Hierarchical fast selection of intraframe prediction mode in HEVC

Jakub Siast*, Jakub Stankowski, Marek Domański

Abstract—**In the new HEVC standard, there are 35 intraframe prediction modes. Therefore, real-time implementations need fast mode pre-selection to reduce the computational load of cost comparison for individual modes. In this paper, a simple technique is proposed to reduce the complexity of the Unified Intra Prediction by decreasing the mode candidate number evaluated in the Rough Mode Decision step. We call this approach hierarchical as we decrease stepwise the angles between the directions of the prediction modes that are tested. Obviously, the fast mode selection results in significant complexity reduction obtained at the cost of choosing a sub-optimum mode related to slightly reduced compression performance. In the paper, it is proposed how to calculate the trade-off between encoder complexity and compression performance, using the ratio of relative coding time reduction and average bitrate increase estimated for constant decoded video quality. Extensive experiments prove that this ratio is much higher for the proposed technique than for many other techniques from the references.**

Keywords—**video coding, High Efficiency Video Coding HEVC, intraframe prediction, fast mode selection.**

I. Introduction

RECENTLY, a new High Efficiency Video Coding (HEVC) technology has been developed and the corresponding international standard [1] has been issued. The new HEVC technology provides halved bitrates as compared to those obtained with the commonly used video compression technology called Advanced Video Coding [2]. This performance improvement has been achieved at the cost of increased encoder complexity that is related to an increased number of selectable modes. The optimum or at least sub-optimum mode selection is crucial for good performance of the encoder. Therefore, fast mode selection techniques are necessary for real-time implementations of HEVC encoders.

In HEVC, a frame is split into variable-size square blocks called coding units (CUs). Two types of CUs are defined in the HEVC standard: intraframe and interframe ones. In an intraframe CU, the intraframe prediction is performed in square blocks called prediction units (PUs). An intraframe CU can be split into 4 PUs or a whole CU can be a single PU. In HEVC, there are four effective intra PU sizes ranging from 4 × 4 to 32 × 32 samples. Fast decisions on frame splitting into CUs and PUs were considered in [3-6] and are out of the scope of this paper.

For a PU, regardless of its size, one of 35 distinct prediction modes can be selected: mode 0 named *Planar*, mode 1 named *DC*, and modes 2 to 34 associated with angular modes with consecutive directions. Fig. 1 depicts angular modes associated with prediction directions. The mode selected for a PU should be optimal in the rate-distortion sense, but the optimal selection needs a substantial amount of computations. In this paper, we seek for a technique that will be much faster than full rate-distortion search, while maintaining slightly reduced rate-distortion efficiency.

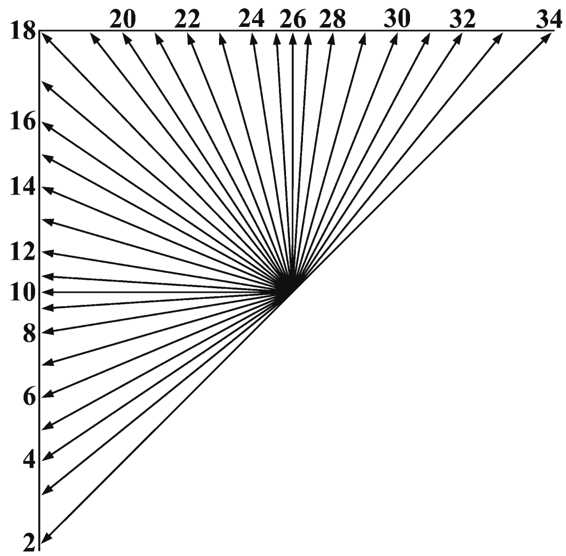

Fig. 1. HEVC angular intraframe prediction modes.

II. State-of-the-Art

For the HEVC intraframe prediction, some techniques for fast prediction mode selection are already described in the references. In the HEVC reference software [7], a technique called Unified Intra Prediction is adopted [8]. This technique consists of two steps: Rough Mode Decision (RMD) and Rate Distortion Optimization (RDO). In the RMD step, for a given PU, all 35 possible prediction modes are evaluated with respect to the coding cost J_{RMD}. The coding cost J_{RMD} is roughly estimated according to (1).

$$J_{RMD} \approx J_H + \lambda \cdot b\,, \quad (1)$$

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where J_H in (1) is the sum of the absolute values of Hadamard coefficients of the residual for a PU, and λ is the Lagrange multiplier related to the number of bits b for encoding of the prediction mode. The number of bits b is constant and equal for almost all modes. In HEVC, 3 modes are defined for which the number of bits is lower than for other modes. Those 3 modes are called the Most Probable Modes (MPMs) [1] and are selected for a PU based on the modes of the neighbouring PUs. After the RMD step, a few modes with the lowest cost J_{RMD} and one or two optional MPMs are selected. For those selected modes, in the RDO step, more complex calculations of the exact coding cost are performed.

The above-mentioned Unified Intra Prediction has been extended in many ways, as described in the references. These approaches may be categorized in the following way:

1. A priori reduction of the number of modes that are evaluated in the RMD step. Our approach belongs to this category, whereas, in the literature, this approach is usually combined with other basic methods (see Category 3).
2. Reduction of the number of modes evaluated in the RDO step [9].
3. A combination of the abovementioned Categories 1 and 2 [10 – 13].
4. A combination of methods not related to the RMD and RDO steps with the methods of Category 1 [14, 15] or 2 [9].

In our technique and the techniques [10-15], the number of modes that are evaluated in the RMD step is reduced. Encoders using the techniques [11-15] compute various gradient statistics of a PU to find an edge inside the PU and the direction of this edge. The angular modes that do not match the estimated direction or are not close to it are disqualified before the RMD step. This strategy is based on the observation that the direction of an edge in the PU and the prediction direction associated with the angular mode chosen by the encoder are correlated.

Contrary to the techniques [11-15], in our technique, no information on edge direction in the PU is used. In our technique we rather exploit the observation that prediction error J_H changes smoothly when computed for consecutive angular modes, i.e., consecutive directions. This observation is used to reduce the number of modes evaluated in the RMD step in a simple and effective way, i.e., without the need to compute additional PU statistics.

The technique presented in [10] is the most similar to our technique. In both techniques, the RMD step is divided into stages in which disjoint subsets of modes are evaluated. The results obtained at one stage are used to choose the modes for evaluation at a further stage. In [10], the modes are evaluated according to cost J_{RMD}, whereas in our technique, the modes are evaluated according to prediction error J_H. Moreover, in the technique [10] the RMD step is divided into more stages, which makes it more complicated than our technique.

III. The Proposed Technique

In the RMD step, the coding cost J_{RMD} is estimated for all prediction modes. It is computationally expensive. The idea is to reduce the complexity of the RMD by estimating cost J_{RMD} only for selected angular modes. Therefore, we propose a technique for the identification of such a subset of all angular modes that the RMD can be efficiently performed only on those selected modes. Efficient performance of the RMD means that the subsequent RDO step yields the mode with nearly the same cost as the cost of the mode chosen in the RDO preceded by the RMD performed for all angular modes.

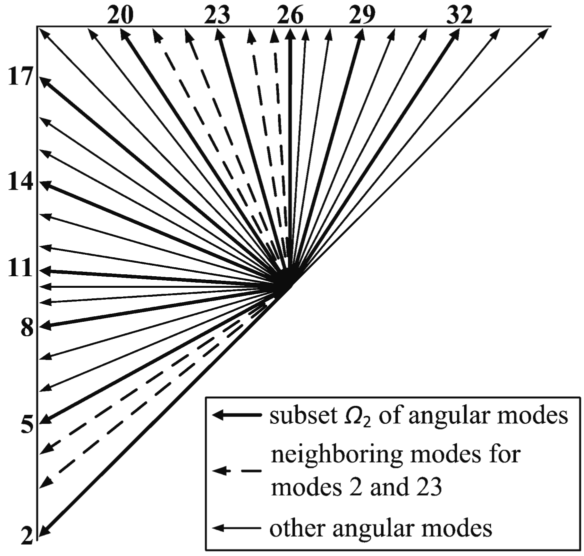

Fig. 2. Subset Ω_2 of angular prediction modes and neighboring modes.

The proposed technique consists of the following stages:

1. From the set $\sum$ of available 33 angular modes, choose a subset $\boldsymbol{\Omega}$ ($\boldsymbol{\Omega} \subset \sum$) and estimate cost J_{RMD} for each mode in $\boldsymbol{\Omega}$. Examples of reasonable choices of $\boldsymbol{\Omega}$ are: every second mode $\boldsymbol{\Omega_1}$ = {2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28, 30, 32, 34}, or every third mode $\boldsymbol{\Omega_2}$ = {2, 5, 8, 11, 14, 17, 20, 23, 26, 29, 32} (cf. Fig. 2), or even every fourth mode $\boldsymbol{\Omega_3}$ = {4, 8, 12, 16, 20, 24, 28, 32}.
2. Find N modes in $\boldsymbol{\Omega}$ with the lowest estimated prediction error J_H, where N = 1, 2 or 3, usually.
3. Identify the modes neighbouring to the above-mentioned N modes. The neighbouring modes are such angular modes that are located between a given selected mode and the next mode from $\boldsymbol{\Omega}$ (both clockwise and counterclockwise if possible). For example, in Fig. 2, the $\boldsymbol{\Omega_2}$ modes are marked by solid lines and the neighbouring modes for modes 2 and 23 are marked by dashed lines.
4. Identify the Most Probable Modes (MPMs) as defined in the HEVC standard [1].

The cost function J_{RMD} is calculated for a set of modes that consists of:

- subset $\boldsymbol{\Omega}$,
- neighbouring modes to N modes with the lowest J_H. It is highly probable that the modes neighbouring to the mode with a low estimated prediction error J_H will also have a low value of J_H. This statement is based on the observation that the prediction error J_H changes smoothly when computed for consecutive angular modes, i.e., consecutive directions.
- *DC* and *Planar* modes. Those modes are always evaluated in the RMD.
- Most Probable Modes, if not already included in the set. MPMs are encoded with a reduced number of bits. As a result,

cost J_{RMD} for MPM can be lower than that for other prediction modes even if its prediction error J_H is relatively high.

The number of modes evaluated in the RMD is shown in Table 1. The results are presented for $\boldsymbol{\Omega_1}$ (every second angular mode), $\boldsymbol{\Omega_2}$ (every third angular mode) and N equals 1 and 2. With those parameters cost J_{RMD} is estimated for 15 to 25 out of 35 prediction modes available in the RMD step.

Table 1. NUMBER OF MODES EVALUATED IN THE RMD STEP

	$\boldsymbol{\Omega_1}$, $N = 1$	$\boldsymbol{\Omega_1}$, $N = 2$	$\boldsymbol{\Omega_2}$, $N = 1$
Minimum number of evaluated modes	20	21	15
Maximum number of evaluated modes	23	25	19

The abovementioned technique may be generalised in some aspects. Firstly, the initial density of directions corresponding to the tested modes may be set arbitrarily. One may use a relatively dense set of directions and the corresponding prediction modes $\boldsymbol{\Omega_1}$, but also more sparse sets $\boldsymbol{\Omega_2}$, $\boldsymbol{\Omega_3}$, or even more sparse set may be used. In the next step also the angular modes are tested around "the best" mode from the used set $\boldsymbol{\Omega_i}$.

One may also generalise this approach onto higher number of steps. In such a case the procedure starts with a very small set $\boldsymbol{\Omega_i}$ and then one tests the modes from an intermediate set of modes around "the best" mode from the previous step. And the next step exploits this intermediate set as previously set $\boldsymbol{\Omega_i}$ was used. Therefore we call this approach "hierarchical" as one stepwise increases the density of directions of predictions but simultaneously one reduces the interval of directions tested.

IV. EXPERIMENT DESCRIPTION

In order to assess the performance of the proposed technique, the respective tool was added to the HEVC HM10.0 reference software [7]. In the experiments, video sequences were coded according to JCT-VC common test conditions [16] in 'All Intra - Main' configuration. These conditions designate 24 video sequences assigned to classes A – F. The sequences from classes A – E are natural, camera-captured material with the highest resolution of 2560 × 1600 in class A, down to 416 × 240 in class D. Class F sequences include computer screen content, as well as mixing natural video and graphics. The average bitrate increase for constant quality of decoded video (*BDBR*) was calculated according to the Bjøntegaard formula [17]. The bitrate increase was calculated over sequences produced by the encoder with and without the proposed technique. According to the JCT-VC common test conditions, the quantization parameters of 22, 27, 32, and 37 were used to obtain four bitrate points required to calculate the average bitrate increase using the Bjøntegaard formula. In order to evaluate the complexity reduction obtained by using the proposed technique, the relative encoding time reduction (ΔT) was calculated according to (2):

$$\Delta T = \frac{T_{org} - T_{prop}}{T_{org}}, \qquad (2)$$

where T_{org} denotes the encoding time of HM10.0 reference software and T_{prop} denotes the encoding time of HM10.0 with the proposed technique implemented.

V. EXPERIMENTAL RESULTS

The proposed technique was tested and the respective values of ΔT and *BDBR* metrics were calculated. Table 2 presents the results for 3 tested configurations of ($\boldsymbol{\Omega}$, N) pairs. It shows that the encoding time was reduced for all test sequences and all configurations of the proposed technique. ΔT values from 3.0% up to 10.4% were achieved with *BDBR* values from -0.13%, indicating a slight quality increase, up to 0.53%, indicating a quality decrease.

The number of modes evaluated in the RMD step depends on the chosen ($\boldsymbol{\Omega}$, N) pair, as discussed in Section III and shown in Table 1. Table 2 presents the average time reduction ΔT for the tested ($\boldsymbol{\Omega}$, N) pairs. Comparing the values from Table 1 with the values from Table 2, it is apparent that the lower the number of modes evaluated in the RMD, the higher the encoding time reduction ΔT. The highest average ΔT of 8.2% is obtained for $\boldsymbol{\Omega_2}$, $N = 1$ that reduces the number of modes evaluated in the RMD step the most. The lowest average ΔT of 5.3% is obtained for $\boldsymbol{\Omega_1}$, $N = 2$ that reduces the number of modes evaluated in the RMD step the least.

For fixed $N = 1$, the results obtained for $\boldsymbol{\Omega_2}$ (every third angle mode) can be compared with the results obtained for denser $\boldsymbol{\Omega_1}$ (every second other angle mode). It is clear that for denser $\boldsymbol{\Omega_1}$, lower *BDBR* is achieved for all sequences, but also lower ΔT. What is interesting, for class F (screen content and graphics sequences) a quality increase is noticed for denser $\boldsymbol{\Omega_1}$ (*BDBR* = -0.01). In contrast, for $\boldsymbol{\Omega_2}$, the highest *BDBR* is observed for class F among all classes.

For $\boldsymbol{\Omega_1}$ and $N = 2$, the average ΔT of 5.3% is achieved with the smallest average bitrate increase (*BDBR*) of 0.01%.

In the proposed technique, the number of modes evaluated in the RMD is reduced. We have measured that the RMD part of the original HM10.0 reference intraframe encoder consumes 17% of the encoding time. When compared with 5.3% of the achieved ΔT, it is apparent that the RMD time is reduced by over 31% with a negligible reduction of reconstructed video quality.

We have checked if the obtained relative encoding time reduction is systematic for various sequences. Considering the average results obtained for classes A – E, it is apparent that the ΔT values tend to be larger and *BDBR* values tend to be lower when the resolutions of encoded videos become higher. Still, the differences are small. We have calculated standard deviation $\sigma_{\Delta T}$ for ΔT in the population of the tested sequences of classes A – F. For each tested ($\boldsymbol{\Omega}$, N) pair, $\sigma_{\Delta T}$ is no more than 22% of the average ΔT. It demonstrates that the obtained relative time reduction is systematic for various content types and resolutions.

The proposed technique is compared with the techniques described in the literature. For this comparison, the results for the techniques proposed in the literature are provided in Table 3. We have implemented some of the presented techniques, but we failed to reproduce the results reported in their source documents. We know that the results may be significantly affected by the chosen compiler and the executing platform.

Table 2. *ΔT* VERSUS *BDBR* INCREASE FOR VARIOUS CONFIGURATIONS

Configuration / Sequence	$\boldsymbol{\Omega}_1$, N = 1 ΔT (%)	$\boldsymbol{\Omega}_1$, N = 1 BDBR (%)	$\boldsymbol{\Omega}_1$, N = 2 ΔT (%)	$\boldsymbol{\Omega}_1$, N = 2 BDBR (%)	$\boldsymbol{\Omega}_2$, N = 1 ΔT (%)	$\boldsymbol{\Omega}_2$, N = 1 BDBR (%)
Class A (2560 × 1600)						
Traffic	5.0	0.04	5.6	0.02	8.8	0.17
PeopleOnStreet	5.5	0.02	5.9	0.00	7.9	0.16
NebutaFestival	7.2	0.03	4.8	0.01	7.9	0.11
SteamLocomotiveTrain	8.3	0.02	6.8	0.01	10.0	0.06
Class A average	6.5	0.03	5.8	0.01	8.7	0.13
Class B (1920 × 1080)						
Kimono1	4.6	0.03	6.0	0.01	8.5	0.05
ParkScene	6.9	0.00	5.0	0.00	9.7	0.07
Cactus	6.8	0.05	5.4	0.02	8.5	0.20
BQTerrace	5.6	0.02	4.9	0.01	7.6	0.13
BasketballDrive	6.7	0.07	5.8	0.04	8.3	0.21
Class B average	6.1	0.03	5.4	0.01	8.5	0.13
Class C (832 × 480)						
RaceHorses	6.8	0.05	7.1	0.00	9.6	0.19
BQMall	7.2	0.04	5.2	0.03	10.2	0.21
PartyScene	3.0	0.06	3.8	0.03	5.7	0.22
BasketballDrill	6.4	0.12	5.3	0.06	8.1	0.40
Class C average	5.8	0.07	5.3	0.03	8.4	0.26
Class D (416 × 240)						
RaceHorses	5.3	0.09	5.8	0.03	6.5	0.28
BQSquare	3.4	0.07	3.9	0.05	5.2	0.27
BlowingBubbles	5.3	0.07	4.2	0.04	7.2	0.29
BasketballPass	4.7	0.05	4.2	0.03	6.5	0.22
Class D average	4.7	0.07	4.5	0.04	6.4	0.27
Class E (1280 × 720)						
FourPeople	5.5	0.02	4.5	0.00	6.7	0.23
Johnny	6.9	0.11	6.0	0.03	10.4	0.32
KristenAndSara	6.2	0.04	6.0	0.02	9.1	0.26
Class E average	6.2	0.06	5.5	0.02	8.7	0.27
Class F (screen content, 832 × 480 to 1280 × 720)						
BasketballDrillText	6.5	0.09	4.4	0.01	7.7	0.34
ChinaSpeed	8.6	-0.13	7.1	-0.07	10.2	0.25
SlideEditing	5.1	-0.08	3.9	-0.04	6.2	0.53
SlideShow	6.4	0.07	6.4	0.00	9.5	0.33
Class F average	6.6	-0.01	5.5	-0.02	8.4	0.36
Average over all classes	**6.0**	**0.04**	**5.3**	**0.01**	**8.2**	**0.23**

That is why we decided to present the results reported in the source documents for each technique. They are compared with the experimental results of our technique in 3 configurations.

Table 3. ENCODING TIME REDUCTION FOR VARIOUS TECHNIQUES

Technique	Category	*ΔT* (%)	*BDBR* (%)	***ΔT/BDBR***
Ours – $\boldsymbol{\Omega}_1$, N=1	1	6.0	0.04	**151**
Ours – $\boldsymbol{\Omega}_1$, N=2	1	5.3	0.01	**389**
Ours – $\boldsymbol{\Omega}_2$, N=1	1	8.2	0.23	**36**
[10]	1	26	0.4	**65**
[9]	2	12.2	0.3	**41**
[11]	3	20	1.3	**15**
[12]	3	44.2	2.8	**16**
[13]	3	20	0.7	**27**
[9]	4	26.2	0.9	**29**
[14]	4	70.9	6.6	**11**
[15]	4	37.6	1.7	**23**

The highest time reduction of 70.9% is achieved for the technique [14], but also the highest *BDBR* increase of 6.6% is observed. In contrast to the technique [14], our technique achieved the lowest *BDBR* increase but also the lowest time reduction.

Comparing fast mode selection techniques using two opposite parameters *ΔT* and *BDBR* is inconclusive and inconvenient. To compare all the propositions in a more conclusive way, we need one efficiency parameter. We introduce such a parameter as relative encoding time reduction per *BDBR* percentage points increase (*ΔT* / *BDBR*). In that metric, our technique, in configuration $\boldsymbol{\Omega}_1$, N = 2 scored 389, and the second best technique [10] scored 65, where a higher metric means a higher efficiency of a technique.

The techniques [9, 11-15] require the computation of gradient statistics for a PU. That kind of calculations are not implemented in the HEVC reference encoder. If a hardware implementation is considered for those techniques, then an additional silicon area is required for a new functional block performing gradient calculations. Our technique is more suitable for hardware implementation because it exploits only prediction cost J_{RMD} and prediction error J_H that are already calculated in the reference encoder.

We closely compared our technique with the most similar technique [10]. For this comparison, we implemented both techniques. With the aim of fair comparison, both implementations were compiled with the same software and executed using the same platform. Results obtained for classes A – F are provided in Table 4.

Our results for the technique [10] and results presented in a source document [10] are broadly similar in a sense of *BDBR* increase. However, for each class of sequences, we obtained significantly lower average time reduction than reported in [10]. Average time reduction over all classes reported in [10] is 26%, whereas for our implementation we obtained 13.7%. The use of a different platform in [10] and in our experiments can be a reason for those discrepancies.

Three implementations summarized in Table 4 can be compared using the proposed efficiency parameter ΔT / $BDBR$. In that metric, our technique, in two configurations: $\boldsymbol{\Omega_1}$, N = 1 and $\boldsymbol{\Omega_1}$, N = 2 scored 151 and 389 respectively, and the technique [10] scored 25, where a higher metric means a higher efficiency of a technique.

Table 4. ΔT VERSUS BDBR INCREASE FOR OUR TECHNIQUE AND pRMS

Technique / Sequences	Ours – $\boldsymbol{\Omega_1}$, N = 1		Ours – $\boldsymbol{\Omega_1}$, N = 2		Our results for pRMS	
	ΔT (%)	$BDBR$ (%)	ΔT (%)	$BDBR$ (%)	ΔT (%)	$BDBR$ (%)
Class A average	6.5	0.03	5.8	0.01	14.0	0.45
Class B average	6.1	0.03	5.4	0.01	14.1	0.56
Class C average	5.8	0.07	5.3	0.03	12.7	0.42
Class D average	4.7	0.07	4.5	0.04	14.5	0.42
Class E average	6.2	0.06	5.5	0.02	13.2	0.63
Class F average	6.6	-0.01	5.5	-0.02	13.4	0.76
Average over all classes	**6.0**	**0.04**	**5.3**	**0.01**	**13.7**	**0.54**
	(ΔT / $BDBR$ = 151)		**(ΔT / $BDBR$ = 389)**		**(ΔT / $BDBR$ = 25)**	

VI. CONCLUSION

The new technique is aimed at the reduction of the computational effort needed in the RMD step of the unified intra mode selection in HEVC encoders. This technique provides an average reduction of the RMD time by over 31% and an average reduction of the encoding time by about 5.3% at the negligible cost of the average bitrate increase of 0.01%. Furthermore, this technique can be combined with other techniques for a fast implementation of the other steps of intraframe encoding in order to obtain further complexity reduction.

This hierarchical approach to mode selection may be also used in other variants that have not been tested experimentally in this paper for the sake of brevity.

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