Fast Intra Prediction Algorithm with Enhanced Sampling Decision for H.265/HEVC

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Abstract: H.265/HEVC is the latest video coding standard, which offers superior compression performance against H.264/AVC at the cost of greater complexity in its encoding process. In the intra coding of HEVC, a Coding Unit (CU) is recursively divided into a quad-tree-based structure from the Largest Coding Unit (LCU). At each level, up to 35 potential intra modes should be checked. However, examining all these modes is very time-consuming. In this paper, an intra mode decision algorithm is proposed that reduces the required computations while having negligible effect on Rate-Distortion (RD) performance. A rough mode decision method based on image component sampling is proposed to reduce the number of candidate modes for rough mode decision and RD optimization. To balance the quality and performance, the decision to reduce the full search is made with a thresholds that is dynamically updated based on the Quantization Parameter (QP) and CU size of each recursive step. Experiments show that our algorithm can achieve a reasonable trade-off between encoding quality and efficiency. The saving in encoding time is between 30.0% to 45.0% while BD-RATE may increase by up to 0.5% for H.265/HEVC reference software HM 16.9 under all-intra configuration.

1 INTRODUCTION

The H.264/AVC video coding standard (Wiegand et al., 2003) is widely used in currently deployed video broadcasting systems. However, there is a need to deliver higher resolution and better quality of video. To respond to this need, ISO/IEC Moving Picture Experts Group (MPEG) and ITU-T Video Coding Experts Group (VCEG) have jointly developed a new video coding standard named High Efficiency Video Coding (H.265/HEVC) (Sullivan et al., 2012).

H.265/HEVC realizes better image quality in comparison with H.264/AVC at the same coding bitrate, but also needs much larger complexity in its encoding process. For intra coding, it has been known that the recursive quad-tree-based structure of the Coding Unit (CU) can improve the processing efficiency while the encoding complexity is increased significantly (Kim et al., 2012). The complexity of H.265/HEVC intra coding increases several times compared with H.264/AVC intra coding (Bossen et al., 2012) since the best intra prediction mode and CU size need to be decided by the Rate-Distortion Optimization (RDO).

1.1 Intra Prediction in H.265/HEVC

In H.265/HEVC, there are three types of coding blocks: Coding Unit (CU), Prediction Unit (PU) and Transform Unit (TU). Coding Tree Unit (CTU) is a concept of Largest Coding Unit (LCU, $size = 64 \times 64$, $depth = 0$). Each CU can be encoded in the best mode achieving the smallest Rate-Distortion (RD) cost among all the possible modes or recursively split into four CUs with equal sizes until the Smallest Coding Unit (SCU, $size = 8 \times 8$. $depth = 3$). The partitioning structure of CU and PU is shown in Fig. 1.

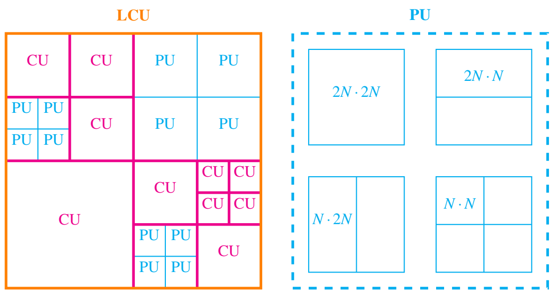

Figure 1: Partitioning structure of CU and splitting of PU, here N is half of the CU size.

After splitting the CU, then the PU and TU can

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be split independently, and selected for the CU if the sum of the RD costs of four sub-CUs is smaller than the RD cost of a large CU (Kim et al., 2012; Huang et al., 2014). In intra mode, there are up to 35 possible intra prediction modes in H.265/HEVC while only 9 modes are allowed in H.264/AVC. Note that the PU can only be split into a square shape, and each PU will choose the best matching prediction mode.

1.2 Related Work

In order to reduce the complexity of intra coding in H.265/HEVC, there have been many algorithms proposed in the literature focusing on fast intra mode decision and fast CU size decision. The decision making can be modified such as in (Piao et al., 2010) to speed up the process. The algorithms used in (Yan et al., 2012) and (Shen et al., 2013a) are based on the correlation of adjacent prediction costs, which speeds up the process but the extra computation load is still high. In (Cho and Kim, 2013), an early CU splitting and pruning method is discussed and the method in (Shen et al., 2013b) replaces the fixed tree-depth range for each CU with an adaptive CU depth decision depending on the previously encoded slices and neighbouring CUs. In (Zhao et al., 2011), a smaller candidate set is proposed that does not lead to noticeable quality loss, this compared various settings with different mode candidates for the full Rate-Distortion Optimized Quantization (RDOQ).

To reduce the complexity, (Choi and Jang, 2012) proposed a tree pruning algorithm for fast CU decision making. It skips the further CU splitting if the current CU chooses the SKIP mode. Such SKIP-mode-based early termination cannot be applied to the intra prediction. Moreover, some papers proposed alternative thresholds condition: a local edge information is obtained by calculating edge feature parameters in (da Silva et al., 2012) and (Jiang et al., 2012) employed a gradient based method to speed up CU decisions. According to (Min and Cheung, 2015; Jamali et al., 2015; Lim et al., 2015), the results of HEVC intra coding based on different versions of HMs are similar due to the fact that HEVC intra coding does not involve significant changes among these versions. Therefore, it is acceptable to compare these methods under different HM versions. Then, a gradient based fast intra mode decision is proposed in (Chen et al., 2013), which based on the gradient directions for each CU, selects only a small set of modes for further intra prediction. Hence, a large portion of modes are removed from the computation.

1.3 Contribution

In this paper, we propose a fast intra mode prediction algorithm while maintaining the RD performance by analysing picture feature statistics. An early termination technique for CU is applied in H.265/HEVC for experiments. Corresponding to the required encoding efficiency and the quality of encoded picture, we use the subsampling result of deviation values of *Luma*/*Chroma* in different sizes for video sequences. Since there are several Chroma-Subsampling in the standard, we propose the weight of *Luma*/*Chroma* will depend on the ratio of common Sampling systems (explained in Sec. 2.2). Further, to balance the quality and performance, we define a thresholds (T) without using static decision thresholds, and rely on a comparison between the Quantization Parameter (QP) and CU size of the coding tree under test, which have to be updated at each recursion. The use of adaptive thresholds is fundamental in H.265/HEVC as the number of possible partitioning and coding modes is more appropriate then static thresholds for each of them.

The rest of the paper is organized as follow: Sec. 2 provides details of the idea of the fast intra prediction algorithm including the proposed weighed sampling operator and adaptive thresholds. Sec. 3 gives the details of the concept about the thresholds and how to achieve this in different depth layers. The simulation results are given in Sec. 4, and Sec. 5 concludes the paper.

2 PROPOSED METHOD

The intra mode prediction defined in the H.265/HEVC standard allows 35 (including Planar, DC mode and 33 angular) predictions. Planar and DC prediction modes can provide predictions for image areas with smooth and gradually changing content. The angular intra predictions are designed to model different directional structures typically present in picture (see Fig. 2).

2.1 Fast Intra Prediction Algorithm

As a range of sample methods, the angular predictions are also useful in smooth PU blocks without high frequency components for complex textures that cannot be properly modelled with any of the directional predictors. It can easily perceive that a large size CU is more suitable for some homogeneous or flat regions in the image. For discriminating texture, CUs that are not split into sub-CUs are expected to have smaller

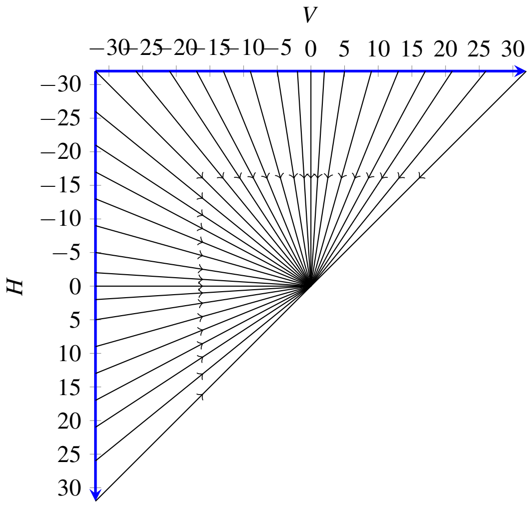


Figure 2: Angle definitions of angular intra prediction in H.265/HEVC. (H,V) is used to indicate the displacement. Prediction mode 2 to 17 is index by $(H,-32)$, and mode 18 to 34 is index by $(-32,V)$.

RD costs than would occur if the CUs were split, while an area with colourful edges or object boundaries is usually split into small CUs. Since the feature of a homogeneous region is that the sampling result approaches the mean value, the Sum of Absolute Difference (SAD) can represent the image complexity. In extreme cases, if ($SAD = 0$), it means there is full homogeneity: *i.e.* there is exactly same sample value in the whole region. Applying to intra prediction, we design to calculate the image complexity before the 33 angular intra predictions as:

$$mean = \frac{1}{N \times N} \sum_{i=1,j=1}^{N,N} C(i,j) \tag{1}$$

$$SAD = \sum_{i=1,j=1}^{N,N} |mean - C(i,j)| \tag{2}$$

where $N \in \{64,32,16\}$ is the size of the current CU, $C(i,j)$ is the (sub)-sampling method that is exploited by a weighted sampling operator and *SAD* represents the image complexity and can be used to determine whether it is necessary to do the angular prediction. After the texture calculation, if the *SAD* is smaller than or equal to the corresponding thresholds, the image is thought to be smooth enough to terminate the prediction early. Therefore, this algorithm avoids checking SCU sizes when they are not likely to be selected by the brute force RDO process.

2.2 Weighted Sampling Operator

For each CU at a given depth, all the allowed coding modes are tested and the mode with the minimum RD cost is selected, then the early termination stops the CU splitting process if the minimum *SAD* is already lower than a given threshold. This mean that a good coding configuration has already been obtained and searching for smaller CUs may only slightly improve the overall performance or, indeed, may even provide a lower performance as smaller CU sizes may imply less compression in transformation. In order to enhance the sampling to the reference results, we must consider the weighted sampling/subsampling of *Luma* and *Chroma* components in prediction block. According to the efficiency of different configurations scenario at quantization settings, we used a weighted sum of the average sampling values for the *Luma* and *Chroma* components, defined by

$$C = \frac{(w_y, w_{uv}) \cdot (Luma, Chroma)}{w_y + w_{uv}} \tag{3}$$

where the weights value (w_y, w_{uv}) must satisfy the conditions $w_y > 0$, $w_{uv} > 0$ and $w_y + w_{uv} \neq 0$, depending on the colour sampling modes,

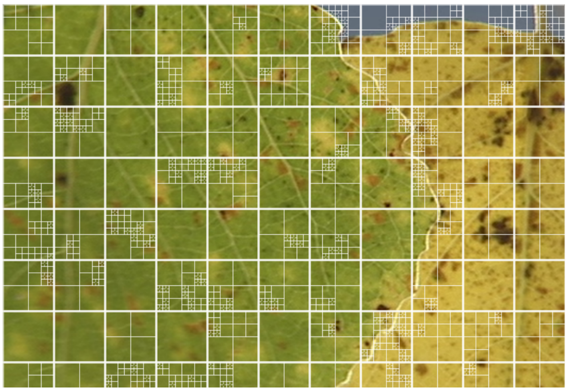
$$(w_y, w_{uv}) = \begin{cases} (8,0), & type = 4:0:0 \\ (8,2), & type = 4:1:1 \\ (8,2), & type = 4:2:0 \\ (8,4), & type = 4:2:2 \\ (8,4), & type = 4:4:0 \\ (8,8), & type = 4:4:4 \end{cases} \tag{4}$$

where *type* means the type of *Luma* sampling and *Chroma* subsampling. To approximate the accurate quality using the PSNR and the average bit-rate of generated bitstreams, the weighted sampling better identifies the homogeneous area which characterizes the coding efficiency.

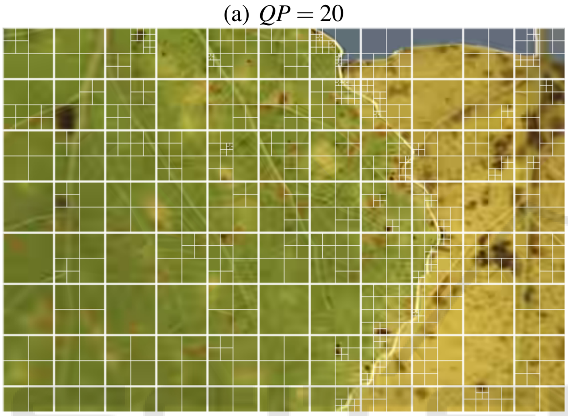
2.3 Adaptive Thresholds

Since our algorithm avoids checking the RD costs when early termination occurs, the values for the thresholds (T) play a central role in the trade-off between encoding quality and efficiency. With different *QP* and CU sizes, the use of adaptive thresholds is fundamental in H.265/HEVC as the number of possible partitioning and coding modes is so high that it is impossible to set up appropriate static thresholds for each of them. In order to find suitable thresholds, we first analyse the *SAD* of different sizes of CU in reference software (see Fig. 3). When the CU texture is complex, then CU is split into smaller subunits to find the best size but if the CU texture is flat enough it will not be divided further into subunits.

As shown in Fig. 3, coding with higher *QP* will lose the detail in video reconstruction, which may



(a) $QP = 20$



(b) $QP = 40$

Figure 3: Indicating the CU splitting by intra mode decision with difference *QP* in HM reference software.

cause lots of homogeneous area that can be split into bigger CU then coding with lower *QP* case. By this reason, we consider the *SAD* as a thresholds (T) to determine the CU splitting and find the relation about the thresholds as $T(QP, CU_{size})$. According to statistics from various videos, the thresholds is adaptive to video content, CU size and QP, given by,

$$T(QP, CU_{size}) = \left\lfloor E(C) - \frac{QP}{2} \right\rfloor \cdot CU_{size}^2 \quad (5)$$

where $E(C)$ is the expected value of sampling, and the partial differential equation of Eq. 5 about QP and CU_{size} as follows:

$$\frac{\partial T}{\partial QP} = -\frac{CU_{size}^2}{2} \quad (6)$$

$$\frac{\partial T}{\partial CU_{size}} = 2 \cdot \left\lfloor E(C) - \frac{QP}{2} \right\rfloor \cdot CU_{size} \quad (7)$$

Therefore, the relationship between the *SAD* and CU size is not very sensitive to *QP*. As the depth increases, the CU will be evenly split into four sub-CUs, while the thresholds are scaled down into approximately one quarter. Using large thresholds will achieve a highly accurate decision but the complexity reduction for intra mode decisions will be very small, and using small thresholds will reduce the complexity but lose accuracy. Thresholds should be determined to provide a good trade-off between encoding quality and efficiency. In order to make the thresholds(T) more adaptive to recent changes, a weighting function is adopted which, similar to Eq. 4, corresponds to the (sub)-sampling method. Thus, it smoothly allows updating the expected values to better take into account the most recent *Luma* and *Chroma* components, defined by

$$E(C) = \frac{(w_y, w_{uv}) \cdot (E(Luma), E(Chroma))}{w_y + w_{uv}} \quad (8)$$

3 IMPLEMENTATION

To verify our method, experiments were conducted by using various test sequences under different QP settings for investigating the RD cost distribution for CUs resulting from the exhaustive search of the H.265/HEVC Test Model (HM 16.9) and using our modified HM software with the fast intra prediction added.

3.1 Fast Intra Predication Walkthrough

The algorithm presented in this paper was implemented in the HM 16.9 reference software. Since the number of intra modes available for the prediction of each CU can be reduced, the number of candidate modes selected in the HM 16.9 intra prediction method is also modified. The overall proposed fast intra predication process for each CU is now presented as pseudo code, integrating the weighting sampling and adaptive thresholds.

We first start from the Planar and DC mode since these modes occur with high probability. Then we calculate the *SAD* of CU that is used to compare with the thresholds (T) by considering the current *QP* and CU_{size}. If the *SAD* is smaller than the thresholds, it means that the texture is flat enough so that there needs to be no further CU splitting, just finding the smallest RD cost between intra Planar, DC and 33 angular modes in the current depth layer. Otherwise, it means that the texture is too complex to be intra predicated in the current *Depth*, so we can skip the remaining angular predication and there is no need to check the intra mode in the current depth layer anymore. We then consider the next *Depth* to find the smallest RD cost between intra Planar, DC and sum of sub-CUs RD cost.

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Algorithm 1: FastIntraPred(*CU*, *QP*, *Depth*).

```
Data: CU: object
Data: QP: int
Data: Depth: int
Result: RD_cost: unsigned int
/* determine the best intra modes
   and provide smallest RD cost                */
begin
    /* first find better intra mode
       between Planar an DC                    */
    RD_cost ←smaller RD cost between mode 0, 1;
    SAD ← calculate the SAD of CU;
    /* compare with thresholds
       condition                               */
    if SAD < T (QP, CU_size) then
        /* if condition is verified
           that means there are lots
           of homogeneous area                 */
        for all the CU to be coded at Depth do
            /* find best intra angular
               modes                           */
            RD_cost ←find the smallest RD cost;
        end
    else
        /* CU is evenly split into
           four units as CU_0,1,2,3            */
        RD_cost ← sum of FastIntraPred(CU_0,1,2,3,
          QP, Depth + 1);
    end
    return RD_cost;
end
```

4 EXPERIMENT RESULTS AND DISCUSSION

The H.265/HEVC reference software HM 16.9 was modified to handle our proposed method, and a series of simulations were carried out to measure the improvement offered by accurate bit estimation. For most of the comparisons, the Bjontegaard PSNR and bit-rate differences (BD-PSNR and BD-RATE) between the proposed and the reference method are shown in the following.

Table 1: Mean of *SAD* of difference CU size and *QP* in HM reference software.

QP	64×64, $depth=0$	32×32, $depth=1$	16×16, $depth=2$	8×8, $depth=3$
20	481236.87	120007.25	30044.54	7479.20
24	472784.87	118100.85	29540.11	7030.81
28	464040.13	115765.73	29057.78	5899.01
32	455679.14	113168.00	28498.35	6827.27
36	448174.94	111326.90	28006.23	6987.15
40	437079.86	108763.22	27449.52	5667.41

As expected in Tab. 1 corresponding to Fig. 3, *QP* values are taken into consideration as the *QP* will scale the range of sample values. Note that these results are matched to Eq. 6 and 7, so the difference between each sample and the *mean* of sampling CU becomes smaller as *QP* increases.

4.1 Performance Verification

The procedure detailed in (Senzaki et al., 2010) is used to calculate BD-PSNR and BD-RATE with $QP \in \{20,24,28,32,36,40\}$. For all tests the the main-profile features of HM in progressive format are enabled, also 100 frames are coded (frame rates given in the table captions) with one intra update every second.

Table 2: H.265/HEVC, proposed *vs.* reference HM 16.9, QCIF@30Hz, all Intra pictures with BD-RATE, BD-PSNR and time reduction.

QCIF_IIIII	*BD-RATE (%)*	*BD-PSNR -Y (dB)*	*Time Reduction (%)*
akio	+0.441	-0.015	-44.99
carp	+0.471	-0.014	-45.12
coast	+0.219	-0.007	-43.98
fore	+0.042	-0.091	-43.86
mobile	+0.123	-0.059	-43.21
news	+0.404	-0.099	-42.71
paris	+0.253	-0.077	-41.88
silent	+0.108	-0.044	-42.90

Table 3: H.265/HEVC, proposed *vs.* reference HM 16.9, 4CIF@30Hz, all Intra pictures with BD-RATE, BD-PSNR and time reduction.

4CIF_IIIII	*BD-RATE (%)*	*BD-PSNR -Y (dB)*	*Time Reduction (%)*
aspen	+0.118	-0.005	-30.44
blue_sky	+0.447	-0.028	-49.90
controlled_burn	+0.176	-0.010	-42.42
crowd_run	+0.352	-0.021	-44.59
in_to_tree	+0.103	-0.004	-42.35
life	+0.176	-0.010	-47.66
park_joy	+0.181	-0.012	-44.56
riverbed	+0.095	-0.004	-31.22
rush_hour	+0.086	-0.003	-46.70
sunflower	+0.264	-0.015	-31.63

Tab. 2 and 3 results of the proposed method for all intra coding, 4CIF and QCIF videos respectively. As expected, since the proposed fast intra-prediction mode decision and fast intra-transform skip-mode decision have been added into the H.265/HEVC scheme, and the weighted sampling and adaptive thresholds condition can find an approximate result with HM reference software, so the BD-Rate just increases by up to 0.5%.

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Table 4: H.265/HEVC, proposed *vs.* reference HM 16.9, QCIF@30Hz, all Intra pictures with difference *QP* and coding time reduction.

QCIF_IIII	$QP = 20$ (%)	$QP = 24$ (%)	$QP = 28$ (%)	$QP = 32$ (%)	$QP = 36$ (%)	$QP = 40$ (%)	*AVERAGE*
akio	-46.40	-45.83	-45.60	-44.06	-44.12	-43.92	-44.99
carp	-45.88	-46.24	-44.67	-45.83	-44.77	-43.30	-45.12
coast	-45.17	-46.08	-45.89	-41.61	-41.38	-43.74	-43.98
fore	-46.62	-47.30	-46.14	-40.24	-41.99	-40.89	-43.86
mobile	-44.88	-45.85	-44.45	-42.55	-40.11	-41.39	-43.21
news	-44.22	-45.38	-45.07	-41.20	-41.14	-39.27	-42.71
paris	-41.68	-44.37	-42.49	-42.92	-40.09	-39.72	-41.88
silent	-44.57	-45.37	-41.21	-44.47	-43.30	-38.45	-42.90

Table 5: H.265/HEVC, proposed *vs.* reference HM 16.9, 4CIF@30Hz, all Intra pictures with difference *QP* and coding time reduction.

4CIF_IIII	$QP = 20$ (%)	$QP = 24$ (%)	$QP = 28$ (%)	$QP = 32$ (%)	$QP = 36$ (%)	$QP = 40$ (%)	*AVERAGE*
aspen	-31.91	-33.30	-33.72	-29.19	-27.80	-26.72	-30.44
blue_sky	-49.37	-48.45	-48.02	-51.52	-51.07	-50.97	-49.90
controlled_burn	-43.70	-36.18	-39.90	-43.19	-44.76	-46.76	-42.42
crowd_run	-42.58	-43.17	-48.39	-45.05	-44.92	-43.40	-44.59
in_to_tree	-48.70	-37.62	-38.43	-42.19	-43.97	-43.17	-42.35
life	-50.68	-43.32	-45.20	-48.94	-48.62	-49.18	-47.66
park_joy	-51.35	-47.75	-36.46	-42.11	-45.59	-44.08	-44.56
riverbed	-38.73	-31.00	-29.38	-28.74	-28.80	-30.64	-31.22
rush_hour	-51.26	-49.97	-47.90	-47.87	-45.44	-37.78	-46.70
sunflower	-36.34	-30.84	-30.49	-30.21	-30.77	-31.11	-31.63

As shown in Tab. 4 and 5, the encoding bit stream size for different values of *QP* with QCIF and 4CIF samples, and encoding time reduction is derived by

$$\Delta t = \frac{t_{proposed} - t_{reference}}{t_{reference}} \times 100.00\% \quad (9)$$

where $t_{reference}$ and $t_{proposed}$ are the encoding time of the original intra mode decision and the proposed fast intra mode decision scheme. Results show that proposed method can generate a speed-up on average of 40.0% and up to 45.0% with the BD-PSNR degradation less than 0.1dB in QCIF, with 4CIF the average speed-up is 30.0% up to 50.0% with BD-PSNR degradation of less than 0.03dB. As discussed in Sec. 2.3, these simulation results are not very sensitive to the *QP* value, but the percentage of time reduction should decrease with increasing *QP* value. Because the textures could be more complex when using small *QP* (which often requires more CU splitting) our proposed approach can be effective to skip lots of angular predication when the coding block is complex enough.

As shown in Fig. 4 to 7, the performance of the proposed method gives a more significant gain in the higher resolution sequence with all inter mode. Our method performs better in terms of BD-RATE and thresholds, and our results approximate very well to the HM reference. It can be seen that the proposed method achieves a reduction in encoding time of between 30.0% to 45.0%. According to the result for each sequence, the average BD-RATE increase for our method is 0.5% while the BD-RATE increase is 0.9% in (Zhang et al., 2016). Both (Zhang et al., 2016) and our method provide a good trade-off between BD-PSNR and encoding time saving.

5 CONCLUSION

This paper proposed a fast intra prediction algorithm to lead to faster encoding time that more accurately approximates the original H.265/HEVC standard results. Our algorithm introduces the weighted sampling and adaptive thresholds condition to determine CU-splitting. The proposed algorithm offers no divergence from the H.265/HEVC standards and can be used in current systems. The result of the performance is shown to offer a more significant gain in the higher resolution sequence with all inter mode. Simulations also show that the proposed method can speed up processing by 30.0% to 45.0% with little BD-PSNR degradation and only 0.5% BD-RATE increase while incurring a controlled precision and adjustable complexity overhead.

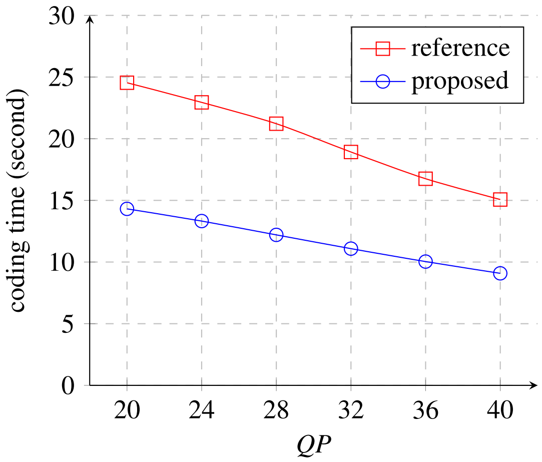

Figure 4: H.265/HEVC, coding time curves proposed *vs.* reference HM 16.9, *paris* QCIF@30Hz, all Intra pictures.

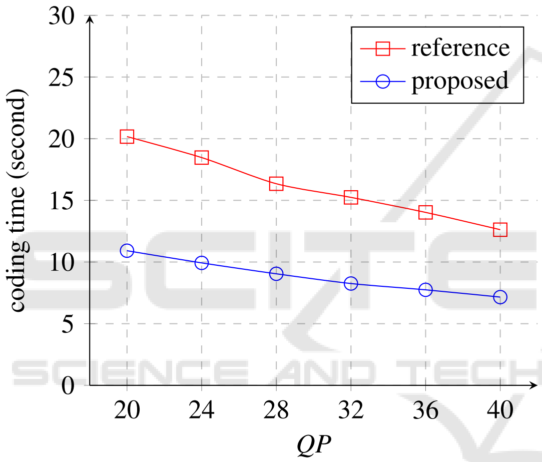

Figure 5: H.265/HEVC, coding time curves proposed *vs.* reference HM 16.9, *carp* QCIF@30Hz, all Intra pictures.

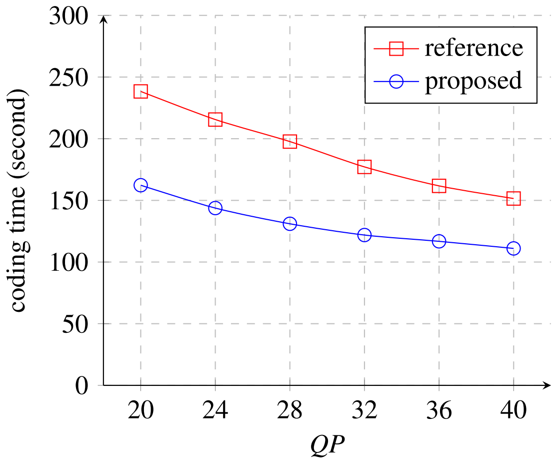

Figure 6: H.265/HEVC, coding time curves proposed *vs.* reference HM 16.9, *aspen* 4CIF@30Hz, all Intra pictures.

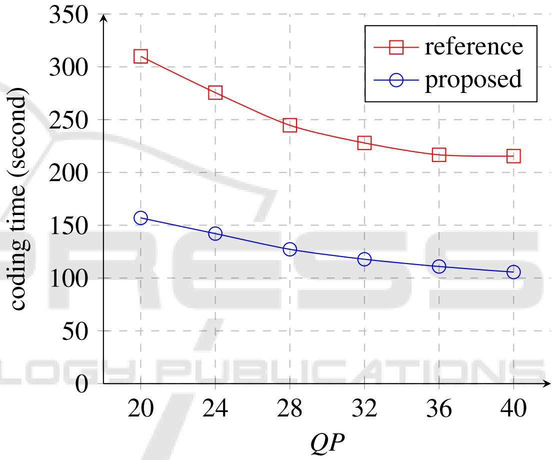

Figure 7: H.265/HEVC, coding time curves proposed *vs.* reference HM 16.9, *blue_sky* 4CIF@30Hz, all Intra pictures.

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REFERENCES

Bossen, F., Bross, B., Suhring, K., and Flynn, D. (2012). Hevc complexity and implementation analysis. *IEEE Transactions on Circuits and Systems for Video Technology*, 22(12):1685–1696.

Chen, G., Pei, Z., Sun, L., Liu, Z., and Ikenaga, T. (2013). Fast intra prediction for hevc based on pixel gradient statistics and mode refinement. In *2013 IEEE China Summit & International Conference on Signal and Information Processing (ChinaSIP)*, pages 514–517. IEEE.

Cho, S. and Kim, M. (2013). Fast cu splitting and pruning for suboptimal cu partitioning in hevc intra coding. *IEEE Transactions on Circuits and Systems for Video Technology*, 23(9):1555–1564.

Choi, K. and Jang, E. S. (2012). Fast coding unit decision method based on coding tree pruning for high efficiency video coding. *Optical Engineering*, 51(3):030502–1.

da Silva, T. L., Agostini, L. V., and da Silva Cruz, L. A. (2012). Fast hevc intra prediction mode decision based on edge direction information. In *2012 Proceedings of the 20th European Signal Processing Conference (EUSIPCO)*, pages 1214–1218. IEEE.

Huang, C.-T., Tikekar, M., and Chandrakasan, A. P. (2014). Memory-hierarchical and mode-adaptive hevc intra prediction architecture for quad full hd video decoding. *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, 22(7):1515–1525.

Jamali, M., Coulombe, S., and Caron, F. (2015). Fast hevc intra mode decision based on edge detection and satd costs classification. In *2015 Data Compression Conference*, pages 43–52. IEEE.

Jiang, W., Ma, H., and Chen, Y. (2012). Gradient based fast mode decision algorithm for intra prediction in hevc.

In *2012 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet)*, pages 1836–1840. IEEE.

Kim, I.-K., Min, J., Lee, T., Han, W.-J., and Park, J. (2012). Block partitioning structure in the hevc standard. *IEEE transactions on circuits and systems for video technology*, 22(12):1697–1706.

Lim, K., Lee, J., Kim, S., and Lee, S. (2015). Fast pu skip and split termination algorithm for hevc intra prediction. *IEEE Transactions on Circuits and Systems for Video Technology*, 25(8):1335–1346.

Min, B. and Cheung, R. C. (2015). A fast cu size decision algorithm for the hevc intra encoder. *IEEE Transactions on Circuits and Systems for Video Technology*, 25(5):892–896.

Piao, Y., Min, J., and Chen, J. (2010). Encoder improvement of unified intra prediction. *JCTVC-C207*.

Senzaki, K., Chono, K., Aoki, H., Tajime, J., and Senda, Y. (2010). Bd-psnr/rate computation tool for five data points. In *Proc. of the Meeting of Joint Collaborative Team on Video Coding. Geneva, Switzerland:[sn]*.

Shen, L., Liu, Z., Zhang, X., Zhao, W., and Zhang, Z. (2013a). An effective cu size decision method for hevc encoders. *IEEE Transactions on Multimedia*, 15(2):465–470.

Shen, L., Zhang, Z., and An, P. (2013b). Fast cu size decision and mode decision algorithm for hevc intra coding. *IEEE Transactions on Consumer Electronics*, 59(1):207–213.

Sullivan, G. J., Ohm, J.-R., Han, W.-J., and Wiegand, T. (2012). Overview of the high efficiency video coding (hevc) standard. *IEEE Transactions on circuits and systems for video technology*, 22(12):1649–1668.

Wiegand, T., Sullivan, G. J., Bjontegaard, G., and Luthra, A. (2003). Overview of the h. 264/avc video coding standard. *IEEE Transactions on circuits and systems for video technology*, 13(7):560–576.

Yan, S., Hong, L., He, W., and Wang, Q. (2012). Group-based fast mode decision algorithm for intra prediction in hevc. In *2012 Eighth International Conference on Signal Image Technology and Internet Based Systems (SITIS)*, pages 225–229. IEEE.

Zhang, T., Sun, M.-T., Zhao, D., and Gao, W. (2016). Fast intra mode and cu size decision for hevc.

Zhao, L., Zhang, L., Ma, S., and Zhao, D. (2011). Fast mode decision algorithm for intra prediction in hevc. In *IEEE Visual Communications and Image Processing (VCIP 2011)*, pages 1–4. IEEE.

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