Low Complexity Joint RDO of Prediction Units Couples for HEVC Intra Coding

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***Abstract*—HEVC is the latest block-based video compression standard, outperforming H.264/AVC by 50% bitrate savings for the same perceptual quality. An HEVC encoder provides Rate-Distortion optimization coding tools for block-wise compression. Because of complexity limitations, Rate-Distortion Optimization (RDO) is usually performed independently for each block, assuming coding efficiency losses to be negligible. In this paper, we propose an acceleration solution for the Intra coding scheme named *Dual-JRDO*, which takes advantage of Inter-Block dependencies related to both predictive coding and CABAC. The *Dual-JRDO* improves Intra coding efficiency at the expense of higher computational complexity. The acceleration of the *Dual-JRDO* scheme includes adaptive use of the *Dual-JRDO* model based on source analysis, short-listing and early decisions strategies. The proposed *Fast Dual-JRDO* reduces the original model complexity by 89.54%, while providing tractable computation for average R-D gains of -0.45% (up to -0.82%) in the *HM16.12* reference software model.**

***Index Terms*—Intra Coding, Joint Block Optimization, HEVC, Dual-JRDO**

I. Introduction

Rate-Distortion Optimization (*RDO*) aims to minimize the distortion D, subject to a target rate constraint $R \leq R_T$. Lagrange multiplier method is usually used to remove the constraint on R [1], with λ the Lagrange multiplier trading between D and R. *RDO* ultimately minimizes the R-D cost function J defined as:

$$J = (D + \lambda \times R) \tag{1}$$

For video compression standards, such as High Efficiency Video Coding (HEVC) [2], source signal is processed by three operations known as prediction, transformation and quantization. D measures the pixel-wise distance between source and decoded signals. R is the amount of bits from quantized residues and syntax data coded with the entropic encoder.

In HEVC Intra coding [2], [3], frames are first equally divided into Coding Tree Units (CTUs). CTUs are square blocks of pixels processed in raster scan order. Each CTU is further recursively split, using a Quad-Tree, into multiple Coding Units (CUs) with possible sizes of 64x64, 32x32, 16x16 and 8x8. A CU of size 2Nx2N is composed of one Prediction Unit (PU) of the same size or four PUs of size NxN for the last depth of the CTU (with $N = 4$). A prediction mode is set for each PU.

In this paper, we focus on Intra coding only and more precisely on the optimization of prediction mode decisions made at PU level. PU_i denotes the i_{th} PU to be encoded with respect to scanning order and p_i denotes the coding parameters, i.e. intra prediction mode, of PU_i. With Nb the number of PUs to process, *RDO* estimates:

$$\{p_k^*\}_{k=0}^{Nb-1} = \underset{\{p_k\}_{k=0}^{Nb-1}}{\arg\min} \sum_{i=0}^{Nb-1} \left(D_{i|_{p_i}} + \lambda \times R_{i|_{p_i}} \right) \tag{2}$$

Since each PU is processed independently, (2) is optimal only if there is no dependency between PUs. Nevertheless, both predictive coding and Context Adaptive Binary Arithmetic Coding (CABAC) introduce dependencies between PUs.

Several studies aimed to take advantage of Inter-Block dependencies to achieve better coding efficiency [4]–[7]. In a previous work, we made explicit the dependencies related to predictive coding and CABAC [8]. Then, we proposed to achieve Joint-RDO (*JRDO*) on a pair of PUs. The model is called *Dual-JRDO* and consists in deciding the current predictor p_i based on both its coding efficiency for current PU (PU_i) and its impact on the following PU (PU_{i+1}) coding efficiency, under a set of constraints.

The original model brings systematic bitrate savings (up to 1.12%) for similar quality, but suffers from a significant computational complexity increase: encoding is 9 times slower. This paper provides efficient acceleration methods for *Dual-JRDO*, leading to a *Fast Dual-JRDO* model. The first proposed solution consists in enabling or disabling the model based on estimation of the spatial prediction complexity of the source, referred to as *spatial activity* in this paper. The two other proposed solutions consist in adaptively limiting the number of prediction modes competing in the joint analysis.

The remaining of the paper is organized as follows. A brief review of *Dual-JRDO* and its computational complexity are first given in Section II. Section III depicts the proposed acceleration solutions. Experimental results of the proposed *Fast Dual-JRDO* model are presented and discussed in Section IV. Finally, Section V concludes this paper.

II. *Dual-JRDO* Method

Let us consider two PUs PU_i, PU_j with $i < j$ and $i, j \in \{0, ..., Nb-1\}$, where Nb is the number of PUs and p_i is the prediction mode associated with PU_i. Two Inter-Block dependencies impact Intra coding. First, prediction error is dependent on the quantization error which affects reference samples. Second, p_j signaling cost in the bitstream depends on p_i, and all CABAC contexts used to compute R_j depend on probabilities update performed when encoding PU_i. By design, the optimal coding for PU_j depends on p_i.

Therefore, we proposed in [8] to jointly optimize PUs subject to these dependencies, i.e. $j = i + 1$. *Dual-JRDO* is summarized in Algorithm 1. *Dual-JRDO* is used when PU_{i+1} is the spatial right neighbor of PU_i, otherwise *classical-RDO* is used to compute p_i^*.

Data: $\{PU_i\}_{i=0}^{Nb-1}$
Result: $\{p_i^*\}_{i=0}^{Nb-1}$
if $isRight\left(PU_{i+1}, PU_i\right)$ **then**

$$p_i^* = \arg\min_{p_i} \left(J_{i|_{p_i}} + \min_{p_{i+1}} J_{i+1|_{p_i,p_{i+1}}} \right) \quad (3)$$

else

$$p_i^* = \arg\min_{p_i} \left(J_{i|_{p_i}} \right) \quad (4)$$

end

Algorithm 1: *Dual-JRDO* Algorithm

During the estimation of p_i^*, PU_i and PU_{i+1} are assumed to be of the same size. An example of *Dual-JRDO* is shown in Figure 1, with d the depth equivalent to PU size. Dotted lines delimit the optimization area, i.e. containing both PU_i and PU_{i+1}; dark gray areas refer to blocks coded independently using *classical-RDO*, i.e. PU_{i+1}.

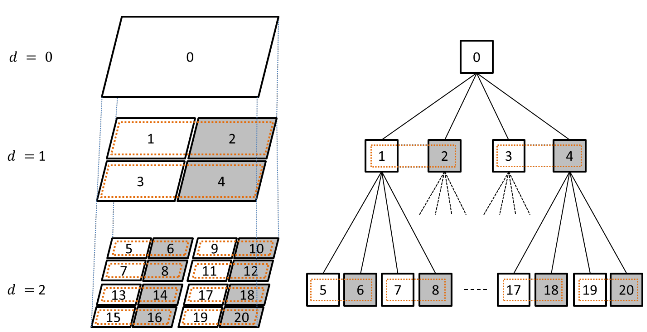

Fig. 1. Example of *Dual-JRDO* on a 3-level Quad-Tree

The next section presents the three proposed methods aiming to accelerate the *Dual-JRDO* coding scheme.

III. Acceleration Methods

In this section, three methods are introduced in order to reduce the computational complexity Cpx of the *Dual-JRDO*. Cpx increase is directly related to Nb, the number of analyzed PUs (of all size) in a frame during *RDO*. In the case of a single CTU of size 64x64, $Nb = 341$: 1 PU 64x64, 4 PUs 32x32, 16 PUs 16x16, 64 PUs 8x8 and 256 PUs 4x4. We note that Nb is composed of 93.84% of PUs with size of 4x4 or 8x8.

TABLE I
The *Dual-JRDO* gain against *classical-RDO* for each depth

PU size	64x64	32x32	16x16	8x8	4x4	**All**
Average	0.00%	0.00%	-0.06%	-0.11%	-0.46%	**-0.63%**
Maximum	0.00%	-0.08%	-0.28%	-0.19%	-1.02%	**-1.12%**
Minimum	0.00%	+0.23%	+0.04%	+0.05%	-0.01%	**-0.19%**

Additional experiments, illustrated in Table I, assess the BD-rate gain of *Dual-JRDO* brought by each PU size (or specific depth). Test conditions are the same as described in Section IV. These results show that the R-D gains introduced by *Dual-JRDO* are mostly brought by coding efficiency improvement of 4x4 and 8x8 PUs. In the following, one focuses on accelerating *Dual-JRDO* applied to 4x4 and 8x8 PUs because of their high complexity. In practice, 64x64 PU size rarely appear to be optimal, which explains that no gains are observed here.

A. Adapting to Spatial Activity

Quad-Tree is responsible for the large Cpx endured by HEVC [9]. Since Intra coding favors large PU size for smooth areas and small PU size for textured areas, many fast algorithms [10]–[12] estimate the spatial activity of the source to adaptively skip *RDO* for some PUs.

Thus, we propose to rely on a spatial activity measure, quite similar to the one defined in [10], for adaptive use of *Dual-JRDO*. In the case of high activity, *classical-RDO* is supposed to be sub-optimal and thus we activate *Dual-JRDO*.

As a good trade-off between metric computational overhead and estimator accuracy, the spatial activity is computed over 16x16 pixel area. Furthermore, in order to be more robust to random noise, the computation is done on a 16x16 block down-sampled to 4x4. Note that sub-blocks (16x8 or 8x4) take the same spatial activity value which is computed from the corresponding upper 16x16 size bloc, as described below:

1) Down-sample all 16x16 blocks into 4x4 blocks, then compute spatial activity g_i as defined in (5)
2) Each PU of 4x4 and 8x8 size is assigned with g_i value of the corresponding 16x16 PU
3) If $g_i \geq Th$, PU_i is processed with *Dual-JRDO*

$$g_i = \frac{1}{16} \sum_{x=0}^{3} \sum_{y=0}^{3} min \left\{ \begin{array}{l} |I_i(x,y) - I_i(x-1,y)| \\ |I_i(x,y) - I_i(x,y-1)| \end{array} \right. \quad (5)$$

with $I_i(x, y)$ the pixel luminance value at relative position (x, y) of down-sampled 16x16 PU_i. In order to exclude neighboring PUs energy, we set $I_i(-1, y) = I_i(x, -1) = 0$.

Th is a predefined threshold computed off-line with a supervised learning using logistic regression [13]. *Dual-JRDO* estimation encloses *classical-RDO* estimation by design, hence we can a posteriori observe if *Dual-JRDO* was of interest.

Supervised learning is used to estimate the optimal threshold for five QP values: $22, 27, 32, 37, 42$. The relationship between QP and Th is then obtained through logistic least square method applied on the previously obtained (QP, Th) couples as:

$$Th(QP) = \alpha \times e^{\beta \times QP} \quad (6)$$

with (α, β) values equal to $(0.0963, 0.107)$ in our case.

During threshold learning, we observe that the classification is more efficient for high QP values. One possible explanation is that for low rates, D tends to be equal to the prediction error. Consequently, since the spatial activity is a coarse estimation of the difficulty to predict a couple of PUs, it becomes at low rates a better predictor of the need to activate *Dual-JRDO*.

B. Short Listing on PU_{i+1}

In the HEVC reference Model *HM16.12* [14] used in our experiments, *classical-RDO* for Intra coding is only applied on a shortlist of modes created by Rough Mode Decision (*RMD*) algorithm [3]. *RMD* consists in short-listing prediction modes with lowest residual Sum of Absolute Transform Differences (SATD) value and syntax cost. Only this short-list is then estimated through *RDO*. In addition to the three Most Probable Modes *MPMs* (which are always evaluated), the minimal number of modes to be considered in *RDO* is respectively set to 8 for 4x4 and 8x8 PUs, and 3 for larger PU sizes.

The set of coding modes to consider (i.e. the possible values of p_i) is denoted M_i. In *Dual-JRDO*, M_{i+1} set consists of 35 intra prediction modes defined in HEVC. Since p^*_{i+1} is selected by the *RMD* process in the HM software, it seems relevant to also construct the M_{i+1} list based on the *RMD* optimization. Residual, syntax mode cost and *MPM*s being all dependent of p_i, we denote as $M_{i+1}(p_i)$ the set of modes to be considered for PU_{i+1} while optimizing PU_i. Therefore, (3) becomes (7) as:

$$p^*_i = \arg\min_{p_i \in M_i} \left(J_{i|_{p_i}} + \min_{p_{i+1} \in M_{i+1}(p_i)} J_{i+1|_{p_i, p_{i+1}}} \right) \quad (7)$$

Note that *RMD* is inherited from the *RDO* implementation in the *HM16.12*. However, any conceivable short-listing approach efficient for HEVC intra coding with *classical-RDO* model, could be also beneficial for the *Dual-JRDO* model.

C. Prediction Modes Clustering based on Residual Analysis

Two sources of dependencies between PUs have been exhibited in Section II: Distortion and CABAC. The CABAC dependency is considered negligible in *Dual-JRDO* coding scheme since both PU_i and PU_{i+1} are subject to very similar contexts. We assume that PU_{i+1} is then affected by a simple dependency: the distortion made on PU_i.

We assume that two prediction modes which result into identical residual signal also result in identical reconstructed signal. This assertion is true if no divergent process impacts the coding of residual. It implies identical transformation and quantization steps for HEVC Intra coding.

Mode Dependent Coding Scan (*MDCS*) [15] used in Intra HEVC does not fulfill the requirement of no mode-dependent process on residuals. However, we ignore the minor difference of process attributed to *MDCS* since it has very little impact on the proposed solution efficiency.

By considering only distortion dependency and the correlation between prediction residual and reconstructed data, we suppose that two modes of PU_i resulting in the same residual data share the exact same impact on PU_{i+1}. Consequently, we define as a *cluster* a set of prediction modes which result into identical residual signal. Let p_i1 and p_i2, two coding parameters of PU_i which result into the same prediction residual. Under the previous statement, equality (8) holds.

$$\min_{p_{i+1}} \left(J_{i+1|_{p_i1, p_{i+1}}} \right) = \min_{p_{i+1}} \left(J_{i+1|_{p_i2, p_{i+1}}} \right) \quad (8)$$

And from (8) we can write (9) and (10).

$$p^*_i = \arg\min_{p_i} \left(J_{i|_{p_i}} + J_{i+1|_{p'_{i+1}}} \right) \quad (9)$$

$$p'_{i+1} = \arg\min_{p_{i+1}} \left(J_{i+1|_{p_i, p_{i+1}}} \right) \quad (10)$$

which is correct with all possible p_i remaining in the same *cluster*. p'_{i+1} is defined as the optimal PU_{i+1} coding mode for all p_i in the cluster. Consequently, p'_{i+1} estimation is common for all p_i in the same cluster.

This method is summarized in three steps:

1) Construct the different clusters by analyzing mode residuals while *RMD* is applied to PU_i
2) If p_i is the first of its cluster, optimize p_{i+1} among all possible modes
3) Otherwise, optimize p_{i+1} among previous p^*_{i+1} of the same cluster and new *MPMs* modes

Many bits are saved if the optimal mode belongs to *MPMs*. Consequently, the third step ensures that *MPMs* of p_{i+1} are always tested if they differ from the *MPMs* previously considered within the cluster, i.e. if different from p_i. This technique is an effective shortcut as long as the number of final clusters is low, which is often verified for small CU sizes.

IV. Experiments and Results

Acceleration methods of Section III have been implemented in *HM16.12* with the *Dual-JRDO* algorithm. Results are presented with five configurations $\{C_k\}_{k=0}^4$ summarized in Table II. The reference is *HM16.12* with *classical-RDO*. Impacts of each solution on both Cpx and R-D efficiency are individually evaluated. For comparison purpose, we include results of *Dual-JRDO* in *HM16.12* without acceleration (C_0).

TABLE II
CONFIGURATIONS

Configurations	C_0	C_1	C_2	C_3	C_4
Spatial Activity Adaptation		x			x
Short-List M_{i+1}			x		x
Residual Based Clustering				x	x

Test conditions follow the recommendations of the Joint Collaborative Team on Video Coding (JCT-VC) [16] in All-Intra configuration. Coding efficiency is measured using Bjøntegaard BD-BR [17] with Peak Signal to Noise Ratio

(PSNR). Since, BD-BR is the difference of areas under two R-D functions, we choose to add a fifth R-D point at $QP = 42$ in order to cover a larger bitrate range with the same metric. We use the configuration files provided with *HM16.12*.

For this experiment, YUV BD-BR results of each configuration against *classical-RDO* are presented in Table III. Cpx savings over initial *Dual-JRDO* (C_0) are presented in Table IV. Cpx saving is estimated according to (11), with encoding times $Time_{ref}$ and $Time_{current}$ of *HM16.12* with *Dual-JRDO* without modification and *Dual-JRDO* with the proposed optimizations, respectively.

$$Cpx(\%) = \frac{Time_{current} - Time_{ref}}{Time_{ref}} * 100 \qquad (11)$$

We observe systematic bitrate savings against *classical-RDO* for all considered coding configurations. However, the more aggressive is the algorithm, in terms of Cpx reduction, the less efficient *Dual-JRDO* is.

TABLE III
Dual-JRDO CODING EFFICIENCY OVER *classical-RDO* IN *HM16.12*.

Classes	C_0	C_1	C_2	C_3	C_4
Class B	-0.45%	-0.42%	-0.38%	-0.46%	-0.35%
Class C	-0.61%	-0.54%	-0.47%	-0.61%	-0.42%
Class D	-0.63%	-0.59%	-0.46%	-0.64%	-0.44%
Class E	-0.64%	-0.58%	-0.52%	-0.64%	-0.47%
Class F	-0.87%	-0.76%	-0.67%	-0.88%	-0.60%
Average	**-0.63%**	**-0.57%**	**-0.49%**	**-0.63%**	**-0.45%**
Maximum	**-1.12%**	**-1.01%**	**-0.87%**	**-1.11%**	**-0.82%**
Minimum	**-0.19%**	**-0.21%**	**-0.20%**	**-0.20%**	**-0.20%**

TABLE IV
Dual-JRDO COMPLEXITY OVER C_0 CONFIGURATION.

Classes	C_1	C_2	C_3	C_4
Class B	-49.94%	-75.21%	-13.01%	-83.80%
Class C	-35.08%	-76.13%	-14.13%	-81.12%
Class D	-20.42%	-72.25%	-0.42%	-77.61%
Class E	-56.59%	-74.26%	-23.30%	-85.28%
Class F	-46.60%	-74.35%	-20.16%	-83.90%
Average	**-41.79%**	**-74.62%**	**-13.97%**	**-82.44%**
Maximum	**-25.89%**	**-75.83%**	**-14.84%**	**-79.63%**
Minimum	**-71.06%**	**-72.78%**	**-33.24%**	**-89.54%**

Adaptive activation of the model based on spatial activity corresponds to configuration C_1. In average Cpx reduction is about 41.79% for 0.06% BD-BR loss. The slight observed loss for C_1 can be explained by the off-line learning to approximate the threshold Th used in the decision.

Configuration C_2 uses *RMD* during the p'_{i+1} estimation. It is one of the most efficient in terms of Cpx reduction. We observe average Cpx decrease of 74.62% against C_0 configuration, at the cost of an average BD-BR increase of 0.14%. The results of this solution imply that any short-listing approach efficient into *classical-RDO* can be easily transposed into *Dual-JRDO* framework.

Configuration C_3 uses prediction mode clustering based on residual analysis. BD-BR gains are better preserves by suppressing redundant coding process without any approximation. Experimental observations show that cases of identical residual for different predictors occur rarely in textured content. The computational cost of comparing all residuals is also a non-negligible overhead. These two facts explain why Cpx is not significantly decreased (-13.97% in average).

TABLE V
FAST *Dual-JRDO* CODING EFFICIENCY AND COMPUTATIONAL COMPLEXITY OVER *classical-RDO* IN *HM16.12*.

Classes	Δ Bit-rate (%)	Encoding Time (%)
Class B	-0.35%	133%
Class C	-0.42%	156%
Class D	-0.44%	160%
Class E	-0.47%	116%
Class F	-0.60%	124%
Average	**-0.45%**	**138%**
Maximum	**-0.82%**	**178%**
Minimum	**-0.20%**	**74%**

Configuration C_4 represents the combination of the three solutions from Section III. For each PU, the algorithm equivalent to C_1 decides whether *Dual-JRDO* is to be used or not. Next, algorithm corresponding to C_3 configuration builds the mode clusters based on *RMD* process. Finally, for the first tested mode of each cluster, *RMD* is enabled while analyzing PU_{i+1}. For any new mode that belongs to the same cluster, the solution described by Section III-C is applied. The final Fast *Dual-JRDO* combination limits Cpx increase to 138% against *classical-RDO*, with an average BD-BR of -0.45% and up to -0.82%, as shown in Table V.

V. CONCLUSION

In this paper, we have proposed three acceleration methods to benefit from Inter-Block dependencies and improve HEVC Intra coding efficiency without tremendous computational cost.

Considering the Intra prediction mode as the coding parameter to optimize, we observe a correlation between the source spatial activity and the *Dual-JRDO* effectiveness. Thus, a robust spatial activity metric, is first designed to efficiently activate or not the *Dual-JRDO* model for each PU. Besides, *RMD* short-listing algorithm is successfully integrated in the p'_{i+1} estimation. Finally, we introduced a prediction mode clustering approach that suppresses redundant computations for modes resulting in identical residue. This last acceleration method is based on the fact that similar residue on PU_i should lead to the same impact on PU_{i+1} optimal coding.

The combination of the three proposed acceleration methods results in a Fast *Dual-JRDO* that improved HEVC coding efficiency by -0.45% BD-BR for a computational complexity of 138% in comparison to the *HM16.12* reference model.

Our future work will focus on dependencies related to Inter-frames prediction, more subject to distortion propagation onto temporal axes, which could lead to higher gains for JRDO approaches. We also note that in this paper, *Dual-JRDO* focus on optimizing intra prediction modes couples. However, one can easily extend the model to other coding parameters, such as QP for CU couples.

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