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Complexity Reduction Opportunities in the Future VVC Intra Encoder

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***Abstract*—The Joint Video Expert Team (JVET) is developing the next-generation video coding standard called Versatile Video Coding (VVC) and their ultimate goal is to double the coding efficiency over the current state-of-the-art standard HEVC without letting complexity get out of hand. This work addresses the complexity of the VVC reference encoder called VVC Test Model (VTM) under All Intra coding configuration. The VTM3.0 is able to improve intra coding efficiency by 21% over the latest HEVC reference encoder HM16.19. This coding gain primarily stems from three new coding tools. First, the HEVC Quad-Tree (QT) structure extension with Multi-Type Tree (MTT) partitioning. Second, the duplication of intra prediction modes from 35 to 67. And third, the Multiple Transform Selection (MTS) scheme with two new discrete cosine/sine transforms (DCT-VIII and DST-VII). However, these new tools also play an integral part in making VTM around 20 times as complex as HM. The purpose of this work is to analyze these tools individually and specify theoretical upper limits for their complexity reduction. According to our evaluations, block partitioning complexity reduction opportunity is up to 98.7%, i.e., the encoding complexity would drop down to 2% for the same coding efficiency if the optimal block partitioning could be directly predicted. The respective percentages for intra mode reduction and MTS optimization are 64.3% and 53.6%. We believe these results motivate VVC codec designers to develop techniques that are able to take most out of these opportunities.**

***Index Terms*—Versatile Video Coding, Complexity reduction, CTU partitioning, Multi-Type Tree (MTT), Intra mode prediction, Multiple Transform Selection (MTS)**

I. INTRODUCTION

IP video traffic is estimated to account for up to 82% of the global IP traffic by 2022 [1]. Considering this evolution through the emerging video formats like 4K Ultra High Definition (UHD) and 360-degree videos, the coding performance of the current High Efficiency Video Coding (HEVC) standard [2] needs to be further enhanced to satisfy the requirements of future video streaming and storage. These new challenges motivated the International Telecommunication Union (ITU) and ISO/IEC Moving Picture Experts Group (MPEG) to form the Joint Video Expert Team (JVET) that is currently developing a new video coding standard called Versatile Video Coding (VVC) [3].

JVET is investigating many new coding tools in All Intra (AI) configuration such as the Multi-Type Tree (MTT) partitioning, 32 new angular intra mode predictions, and 2 new transforms. These new tools have been integrated into the VVC reference software called VVC Test Model (VTM). VTM extends the Quad-Tree (QT) block partitioning scheme of HEVC by adding the nested recursive MTT partitioning with additional Coding Unit (CU) types. This new block partitioning scheme forms the basis of the VTM encoding process with the highest coding gain. So, VTM allows five different splits with QT, Binary-Tree (BT) and Ternary-Tree (TT). BT and TT include both horizontal or vertical partitioning. In addition, the number of intra prediction modes is extended from that of 35 in HEVC to 67 in VTM 3.0 to better leverage spatial redundancy of the reconstructed neighboring blocks. Moreover, VTM introduces the Multiple Transform Selection (MTS) process that tests different core transforms and selects the one with the best coding efficiency. In addition to the Discrete Cosine Transform (DCT)-II adopted from HEVC, two new transforms, DCT-VIII and Discrete Sine Transform (DST)-VII, are included in MTS.

The new coding tools of VTM 3.0 improve average coding efficiency by 21.08% [4] over that of HEVC test Model (HM) 16.19, AI coding configurations. These improvements come at the expense of 1919% [4] encoding complexity. Reduction of encoding complexity was already a hot topic during HEVC standardization. Considering the aforementioned complexity increase of VTM 3.0, encoding complexity reduction is supposed to remain an active research field during the VVC standardization.

In this context, we propose a hierarchical characterization and evaluation of the VVC encoding complexity with the VTM encoder. We first present an overview of the impact of encoding parameters on the encoding complexity. The investigated parameters include spatial resolution and the Quantization Parameter (QP). Then, we define and evaluate the complexity reduction opportunities offered by the three algorithmic encoding levels: Coding Tree Unit (CTU) partitioning, intra mode prediction and MTS process.

The remainder of this paper is organized as follow. Section II presents an overview of the VVC encoding tools and the state-of-the-art of complexity reduction techniques. Section III details the experimental setup and evaluates the encoding complexity with different encoding parameters. Section IV presents the identified complexity reduction opportunities and analyses their impact on the VVC encoding process. Finally, Section V concluded the paper.

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II. Related Works

This section first presents an overview of the encoding process, from the last standard HEVC to the future one VVC. As this work is dedicated to AI configuration, the rest of this paper is focused on Intra tools. State-of-the-Art complexity reduction techniques are then introduced.

A. From HEVC to VVC encoding process overview

1) HEVC: In HEVC [2], adaptive block partitioning is the most improvement in terms of encoding efficiency. While encoding in HEVC, each frame is split into equally-sized blocks named CTUs. Each CTU is then divided into CUs, which are recursively split into sub-CUs following a QT partitioning. CUs may be split into Prediction Units (PUs) of smaller size, on which the prediction is performed. HEVC enables 35 intra prediction modes including DC, planar and 33 angular modes. After prediction, the transform and quantization steps are applied on the residual blocks, called Transform Units (TUs). HEVC includes DCT-II and DST-VII transforms, where DST-VII is only applied on luma 4×4 blocks.

2) VVC: Versatile Video Coding (VVC) is defined to be the next generation video coding standard, which has as primary target to provide a significant performance improvement over HEVC. VTM is the VVC reference software used by JVET to evaluate the performance of the new encoding tools. As VVC is expected to be standardized by 2020, the following description of the encoding process is focused on VTM3.0.

In addition to the recursive QT partitioning processed in HEVC, VTM integrates a nested recursive MTT partitioning, i.e. BT and TT splits. Fig. 1 illustrates all available split in VTM for a $4N \times 4N$ CU. The BT partitioning consists of symmetric horizontal splitting (BT-H) and symmetric vertical splitting (BT-V) while the TT partitioning allows horizontal triple-tree splitting (TT-H) and vertical triple-tree splitting (TT-V) corresponding to split the CU in three blocks with the middle blocks size equal to the half of the CU. In the AI configuration file defined in the Common Test Conditions (CTC), BT and TT are available on CUs with sizes lower or equal than 64×64 and 32×32, respectively. Moreover, the partitioning process includes restrictions to avoid generating the same CU with different succession of split. For example, BT partitioning is not allowed on the middle CU of a TT split in the same direction. Once BT or TT split is performed on a CU, QT split is not allowed any more on its sub-CUs. Fig. 2 presents on the left an example of a CTU split into several CUs after performing the VTM CTU partitioning with QT and MTT splits and on the right a part of CTU partitioning corresponding tree representation. Dark, green and blue lines represent QT split, BT split and TT split, respectively. Yellow and red background show two examples of the corresponding CUs on the CTU partitioning and corresponding tree. To the best of our knowledge, no performance comparison between CTU partitioning of VTM and HM has been made in AI configuration. For information, adding BT and TT to HM16.14 encoder in Random Access (RA) configuration increases the Bjøntegaard Delta Bit Rate (BD-BR) performance by -14.42% at the expanse of encoding complexity increase of 183% [5].

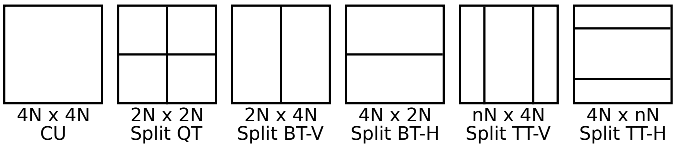


Fig. 1. Available split included in VTM of a $4N \times 4N$ CU.

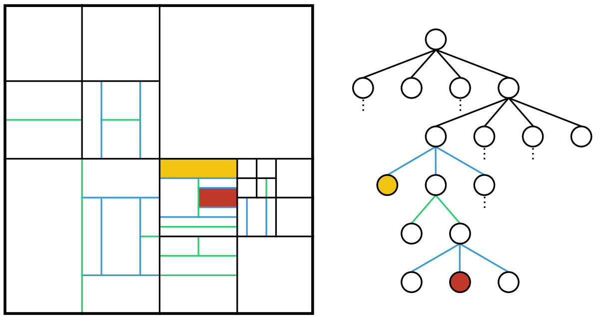


Fig. 2. Example of a CTU partitioning with a part of its corresponding tree representation.

Intra mode prediction in VTM is similar to HEVC. Intra prediction is made from reconstructed pixel samples of neighboring PUs. Angular modes in VTM are extended to 65. As the VTM allows rectangular shape for a PU, wide-angle modes replace some angular modes according to the ratio width by height of the PU [6]. The increase of intra mode prediction from 35 in HEVC to 67 in VVC provides in average -0.51% BD-BR saving for 108% encoding complexity increase in AI configuration [7].

For the transform step, VTM introduces the MTS process that enables two new transforms including DST-VII and DCT-VIII. MTS test a set of transforms and select the one that achieves the best encoding efficiency. For luma component, MTS is processed on TU of size equal or lower than 32×32, otherwise DCT-II is selected. For chroma component, only DCT-II is considered. The MTS provides in the VTM3.0 significant BD-BR saving, up to -2.8% for an encoding complexity increase of 238% in AI configuration [7].

To achieve the best RD performance, the encoder performs an exhaustive search process, named Rate-Distortion Optimization (RDO), testing all possible combinations of CTU partitioning structures, intra prediction modes and transforms. The RDO process minimizes the cost J, called Rate-Distortion (RD)-cost, defined by Equation 1:

$$J = D + \lambda \cdot R \tag{1}$$

where D is the distortion, R the bit-rate and λ the Lagrangian weighting factor, which depends on the QP.

B. State-of-the-Art of complexity reduction techniques

The new encoding tools presented in Section II-A1, in particular adaptive block partitioning, have increased encoding complexity compared to previous standards. Many methods have already been proposed to reduce the encoding complexity of HEVC. To evaluate their results, authors in [8] presents an analysis of complexity reduction opportunities of an HEVC real-time intra encoder *Kvazaar*. This study shows that the CTU partitioning process has a potential of complexity reduction up to 78.1% whereas the intra mode prediction offers at best 30% of complexity reduction. This section presents the State-of-the-Art of complexity reduction focused on CTU partitioning and intra mode prediction whether on HM and Joint Exploration Model (JEM) software.

The following methods reduce the complexity of QT partitioning. In methods proposed in [9] and [11], authors predict split decision with machine learning techniques on HM12.0. The first method [9] which uses multiple Convolutional Neural Networkss (CNNs) depending of the CU size to predict CU and PU split decision achieves in average 61.1% complexity reduction in AI configuration for a BD-BR loss of +2.67%. The second method [11] presents three sets of decision trees that early terminate the RDO process of CU, PU and TU. This technique enables 65% complexity reduction for +1.36% BD-BR loss in RA configuration. Authors in [10] proposes a solution combining CU depth pre-selection, early CU and PU terminations and fast TU tree decision based on a RD complexity optimization formula. The gain of the four combined propositions on HM16.7 in RA configuration is 46% to 70% complexity reduction for +0.48% to +2.36% BD-BR loss, respectively.

QTBT partitioning was introduced in HM13.0-QTBT which has considerably increased the encoding complexity compare to QT partitioning. The method proposed in [12] combines two solutions to reduce the complexity of HM13.0-QTBT. The first solution dynamically sets partition parameters at CTU level to adapt to the CTU local content properties according to splitting information of neighboring blocks. The second solution is a joint-classifier that early terminates the CTU partitioning process. With +1.34% BD-BR loss, this method obtains a complexity reduction of 67.6% in AI configuration. In [13], authors proposes early termination algorithm stand on their proposed RD model. This RD model is based on motion divergence field and predicts the RD cost at each partition pattern without full RDO process. This method implemented on JEM7.0 enables 50.60% complexity reduction for +1.23% BD-BR loss in RA configuration. The method presented in [14] uses CNN to predict the depth range of 32×32 block size. The use of CNN come with an overhead of 3.36% and introduces +0.69% BD-BR loss for complexity reduction of 42.33% on JEM3.1.

In order to reduce the complexity of intra mode prediction, authors in [15] proposes a progressive rough mode search based on the Hadamard cost to selectively evaluate potential prediction modes. Furthermore, this progressive rough mode search is completed by early rate-distortion optimized quantization skip to further reduce the set of tested intra modes. The combination of these two methods implemented in HM4.0 offers a gain of 45% complexity reduction for +0.8% BD-BR loss. Machine learning solutions [16] [17] limit the number of intra prediction mode. These solutions reduce the encoding complexity of 23.61% and 18.3% for +0.03% and +0.5% BD-BR loss on HM16, respectively.

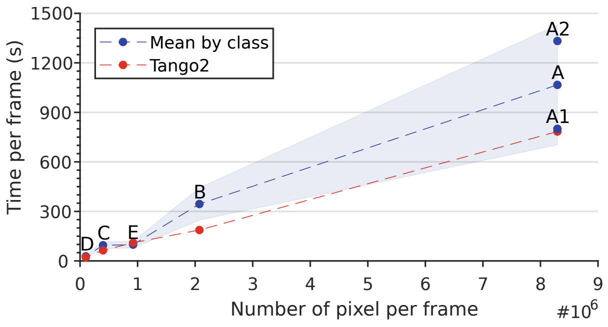


Fig. 3. Encoding time per frame is seconds according to the number of pixels per frame for each class and Tango2 downscaled encodings.

As presented in Section II-A, MTS process included since the first version of VTM brings a significant complexity increase. To the best of our knowledge, no solution have been proposed to reduce the complexity of the MTS process. Finally, a first method [18] implemented in VTM2.0 proposes early termination of QT plus MTT partitioning and intra mode prediction to skip unnecessary partition and intra modes. The proposed method obtains 63% complexity reduction at the expense of +1.93% BD-BR loss.

III. COMPLEXITY OVERVIEW

Complexity reduction is a key aspect on VTM. Complementary to State-of-the-Art complexity reduction techniques introduced in the previous section, we present in this paper a characterization and evaluation of the encoding complexity of VTM encoder. This work is organized following a hierarchical approach, from a parameters level with encoding parameters, to algorithmic encoding level including CTU partitioning, intra mode prediction and MTS process.

A. Experimental setup

The following experiments are performed on VTM3.0 in AI configuration under the JVET CTC [19]. CTC are defined by JVET to conduct experiments in a well-defined environment. 22 different sequences are used for the experiments, which are belonging to the 5 classes A (3840×2160), B (1920×1080), C (832×480), D (416×240) and E (1280×720), each one differ broadly from one another in terms of frame rate, bit depth, motion, texture and spatial resolution. Class A is divided in two sub-classes A1 and A2. Each video sequences is encoded at four QP values 22, 27, 32 and 37. All encodings are carried out sequentially on Intel Xeon E5-2603 v4 processors running the Ubuntu 16.04.5 operating system. The following sections present the impact of two encoding parameters: video resolution and QP.

B. Complexity analysis on video resolution

Resolution and frame rate have an impact on the complexity consumption of the encoding process. Indeed, as VTM encoder applies the same process on each CTU, the encoding complexity is directly linked to the number of CTUs and consequently to the resolution and to the frame rate of the encoded sequence. Fig. 3 displays the average encoding time per frame in second according to the number of pixel per frame. The average encoding time per frame is plotted in blue for the the different CTC classes (detailed in Section III-A). Blue area represents the standard deviation of the results across the different sequences of the same class. In addition, the red line shows the average encoding time per frame of the *Tango2* sequence which was downscaled in all CTC resolution by the Fast Forward MPEG (FFmpeg) downscale tool using the default bilinear filter. *Tango2* video is chosen due to the proximity of *Tango2* average time per frame with the average time per frame of its class A1. Due to high resolution difference, the average time per frame goes from 28s to 1067s for class D and A, respectively. Figure 3 shows that the complexity of VTM encoder increases with the number of pixels per frame excepted for sequence of class E. Sequences from class E have specific content (screen content) properties such as fixed unified background that explains the irregularity. Indeed, averages encoding times per frame of downscaling *Tango2* sequences (in red on Fig. 3) show that for the same video content, the complexity increases linearly with the number of pixels per frame.

However, the high standard deviation, included between 19% and 34% relatively of the average, highlights that the encoding complexity is highly link to the video content. VTM encoder includes early termination methods in the RDO process which are content dependent. One of these methods compares the RD-cost of the unsplit CU with the accumulated RD-cost of sub-CUs to stop the partitioning process when the accumulated cost becomes higher than the one of the unsplit CU. These complexity reduction methods explain the non stability of encoding complexity across different sequence which differ in terms of video content. High complexity difference in the same resolution is further shown by the two sub-classes A, with the difference of 532s between average time per frame for class A1 and A2.

C. Complexity analysis on QP

As explained in Section II-A, the QP is used both in the RD-cost calculation and in the quantification step of the encoding process. Fig. 4 illustrates the average encoding time in second per CTU per class as a function of QP. The results show that the encoding complexity decreases as QP increases for all classes. For example, for class B, QP 22 has an encoding time per CTU of 4.75s and QP 37 has an encoding time per CTU of 1.02s. This is mainly due to the fact that an encoding with higher QP quantizes data more aggressively, leading to a larger number of zero coefficients after quantization.

The results of Fig. 4 also show that the complexity reduction due to QP do not have the same ratio according to the class and thus the resolution. When dividing the time per CTU of QP 22 by QP 37, the factors are 7.61 and 2.24 for class A and D, respectively. The higher the resolution, the greater the factor of encoding times per CTU between QP values. This can be explained by the complexity reduction techniques mentioned in the Section III-B. Indeed, according to Equation 1, when a sequence is encoded with high QP, more weight is assigned to rate which leads the encoder to select larger blocks. The early termination methods included in VTM are more likely to stop the partitioning process earlier for high QP, this tends to reduce complexity further. This observation also explain why the encoding time per CTU is lower for class E. These sequences have fixed unified background which leads the encoder to select larger blocks.

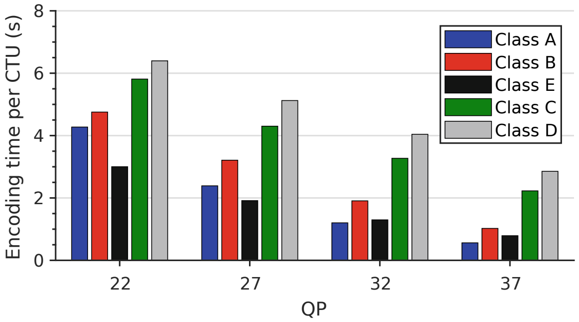


Fig. 4. Average encoding time per CTU in second according to QP for each class.

As a first conclusion, the encoding parameters analysis shows that the complexity of a video encoding grows with the frame rate, the resolution and the QP value. However, high standard deviations and non linear increase shown by Fig. 3 highlight that encoding complexity is content dependent. In the next section, we analyze the complexity impact of the algorithmic encoding level.

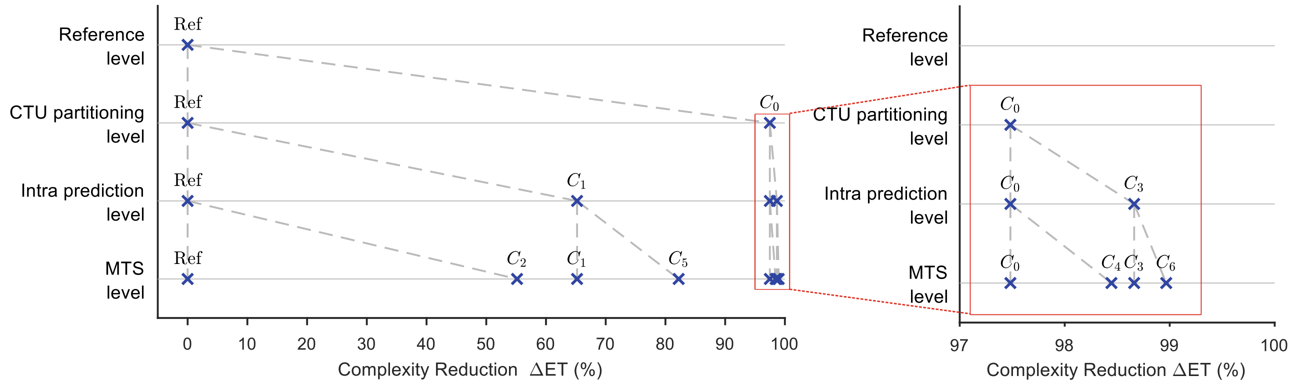
IV. COMPLEXITY OPPORTUNITIES OF THE VTM ENCODER

In VTM encoder, exhaustive RDO search that leads to the minimal RD-cost is performed on three nested levels: CTU partitioning, intra mode prediction and MTS process. As described in Section II-B, complexity reduction techniques commonly reduce the number of tested configurations while trying to limit the degradation of the RD-cost. The next section determines the complexity reduction opportunities on the three nested levels.

A. Determination of the complexity reduction opportunities

In this this work, we define the complexity reduction opportunities for the three algorithmic encoding levels of the RDO process: CTU partitioning level, intra mode prediction level and MTS level. The theoretical complexity reduction opportunity is obtained when the encoder is able to predict perfectly the best configuration and thus only this configuration is considered to encode the CTUs. Therefore, for a given level, the complexity of the search process is reduced to the minimal complexity consumption for the exact same encoding performance. This encoding complexity sets the theoretical complexity reduction opportunities of the according level.

We define *optimal configurations* of CTU partitioning, intra mode prediction and MTS process to be the configurations



(a) (b)

Fig. 5. Complexity reduction (ΔET) normalized by R for all configurations. (a) Results from 0% to 100%. (b) Focus between 97% and 100%.

that are selected during the RDO process minimizing the RD-cost. To determine the complexity reduction opportunities, a two-pass encoding is carried-out. The first pass is unconstrained, i.e. an exhaustive RDO search is processed, and the optimal configurations of the three levels are extracted. The second encoding pass uses these previous extracted optimal configurations to force the RDO process to encode only these configurations and thus remove unnecessary complexity. The encodings resulting of these two-pass are identical in term of both bit-rate and distortion, only the encoding complexity differs. Finally, the complexity reduction opportunities are defined by the difference of encoding complexity Δ Encoding Time (ΔET) between these both encodings averaged by the four QP. ΔET is defined by Equation 2

$$\Delta ET = \frac{1}{4} \sum_{QP_i \in \{22,27,32,37\}} \frac{T_R(QP_i) - T_C(QP_i)}{T_R(QP_i)}, \qquad (2)$$

with T_R the reference encoding time of the anchor VTM3.0 encoder and T_C the encoding complexity reduction time of the VTM forced to only encode the optimal configurations.

B. Analysis of complexity reduction opportunities

Table I presents all configurations which define the complexity reduction opportunities according to the three levels defined in Section IV-A. Each level of the RDO process offering complexity reduction opportunities independently, 7 configurations are defined in Table I with the corresponding labels. For each configuration, the exhaustive search is enabled (E) or disabled (D). When the exhaustive search is disabled at one level, only the optimal configurations of this level are performed. Following the Equation 2, Ref represents the reference encoding complexity (exhaustive search) that is used as reference encoding time T_R to compute the complexity reduction ΔET. C_0, C_1 and C_2 are the complexity reduction opportunities of the CTU partitioning, intra mode prediction and MTS levels, respectively. The other configurations are combinations of the previous ones.

TABLE I
CONFIGURATIONS DESCRIPTION WITH THE CORRESPONDING LABELS.

	Configuration							
Level	Ref	C_0	C_1	C_2	C_3	C_4	C_5	C_6
CTU partitioning	D	E	D	D	E	E	D	E
Intra mode prediction	D	D	E	D	E	D	E	E
MTS process	D	D	D	E	D	E	E	E
ΔET (%)	0	97.03	64.32	53.64	98.31	98.01	81.28	98.67

D: Disable, E: Enable.

Fig. 5(a) shows complexity reduction of the different configurations presented in Table I organized following the three nested levels. The experimental setup is described in Section III-A. The results are the complexity reduction ΔET computed by the Equation 2 average on the 22 sequences. The complexity reduction are computed based on the reference Ref and as explained in the previous section, encodings of all configurations are identical in term of both bit-rate and distortion, i.e BD-BRs difference between the reference and the other configurations are equal to 0. Fig. 5(b) focuses on the results between 97% and 100% of Fig. 5(a) as the points are too close to be distinguished. The average standard deviation of the results presented in Fig. 5(a) and (b) is equal to 2.11% (with a maximum of 4.89%) which confirms that the average results across QP and classes are representative. To interpret the following results, it is important to notice that the experiments are performed under the VVC reference software VTM3.0, which is not implemented to be a practical real-time encoder.

As shown by the C_0 point on Fig. 5(a), restraining the encoder to process only the optimal configuration for the CTU partitioning level offers the best complexity reduction opportunity among the three levels, until 98.7%. In other words, being able to perfectly predict the CTU partitioning without testing the unnecessary splits would reduce the encoding complexity at 2% of the reference encoding time. This result is due to the multitude of partitioning possibilities introduced in VTM, including QT, BT and TT, as described in Section II-A.

The RDO process, including the search of intra mode and transform, is applied for each CU. Reducing the number of intra modes tested by the RDO process for all CUs offers a complexity reduction opportunity of 64.3% compared to the reference encoding time, as presented by the C_1 point on Fig. 5(a). The amount of intra prediction modes is considerably increased in VTM compared to HEVC, up to 67 modes by CU, which increases the encoding complexity of this process. Finally, reducing the complexity of the MTS process enables a complexity reduction opportunity of 53.6% when the optimal horizontal and vertical transforms can be predicted for all TUs. The MTS introduced in VTM tests several transform for each TU that significantly increases the encoding complexity.

The three levels being nested but independent, processing only the optimal configurations of multiple levels simultaneously is possible. Reducing the complexity of multiple levels is interesting as it was previously done on several works in HEVC [10], [11]. As shown by the C_5 point on Fig. 5(a), combining complexity reduction of the intra mode prediction and MTS offers a complexity reduction opportunity up to 82.21%. This result matches with the complexity reduction opportunity of the intra prediction and MTS level $(65.2\% + (100\% - 65.2\%) \times 55.16\% = 84.40\% \approx 82.21\%)$. As shown in Fig. 5(b) with the C_3, C_4 and C_6 points, when intra prediction and MTS levels are combined with the CTU partitioning level, the complexity reduction opportunities are not much higher than the complexity reduction opportunity of the CTU partitioning level (less than 2% of difference). Indeed, if the CTU partitioning is predicted perfectly, the complexity used by the RDO process to select the intra prediction mode and transform is very low as the RDO process is only done on the selected CUs.

From this analysis, considering the current version of VTM3.0, we can conclude that the complexity reduction issue can be more efficiently addresses by reducing the complexity of the CTU partitioning process rather than the intra mode prediction or MTS process. Furthermore, knowing the theoretical maximum complexity reduction of the different algorithmic encoding levels of VVC encoding process may help to better evaluate current and future complexity reduction techniques. To illustrate that, a method that will offers 50% complexity reduction reducing the MTS process have almost reach the maximum opportunities. Instead, having the same result on the CTU partitioning represent the half complexity opportunities.

V. CONCLUSION

Complementary to State-of-the-Art complexity reduction techniques, this paper proposes an analysis of complexity reduction opportunities of VVC encoding process by considering a hierarchical approach, from encoding parameters to algorithmic encoding level. This study demonstrates at the parameters level, that the complexity of VTM encoding is proportional to video resolution and QP. At the algorithmic encoding level, the CTU partitioning level has a potential of complexity reduction up to 98% whereas the intra mode prediction and MTS levels offers at best 64% and 54% of complexity reduction, respectively. The main contribution of this paper is to allow a better comparison and evaluation of current and future complexity reduction techniques of VVC encoding for AI configuration.

Future works will extend this study and evaluate the complexity reduction opportunities of the RA configuration. Moreover, the results of this study will be used to guide and evaluate our future complexity reduction techniques of VVC encoding process.

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