map coding unit (CU) prediction mode and early skip unnecessary variable-size mode decision. It consists of four fast mode decision strategies: adaptive depth map coding levels determination, early depth map SKIP/Merge mode detection, fast depth map inter mode size decision and Selective depth map intra prediction. Extensive experimental results demonstrate that the proposed fast mode decision algorithm can significantly reduce the depth map encoding time of 3D-HEVC while maintaining almost the same RD performance as the original encoder.

The rest of this paper is organized as follows. The proposed fast depth map mode decision algorithm is detail in Section 2. Simulation results and conclusions are given in Sections 3 and 4, respectively.

2. Proposed fast depth map mode decision algorithm

2.1. Adaptive depth map coding levels determination based on the depth–texture correlation

3D-HEVC inherits an advanced quadtree-based coding approach from HEVC, wherein a picture is divided into coding tree unit (CTU) [35]. The CTU can then be split into four CUs, and the CU is the basic unit of region splitting used for inter/intra prediction, which allows recursive subdividing into four equally sized blocks. A specified maximum coding level is set to limit the CU split recursion. In the joint model of 3D-HEVC, a complex RD optimization process is performed all the possible coding level to find one with the minimum RD cost and determine the best coding mode for a CU at that level. This technique achieves the highest possible depth map coding efficiency, but requires a very high encoding time. Since the depth map and texture video represent the same scene at the same time instant (they have the same motion characteristics), there is a high correlation among the coding levels from depth map and texture video. Based on this concept, if we can exploit depth map and texture video correlations to determine depth map CU coding level, the time-consuming process of computing RD costs on unnecessary coding level can be skipped in 3D-HEVC depth map coding.

Depth map is used to represent the same scene at the view point and same time instant captured by the corresponding texture video cameras. Therefore, CU coding level of depth map and texture video are closely linked. The optimal depth map coding level of a certain CU is the similar or very close to the coding level of its corresponding texture video CUs due to the two CUs have the same motion characteristics. The coding levels of the corresponding texture video CU affects the coding level determination process of the current depth map CU. Thus we can make use of the texture video coding information to analyze current depth map CU properties and early skip unnecessary depth map coding level.

On the basis of these observations, we propose to analyze the depth map CU coding level using the coding information from the co-located texture video CU. The co-located texture video CU are described as in Fig. 1. D_c denotes the current depth map CU, C_c denotes the co-located CU in the texture video and C_l, C_u, C_{ul} and C_{ur} its left, up, upleft and upright CU in corresponding texture video as in Fig. 1.

According to the coding information correlation with the mode maps of encoded texture video frames, we define a set of mode predictors (Ω) for D_c as follows,

$$\Omega = \{C_c, C_l, C_{ul}, C_u, C_{ur}\} \quad (1)$$

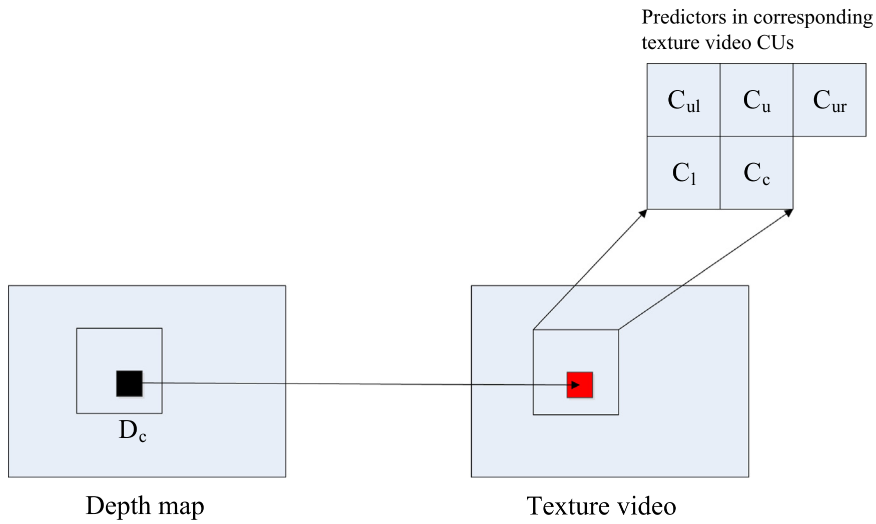

Fig. 1. The current depth map CU and corresponding texture video CUs.

Based on the predictors Ω, the optimal coding level parameter (DCL_{opt}) of current depth map CU is defined according to the mode context of corresponding texture video CUs as follows,

$$DCL_{opt} = \left\lfloor \frac{1}{N} \cdot \sum_{i \in \Omega} \omega_i \cdot \gamma_i \cdot TCL_i \right\rfloor \quad (2)$$

where N is the number of texture video CUs in all predictors Ω (including C_c, C_l, C_u, C_{ul}, and C_{ur}) equal to 5, i is the number of texture video CUs up to 5 base on predictors Ω. TCL_i is the coding level selected for coding of the corresponding texture video CU. γ_i denotes an adjust parameter. Hence, γ_i is set to "1", when corresponding texture video CU i is available; otherwise, λ_i is set to "0". ω_i is the CU weight factor of each predictor. The stronger correlation between the corresponding texture video CU and the current depth map CU, the larger weight should be assigned. Meanwhile, the CU weight factors of these five predictors have an additional property, $\sum_{i=1}^{5} \omega_i = 1$. Since related texture video CUs in the horizontal and vertical directions have a large effect on the current depth map CU compared to CUs in the diagonal direction, the weight factors ω_i for the horizontal and vertical treeblocks (C_l and C_u) are set to 0.2, and that of the diagonal direction treeblocks (C_{ul} and C_{ur}) are set to 0.1. ω_i for C_c is set to 0.4. According to the predicted value of the optimal depth map coding level, RD cost computation of each coding level in 3D-HEVC can be skipped on current depth map CU size.

Extensive simulations have been conducted on a set of 3D video sequences to verify the accuracy of the proposed adaptive depth map coding levels range determination algorithm. We encode eight 3D video test sequences with different motion activities and spatial resolutions of 1024 × 768 (Kendo, Newspaper, Balloon) and 1920 × 1088 (Shark, Poznan_Street, Undo_Dancer, GT_Fly and Poznan_Hall2), respectively. Among these eight sequences, the "Shark" and "Undo_Dancer" sequences are with a large global motion or rich texture, the "Kendo", "Balloons", "Newspaper", "GT_Fly" and "Poznan_Street" sequences are with a medium local motion or a smooth texture, "Poznan_Hall2" is a small global motion or a homogeneous texture sequence. Experimental conditions are set as follows: 3-view case (the coding order of the 3 views is: center, left and right), I-B-P view structure, QPs are chosen with 20, 30, 40 and 45; Group of pictures (GOP) Size = 8; Treeblock Size = 64, coding level range is from 0 to 3, the number of test frames for each sequence equals to 100. Table 1 shows the accuracy of the proposed adaptive depth map coding levels range determination algorithm. The average accuracy of the proposed algorithm achieves a high accuracy with more than 91.6%, which is consistently high for all test sequences and QPs with different properties. Although the proposed adaptive depth map coding levels determination misses some cases when some skipped depth coding levels are still selected as best coding level, the miss rate is negligible, less than 8.4% for most cases in 3D-HEVC mode prediction. The result shown in Table 1 verifies the rationality of the proposed adaptive depth map coding levels determination algorithm. Therefore, the performance of the depth map mode decision can be improved significantly by adopting the proposed algorithm which adaptively omits the unnecessary coding levels in 3D-HEVC encoders.

2.2. Early depth map SKIP/Merge mode detection based on the depth–texture correlation

SKIP/Merge mode provides good coding performance and requires a lower computational complexity in 3D-HEVC encoder, where the motion vector predictor is adopted for the current treeblock to generate a compensated block. Thus, once SKIP/Merge mode can be pre-decided, variable size motion estimation and disparity estimation computation for a depth map CU can be entirely saved in 3D-HEVC mode decision procedure. However, the decision to use SKIP/Merge mode is delayed until the RD costs of all other prediction modes (inter, intra, and disparity estimation modes) have been determined and it is found that SKIP/Merge mode costs less. Since depth map have the large areas of nearly constant and homogeneous regions, many depth map CU finally end up with being decided as SKIP/Merge mode after computing the RD costs of all prediction modes in 3D-HEVC encoders. Based on this consideration, we propose a novel early depth map SKIP/Merge mode decision algorithm to avoid the whole variable-size motion estimation and disparity estimation procedure.

Since both depth map and texture video are generally captured at the same time, it is likely for each CU to have the same motion information. So when a CU of depth map is encoded, we consider how the corresponding texture video CU was encoded. To analyze the SKIP/Merge mode correlation among the current depth map CU and CUs in corresponding texture video predictors Ω, we define

Table 1
Accuracy of the propose adaptive depth map coding levels range determination algorithm.

Sequences	QP = 20 (%)	QP = 30 (%)	QP = 40 (%)	QP = 45 (%)
Kendo	95.7	93.1	92.30	91.9
Balloons	95.3	92.8	92.20	91.5
Newspaper	94.1	92.2	91.70	91.1
Shark	92.4	91.7	90.90	90.4
Undo_Dancer	91.9	91.4	90.80	90.3
GT_Fly	94.6	92.1	91.40	90.9
Poznan_Street	96.2	93.8	92.50	92.2
Poznan_Hall2	97.1	95.3	94.70	94.1
Average	94.7	92.8	92.1	91.6

two types of depth map CU, i.e., "D_1" and "D_2". "D_1" denotes the neighboring texture video CUs (including C_c, C_l, C_u, C_{ul}, and C_{ur} in Fig. 1), which are all coded with SKIP/Merge mode. "D_2" represents the remaining depth map CUs.

By exploiting the full mode decision in 3D-HEVC under the aforementioned experimental conditions in Section 2.1, we investigate the SKIP/Merge mode distribution for two types of depth map CUs in Table 2. As shown in Table 2, SKIP/Merge mode are more frequently selected than the other modes, and the average probability of choosing SKIP/Merge mode is more than 84.7% for whole depth map CUs. For type "D_1" CU (the corresponding texture video predictors in Ω are all with SKIP/Merge mode), the probability of SKIP/Merge in depth map coding is about 97.6%. For type "D_2" CU, the probability of SKIP/Merge in depth map coding is about 35.7%. In addition, we can find that many CUs in depth map belong to the type "D_1" CU; the average ratio of type "D_1"CU is about 79.5%. Therefore, if the corresponding texture video CU modes in Ω are encoded with SKIP/Merge mode, then it is reasonable to consider SKIP/Merge mode as the only candidate mode. If the encoder can decide SKIP/Merge mode for type "D_1" CU at early stage, then 79.5% variable-size motion estimation and disparity estimation time will be skipped, and the 3D-HEVC encoding time can be dramatically reduced.

Based on this experiment result, the proposed fast depth intra mode decision for 3D-HEVC is described as follows: for type "D_1" CU, we will select the optimal mode with SKIP/Merge mode and perform early SKIP/Merge mode detection in 3D-HEVC depth map coding; for type "D_2" CU, the normal mode decision procedure will be performed.

2.3. Fast depth map inter mode size decision based on edge classification

In contrast to texture video, depth map is characterized by sharp object edges and large homogeneous regions with nearly constant values. Base on these characteristics, depth map edge information is easier to use and more robust for detecting object boundaries since depth map has large homogeneous regions with nearly constant values usually lack textures and shadows.

We extract the depth map edge information using Canny operator algorithm, which is less affected by depth map sharp discontinuity noise and is more likely to detect true object edges than other edge detection operator algorithms. According to the Canny operator, each CU of depth map can be classified into two types, including object edge region and no object edge region.

$$D_c \subset \begin{cases} \text{object edge region} \\ \text{no object edge region} \end{cases} \tag{3}$$

In the joint model of 3D-HEVC, various partition sizes are adopted in the depth map inter mode decision process. In fact, small partition sizes are suitable for CUs in the object edge region, and large partition sizes are appropriate for CUs with no object edge region. The pixels of depth map in one object edge region should have the same motion characteristics. Thus, the exhaustive mode decision of depth map coding is inefficient, and various partition sizes should be adaptively determined based on the object edge properties of the current depth map CU. Based on this concept, we can take advantage of object edge classification to analyze CU properties and skip the time-consuming process of computing RD costs on unnecessary variable size CUs.

By exploiting the exhaustive depth map inter mode decision in 3D-HEVC encoder under the aforementioned test experimental conditions in Section 2.1, we investigate the mode size distribution for two types of depth map CUs in Tables 3 and 4. It can be seen from Table 3 that for a depth map CU with object edge region, the average probabilities of choosing Inter 2N × 2N, Inter 2N × N and Inter N × 2N are no more than 0.5%. The total probabilities of SKIP/Merge Mode, Small inter modes and Intra modes are about 99.1%, and thus it is not necessary to perform motion estimation and disparity estimation on sizes of Inter 2N × 2N, Inter 2N × N and Inter N × 2N. For a depth map CU with no object edge region, the average probabilities of choosing SKIP/Merge mode, Inter 2N × 2N and Intra modes are 93.9%, 1.5% and 3.3%, respectively, and the average probability of other inter mode sizes are all less than 0.5%. For the "Poznan_Hall2" sequence, the percentage of

Table 2
SKIP/Merge distribution for two types of depth map CUs.

Sequences	D_1		D_2		Whole		Ratio of D_1 (%)
	SKIP/Merge (%)	Other mode (%)	SKIP/Merge (%)	Other mode (%)	SKIP/Merge (%)	Other mode (%)	
Kendo	97.8	2.2	39.1	60.9	86.8	13.2	81.2
Balloons	98.3	1.7	38.1	61.9	86.6	13.4	80.6
Newspaper	96.9	3.1	34.3	65.7	83.6	16.4	78.8
Shark	96.3	3.7	26.2	73.8	77.7	22.3	73.4
Undo_Dancer	95.8	4.1	25.7	74.3	76.7	23.3	72.8
GT_Fly	97.9	2.2	39.4	60.6	87.2	12.8	81.7
Poznan_Street	98.2	1.8	40.2	59.8	87.9	12.1	82.3
Poznan_Hall2	99.3	0.7	43.1	56.9	91.0	9.0	85.2
Average	97.6	2.4	35.7	64.2	84.7	6.3	79.5

Table 3
Inter mode size distribution for a CU with object edge region.

Sequences	SKIP/Merge mode (%)	Inter 2 N × 2 N (%)	Inter 2 N × N (%)	Inter N × 2 N (%)	Small inter modes (%)	Intra modes (%)
Kendo	5.6	0.6	0.2	0.2	67.4	26.0
Balloons	6.1	0.5	0.2	0.1	71.3	21.8
Newspaper	4.6	0.3	0.3	0.2	66.5	28.1
Shark	3.1	0.8	0.4	0.3	80.7	14.7
Undo_Dancer	2.9	0.7	0.4	0.4	81.3	14.3
GT_Fly	5.7	0.5	0.1	0.1	73.3	20.3
Poznan_Street	6.4	0.4	0.2	0.1	75.1	17.8
Poznan_Hall2	7.1	0.3	0.1	0.1	65.1	27.3
Average	5.2	0.5	0.2	0.2	72.6	21.3

Small inter modes include Inter N × N, Inter 2N × nU, Inter 2N × nD, Inter nL × 2N, Inter nR × 2N, intra modes include Intra 2N × 2N, Intra N × N, DMM1 and SDC.

Table 4
Inter mode size distribution for a CU with no object edge region.

Sequences	SKIP/Merge mode (%)	Inter 2 N × 2 N (%)	Inter 2 N × N (%)	Inter N × 2 N (%)	Small inter modes (%)	Intra modes (%)
Kendo	94.8	1.3	0.3	0.3	0.4	2.9
Balloons	95.7	1.1	0.3	0.2	0.3	2.4
Newspaper	93.4	1.6	0.5	0.3	0.5	3.7
Shark	88.9	2.6	0.9	0.8	1.2	5.6
Undo_Dancer	88.6	3.1	0.8	0.6	1.1	5.8
GT_Fly	95.9	1.0	0.2	0.2	0.3	2.5
Poznan_Street	96.3	0.9	0.2	0.1	0.2	2.3
Poznan_Hall2	97.5	0.7	0.2	0.1	0.0	1.5
Average	93.9	1.5	0.4	0.3	0.5	3.3

Small inter modes is very low, i.e., 0.0%, because it contains a large area having small global motion or a homogeneous texture with the static background. The percentage of optimal mode sizes (SKIP/Merge mode, Inter 2N × 2N and Intra modes) that are covered by the selected candidate modes reaches about 98.8%. Thus, we can conclude from experimental results in Table 4 that a CU with no object edge region is much more possible to choose SKIP/Merge mode, Inter 2N × 2N and Intra modes in 3D-HEVC depth map coding. Based on the aforementioned analysis, the optimal inter mode sizes that will be used in 3D-HEVC depth map coding of two types CUs are summarized in Table 5.

2.4. Selective depth map intra prediction based on edge classification

In the current 3D-HEVC, 35 traditional intra modes inherited from HEVC are used for depth map intra coding. Besides, new DMM is utilized together with the traditional intra modes for a better representation of object edge in depth map. DMM provides a great flexibility to represent the sharp object edge, produces more accurate prediction signals, and achieves better depth map compression efficiency. It can save about 5% of the coding bitrate for the same rendered image quality. However, testing the DMM introduces more possible intra mode candidates and each of them requires complicated RD calculation in the process of 3D-HEVC intra mode selection. They lead to unacceptable high computational complexity cost in 3D-HEVC encoders. Thus, the complexity of the depth map intra mode prediction should be reduced significantly without compromising 3D-HEVC coding efficiency.

In 35 traditional HEVC intra coding, Planar mode is often selected as the best intra prediction mode for block with slowly varying sample values. It is observed that when the best mode is Planar mode in 3D-HEVC full-RD cost calculation list, the block is very likely to be homogeneous or smooth. Moreover, beside Planar mode, the DC mode is also a good indicator for the flat or smooth block [36]. It designed for flat surface with a value matching the mean value of the boundary samples. Since depth maps contain large areas of nearly constant or slowly varying sample values, Planar and DC modes have very large probability to be selected as best mode in traditional HEVC intra coding. Meanwhile, DMM is designed for depth map area with sharp object edge transition thus is less efficient for homogeneous or smooth areas compression. Therefore, most of the DMM search process could be skipped in the area of homogeneous or smooth. After full-RD cost calculation in 3D-HEVC encoder, DMM has very low probability to be selected as best mode, because most of the areas in depth map are homogeneous or smooth. Based on those observations, we propose a selective depth map intra prediction based on edge classification to early terminate the DMM and traditional HEVC intra mode in 3D-HEVC full-RD cost calculation.

Table 5
Optimal inter mode sizes for two CUs type of depth map.

CU type	Candidate mode sizes
CU with no object edge region	SKIP/Merge mode, inter 2 N × 2 N, and intra modes
CU with object edge region	SKIP/Merge mode, small inter modes, and intra modes

Table 6 shows the intra mode distribution in 3D-HEVC for two types of depth map CUs according to the edge classification in Eq. (3). In the latest joint model of 3D-HEVC, only DMM1 is used for intra mode decision (DMM4 is regarded as an inter-component prediction tool and is no longer used for depth map intra decision). In this paper, we focus our experimental discussion on DMM1. It can be observed from Table 6 that for CUs with object edge region, the average probabilities of choosing Planar mode, DC mode, DMM1, and other intra modes are all more than 4.4%, which is no negligible. Therefore, a CU with object edge region needs ro perform all intra modes decision in depth map coding. For a CU with no object edge region, the average probabilities of choosing Planar mode, and DC mode are 84.0%, and 10.8%, respectively, and the total average probability of DMM1 and other intra mode are no more than 5.2%. For the "Poznan_Hall2" sequence, the percentage of DMM1 is very low, i.e., 0.1%, because it contains a large area of homogeneous texture and less motion. The percentage of optimal depth map intra mode (Planar mode, and DC mode) that are covered by the selected candidate modes reaches about 94.8%. Thus, we can conclude from experimental results in Table 5

Table 6
Intra mode distribution for two CUs type of depth map in 3D-HEVC depth map coding.

Sequences	CU with object edge region				CU with no object edge region			
	Planar mode (%)	DC mode (%)	DMM1 (%)	Other modes (%)	Planar mode (%)	DC mode (%)	DMM1 (%)	Other modes (%)
Kendo	59.3	4.1	16.6	20.0	84.3	12.5	0.3	2.9
Balloons	56.4	5.2	17.8	20.6	85.1	11.9	0.2	2.8
Newspaper	54.7	3.9	18.9	22.5	82.2	11.2	0.3	6.3
Shark	43.2	3.2	22.6	31.0	78.8	10.8	0.5	9.9
Undo_Dancer	44.1	3.4	21.7	30.8	79.3	10.6	0.5	9.6
GT_Fly	56.7	5.1	17.9	20.3	85.1	12.1	0.2	2.6
Poznan_Street	59.2	4.7	18.2	17.9	87.4	8.7	0.2	3.7
Poznan_Hall2	71.2	5.4	10.3	13.1	90.1	8.2	0.1	1.6
Average	55.6	4.4	18.0	22.0	84.0	10.8	0.3	4.9

that a CU with no object edge region is much more like to choose Planar mode, and DC mode in depth map coding. Based on the aforementioned analysis, the selective intra modes that will be used in 3D-HEVC depth map coding of two types CUs are summarized in Table 7.

2.5. Overall algorithm

According to the aforementioned analysis, the main idea of the proposed algorithm is that the correlation of depth map–texture video and the edge information of depth map are used to analyze the current depth map CU prediction mode and early skip unnecessary variable-size mode decision. The proposed overall algorithm incorporates adaptive depth map coding levels determination, early depth map SKIP/Merge mode detection, fast depth map inter mode size decision and selective depth map intra prediction. The proposed overall algorithm is summarized as follows:

Step (1) Start mode decision for a treeblock in 3D-HEVC encoders.
Step (2) Derive the coding information from predictors Ω in corresponding texture video CUs (shown in Fig. 1).
Step (3) Perform adaptive depth map coding levels range determination. Compute DCL_{opt} for current depth map CU based on Eq. (2), loop depth map CU coding levels form minimum coding level to maximum coding level.
Step (4) Perform early depth map SKIP/Merge mode detection. If the CU modes of the predictors Ω in corresponding texture video CUs are all with the SKIP/Merge mode, skip motion estimation and disparity estimation, and go to Step 8.
Step (5) Compute D_c for current depth map CU based on Eq. (3), classify the current depth map CU into object edge region and no object edge region.
Step (6) Perform fast depth map inter mode size decision. When current depth map CU with no object edge region, the optimal inter candidates modes are SKIP/Merge mode, Inter 2N × 2N, and Intra modes. When the current depth map CU with object edge region, the optimal inter candidates modes are SKIP/Merge mode, Small inter modes, and Intra modes. Otherwise, the optimal intra modes include all intra prediction modes.
Step (7) Perform selective depth map intra prediction. When current depth map CU with no object edge region (the area without object boundaries), the optimal intra modes are only Planar mode, and DC mode. Otherwise, the optimal modes include all intra prediction modes.
Step (8) Determine the best prediction mode. Go to step 1 and proceed with next depth map CU.

Table 7
Selective intra modes for two CUs type of depth map.

CU type	Candidate intra mode
CU with no object edge region	Planar mode, and DC mode
CU with object edge region	All intra modes

3. Experimental results

In order to evaluate the efficiency of the proposed fast depth map mode decision algorithm for 3D-HEVC including four components, adaptive depth map coding levels determination, early depth map SKIP/Merge mode detection, fast depth map inter mode size decision and selective depth map intra prediction, they have been implemented on the recent 3D-HEVC reference software HTM 16.0 [37]. The proposed algorithm is evaluated with eight sequences recommended by JCT-3V Group with two resolutions (1024 × 768/1920 × 1088) which are shown in this paper. The detailed information of the test multi-view sequences is listed in Table 8. The Each test multi-view sequence contains three texture video and depth map views, respectively. All the experiments are defined under the JCT-3V common test conditions (CTC) for 3D-HEVC [38]. Test coding conditions are set as follows: 3 view case, which includes an independent (center) view and two dependent (left and right) views. The coding order is presented as the following: $T_0, D_0, T_1, D_1, T_2, D_2$ (where T_i and D_i are the texture video and depth map frames in the ith view, respectively). Hierarchical B frame structure, the temporal prediction length of a group of pictures (GOP) is 8, intra every 24 frames (random access at roughly each second), CTU has a fixed size of 64 × 64 pixels, a maximum depth level of 4, Fast Options-QTL on, depth map quantization parameter (QP) values: 45, 42, 39, 34, texture video QP values: 40, 35, 30, 25. The "VSRS-1D-Fast" software [39] is used for the view synthesis. In this section, we compare the proposed algorithm in Tables 9–11 with the 3D-HEVC encoder using exhaustive mode decision and the state-of-the-art fast methods [27,29], where coding efficiency is measured by the rendered view peak signal-to-noise ratio (PSNR) and total bitrate, and the computation complexity is measured by the consumed running time. The Bjontegaard Delta PSNR (BDPSNR) [40] represents the average PSNR gain, Bitrate (BDBR) represents the improvement of total bitrates for 3D video coding, and "Dtime (%)" represents the entire coding time change of the overall coding in percentage, which is computed as follow,

$$\text{Dtime} = \frac{Time_{proposed} - Time_{origional}}{Time_{origional}} \times 100\% \quad (4)$$

where $Time_{proposed}$ and $Time_{origional}$ denote running time of the proposed algorithm and the original 3D-HEVC encoders, respectively. Since the efficiency of depth map is improved by considering the quality of virtual rendered views, the intermediate rendered views are synthesized between each view after texture video and depth map encoding. PSNR on rendered view distortion can be measured by comparing the coded rendered view with the image rendered

Table 8
Test multi-view sequences and configuration parameters information.

Sequence	Resolution	Frame rate	Frames	3-view input
Kendo	1024 × 768	30	200	1–3–5
Balloons	1024 × 768	30	200	1–3–5
Newspaper	1024 × 768	30	200	2–4–6
Shark	1920 × 1088	25	150	1–5–9
Undo_Dancer	1920 × 1088	25	150	1–5–9
GT_Fly	1920 × 1088	25	150	9–5–1
Poznan_Street	1920 × 1088	25	150	5–4–3
Poznan_Hall2	1920 × 1088	25	150	7–6–5

Table 9
Results of the proposed ADCLD and EDSMD algorithms compared with 3D-HEVC encoders.

Sequences	ADCLD			EDSMD		
	BDBR (%)	BDPSNR (dB)	Dtime (%)	BDBR (%)	BDPSNR (dB)	Dtime (%)
Kendo	0.21	−0.01	−19.9	0.36	−0.02	−26.7
Balloons	0.24	−0.01	−20.3	0.38	−0.02	−27.1
Newspaper	0.39	−0.02	−18.6	0.62	−0.03	−25.4
Shark	0.11	−0.01	−17.4	0.22	−0.01	−21.9
Undo_Dancer	0.13	−0.01	−17.7	0.24	−0.01	−22.3
GT_Fly	0.22	−0.01	−20.6	0.39	−0.02	−27.7
Poznan_Street	0.21	−0.01	−21.2	0.41	−0.02	−28.2
Poznan_Hall2	0.24	−0.01	−23.8	0.45	−0.02	−30.2
1024 × 768	0.28	−0.01	−19.6	0.45	−0.02	−26.4
1920 × 1088	0.18	−0.01	−20.1	0.34	−0.02	−26.1
Average	0.22	−0.01	−19.9	0.38	−0.02	−26.2

Table 10
Results of the proposed FDISD and SDMIP algorithms compared with 3D-HEVC encoders.

Sequences	FDISD			SDMIP		
	BDBR (%)	BDPSNR (dB)	Dtime (%)	BDBR (%)	BDPSNR (dB)	Dtime (%)
Kendo	0.43	−0.02	−20.1	0.19	−0.01	−4.8
Balloons	0.45	−0.02	−20.4	0.23	−0.01	−5.1
Newspaper	0.59	−0.03	−18.2	0.39	−0.02	−4.2
Shark	0.18	−0.01	−15.6	0.12	−0.01	−3.6
Undo_Dancer	0.21	−0.01	−15.8	0.14	−0.01	−3.8
GT_Fly	0.38	−0.02	−19.7	0.17	−0.01	−4.7
Poznan_Street	0.46	−0.02	−21.1	0.25	−0.01	−5.7
Poznan_Hall2	0.64	−0.03	−24.5	0.42	−0.02	−6.8
1024 × 768	0.49	−0.02	−19.6	0.27	−0.01	−4.7
1920 × 1088	0.37	−0.02	−19.3	0.22	−0.01	−4.9
Average	0.42	−0.02	−19.4	0.24	−0.01	−4.8

Table 11
Results of the proposed overall algorithm compared with 3D-HEVC encoders.

Sequences	BDBR (%)	BDPSNR (dB)	Dtime (%)
Kendo	0.72	−0.03	−43.4
Balloons	0.79	−0.03	−44.2
Newspaper	1.23	−0.04	−42.8
Shark	0.39	−0.02	−38.9
Undo_Dancer	0.42	−0.02	−39.3
GT_Fly	0.75	−0.03	−43.9
Poznan_Street	0.84	−0.03	−45.1
Poznan_Hall2	1.09	−0.04	−47.8
1024 × 768	0.91	−0.03	−43.5
1920 × 1088	0.70	−0.03	−43.0
Average	0.78	−0.03	−43.2

with uncompressed texture video and depth map. The rendered PSNR is the average PSNR of all the synthesized views. The bitrate under consideration is the sum of the bitrates of the three coded texture video and depth map views. The hardware platform is two Intel Xeon E5-2640 v2 2.0 GHz processor with 32 GB DDR3 random access memory. The operating system was Windows 7 SP1.

3.1. Results of the individual algorithms compared with 3D-HEVC encoders

Table 9 shows the experiment results of the adaptive depth map coding levels determination (ADCLD) and early depth map SKIP/Merge mode detection (EDSMD) compared with the 3D-HEVC encoder. It can be seen that the proposed two algorithms can greatly reduce the coding time with similar RD performance for all test sequences. As shown in Table 9, for ADCLD approach, about 19.9% encoding time has been reduced with 0.22% bitrate increase or 0.01 dB PSNR decrease. This encoding time reduction is particularly high for small global motion sequence such as "PoznanHall2" (20.1%), but is still evident for large global motion sequences such as Shark (17.4%). This result indicates that ADCLD algorithm can efficiently skip unnecessary coding level in 3D-HEVC depth map coding. As for the EDSMD approach, about 26.2% encoding time has been reduced with the maximum of 30.2% and the minimum of 21.9%. According to Table 9, the sequence which will present the most runtime gain is the one which will have the most CUs with large homogeneous texture because in those CUs only the SKIP/Merge modes are checked. Since the "PoznanHall2" sequence has a large homogeneous texture, it presents the most CUs of this

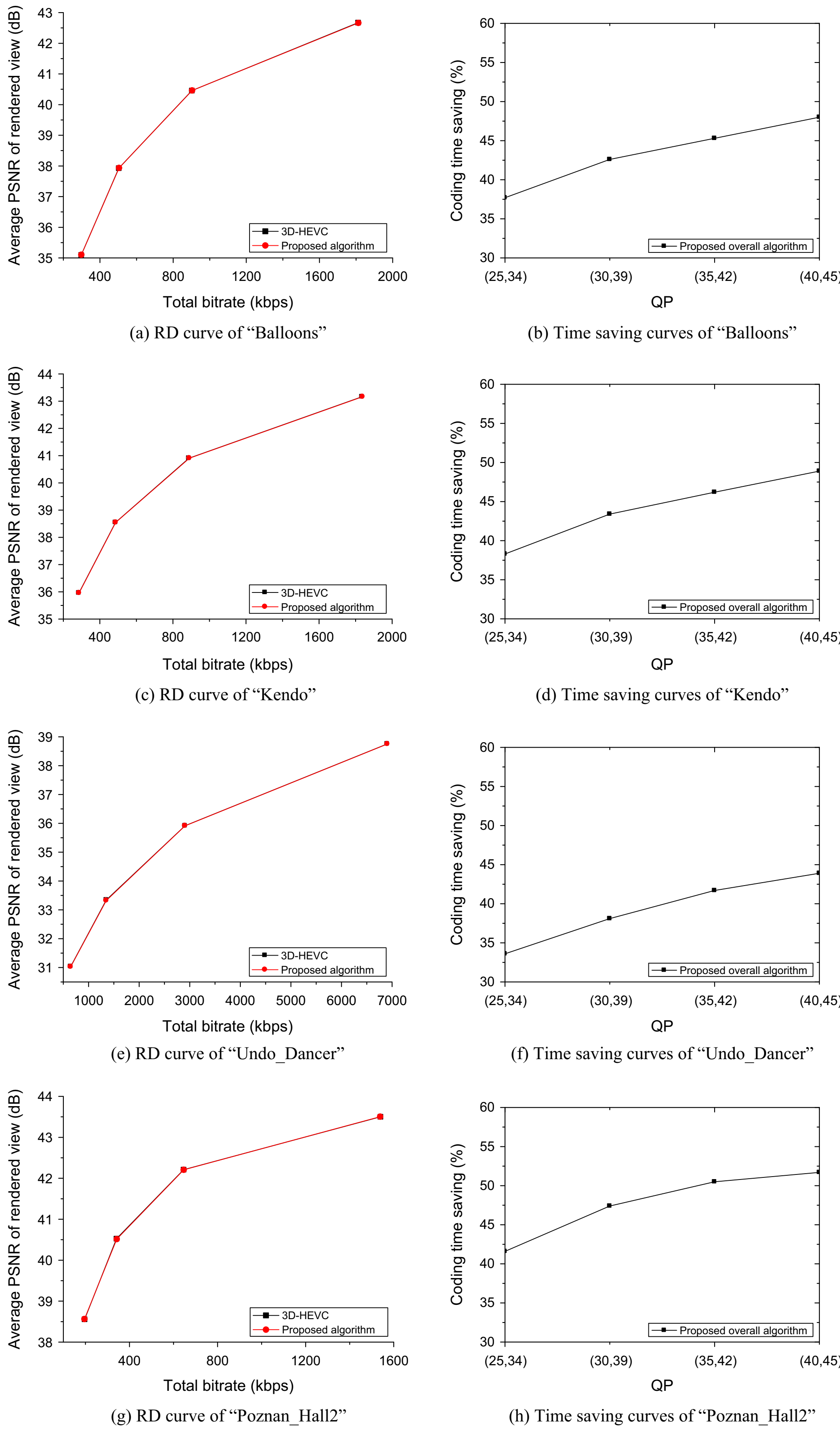

Fig. 2. Experimental results of “Balloons”, “Kendo”, “Undo_Dancer”, and “Poznan_Hall2″ (1920 × 1088) under different QPs combinations for texture video and depth map (25, 34), (30, 39), (35, 42) and (40, 45).

kind and consequently, the most runtime gains (30.2%). The computation complexity reduction is extremely high because the detailed mode decision procedures of a great number of depth map CUs are not processed by the 3D-HEVC encoder. Meanwhile, the average PSNR drop for all the test sequences is 0.02 dB (bitrate increase 0.38%), which is negligible. This indicates that the proposed EDSMD algorithm can efficiently reduce the depth map coding time while maintaining nearly the RD performance for 3D-HEVC.

Table 10 shows the experiment results of the fast depth map inter mode size decision (FDISD) and selective depth map intra prediction (SDMIP) compared with the 3D-HEVC encoder. It can be seen that the proposed two algorithms can greatly reduce the encoding time with only a negligible loss of encoding efficiency for all test sequences. For FDISD approach, about 19.4% encoding time has been reduced with the maximum of 24.5% and the minimum of 15.6%. Meanwhile, the average PSNR reduce for all the test sequences is 0.02 dB (bitrate increase 0.19%), which indicates that the proposed FDISD algorithm can efficiently reduce the depth map coding time of the 3D-HEVC. As for the SDMIP approach, 4.8% coding time has been reduced over all sequences, with a maximum of 6.8% in "Poznan_Hall2" and a minimum of 3.6% in "Shark". It can be also observed that a consistent gain is obtained over all test sequences. On the other side, the coding efficiency loss is very negligible, with a 0.01 dB PSNR drop (0.24%bitrate increase). This indicates that the proposed SDMIP algorithm can efficiently reduce the coding time while keeping the same coding efficiency performance as the original 3D-HEVC encoder.

3.2. Results of the overall algorithm compared with 3D-HEVC encoders

In the following, we analyze the simulation results of the proposed overall algorithm, which incorporates ADCLD, EDSMD, FDISD, and SDMIP approaches. Table 11 shows the performance evaluation results with the original 3D-HEVC encoders. It can be seen that the proposed overall algorithm reduces the 3D-HEVC encoding time for all test sequences with similar RD performance. As shown in Table 11, the proposed overall algorithm reduced the encoding time in 43.5% on average for 1024 × 768 test sequences and in 43.0% for 1920 × 1088 test sequences, totalizing an average decrease 43.2% encoding time with the maximum of 47.8% for "Poznan_Hall2" and the minimum of 38.9% in for "Shark". The encoding time saving of the proposed overall algorithm is constant for test sequences with different motion activities: the encoding time reduction is particularly high for large homogeneous texture sequence like "Poznan_Hall2", because the exhaustive mode decision procedures of a significant number of depth map CUs are not processed by the 3D-HEVC encoder. For large global motion sequences like "Shark" and "Undo_Dancer", the proposed overall algorithm also can save about 38.9–39.3% running time. On the other hand, the coding efficiency loss is low in Table 11, where the average BDPSNR loss is 0.03 dB (0.78% BDBR increment). Therefore, the proposed overall algorithm can efficiently reduce complexity of depth map coding with only incurring a negligible loss of RD performance compared to the original 3D-HEVC encoder.

Fig. 2 gives more detail experiment results (RD and time saving curves) of the proposed overall algorithm compared to 3D-HEVC under different QPs ((25, 34), (30, 39), (35, 42) and (40, 45)) for four typical sequences "Balloons" (1024 × 768), "Kendo" (1024 × 768), "Undo_Dancer" (1920 × 1088) and "Poznan_Hall2" (1920 × 1088). As shown in Fig. 2, the proposed fast depth map mode decision algorithm can achieve a consistent time saving over a large bitrate range with almost negligible loss in PSNR and increment in bitrate. Moreover, with the coding bitrate decreases in RD curves, the encoder runtime savings increase in time saving curves. The reason is with the QP increases, both the probability of only testing SKIP/Merge mode for depth map CUs due to EDSMD, and the probability of only checking Planar/DC mode for depth map CUs due to SDMIP are all increased.

3.3. Results of the proposed algorithm compared with the state-of-the-art fast algorithms

In addition to the 3D-HEVC encoder, the results of the overall algorithm are also compared with the fast 3D-HEVC methods. Figs. 3 and 4 compare the proposed overall algorithm with two

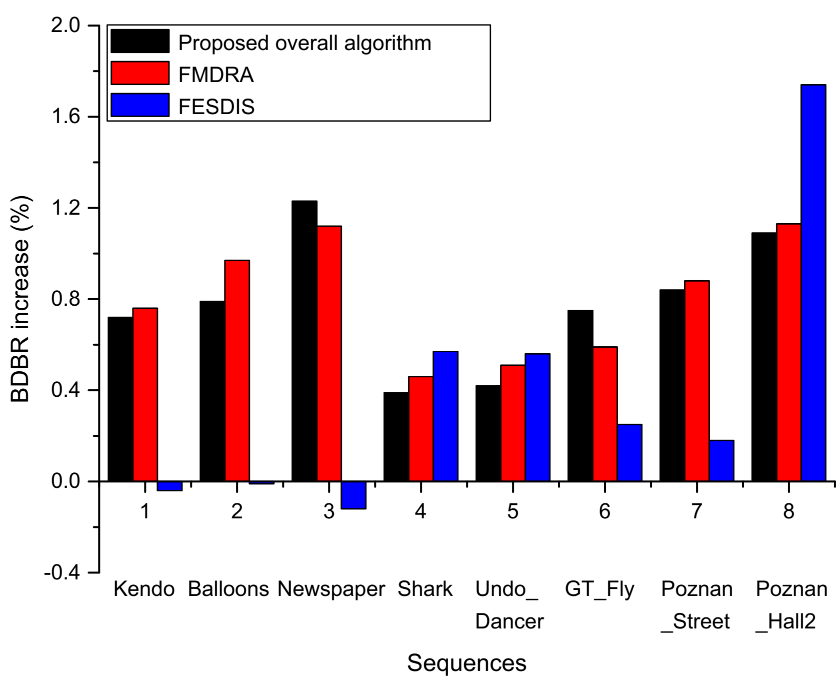

Fig. 3. BDBR increase of proposed overall algorithm, FMDRA, and FESDIS under the CTC random access configuration.

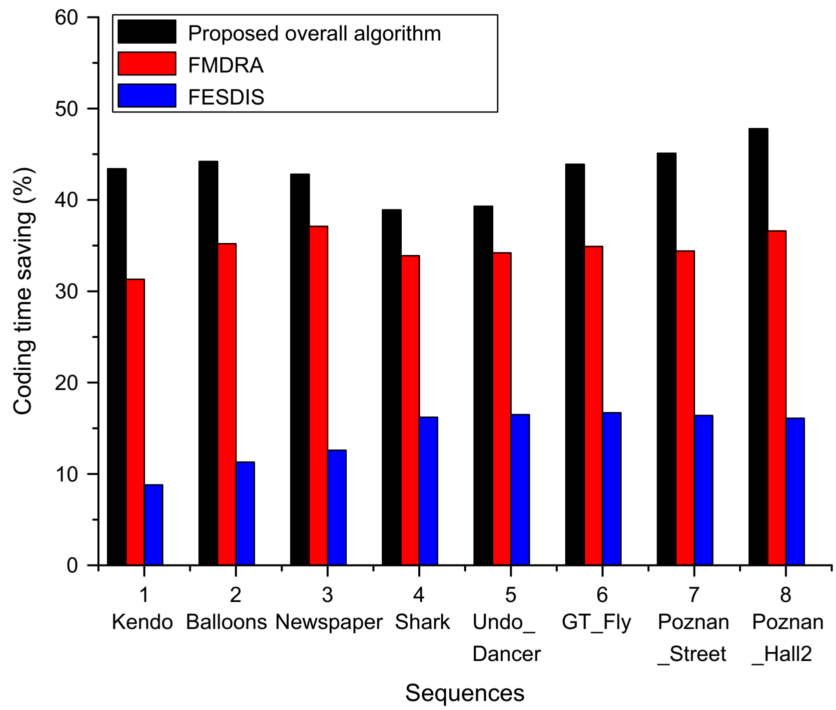

Fig. 4. Coding time saving of proposed overall algorithm, FMDRA, and FESDIS under the CTC random access configuration.

state-of-the-art fast methods, fast mode decision algorithm for 3D-HEVC real-time applications (FMDRA) [27], and fast 3D-HEVC depth map coding based on early Skip and early DIS scheme (FESDIS) [29] for 3D-HEVC under "CTC" in random access configuration. In FMDRA method, only use the depth map optimization approach. FESDIS performs good RD performance in Fig. 3, but its computation reduction is poor in Fig. 4. As shown in Figs. 3 and 4 the proposed overall algorithm and FMDRA have good computation reduction at the cost of RD performance. Among these three methods, the proposed overall algorithm achieves the better gain in encoding speed compared to FMDRA and FESDIS methods. For all test sequences, the proposed overall algorithm achieves 38.9–47.8% total encoding time reduction as well as appropriate coding performance with only 0.2–0.4% BDBR increase on average. The proposed overall algorithm can achieve about 5–12% coding time saving compared with FMDRA method, and with a better RD performance (0.03% bitrate decrease on average). Compared with FESDIS method, the proposed overall algorithm can achieve better performance on encoding time saving. About 22–34% encoding time can be further reduced. Meanwhile, the average RD efficiency loss is negligible, less than 0.39% BDBR increase. The above simulation results demonstrate that the proposed fast depth map mode decision based on depth–texture correlation and edge classification is efficient for all test sequences and consistently outperforms the recent fast methods for 3D-HEVC.

4. Conclusion

In this paper, we propose a fast depth map mode decision based on depth–texture correlation and edge classification to reduce the computational complexity of 3D-HEVC encoders, which includes four approaches, i.e., adaptive depth map coding levels determination, early depth map SKIP/Merge mode detection, fast depth map inter mode size decision and selective depth map intra prediction. It makes use of the correlation of depth map–texture video and the edge information of depth map to predict the current CU prediction mode and skip unnecessary modes in 3D-HEVC depth map coding in advance. The proposed fast depth map mode decision algorithm is implemented on the recent 3D-HEVC reference software HTM 16.0. Experimental results show that the proposed algorithm can reduce up to 43.2% computational complexity of the original 3D-HEVC encoders while maintaining almost the same coding efficiency. Meanwhile, the proposed fast depth map mode decision algorithm outperforms the recent state-of-the-art fast coding algorithms, in terms of encoding time saving with better or similar RD performances.

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