https://doi.org/10.2352/ISSN.2470-1173.2017.2.VIPC-399

A Fast Intra Mode Decision algorithm for HEVC

Weihang Liao, Daiqin Yang and Zhenzhong Chen;
School of Remote Sensing and Information Engineering, Wuhan University

Abstract

The latest High Efficiency Video Coding (HEVC) standard achieves about 50% bit rate saving while maintaining the same subjective quality compared to H.264/AVC High Profile. However, the better coding efficiency is obtained at the cost of significantly increased encoder complexity. In this paper, a fast mode decision algorithm is proposed to relieve the computational burden. The proposed algorithm consists of two steps. Firstly, depth information of CU block is used to reduce the mode candidates, with the assumption that the exhaustive search for a large CU is unnecessary. Secondly, a directional ratio is applied to estimate the rough orientation of each CU, thus some unlikely selected directional modes can be further eliminated. On average, the proposed algorithm can achieve 34.1% encoder time saving while cause an negligible coding performance loss under the All-Intra configuration compared with HM 16.0.

Introduction

High Efficiency Video Coding (HEVC) [1] is the latest video coding standard which developed by the Joint Collaborative Team on Video Coding (JCT-VC). HEVC is a milestone because it can achieve almost 50% bit rate saving compared to the popular H.264/AVC [2] with the same subjective video quality. This significant performance improvement on compression ratio comes from the development of new coding tools, such as recursive quad-tree coding structure, large block transform, advanced loop filter, and sample adaptive offset (SAO), etc.

HEVC employs a more flexible hierarchy to replace the macro block in previous H.264/AVC, which contains three different types: the coding unit (CU), the prediction unit (PU), and the transform unit (TU) [3]. CU is the basic coding unit and can be recursively split into different size from 64x64 pixels to 8x8 pixels. Each CU consists of one or more PU, which is the basic unit for prediction. PU has two different types for intra prediction process (i.e. PART_2Nx2N and PART_NxN) and its size varies from 64x64 to 4x4. TU is the basic unit for transformation and quantization, which can adaptively chose the optimal size dependent on the feature of prediction residual. Both CU, PU and TU are arranged in a recursive quad-tree structure, Fig. 1 gives a brief illustration. This quad-tree structure makes the CU size more adaptive to the video content than the macro block in H.264/AVC. The homogenous regions can be handled well by CU with large size, while the complex regions can get a more precise describe by adopting small CU. More details can be found in [4]. Besides, HEVC adopts 35 spatial intra prediction modes (Planar, DC and 33 angular modes), increased from 9 modes of H.264/AVC. Due to the more fine-granular prediction modes, a higher accuracy and smaller residuals are achieved, which lead to a significant improvement in the compression efficiency.

For each coding tree unit (CTU), the HEVC encoder executes a recursively search in depth first order to obtain the optimal coding tree structure. And on every possible CU size, a complex rate distortion optimization (RDO) is performed among all 35 candidate modes, in order to screen out the best prediction mode. As we can see, while the new techniques bring significant performance improvement, they also introduce vast coding complexity. The complexity of HEVC increases several times compared with H.264/AVC intra coding [5], which is intolerable in power-constrained and real time applications.

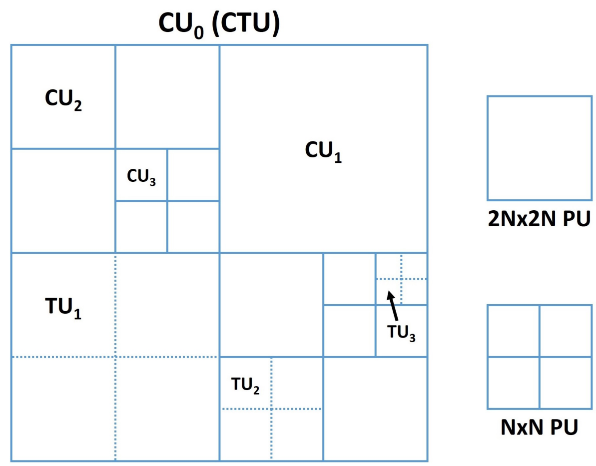

Figure 1. *The recursive quad-tree sctructure of CU, PU and TU in HEVC, where k indicates the depth for CU_k and TU_k.*

In order to reduce the coding complexity of intra coding, the HM reference encoder [6] adopts a three-step fast intra mode decision technique as shown in Fig. 2.

First, rough mode decision (RMD) [7] is performed to select a set of candidate modes out of all 35 possible modes. During the RMD process, a low complexity cost J_{SATD} is computed as:

$$J_{SATD} = SATD + \lambda \cdot B \tag{1}$$

Where $SATD$ means Sum of Absolute Transform Difference between the predicted pixels and original pixels, λ is the Lagrangian multiplier, B is the bit cost needed to encode the prediction mode. To some extent, J_{SATD} can be regarded as an approximation of the RD cost, thus the modes with small J_{SATD} are selected to form a candidate list. Eight modes are added to the list for PU of size 4x4 and 8x8, three modes are added for PU with larger size. Only these modes in candidate list will be checked during RDO. In the second step, three modes called Most Probable Modes (MPM) [8] are generated based on the already encoded neighboring PUs, and they will be added to the candidate list if they are not included yet. The Motivation of MPM is that there is a high correlation of

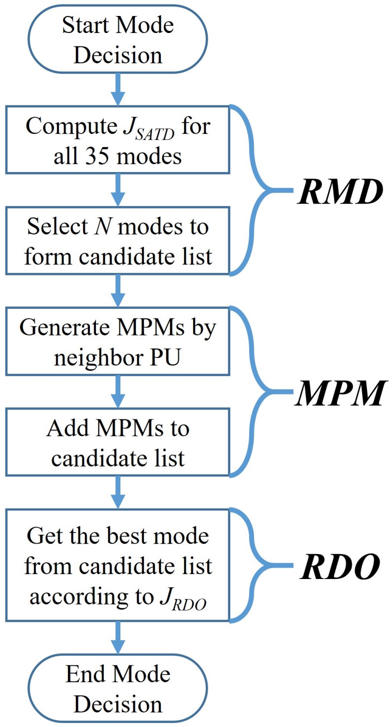

Figure 2. *The three-step fast intra mode decision algorithm in HEVC reference software HM 16.0*

the spatial neighboring PUs, thus the MPMs have high probability to be chosen as the optima of the current PU. Finally, the RDO process is applied to the candidate list, to decide a best intra prediction mode having the minimum RD cost. The RD cost J_{RDO} is calculated as:

$$J_{RDO} = SSE + \lambda \cdot R \tag{2}$$

Where SSE means the Sum of Squared Errors between the reconstructed pixels and original pixels. R is the total number of bits used to encode this mode. Thus the RD cost can synthetically reflect how the distortion and bit rate of different modes impact the coding efficiency. By comparing the RD cost, the encoder is able to obtain a best mode which can achieve a minimum distortion while not exceeding the bit rate constraint.

As this fast coding technique is applied, the HM encoder can reduce some computational burden. But the complexity is still high, because the RMD process need to traverse all 35 possible modes, and the candidate list for full RDO check is still large. Thus, there is still room for improvement in terms of complexity reduction. In this paper, a novel two-step fast RMD algorithm is proposed for HEVC intra prediction. Firstly, the depth information is used to skip some modes and fewer modes are added to the candidate list, with the assumption that the exhaustive search for large CU is unnecessary. Meanwhile, the vertical and horizontal (mode 10 and mode 26) are calculated in advance, and the J_{SATD} of the two modes are used to forecast an approximate orientation of current CU. Thus the number of modes calculated in RMD can be further reduced since some unlikely selected modes are omitted. Finally, the order of MPM and RMD is adjusted, with the motivation that MPMs should be directly checked in RDO, thereby averting some unnecessary calculation.

The rest of this paper is organized as follows. Section 2 presents a brief review of recently published fast algorithm for HEVC intra prediction. Section 3 provides an introduction of the proposed algorithm. Section 4 demonstrates and analyzes the experimental results and the conclusion is given in section 5.

Relative Works

Recently, some fast algorithms have been proposed, in order to reduce the complexity of the HEVC intra prediction process. In general, these fast algorithms can be classified into two main categories: fast mode decision and fast CU size decision, which are briefly introduced as follows.

Fast Mode Decision

Zhao *et al.* [8] have studied the spatial correlation between current block and neighboring blocks. They proposed a method to reduce the candidates in RDO process, by using the direction information of the neighboring blocks. This method achieved 20% time saving in intra High Efficiency (HE) condition and 28% time saving in Low Complexity (LC) condition on HM 1.0 , with a negligible coding efficiency loss. It should be noted that HE and LC test conditions were used in the early days, now they are merged.

Zhang and Ma [9] have proposed an integrated algorithm to reduce complexity of intra prediction. First they used a 2:1 down-sampled Hadamard transform to replace the original Hadamard transform in RMD process. Then a progressive mode search is applied to reduce the mode candidates for full RDO. Compared to HM 6.0, this algorithm can obtain 38% time saving on average, with about 2.9% BD-rate loss.

Na *et al.* [10] adopted an edge detection method to establish an edge map, and they accordingly classified CU into five different types. For each type, a reduced candidate set was defined so the process of intra mode selection was speeded up. This method achieved 56.8% time saving at the cost of 2.5% BD-rate loss compared to HM 10.0.

Zhang and Ma have improved their previous work [9] by proposing a progressive rough mode search (pRMS) [11]. In this algorithm, original RMD process was replaced and fewer candidates were selected for RDO. Besides, an early RDO skip method was also introduced to further release the complexity. On average, 60% time saving was acquired with 1% BD-rate loss compared to HM 10.0.

Kim *et al.* [12] have proposed a Hierarchical Mode Decision (HMD) method to take the place of original RMD process. This method applied a five-step progressive search to select an optimal mode instead of traversing all 35 modes. Compared to HM 10.0, this method could reduce coding time about 39% with a 1.2% BD-rate loss.

Gwon *et al.* [13] have proposed a two-step algorithm to speed up the intra coding. They reduced the number of candidates in RMD process according to the edge orientation features. After that, a Bayesian classification framework was applied to select the RDO candidates. This algorithm was implemented on HM 12.0, achieved 30.3% time saving on average with a loss of 0.9%.

Gao *et al.* [14] have put forward an Optimal Adjacent Modes (OAM) algorithm to reduce the number of candidate modes for RDO. The OAM list was obtained by analyzing the cost of several general direction modes, and MPM was used to update this list according to the spatial correlation. This algorithm could saving 27.3% coding time compared to HM 14.0, with a loss of 1%.

Fast CU Size Decision

Shen *et al.* [15] have proposed a fast algorithm to speed up the CU size decision process based on the Bayesian decision theory. The split or non-split decision was made according to the Lagrangian cost, class-conditional probability density function, and priori probabilities. This algorithm was implemented on HM 4.0 and 41.4% time reduction was obtained under the Random Access (RA) and Low Delay (LD) configurations, with a loss of 1.88% on average.

Wang *et al.* [16] have studied the correlation of the neighboring CTUs. A depth range prediction method was proposed to reduce the complexity. Besides, the RD cost and HSAD were used to make CU size decision. This algorithm could achieve 54% time saving compared to HM 10.0, while causing 1% BD-rate loss.

Min and Cheung [17] have utilized the global and local edge complexities in four diagonal directions to represent the smoothness of a CU. In this way a CU could be decided to be split, non-split, or undetermined for each depth. Compared to HM 10.0, this algorithm could obtain 52% time reduction with a loss of 0.8%.

Zhang *et al.* [18] have proposed a two-step algorithm to make a fast CU size decision. Frist, each CU was classified into three categories (compound, homogeneous, and undetermined) according to the weighted variance and Hadamard cost. Besides, a RD cost estimation was applied to make an early prune decision for those undetermined CU. Compared to HM 13.0, this algorithm provided 49% time saving at the cost of 0.9% BD-rate loss.

Zhang *et al.* [19] employed a two linear Support Vector Machines (SVM) to speed up the CU partition process. The depth difference, HAD cost ratio, and RD cost ration were used as features to perform the early split and termination decision. This algorithm achieved 54% time saving with 0.7% BD-rate loss, compared to HM 14.0 all-intra configuration.

Proposed Algorithm

As mentioned in part 1, the complexity of intra mode decision is very high, because the encoder need to traverse all 35 possible modes at each CU size to derive the optimal mode. Therefore, the speed up of this process comes down to the reduction of mode candidates, namely, skipping some redundant modes instead of performing search among all 35 modes. Given this motivation, a two-step algorithm is proposed.

Depth-Based RMD Mode Skip

In HEVC, CUs can have different depth from 0 to 3. Where depth 0 means a CU with size of 64x64, and depth 3 means a CU with size of 8x8. Small depth is adapt to flat and homogeneous regions, which hold a similar content and features. And for these regions, DC, Planar, and some simple directional modes (i.e. Vertical mode and Horizontal mode) are likely to be chosen as the best mode, because they dont contain much complex textural information. To the contrary, large depth is suitable for those inhomogeneous and unsmooth regions, because a further split is preferred for these blocks. Therefore, an exhaustive mode check for a CU with small depth is unnecessary.

An experiment has been conducted to verify this assumption. Five sequences with different resolution (PeopleOnStreet, Kimono, BQMall, RaceHorses, FourPeople) are tested, and the optimal modes for depth 0 CUs (i.e. 64x64 CUs) are analyzed. The result is displayed in Fig. 3. It is noted that for LCUs, most of the selected modes are Planar, DC, mode 10 and mode 26, which account for about 89% of the selected modes. Therefore, we adopted a cursory direction prediction for small CU depth, while employing a fine-direction prediction for large CU depth.

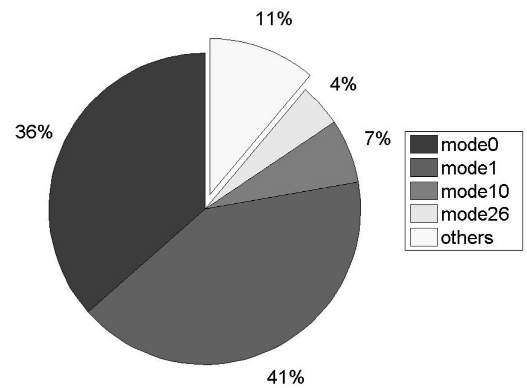

Figure 3. *The selected optimal modes for CUs in depth 0.*

Formally, we define a prediction mode set $\boldsymbol{A}$, and the set $\boldsymbol{A}$ for CU with different depth is obtained as follows:

$$\begin{cases} A = \{0,1\} \cup \{8i+2 | i = 0,1...4\}, & \text{if}(depth = 0) \\ A = \{0,1\} \cup \{4i+2 | i = 0,1...8\}, & \text{if}(depth = 1) \\ A = \{0,1\} \cup \{2i | i = 1,2...17\}, & \text{if}(depth = 2,3) \end{cases} \quad (3)$$

During the RMD process, {2,2,2,1,1} modes instead of {8,8,3,3,3} modes for PU with size of 4x4, 8x8, 16x16, 32x32, 64x64 are selected to form a candidate list. Meanwhile, the MPM-s are obtained before the RMD process, and they are included into the candidate list without RMD check. Through this way fewer modes are checked in RDO process, thus the computational burden can be further removed.

Redundant Directional Mode Elimination

Besides the depth information, the directional information of a CU is also utilized to reduce the mode candidates in the proposed algorithm. Let J^{H}_{SATD} be the HAD cost of the horizontal mode (mode 10) of current CU, and J^{V}_{SATD} be the HAD cost of the vertical mode (mode 26) of current CU. And the directional ratio Dr is calculated as follows:

$$Dr = {J^{H}_{SATD}} / {J^{V}_{SATD}} \quad (4)$$

If Dr is very large, this CU can be considered to have directions near vertical so those horizontal modes are less likely to be selected, and vice versa. In the proposed algorithm, CUs are divided into three types. If the Dr is smaller than a given threshold, this CU is classified into horizontal type, and all vertical modes are skipped during the RMD process. If the Dr is bigger than another given threshold, this CU is considered to a vertical one and all horizontal modes are omitted. The rest CUs are undetermined type and are considered to have no obvious orientation.

Five sequences with different resolution are used for threshold training and totaling 36600 CUs are analyzed. For those horizontal CUs (i.e. the best mode falls within the range [2,17]), the distribution of Dr^H is shown in Fig. 4.

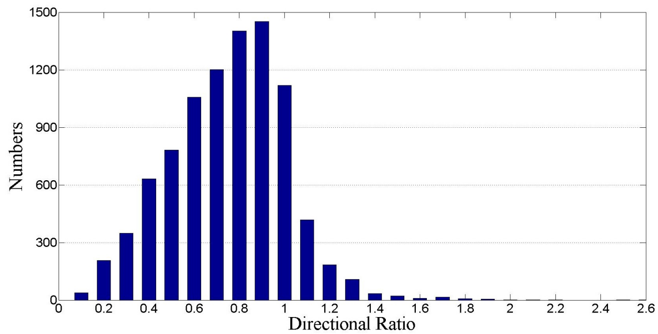

Figure 4. *The distribution of directional ratio of those horizontal CUs*

The mean of Dr^H is 0.7512, and the standard deviation is 0.2562. It is easily to find out that the vast majority of horizontal CUs own a quite small Dr^H. Thus the aim is to find a proper threshold ***Th1***, which can make sure that when a CU have a Dr bigger than ***Th1***, it is nearly impossible for this CU to have a horizontal direction. The error ratio $\boldsymbol{r}$ is applied to decide the threshold. $\boldsymbol{r}$ is culculated as follows:

$$r = \frac{E_{num}}{(E_{num} + C_{num})} \tag{5}$$

Where E_{num} represnets the number of CUs which have a horizontal orientation but their Dr^H are above the threshold, and C_{num} denotes the number of horizontal CUs which their Dr^H are beneath the threshold. For each given threshold, the E_{num} and C_{num} are count and $\boldsymbol{r}$ is computed according to formula (5). Finally the threshold 1.2 is obtained by experiments, the corresponding $\boldsymbol{r}$ is 0.031, which is almost negligible.

Meanwhile, for those vertical CUs (i.e. the best mode falls within the range [19,34]), the distribution of Dr^V is shown in Fig. 5.

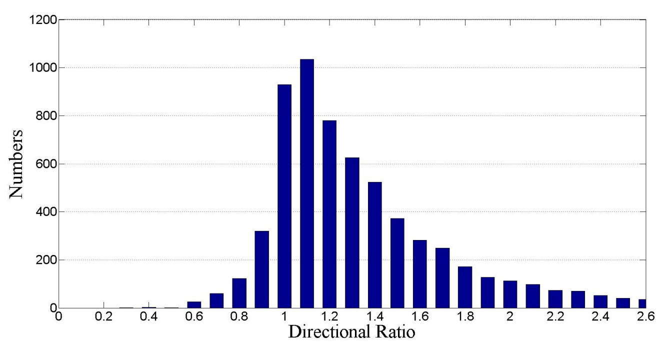

Figure 5. *The distribution of directional ratio of those Vertical CUs*

The mean of Dr^V is 1.3781, and the standard deviation is 0.5445. It is obvious that most of vertical CUs have a biggish Dr^V which value is bigger than 1. Thus, another threshold ***Th2*** is obtained by applying similar method. Finally, ***Th2*** is set to 0.85 by experiments, the corresponding $\boldsymbol{r}$ is 0.033.

As the two threshold are obtained, the classification of CU tpye can be formally defined as:

$$type = \begin{cases} horizontal, & \text{if}\,(Dr \leq 0.85) \\ vertical, & \text{if}\,(Dr \geq 1.2) \\ undetermined, & \text{otherwise} \end{cases} \tag{6}$$

Integrated Fast Algorithm

The proposed algorithm combines the above two part to reduce the complexity in HEVC intra mode decision process. Firstly, the MPMs are obtained and included into the candidate list without any evaluation. After that, mode 10 and 26 are checked to generate the directional ratio. Then a modified RDM is performed, both depth and directional information are utilized to skip some unnecessary search. Finally, fewer modes are selected for full RDO process. The integrated algorithm is depicted as follows.

Algorithm 1 Integrated fast mode decision algorithm

```
//use fast mode decision algorithm to form the final RDO candidate list R
M = MPMs
form set A by Formula (3)
calculate ratio Dr by Formula (4)
classify the CU type by Formula (6)
if horizontal CU then
    A = A - vertical modes
else
    if vertical CU then
        A = A - horizontal modes
    end if
end if
for mode A_i in set A do
    if A_i ∈ M then
        skip A_i
    else
        perform RMD process
    end if
end for
select N modes to form RMD candidate list C
for mode C_i in set C do
    check the neighbour mode N_i
    update set C
end for
R = R ∪ C
```

Experimental Results

In this section, experimental results are given to verify the fast intra mode decision algorithm. As the proposed algorithm is implemented on HEVC reference software HM 16.0 [6], the default algorithm in HM 16.0 is used as an anchor. In the experiments, the QP values are 22,27,32, and 37, all-intra main configuration is used. HEVC test sequences [20] Class A (2k), Class B (1080p), Class C (WVGA), Class D (QWVGA), Class E (720p) are tested. Besides, some 4K sequences are also employed for the algorithm performance verification. BD-rate [21] and time saving

BD-rate Loss and Time Saving of Proposed Algorithm

Class	Sequence	Y	U	V	*TS*
4K	CampfireParty	0.6%	-0.5%	-0.4%	33.46%
	Fountains	0.6%	-0.7%	-0.7%	35.46%
	Marathon	0.8%	-0.5%	-0.5%	34.02%
	Runners	0.6%	-0.6%	-0.4%	34.01%
	RushHour	0.7%	0.3%	0.2%	35.17%
	TallBuildings	0.8%	-0.4%	-0.3%	33.95%
	TrafficFlow	0.8%	0.0%	0.0%	33.94%
	Wood	0.8%	-0.2%	-0.2%	33.94%
A	NebutaFestival	0.3%	0.2%	0.1%	34.30%
	PeopleOnStreet	1.0%	-0.1%	-0.1%	34.70%
	SteamLocomotive	0.3%	0.1%	0.3%	35.78%
	Traffic	0.9%	0.0%	0.0%	34.65%
B	BasketballDrive	0.9%	0.1%	0.0%	34.85%
	BQTerrace	0.6%	-0.3%	-0.4%	33.98%
	Cactus	0.9%	-0.2%	-0.2%	33.80%
	Kimono	0.4%	-0.1%	0.0%	34.86%
	ParkScene	0.6%	-0.5%	-0.5%	34.34%
C	BasketballDrill	1.0%	0.0%	0.1%	31.96%
	BQMall	1.2%	-0.1%	-0.1%	34.97%
	PartyScene	1.3%	-0.3%	-0.3%	33.63%
	RaceHorses	0.8%	-0.2%	-0.1%	33.02%
D	BasketballPass	1.2%	0.1%	0.1%	33.67%
	BlowingBubbles	1.3%	-0.3%	-0.3%	32.57%
	BQSquare	1.4%	-0.1%	0.0%	32.99%
	RaceHorses	1.1%	0.0%	0.1%	32.79%
E	FourPeople	1.1%	0.0%	0.0%	34.92%
	Johnny	1.1%	0.1%	0.4%	35.32%
	KristenAndSara	1.2%	0.4%	0.5%	34.19%
Ave.		0.9%	-0.1%	-0.1%	34.12%

TS are used for evaluation. The ***TS*** is defined as follows:

$$TS = \frac{(T_{org} - T_{prop})}{T_{org}} \times 100\% \quad (7)$$

Where T_{org} represents the time consumption of the default HM 16.0, while T_{prop} denotes the time spent by the proposed algorithm. The results are shown in Table. On average, the proposed algorithm can achieve about 34% time saving at the cost of 0.9% BD-rate loss for all-intra coding. It can be observed that the proposed algorithm performs well for high resolution sequences (4K, Class A and Class B). The BD-rate losses are not higher than 1% for high resolution sequences, and not higher than 1.4% for all the sequences. In terms of time saving, the smallest saving is 31.96% for the sequence *BasketballDrill*, while the largest saving is 35.78% for the sequence *SteamLocomotive*. The experimental results can prove that the proposed algorithm is able to provide satble coding performance as well as time saving.

Conclusion

In this paper, a fast intra mode decision algorithm is proposed to speed up the HEVC intra prediction process. The overall algorithm consists of two step. Firstly, the depth information of current coding block is utilized to reduce the number of modes in the candidate set with the assumption that an exhausted search for large CU is unnecessary. And meanwhile the order of MPM is adjusted, in order to skip some redundant check during RMD process. Secondly, a directional ratio is calculated to estimate the rough orientation of each CU, so as to further eliminate some irrelevant directional modes. The experimental results show that the proposed two-step algorithm can achieve 34% encoding time saving on average while cause a negligible quality loss under All-Intra configuration with HM 16.0.

Acknowledgments

This work was supported in part by the Hi-Tech Research and Development (863) Program of China (No. 2015AA015903), National Natural Science Foundation of China (No. 61471273), and Natural Science Foundation of Hubei Province of China (No. 2015CFA053)

References

[1] G. J. Sullivan, J.-R. Ohm, W.-J. Han, and T. Wiegand, "Overview of the high efficiency video coding (hevc) standard," *IEEE Transactions on circuits and systems for video technology*, vol. 22, no. 12, pp. 1649–1668, 2012.

[2] T. Wiegand, G. J. Sullivan, G. Bjontegaard, and A. Luthra, "Overview of the h. 264/avc video coding standard," *IEEE Transactions on circuits and systems for video technology*, vol. 13, no. 7, pp. 560–576, 2003.

[3] J. Lainema, F. Bossen, W.-J. Han, J. Min, and K. Ugur, "Intra coding of the hevc standard," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 22, no. 12, pp. 1792–1801, 2012.

[4] I.-K. Kim, J. Min, T. Lee, W.-J. Han, and J. Park, "Block partitioning structure in the hevc standard," *IEEE transactions on circuits and systems for video technology*, vol. 22, no. 12, pp. 1697–1706, 2012.

[5] F. Bossen, B. Bross, K. Suhring, and D. Flynn, "Hevc complexity and implementation analysis," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 22, no. 12, pp. 1685–1696, 2012.

[6] "HEVC Test Model Reference Software (HM)," https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/.

[7] Y. Piao, J. Min, and J. Chen, "Encoder improvement of unified intra prediction," *JCTVC-C207*, 2010.

[8] L. Zhao, L. Zhang, S. Ma, and D. Zhao, "Fast mode decision algorithm for intra prediction in hevc," in *IEEE International Conference on Visual Communications and Image Processing (VCIP)*. IEEE, 2011, pp. 1–4.

[9] H. Zhang and Z. Ma, "Fast intra prediction for high efficiency video coding," in *Pacific-Rim Conference on Multimedia*. Springer, 2012, pp. 568–577.

[10] S. Na, W. Lee, and K. Yoo, "Edge-based fast mode decision algorithm for intra prediction in hevc," in *IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, 2014, pp. 11–14.

[11] H. Zhang and Z. Ma, "Fast intra mode decision for high efficiency video coding (hevc)," *IEEE Transactions on circuits and systems for video technology*, vol. 24, no. 4, pp. 660–668, 2014.

[12] T. S. Kim, M. H. Sunwoo, and J.-G. Chung, "Hierarchical

fast mode decision algorithm for intra prediction in hevc," in *IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2015, pp. 2792–2795.

[13] D. Gwon, H. Choi, and J. M. Youn, "Hevc fast intra mode decision based on edge and satd cost," in *Asia Pacific Conference on Multimedia and Broadcasting (APMediaCast)*. IEEE, 2015, pp. 1–5.

[14] L. Gao, S. Dong, W. Wang, R. Wang, and W. Gao, "Fast intra mode decision algorithm based on refinement in hevc," in *IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2015, pp. 517–520.

[15] X. Shen, L. Yu, and J. Chen, "Fast coding unit size selection for hevc based on bayesian decision rule," in *Picture Coding Symposium (PCS)*. IEEE, 2012, pp. 453–456.

[16] Y. Wang, X. Fan, L. Zhao, S. Ma, D. Zhao, and W. Gao, "A fast intra coding algorithm for hevc," in *IEEE International Conference on Image Processing (ICIP)*. IEEE, 2014, pp. 4117–4121.

[17] B. Min and R. C. Cheung, "A fast cu size decision algorithm for the hevc intra encoder," *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 25, no. 5, pp. 892–896, 2015.

[18] Q. Zhang, J. Sun, Y. Duan, and Z. Guo, "A two-stage fast cu size decision method for hevc intracoding," in *IEEE 17th International Workshop on Multimedia Signal Processing (MMSP)*. IEEE, 2015, pp. 1–6.

[19] T. Zhang, M.-T. Sun, D. Zhao, and W. Gao, "Fast intra mode and cu size decision for hevc," 2016.

[20] F. Bossen *et al.*, "Common test conditions and software reference configurations," *Joint Collaborative Team on Video Coding (JCT-VC), JCTVC-F900*, 2011.

[21] G. Bjontegaard, "Calcuation of average psnr differences between rd-curves," *Doc. VCEG-M33 ITU-T Q6/16, Austin, TX, USA, 2-4 April 2001*, 2001.