A Fast Local Mode Decision for the HEVC Intra Prediction Based on Direction Detection

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***Abstract*—This work presents a fast local mode decision for the HEVC intra prediction based on a direction detection algorithm first proposed in the Daala video format and currently used in the AV1 deringing filter. The main objective is to reduce the number of intra candidates entering the very expensive RDO loop by locally detecting the dominant edge direction of the original block, without the need of computing any of the intra prediction modes and associated RD costs. The proposed method was implemented on the latest HEVC reference encoder (HM 16.20), replacing the original local mode decision by the algorithm proposed in this paper. Experiments under the HEVC common test conditions, including UHD 4K (3840x2160 pixels) test sequences, showed, on average, 28.2% encoding time reduction, at a cost of 1.0% BD-BR (YUV) increase. Specifically for UHD 4K sequences, the experiments showed, on average, 30.0% encoding time reduction, at cost of 0.9% BD-BR (YUV) increase.**

Keywords—video coding, HEVC, intra prediction, fast mode decision

I. Introduction

Video coding is an important research area due to the increasing demand for ultra-high definition (UHD) digital video for applications such as digital television broadcasting, video streaming, storage of video content and others. The High Efficiency Video Coding (HEVC) [1, 2] is the state-of-the-art video encoder of ITU-T and ISO/IEC. It was released in 2013 by the joint collaborative team of the ITU-T Video Coding Experts Group (VCEG) and ISO/IEC Moving Picture Experts Group (MPEG). Currently, there is a notable work in progress for the development of the Versatile Video Coding (VVC) [3], which will be the next video coding standard of the VCEG and MPEG groups.

The HEVC intra prediction module, which is the focus of this paper, reduces the spatial redundancy of the video frames by referring to samples from previously coded blocks located above and to the left of a given Coding Block (CB). In HEVC, the CB sizes allowed are 4x4 (intra only), 8x8, 16x16, 32x32 and 64x64 samples. Specifically, in HEVC, intra prediction happens at Transform Block (TB) level and 35 prediction modes are defined for four different TB sizes: 4x4, 8x8, 16x16, and 32x32 samples.

Fig. 1 shows all 33 angular modes ids and their associated directions (e.g., directly vertical is called Angular 26). The mode ids 0 and 1 refer, respectively, to non-angular modes called Planar and DC, suited specifically for the most homogeneous areas of the image.

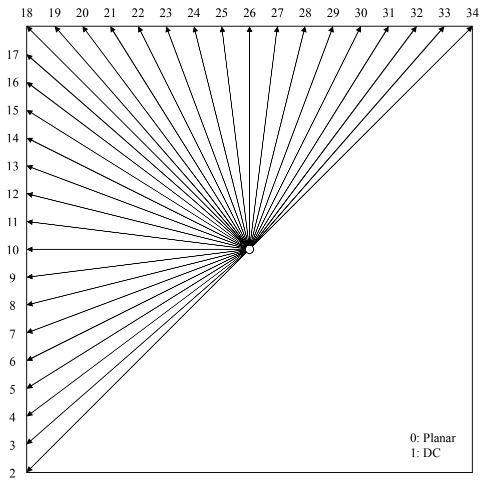

Fig. 1. HEVC intra prediction modes as specified in [2].

When intra predicted, the CBs can be treated as a single TB of the same size or be recursively divided into four smaller TBs, all signaling the same prediction mode. It is important to mention that CBs of size 64x64 will always be divided into at least four TBs of size 32x32.

Although the large number of CB sizes and prediction modes leads to a very accurate prediction, it also leads to a heavy computational burden in the global mode decision. To reduce the coding complexity of intra prediction, the HEVC Test Model (HM) reference encoder uses a fast local mode decision algorithm called Rough Mode Decision (RMD) [4] since its earliest versions. In HM 16.20 [5], the RMD reduces the list of modes (RD-list) sent to the Rate-Distortion Optimization (RDO), which is the global mode decision algorithm, to eight for CBs of size 4x4 and 8x8, and three for CBs of size 16x16, 32x32 and 64x64. The RMD computes all the 35 prediction modes and their respective SATD (Sum of Absolute Transformed Differences) versus the original block and, then, selects the modes with the lowest SATD values to be inserted in the RD-list. The three Most Probable Modes (MPMs) [2], derived by looking into neighbor blocks decisions, are also included in the RD-list, intending to increase the quality of the results generated by RMD. Reducing the RD-list at the prediction stage is crucial, because the RDO process requires blocks to go through the entropy encoder and the whole prediction and reconstruction loop, hence being the bottleneck of a video encoder.

This paper presents a fast local mode decision solution for the HEVC intra prediction inspired by the direction detection algorithm from the Constrained Directional Enhancement Filter (CDEF) [6]. The CDEF is currently used as one of the in-loop filters defined in the AOMedia Video 1 (AV1) [7, 8], a royalty-free video format released in 2018 by the Alliance for Open Media (AOM) industry consortium.

The rest of this paper is organized as follows: Section II presents some relevant related works also intending to reduce the HEVC intra prediction computational effort, section III details the solution proposed in this work, section IV presents the experimental results and, finally, section V concludes this work.

II. Related Works

There are works in the literature intending to reduce the computational effort of the HEVC intra prediction through the reduction of the RD-list sent to the RDO loop, the most notable being [9-12]. Some of these solutions, such as [9, 10, 12], are also based on edge direction or block homogeneity. However, none of these works were developed with UHD resolutions in mind, since experiments for UHD 4K (3860x2160 pixels) were not presented.

In [9], the authors propose a two-stage local intra mode decision based on: (i) verifying the average of the reference samples to exclude all angular modes if the reference samples are homogeneous enough, and (ii) comparing the average of the reference samples against the average of the original block to select a reduced number of intra modes to enter the original RMD algorithm. An encoding time variation (ΔT) of -25% was reported at cost of 1.0% $BD\text{-}BR_{YUV}$. The authors did not evaluate resolutions higher than 1080p (1920x1080 pixels). The encoder version used was HM 16.2 (Oct/2014) [5].

In [10], the authors propose a local intra mode decision based on edge detection using Sobel filters with 3x3 convolution masks and SATD metric to reduce the number of intra modes entering the RDO loop or, under certain conditions, locally choose the final mode without using the RDO. A -35.6% ΔT was reported at cost of 1.07% $BD\text{-}BR_Y$. The encoder version used was HM 15.0 (Jul/2014) [5].

In [11], the authors propose an iterative local intra mode decision that initially tests the reduced set of intra modes {2, 10, 18, 26, 34} and selects the two best candidates based on a cost function very similar to the one used in RMD, then it discards the remaining modes and prepares a new iteration using four new modes that are closest to the two best candidates. The algorithm iterates a total of five times. The authors report an average of SATD operations per block of 19 versus 35 of the RMD algorithm and an average of five mode sent to the RDO. A -39.17% ΔT at cost of 1.19% $BD\text{-}BR_?$ was reported. The authors conducted their experiments using a group of only eight video sequences. The encoder version used was HM 10.0 (Feb/2013) [5].

In [12], the authors propose an arithmetical method of classifying blocks of size 4x4 by their dominant edges, although 8x8, 16x16 and 32x32 blocks can also be classified by repeating the process for every 4x4 sub-block. Edges are classified as either horizontal, vertical, 45° diagonal, 135° diagonal or undefined. Each edge classification is associated with a reduced set of nine prediction modes, to be further evaluated by a slightly modified RMD. A -18.9% ΔT was reported at cost of 1.3% $BD\text{-}BR_Y$. This work was based on a draft [13] version of the standard, which only allows a reduced number of intra prediction modes for 4x4 and 64x64 CBs, 17 and 4 respectively. The encoder version used was HM 4.0 (Aug/2011) [5].

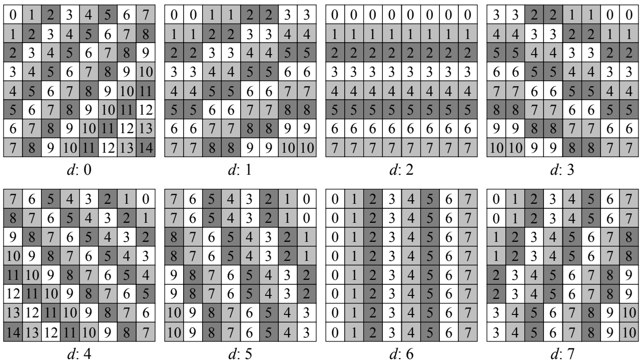

Fig. 2. Arrangement of lines k for each direction d in a 8x8 block. The numbers identify to which set k a given sample belongs to [6].

III. Fast Local Mode Decision Algorithm

The proposed method is divided in two main steps: (i) detection of the dominant edge direction in the original block, and (ii) definition of a reduced RD-list based on the detected direction and on MPMs. The algorithm used to detect the edge direction is presented in the next subsection and the local mode decision using the direction information is presented in subsection II-B.

A. Direction Detection Algorithm

The direction detection algorithm used in this work was based in a solution first mentioned in [14] as part of the Daala development, and later adopted as part of the AV1 CDEF [6]. The idea to use this algorithm to develop a fast intra prediction local mode decision was based on the fact that this algorithm is very efficient to detect directions in the image blocks and, naturally, this is a very valuable information for the intra prediction process to define which directional mode tends to be the best option to encode a CB before running the expensive RDO process.

For each 8x8 input, the algorithm determines the direction (identified as d from 0 to 7) that best matches the original block by minimizing the error between the Perfectly Directional Block (PDB) associated to each of the eight directions and the original block. The eight d directions are illustrated in Fig. 2. As defined in [6], a PDB is a block where all the samples along a line k following a given direction d have the exact same value (Fig. 2), which is the average of the samples from that same line, and the error is calculated using the Sum of Squared Differences (SSD) metric.

More precisely, for each direction d, the sample average for a line k is defined as in (1), where x_p is the value of sample p in the original block ranging from -128 to 127 (8 bits), $P_{d,k}$ is the set of samples in line k from direction d, and $N_{d,k}$ is the number of samples contained in $P_{d,k}$. If the input bit depth is larger than 8 bits, then the samples must be downscaled before computing (1).

$$\mu_{d,k} = \frac{1}{N_{d,k}} \sum_{p \in P_{d,k}} x_p \tag{1}$$

The SSD between the original block and the PDB with direction d is defined as in (2).

$$E_d = \sum_k \left(\sum_{p \in P_{d,k}} \left(x_p - \mu_{d,k} \right)^2 \right) \tag{2}$$

After substituting (1) into (2) and simplifying it, the SSD can be expressed as defined in (3).

$$E_d = \sum_p x_p^2 - \sum_k \frac{1}{N_{d,k}} \left(\sum_{p \in P_{d,k}} x_p \right)^2 \quad (3)$$

To conclude, since the first term of (3) refers only to samples from the original block, it is constant with respect to the variable d. Thus, this term can be removed from the equation, and instead of minimizing the error E_d, we want to maximize the sum S_d, expressed as (4).

$$S_d = \sum_k \frac{1}{N_{d,k}} \left(\sum_{p \in P_{d,k}} x_p \right)^2 \quad (4)$$

After calculating all eight PDBs, the direction detection algorithm selects as the best direction d the one which resulted in the highest S_d.

After finding the dominant edge direction, the algorithm also classifies the original block as being homogeneous or heterogeneous by subtracting the S_d of the dominant direction from the S_d of the orthogonal direction. If the subtraction result is lower than a certain threshold, the block is considered homogeneous, otherwise, heterogeneous. For homogeneous blocks, the angular prediction modes can be discarded, as better discussed in the next subsection. Many different thresholds were tested and their performance are discussed in section IV.

Since this algorithm was developed targeting a fixed block size of 8x8 samples, some adaptations were necessary to use it in all available HEVC CB sizes. In this work, CBs of size 4x4 are directly processed, but requiring only 25% of the calculations when compared to CBs of size 8x8. For larger CB sizes (16x16, 32x32 and 64x64), a subsampling operation (2:1, 4:1 and 8:1, respectively) is applied to reduce these CBs to the 8x8 size. We verified that although the subsampling operation discards information, it is good enough to conserve directional edges and homogeneity information, whilst keeping the much-desired low overhead.

B. Decision Algorithm

In HM 16.20, the RMD implementation has to locally compute the prediction for all 35 modes in order to check their SATD against the original block. Then, a reduced RD-list is created with the eight best candidates if the CB size is 4x4 or 8x8, or with the three best candidates if the CB size is 16x16, 32x32 or 64x64. Finally, the MPM candidates are appended to the list if those modes are not already included by RMD. Finally, the RD-list is sent to the RDO algorithm, responsible for taking the final decision.

In contrast, the fast intra prediction mode decision proposed in this paper only needs information from the direction detection algorithm in order to make a very effective reduced RD-list. The decision algorithm works as follows:

The first step of the mode decision is to verify whether the CB was classified as homogeneous or heterogeneous.

If homogeneous, then a very small RD-list is created from the set {0, 1}, which are the Planar and DC modes respectively.

Otherwise, if heterogeneous, then a reduced RD-list of five to six modes is created from the union of sets listed in Table I, according to the dominant direction and its best adjacent direction provided by the detection algorithm. Table I shows the definition of how the dominant and best adjacent directions are associated to directional modes of intra prediction. It is important to emphasize that the modes {0, 1} are also used to predict heterogeneous CBs.

The second and final step for both homogeneous and heterogeneous CBs is to append the three MPMs to the RD-list (if not already included). For more information about the MPM selection algorithm, please refer to the standard [2].

TABLE I. REDUCED RD-LIST FOR HETEROGENEOUS BLOCKS ACCORDING TO THE DOMINANT AND BEST ADJACENT DIRECTION DETECTED.

Dominant direction	**Best adjacent direction**	**Reduced RD-list** (for direction ids refer to Fig. 1)
0	7	{0, 1} ∪ {2, 34} ∪ {32, 33}
	1	{0, 1} ∪ {2, 34} ∪ {3, 4}
1	0	{0, 1} ∪ {6} ∪ {4, 5}
	2	{0, 1} ∪ {6} ∪ {7, 8}
2	1	{0, 1} ∪ {10} ∪ {8, 9}
	3	{0, 1} ∪ {10} ∪ {11, 12}
3	2	{0, 1} ∪ {14} ∪ {12, 13}
	4	{0, 1} ∪ {14} ∪ {15, 16}
4	3	{0, 1} ∪ {18} ∪ {16, 17}
	5	{0, 1} ∪ {18} ∪ {19, 20}
5	4	{0, 1} ∪ {22} ∪ {20, 21}
	6	{0, 1} ∪ {22} ∪ {23, 24}
6	5	{0, 1} ∪ {26} ∪ {24, 25}
	7	{0, 1} ∪ {26} ∪ {27, 28}
7	6	{0, 1} ∪ {30} ∪ {28, 29}
	0	{0, 1} ∪ {30} ∪ {31, 32}

IV. EXPERIMENTAL RESULTS

The following experiments were conducted with the HM 16.20 (Sep/2018) [5] reference encoder, using the *encoder_intra_main* configuration, all quantization parameters (QPs) and all frames from the sequences recommended by the Common Test Conditions document AF1100 (Jul/2018) [15].

In the experimental results, coding efficiency is expressed in Bjøntegaard Delta Bit-rate (BD-BR) [16, 17], which considers the bitrate and the Peak Signal-to-noise Ratio (PSNR) for a certain channel. Specifically, $\text{BD-BR}_{\text{YUV}}$ combines all three channels, using the PSNR_{YUV}, which is a weighted mean expressed as in (5). Encoding time variation (ΔT) is expressed as in (6).

$$\text{PSNR}_{\text{YUV}} = \frac{6 \times \text{PSNR}_{\text{Y}} + \text{PSNR}_{\text{U}} + \text{PSNR}_{\text{V}}}{8} \quad (5)$$

$$\Delta\text{T} = \frac{T_{modified} - T_{reference}}{T_{reference}} \times 100 \quad (6)$$

A. Threshhold Experiments

As mentioned in subsection III-A, the direction detection algorithm also classifies the original block as homogeneous or heterogenous, which is a key information for our algorithm to achieve small RD-lists. As (7) shows, the algorithm first computes a contrast (C) between the S_d values of the dominant direction (highest S_d) and its orthogonal direction, then shifts the result to the right according to a certain threshold (Thr).

As (8) shows, only if C results is zero, the block is classified as homogeneous.

$$C = \left(S_{dominant\_d} - S_{orthogonal\_d}\right) \gg Thr \quad (7)$$

$$Homogeneous_C = \begin{cases} True, & C = 0 \\ False, & C > 0 \end{cases} \quad (8)$$

The original algorithm from CDEF [6] is used in a very different context (in-loop deringing filter), and for that context, the authors found Thr=10 to be a good operation point. For the local intra mode decision context, we evaluated all thresholds from the interval $10 \leq Thr \leq 20$. The $BD\text{-}BR_{YUV}$ and ΔT results are listed in Table II.

TABLE II. THRESHOLD VALUES AND THEIR IMPACT IN ENCODING TIME AND CODING EFFICIENCY.

Threshold	ΔT (%)	$BD\text{-}BR_{YUV}$ (%)
10	-21.05	0.98
11	-21.71	0.96
12	-21.91	0.95
13	-22.36	0.96
14	-23.22	0.96
15	-24.17	0.97
16	-26.37	0.98
17	-28.19	1.04
18	-31.29	1.16
19	-32.38	1.37
20	-35.19	1.70

Fig. 3 shows, the ΔT gains for every 1% loss in $BD\text{-}BR_{YUV}$. We chose Thr=17 as the default point of operation for our algorithm, because it offers the best trade-off between encoding time (-28.2%) and loss in coding efficiency (1.0%).

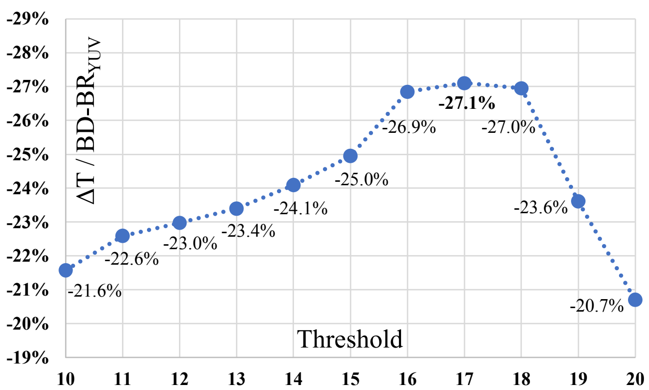

Fig. 3. Trade-off between encoding time reduction and loss in coding efficiency. The threshold 17 offers the best results.

B. In-depth Results (Thr=17)

Table III shows the encoding time and coding efficiency results per-sequence, per-class average and also as an overall average. It can be verified that larger resolutions achieve the best results in terms of ΔT / $BD\text{-}BR_{YUV}$ trade-off, that is, -41.1% for A1 class and -27.1% for C class. Hence, it can be concluded that the proposed algorithm is very suitable for the next-generation UHD resolutions. On average, for UHD 4K videos, -30.0% ΔT was achieved at cost of 0.9% $BD\text{-}BR_{YUV}$. Overall, -28.2% ΔT was achieved at cost of 1.2%, 0.4% and 0.4% per channel BD-BR, or at cost of 1.0% $BD\text{-}BR_{YUV}$.

TABLE III. IN-DEPTH RESULTS FOR ENCODING TIME AND CODING EFFIENCY CONSIDERING THE THRESHOLD SET TO 17.

CTC Class	CTC Sequence	BD-BR (%) Y	U	V	YUV	ΔT (%)
A1 (4K)	*Tango2*	1.0	0.6	0.0	0.8	-32.5
	FoodMarket4	0.3	0.5	0.7	0.4	-36.8
	Campfire	1.7	-0.2	-0.1	1.2	-30.0
	A1 Average	**1.0**	**0.3**	**0.2**	**0.8**	**-32.9**
A2 (4K)	*CatRobot*	1.9	1.1	0.9	1.7	-30.2
	DaylightRoad2	1.5	-0.1	-0.4	1.1	-27.2
	ParkRunning3	0.3	0.2	0.2	0.3	-24.2
	A2 Average	**1.3**	**0.4**	**0.2**	**1.0**	**-27.1**
B (1080p)	*MarketPlace*	0.6	-0.3	-0.3	0.4	-26.8
	RitualDance	2.1	1.0	1.1	1.8	-32.9
	Cactus	1.3	0.7	0.3	1.1	-23.2
	BasketballDrive	1.0	0.0	0.6	0.8	-27.3
	BQTerrace	1.0	0.2	0.2	0.8	-20.8
	B Average	**1.2**	**0.3**	**0.4**	**1.0**	**-25.7**
C (480p)	*BasketballDrill*	1.8	0.5	1.1	1.5	-20.7
	BQMall	1.5	-0.3	-0.1	1.1	-20.4
	PartyScene	0.1	-0.2	-0.2	0.1	-14.7
	RaceHorses	1.2	0.3	-0.2	1.0	-21.7
	C Average	**1.2**	**0.1**	**0.2**	**0.9**	**-16.5**
E (720p)	*FourPeople*	1.5	1.4	0.2	1.4	-28.0
	Johnny	1.9	1.1	1.8	1.8	-32.8
	KristenAndSara	1.6	0.8	2.2	1.5	-31.5
	E Average	**1.7**	**1.1**	**1.4**	**1.6**	**-30.7**
Overall (ABCE) Average		**1.2**	**0.4**	**0.4**	**1.0**	**-28.2**

The proposed local mode decision algorithm achieved a notable encoding time reduction not only because it requires less operations than the RMD, but also because it sends less candidates to the expensive RDO process. An experiment based on the first three frames of each sequence was done in order to count the number of candidates sent to the RDO in terms of 4x4 sub-blocks (i.e., a 64x64 CB counts as 256 sub-blocks of size 4x4). Fig. 4 shows that our algorithm sends more candidates of size 64x64, 32x32 and 16x16, but far less candidates of size 8x8 and 4x4, resulting in only 76.5% of the total candidates when compared to the RMD from HM 16.20.

Fig. 5 shows the rate-distortion results for the worst case tested, which was the test sequence Johnny (1.8% $BD\text{-}BR_{YUV}$). It can be seen that even in the worst case, the curves of the proposed algorithm and the original HM 16.20 are almost overlapping. Therefore, the overall average increase of 1.0% $BD\text{-}BR_{YUV}$ can be considered a negligible loss in order to achieve a notable -28.2% ΔT.

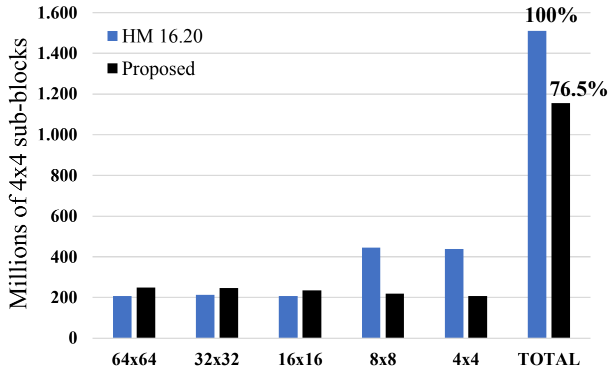

Fig. 4. Amount of information sent to the expensive RDO process in terms of 4x4 sub-blocks.

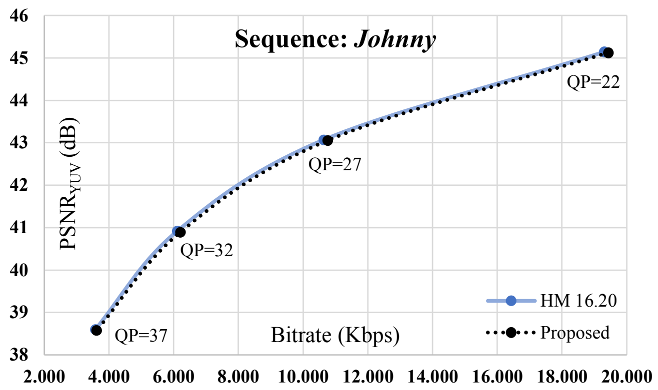

Fig. 5. Rate-distortion curves of the *Johnny* test sequence (worst case).

C. Comparison

A direct comparison with related works is not easy, mainly because the experimental setup is not the same between any of the related works.

None of the related works included UHD 4K sequences in their experiments, whereas the current CTC document [15] recommends six, as Table III shows.

Also, all the related works used older versions of the HM. According to our experiments involving UHD 4K sequences, the HM 16.20, for the *encoder_intra_main* configuration, already achieves -10.1%, -3.2% and -8.5% ΔT when compared to versions 10.0, 15.0 and 16.2 respectively. Therefore, achieving an expressive encoding time reduction is relatively more difficult on version 16.20.

That being said, Table IV shows that the proposed algorithm is faster and has the same coding efficiency when compared to [9], competitive when compared to [10], and faster and superior in coding efficiency when compared to [12]. A reliable comparison is not possible with [11], because the BD-BR channel was not specified.

TABLE IV. COMPARISON AMONG RELATED WORKS.

Work	BD-BR (%)	Channel	ΔT (%)
This	1.0	YUV	-28.2
	1.2	Y	
[9]	1.0	YUV	-25.0
[10]	1.1	Y	-35.6
[11]	1.2	unspecified	-39.2
[12]	1.3	Y	-18.9

V. CONCLUSIONS

This work presents a fast local mode decision for the HEVC intra prediction based on direction detection and block homogeneity classification. The proposed algorithm was implemented on the HM 16.20 reference encoder, replacing the original mode decision algorithm.

On average, a notable encoding time reduction of -28.2% ΔT at cost of a negligible loss of 1.0% $BD\text{-}BR_{YUV}$ was achieved. Specifically, the algorithm performed above the average for UHD 4K videos (one of the most relevant resolutions for current works), achieving -30.0% ΔT at cost of 0.9% $BD\text{-}BR_{YUV}$.

As future work, we plan to increase the number of directions from 8 to 16, aiming to create smaller and more accurate RD-lists.

ACKNOWLEDGMENT

This study was financed in part by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – Brazil (CAPES) – Finance Code 001, and also by the Brazilian research support agencies CNPq and FAPERGS.

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