Constrain the Docile CTUs: an In-Frame Complexity Allocator for HEVC Intra Encoders

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***Abstract*—High Efficiency Video Coding (HEVC) is one of the latest released video standards and offers up to 40% bitrate savings when compared to the widespread H.264/AVC standard, at the cost of a substantial complexity growth. Constraining the complexity of HEVC encoding is a challenging task for embedded applications based on a software encoder. The most frequent approach to solve this problem is to optimise the coding tree structure to balance compression efficiency and computational complexity.**

In this context, we propose and assess a method to adequately allocate the computational complexity among coding units in a frame encoded in Intra mode. By studying an open-source real-time HEVC encoder, correlations are observed between Rate-Distortion (RD)-cost and encoding complexity that motivate a new complexity allocation technique. This technique, called *"Constrain the Docile CTUs" (CDC)*, consists of allocating less computational complexity to units with low RD-costs and using RD-costs from preceding images as predictors for the current RD-costs. Experimental results demonstrate substantial gains, up to 36% of Bjøntegaard Delta Bit Rate (BD-BR), when using CDC method instead of other allocation methods.

***Index Terms*—Complexity allocator, HEVC, quad-tree partitioning, embedded platforms, Intra encoding, RD-cost.**

I. Introduction

The HEVC [1]–[3] standard represents the state-of-the-art of video coding. When compared with the previous MPEG Advanced Video Coding (AVC) standard, HEVC Main profile reduces bitrate by 40% on average for a similar objective video quality [4], [5]. However, the complexity ratio between the reference HEVC encoder (HM 6.0) and the reference AVC encoder (JM 18.0) is about 3.2x for All Intra (AI) coding configuration [6], 1.2x for Random Access (RA), 1.5x for Low Delay B (LB) and 1.3x for Low Delay P (LP) [4]. In this paper, we focus on the AI configuration.

The additional encoding complexity of HEVC is mainly due to a new quad-tree block partitioning structure, called coding tree in the rest of the paper, and to a large number of Intra-prediction modes tested during the Rate-Distortion Optimisation (RDO) process. In Intra coded blocks, HEVC uses 35 intra prediction modes [1].

To reduce the computational complexity of HEVC encoders, several algorithmic solutions have been proposed to speedup the coding tree partitioning by testing less partition configurations. They consist in choosing as inexpensively as possible the adequate degree of partitioning configuration that offers a low RD-cost. A fast partitioning and pruning method for intra-encoding is proposed in [7], composed of two complementary steps: the early CU splitting decision and the early CU pruning decision, using a Bayes decision rule. In [8], authors introduce an *Early Termination* technique for fast RDO. This technique stops the CU partitioning process when the best found RD-cost is already lower than a given dynamic threshold based on both spatial and temporal correlations. The methods proposed in [9]–[11] use intermediate information of encoding steps to determine whether the current CU needs to be partitioned into smaller CUs or can be encoded globally.

In this paper, we propose a complexity allocator for HEVC Intra encoder. The proposed allocator is orthogonal to these complexity reduction methods and can be combined with each of them. In the context of software video encoding on embedded systems, where computational resources are scarce, the proposed allocator saves encoding complexity by *constraining CTUs*, i.e. by limiting the effort of looking for optimal compression solution for these particular CTUs. Using RD-costs to choose the CTUs to constrain is briefly evoked by Correâ, et al. in [12]–[14] without defining the method and evaluating the gains. We define and assess in this paper a method named *Constrain the Docile CTUs (CDC)* that allocates the complexity in a frame while minimizing the RD performance loss. Experimental studies are carried out with the real time HEVC encoder *Kvazaar* [15]–[17].

The rest of this paper is organized as follows. Section II analyses the correlation between CTU partitioning depths and the RD-cost of CTUs. This analysis motivates the complexity allocator introduced in Section III.

II. Relation between CTUs partitioning depths and the RD-cost

When encoding under a bit rate constraint, the HEVC encoder must select the optimal intra prediction mode i with $i \in \{1, ..., 35\}$ that minimizes a rate-distortion criterion. As explained in [18], this optimization problem can be represented by an unconstrained problem using the Lagrangian method in Equation 1 where $J(i)$ is the RD-cost, $D(i)$ and $R(i)$ are respectively the resulting distortion and bit rate when using intra prediction mode i and λ is the Lagrangian multiplier [19], [20]. The RDO process consists in testing all possible coding modes and selecting the one that minimizes the RD-cost:

$$\min_i J(i) = D(i) + \lambda \cdot R(i) \tag{1}$$

In HEVC, a frame is partitioned into square blocks of equal size called CTUs. Each CTU can be recursively partitioned

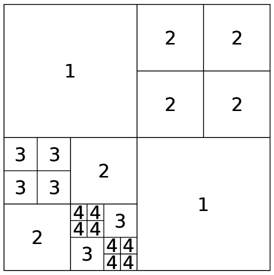


Fig. 1. CTU Partitioning into CUs

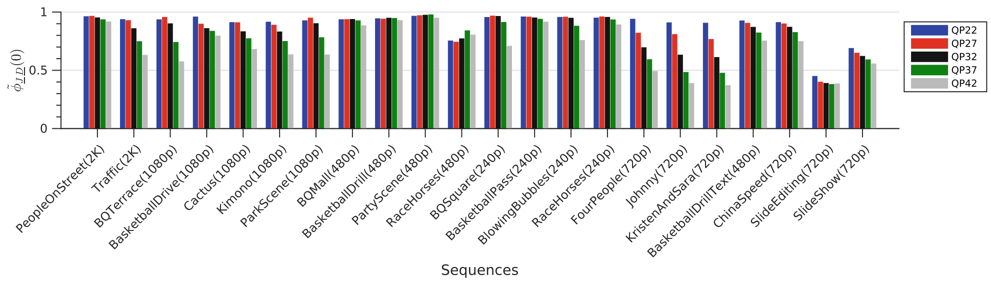


Fig. 2. Correlation coefficient between the CTU depth metric and the RD-cost

into smaller blocks, called CUs, forming a quadtree structure. A CU is composed of luma and chroma Coding Blocks (CBs) and the size of a CBs is $2N \times 2N$ samples with $N \in \{32, 16, 8, 4\}$. To predict the unit content from other units, CUs may be partitioned into Prediction Blocks (PBs) of smaller size. In intra prediction, PBs are square and are $2N \times 2N$ samples, or $N \times N$ only when $N = 4$. The RDO process selects the best quad-tree partitioning configuration from a search over coding configurations. Figure 1 shows an example of a 64×64 CTU divided into several CUs.

In this section, the relation between partitioning depth and RD-cost is analyzed in order to check whether an encoder can use the RD-cost to allocate the complexity within the frame.

A. Correlation between a CTUs partitioning depths and its RD-cost

To estimate the correlation between the partitioning depths and the RD-cost of a CTU, we introduce a novel depth metric $\mathbf{D}_{p,x,y} \in \mathbb{N}$ to quantify the partitioning depths of each CTU:

$$\mathbf{D}_{p,x,y} = \sum_{x \in [1, N_{p,x,y}]} d_x \tag{2}$$

where x and y are respectively the horizontal and vertical coordinates of the CTU in the frame p and $d_x \in [0, 4]$ is the depth of the considered PB with $N_{p,x,y}$ the number of PBs in the CTU. $\mathbf{D}_{p,x,y}$ takes one of the 687 values in the range $[0, 1024]$. A high partitioning complexity for a CTU (i.e. many small CUs) implies a high value of $\mathbf{D}_{p,x,y}$. For the CTU in Figure 1, $\mathbf{D}_{p,x,y}$ is equal to $2 \times 1 + 6 \times 2 + 6 \times 3 + 8 \times 4 = 64$.

To measure the correlation between $\mathbf{D}_{p,x,y}$ and $\mathbf{J}_{p,x,y}$, a normalized cross-correlation $\tilde{\phi}_{\mathbf{j}\,\mathbf{d}}(n)$ defined by Equations 4 and 3 is performed. $\mathbf{d}$ and $\mathbf{j}$ are two N length vectors with N the total number of CTU in the sequence, respectively formed by $\mathbf{D}_{p,x,y}$ and $\mathbf{J}_{p,x,y}$, reshaped in 1 dimension for each video sequence.

$$\tilde{\phi}_{\mathbf{j}\,\mathbf{d}}(n) = \frac{\phi_{\mathbf{j}\,\mathbf{d}}(n)}{\sqrt{\phi_{\mathbf{j}\mathbf{j}}(0)\phi_{\mathbf{d}\,\mathbf{d}}(0)}} \quad \text{, with} \tag{3}$$

$$\phi_{\mathbf{j}\,\mathbf{d}}(n) = \sum_{k=0}^{N-1} \mathbf{j}(k)\mathbf{d}^*(k-n), \forall n \in [-(N-1), (N-1)] \tag{4}$$

Figure 2 shows $\tilde{\phi}_{\mathbf{j}\,\mathbf{d}}(0)$ for a set of 22 sequences with $QP \in \{22, 27, 32, 37, 42\}$ (from high to low quality). A high correlation is observed between the RD-cost $\mathbf{j}$ and the depth metric $\mathbf{d}$ for most of the configurations. The degree of correlation decreases when the Quantization Parameter (QP) increases. This effect is more prominent in the sequences of class E [6]. These results lead to the conclusion that a strong link exists between the RD-cost and the partitioning depths of the CTUs in HEVC which slightly decreases at low bitrate. Intuitively, CTUs with low entropy have low RD-cost (they require low information to be coded at low distortion) and lead to coarse grain tree partitioning. We call these CTUs "docile CTUs".

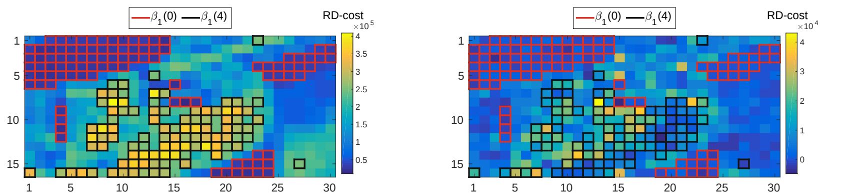
B. Impacts of a CTU constraint on the RD-cost

In the next sections, as the major part of complexity reduction techniques (called *Eraly Termination*), a CTU is constrained by preventing the use of level 4. Since the RD-cost and the partitioning depths of a CTU are correlated, this section analyzes the impact of the CTU partitioning constraint on the RD-cost. Two encodings are performed for that purpose: one with constraint (lowering max depth from $d_{max} = 4$ to 3) in the RDO process and one without any constraint (anchor). The RD-cost obtained for both constrained and anchor encodings, respectively $\mathbf{J}'_{p,x,y}$ and $\mathbf{J}_{p,x,y}$, are compared.

Each frame is split into bins, grouping CTUs with similar RD-costs, each bin including the same number of CTUs. The following equation defines the interval of bin $\beta_p(k)$:

$$\beta_p(k) = \left[F_p^{-1}\left(\frac{k}{N_b}\right), F_p^{-1}\left(\frac{k+1}{N_b}\right) \right], \text{ with } k \in [0, N_b - 1] \tag{5}$$

where F_p is the cumulative distribution function of the RD-cost $J_{p,x,y}$ for frame p and N_b is the number of bins (uniform CTU intervals). To illustrate the impact of the CTU constraint on the RD-cost, Figure 3 presents the RD-cost of the 1^{st} frame of the BQTerrace sequence (in 1080p) coded in the AI configuration at QP32. Figure 3a is a CTUs heat map of the RD-costs. These costs are split into 5 bins ($N_b = 5$), with $\beta_1(0)$ and $\beta_1(4)$ (i.e. the bins including CTUs with respectively lowest and highest RD-costs) being highlighted. Figure 3b shows the difference $\mathbf{J}_{1,x,y} - \mathbf{J}'_{1,x,y}$, representing the impact of the CTU constraint. The RD-cost increase due



(a) Absolute RD-cost per CTU with unconstrained encoding $\mathbf{J}_{1,x,y}$

(b) Relative RD-cost gain per CTU when removing a constraint $\mathbf{J}_{1,x,y} - \mathbf{J}'_{1,x,y}$

Fig. 3. Heat maps of the RD-cost of the first frame of the sequence BQTerrace(1080p) with $QP = 32$

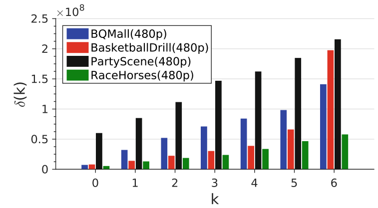


Fig. 4. RD-cost increase per bin when constraint is removed with $Nb = 7$ bins

to removing the constraint is not uniformly distributed in the frame: it is much higher for $\beta_1(4)$ than it is for $\beta_1(0)$. As a consequence, the RD-cost of docile CTUs is less impacted by a constraint than the RD-cost of the non docile CTUs.

The total RD-cost increase $\delta(k)$ for bin k and for all the sequences is defined by Equation 6. It is used to quantify the impact of the CTU constraint on the sequences.

$$\delta(k) = \sum_{p,x,y} \left(\mathbf{J}_{p,x,y} - \mathbf{J}'_{p,x,y}\right), \forall \mathbf{J}_{p,x,y} \in \beta_p(k) \qquad (6)$$

Figure 4 shows $\delta(k)$ for all sequences of class C encoded with $N_b = 7$. The figure presents the results for QP=32, other values were also tested and show similar behaviour. The histograms show that $\delta(k)$ follows a monotonically increasing curve. For the constrained CTUs, the RD-cost increase is thus minimal for docile CTUs, i.e. CTUs with low RD-cost in unconstrained encoding.

Further results that consider a wider range of QP values (27, 32 and 37) are presented in Table I. The number of bins is fixed to 3. The table presents results for the sequences Traffic, Cactus, RaceHorses, BQSquare, FourPeople and ChinaSpeed (one per class). The cost increase for bin k is normalized to $\delta(0)$:

$$\tilde{\Delta}_{0,k} = \frac{\delta(k) - \delta(0)}{\delta(0)} \times 100 \qquad (7)$$

$\tilde{\Delta}_{0,1}$ and $\tilde{\Delta}_{0,2}$ represent the increase (in %) of RD-cost between the first bin $\delta(0)$ and respectively the second $\delta(1)$ and third $\delta(2)$ bins. The results show that in most cases the constraint has a larger impact on the RD-cost for the last bin than for the second one, for every sequence and QP.

TABLE I
INCREASE COST (%) BY BIN FOR $N_b = 3$

Class/Sequence	QP 27 $\tilde{\Delta}_{0,1}$	QP 27 $\tilde{\Delta}_{0,2}$	QP 32 $\tilde{\Delta}_{0,1}$	QP 32 $\tilde{\Delta}_{0,2}$	QP 37 $\tilde{\Delta}_{0,1}$	QP 37 $\tilde{\Delta}_{0,2}$
A/Traffic	237	596	259	723	214	591
B/Cactus	162	671	135	383	1028	1522
C/RaceHorses	165	278	207	408	247	568
D/BQSquare	169	647	890	3059	116	479
E/FourPeople	13	127	108	135	1015	826
F/ChinaSpeed	300	936	469	1328	684	2314

These experiments show that the CTUs with lowest RD-cost have less increase of bit rates and/or distortion if constrained encoding is applied to them. As a conclusion, when a CTU complexity reduction technique has to be applied on a part of a frame, CTUs with the lowest RD-cost should be constrained, i.e. less encoding effort should be spent to encode them.

C. Temporal RD-cost stability of consecutive frames

In previous section, the RD-cost of unconstrained encoding is used to choose which CTUs to constrain. Yet, an encoder applying complexity reduction techniques does not compute unconstrained RD-cost. Consequently, RD-cost prediction should be performed from existing information. A precise distribution modeling of RD-costs is a challenging problem because RD-cost distribution depends on both QP values and video content such as texture complexity, noise, and irregular illumination.

The RD-cost of the previous frame in the video can however be used to predict the RD-cost of the current frame. To justify the RD-cost temporal stability, a normalized autocorrelation (as in Equation 3) is performed on every vector $\mathbf{j}_{x,y}$ formed of the RD-cost of the CTU located at coordinates i, j for the entire sequence. To observe the temporal stability, the correlations are taken at $n = 1$ which correspond to frame p being correlated to frame $p-1$. The average of every correlation coefficient $\tilde{\phi}_{\mathbf{jj}}(1)$ is performed as shown in Equation 8.

$$\overline{\phi}_{\mathbf{jj}} = \underset{x,y}{mean}(\tilde{\phi}_{\mathbf{j}_{x,y}\mathbf{j}_{x,y}}(1)) \qquad (8)$$

The results are presented in Table II considering five values of QP (22, 27, 32, 37 and 42) and averaged by class. A high correlation (with correlation coefficient higher than 0.95) between RD-cost on consecutive frames is observed. It is thus justified to use the RD-cost of the previous frame to predict the RD-cost of the current one. Furthermore, the CDC allocator does not need the exact RD-cost values and approximations are sufficient for comparison against dynamic thresholds.

TABLE II
AVERAGE OF CORRELATION COEFFICIENT OF CTU COST OF CONSECUTIVE FRAMES

	QP22	QP27	QP32	QP37	QP42	Av.
Class A	0.991	0.989	0.987	0.985	0.983	**0.987**
Class B	0.988	0.987	0.986	0.985	0.985	**0.986**
Class C	0.986	0.986	0.986	0.985	0.985	**0.986**
Class D	0.985	0.985	0.985	0.985	0.985	**0.985**
Class E	0.986	0.986	0.986	0.986	0.986	**0.986**
Class F	0.971	0.959	0.958	0.958	0.960	**0.961**
Average	**0.985**	**0.982**	**0.981**	**0.981**	**0.981**	**0.982**

TABLE III
BD-BR between our allocator and four others (in %)

Class	Sequences	Upper			Lower			Tick			Inverse		
		30%	50%	70%	30%	50%	70%	30%	50%	70%	30%	50%	70%
Class A	Traffic	0.134	0.408	0.684	0.5	1.024	1.038	0.68	0.813	0.81	1.278	1.498	1.212
	PeopleOnStreet	1.306	1.702	1.573	0.638	0.955	0.93	1.38	1.523	1.495	2.472	2.816	2.262
Class B	ParkScene	0.326	0.459	0.266	0.701	0.822	0.64	0.728	0.744	0.576	1.073	1.334	1
	Cactus	0.814	1.588	1.684	0.858	1.261	1.717	1.115	1.522	1.867	2.666	2.886	2.544
	BQTerrace	0.818	1.175	0.692	1.861	1.872	1.723	1.382	1.757	1.659	2.769	3.174	2.57
	BasketballDrive	0.467	0.47	0.628	0.674	0.949	0.825	1.026	0.829	0.861	1.422	1.512	1.342
Class C	RaceHorses	0.167	0.828	1.351	1.503	2.258	2.554	1.386	1.649	1.86	2.746	3.097	2.667
	BQMall	0.973	1.302	1.007	1.274	1.504	1.372	1.752	1.644	1.515	2.276	2.72	2.159
	PartyScene	1.025	1.117	1.005	3.514	3.661	3.525	2.224	2.878	3.449	4.588	4.941	4.482
	BasketballDrill	1.155	1.761	1.913	1.816	2.507	2.618	2.367	2.344	2.185	3.714	4.239	3.511
Class D	RaceHorses	0.326	0.965	1.515	2.003	2.682	2.91	1.659	1.916	1.787	2.783	3.19	2.752
	BQSquare	2.495	3.798	3.205	2.827	2.963	3.346	4.011	3.642	3.147	4.749	5.527	4.601
	BlowingBubbles	0.908	1.469	1.205	1.04	1.055	1.541	1.444	1.485	1.204	1.713	2.068	1.762
	BasketballPass	1.028	2.48	3.436	2.601	3.714	4.114	2.299	2.944	3.53	4.736	5.489	4.734
Class E	FourPeople	0.261	1.098	0.958	2.28	3.133	2.953	2.041	2.457	1.999	3.456	4.215	3.2
	Johnny	2.107	2.919	4.073	1.018	2.847	2.956	2.299	2.756	3.88	5.313	5.791	5.056
	KristenAndSara	1.398	2.317	2.983	4.054	5.318	5.662	2.845	3.876	5.357	7.121	7.78	6.952
Class F	BasketballDrillText	5.107	4.384	2.563	3.78	3.114	1.306	3.629	4.34	4.42	6.428	7.665	6.429
	ChinaSpeed	12.038	15.66	14.018	7.834	10.407	10.196	10.729	14.581	15.027	23.199	26.899	21.446
	SlideEditing	10.28	15.088	14.402	14.742	19.901	18.556	16.875	17.955	17.559	31.623	35.672	27.412
	SlideShow	7.861	14.244	20.912	7.828	16.885	20.475	11.3	16.279	21.214	28.967	31.872	28.576

The next part describes the CDC allocation method to improve RD performance of HEVC.

III. The CDC Complexity Allocator

The previous analysis leads to three observations:

1) RD-cost is linked to the partitioning depths of CTUs.
2) CTUs with low RD-cost have less increase of bit rates and/or distortion than CTUs with high RD-cost when constrained (i.e. when the partitioning depth is limited).
3) The RD-costs of the previous frame can be used to predict the RD-costs of the the current frame.

Motivated by these observations, we propose a method to allocate complexity in a frame.

A. Presentation

The proposed complexity allocator can be adapted to different CTU complexity reduction techniques that require the HEVC encoder to constrain X_p% of the frame p.

Initially, the first frame of the video sequence is encoded unconstrained and the RD-cost of CTUs of that frame is stored. Then, for each constrained frame, the CDC method constrains CTUs which RD-cost belongs to the following interval:

$$J_{p-1,x,y} \in \left[0; F_{p-1}^{-1}(X_p/100)\right[\tag{9}$$

where F_{p-1} is the cumulative distribution function of the RD-cost $J_{p-1,x,y}$ of the frame $p-1$ and X_p is the percentage of constrained CTUs in the current frame p. CDC is called "Constrain the Docile CTUs" because it consists of reducing the encoding effort for the CTUs that lend themselves the most to encoding.

B. Experimental Results

The performance of the CDC allocator is evaluated by measuring the Bjøntegaard Delta Bit Rate (BD-BR) between CDC and four methods described below:

1) *Upper*: The first X_p% of the CTUs in raster scan order of the frame p are constrained.
2) *Lower*: The last X_p% of the CTUs in raster scan order of the frame p are constrained.
3) *Tick*: every CTU out of a percentage (for example $X_p = 33\%$ means every three CTUs) is constrained.
4) *Inverse*: The exact inverse of our allocator method, i.e. the CTUs with the highest RD-cost in the previous frame are constrained.

CDC and the four reference allocators are implemented in the real-time HEVC encoder *Kvazaar*. CTU complexity reduction is implemented by removing the last depth level ($d = 4$) in the RDO process on the constrained CTUs. The proposed method performance is evaluated with three shares of constrained CTUs per frame (30%, 50% and 70%) and four different QP values (22, 27, 32 and 37). Table III presents the BD-BR between CDC and the four others for 22 standard sequences. For most of the tests, CDC has better RD performance with a negligible memory footprint and a very low computational overhead. CDC saves a significant amount of bitrate compared to the *inverse* one, which confirms the approach. The best results are obtained for the video sequences of class F with up to 36% BD-BR savings between CDC and the inverse allocator.

IV. Conclusion

Complementary to State-of-Art complexity reduction techniques, this paper proposes a complexity allocator for HEVC based on RD-costs. This study focuses on AI configuration. The results, obtained with the real time open source HEVC encoder *Kvazaar*, demonstrate that the proposed CDC allocator is able to save up to 36% of BD-BR compared to other allocation methods. As future work, the results of this study will be applied to the RA and Low Delay (LD) encoding configurations. Moreover, this work will be used to allocate complexity with different complexity reduction techniques.

Acknowledgments

This work is partially supported by the French ANR ARTEFaCT project, by COVIBE project funded by Brittany region and by the European Celtic-Plus project 4KREPROSYS.

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