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Statistical analysis of inter coding in VVC Test Model (VTM)

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Abstract—The promising improvement in compression efficiency of Versatile Video Coding (VVC) compared to High Efficiency Video Coding (HEVC) [1] comes at the cost of a non-negligible encoder side complexity. The largely increased complexity overhead is a possible obstacle towards its industrial implementation. Many papers have proposed acceleration methods for VVC. Still, a better understanding of VVC complexity, especially related to new partitions and coding tools, is desirable to help the design of new and better acceleration methods. For this purpose, statistical analyses have been conducted, with a focus on Coding Unit (CU) sizes and inter coding modes.

Index Terms—Versatile Video Coding, Inter Coding, Rate Distortion Optimization, Complexity Analysis

I. INTRODUCTION

Standardization of VVC in 2020 has brought significant improvement to the capacity of video compression in terms of bitrate saving. It offers the 50% compression efficiency [2] compared to one of the most efficient video compression standards HEVC. This improvement in VVC is mainly due to newly adopted coding techniques. Most decoder devices could afford the additional complexity brought by these novel coding techniques taking into account current hardware capacities of these devices. Specifically, studies in [3] have shown that the relative complexity of the decoder of VVC is from 150% to 200% compared to HEVC in different configurations.

On the contrary, it is far from affordable for real time application for VVC encoder side since industrial encoding applications have strict limitations in terms of resources and execution time. Tests in [4] in VVC reference software VVC Test Model (VTM) 7 show that the encoding time of VVC is 5x, 7x, and 37x times of the encoding of HEVC in the configurations Low-Delay (LD), Random-Access (RA), and All-Intra (AI), respectively. Hence, it is vital to develop acceleration algorithms or methods to largely reduce the encoding complexity while preserving the majority of encoding efficiency. Complexity analysis papers could help researchers to have a clear understanding of what is happening inside a VVC encoder (*e.g.* VTM), and what potentially interests them for their design process of the acceleration method.

Various studies have contributed to the complexity analysis of VVC. In [5], a detailed complexity analysis based on VVC intra prediction tools has been performed. Pakdaman *et al.* in [3] have broken down the encoding process into encoding modules such as motion estimation, intra prediction, entropy coding, etc. and then analyzed the complexity

partition of modules in multiple encoding configurations. [6] reviews complexity aspects of the different modules of the VVC standard and provide a complexity breakdown of these modules in a more precise way. In [4], VVC and HEVC are compared in terms of rate-distortion and complexity analysis. These aforementioned papers present complexity analysis at the level of encoding modules for inter coding. Our paper is the first to provide an analysis from CU sizes and coding modes perspective for inter coding in VVC.

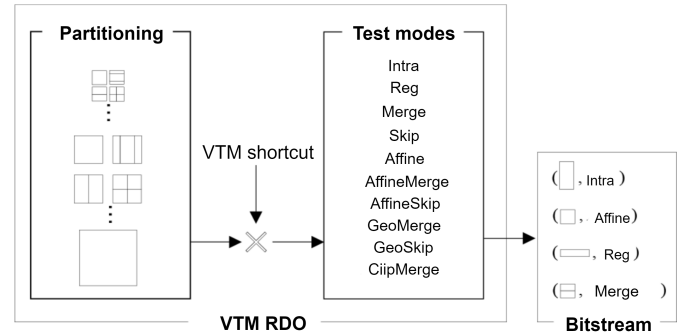


Fig. 1. High-level view of the RDO process involving partitioning, test modes and possible VTM shortcuts.

In this paper, a statistical analysis of the Rate-Distortion Optimization (RDO) process in inter coding of VTM-15.0 is presented. The main focus is put on the statistics of two factors: CU sizes and inter coding modes. The goal is to provide useful information for related works aimed at speeding up inter coding in VVC. The rest of this paper is organized as follows. Section II presents a summary of VVC specification in terms of CU sizes and available coding modes. In Section III, all statistical observations are presented, which are later analyzed and concluded in Section IV.

II. RDO OF INTER CODING IN VTM

To represent the RDO process in VTM, there exist numerous coding parameters such as Intra Prediction Mode (IPM) of intra coding, Motion Vector (MV) representation mode, choice of transform *etc.*. However, if we ignore these trivial parameters, the RDO process could be described as the search for the best trade-off between bit rate and distortion. More precisely, this search is executed on different coding modes of different

CU sizes. Therefore, in this paper, the statistics of CU sizes and coding modes are jointly considered.

As presented in Fig.1, various CU sizes are the result of partitioning in the RDO process. The partitioning consists of splitting the CU of size 128×128 recursively by five split modes, namely Quaternary Tree (QT) split, Horizontal Binary Tree (HBT) split, Vertical Binary Tree (VBT) split, Horizontal Ternary Tree (HTT) split, Vertical Ternary Tree (VTT) split. Compared to codec HEVC in which only QT is available for partitioning, the added directional splits give rise to a larger variety of CU sizes. In VVC CU size is authorised if its widths and heights are any power of two between 4 and 128, except for sizes 128×4 , 128×8 , 128×16 and 128×32 . It is worth noting that the same CU size could be obtained by different series of split modes.

For each CU, 12 coding modes are available. Two of these modes, namely hash-based inter prediction and palette modes are not enabled in JVET Common Test Condition (CTC). Hence, they are not included in the analysis of this paper. In the inter prediction of VVC, motion compensation is executed after motion estimation. Subsequently, the residuals and MV information need to be transmitted. Depending on the transmission of MV and residuals, three coding modes are available: Advanced Motion Vector Prediction (AMVP)[7] mode, *Merge* mode, and *Skip* mode. For the purpose of simplification, we refer to AMVP as *Reg* mode for the remainder of the paper. Before transmitting MVs, a candidate list of MVs is constructed based on the spatial and temporal neighboring CUs by exploiting the correlations of MVs between them. Four types of inter prediction data can be signaled, including the index of reference frame (*i.e.* Ref Frame Idx), the index of the best MV candidate (*i.e.* MV Cand Idx), the difference between the best candidate and MV determined by motion estimation (*i.e.* Motion Vector Difference (MVD)), and residuals. Tab.I presents the signaled data types for *Reg*, *Merge* and *Skip*.

TABLE I
DATA TYPES TO TRANSMIT FOR MOTION DATA CODING

	Ref Frame Idx	MV Cand Idx	MVD	Residuals
<i>Reg</i>	✓	✓	✓	✓
<i>Merge</i>	X	✓	X	✓
<i>Skip</i>	X	✓	X	X

In addition to the *Affine* mode and the *Intra* mode, two novel coding modes are available in VVC. For CUs coded in merge mode, Combined Intra-Inter Prediction (CIIP)[8] combines the inter prediction and the intra prediction to form a final prediction. The Geometric Partitioning Mode, denoted as *Geo*, is designed to better predict moving objects in video. Additionally, *Geo* is conventionally coded with *Merge* mode. For inter coding configuration, coding modes of *Reg*, *Merge* and *Skip* could combine with *Affine*, *CIIP*, and *Geo*, which results in a total of 10 coding modes: *Intra*, *Reg*, *Merge*, *Skip*, *Affine*, *AffineMerge*, *AffineSkip*, *GeoMerge*, *GeoSkip*, *CiipMerge*. Statistics of these coding modes are further collected and analyzed in the following part.

Although VVC is computationally expensive, the Joint Video Exploration Team (JVET) group has already adopted various shortcuts or conditional early exits as presented in [9] for the VTM. We have deactivated existing shortcuts in VTM-15.0 and evaluated its performance. As a result, the complexity increases by 138%. Furthermore, the performance of the tested encoder (*i.e.* without shortcuts) is 0.76% better than the reference encoder (*i.e.* with shortcuts), in terms of BD-rate. This trade-off might be interpreted as an indicator that the shortcuts in VTM are efficient in terms of identifying useless tests and partitioning depths. Many of shortcuts are based on history of the tested split modes. However, aspects of CU sizes and coding modes are overlooked.

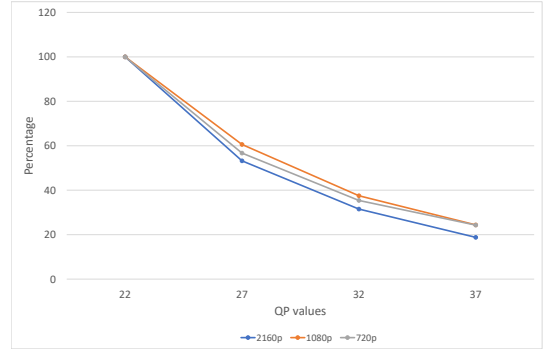


Fig. 2. Encoding time in different QPs comparing to QP 22

III. STATISTICS

Our main purpose in the following analysis is to find CU sizes and/or coding modes with a relatively high complexity occupation and a low selection rate in the RDO process. From the perspective of encoder acceleration, CU sizes or coding modes with a higher complexity portion and a significantly lower selection rate are more favorable to the design of acceleration rules based on CU size/coding mode. The size or mode with larger complexity portion has more potential in accelerating. Lower selection rate indicates it is less likely to make wrong decisions when skipping the RDO of current CU size or mode.

All our experiments and analyses are performed on the first 64 frames of the CTC sequences in the RandomAccess Group Of Picture 32 (RAGOP32) configuration in which intra frames are excluded. Exceptionally, Fig.2 is based on sequences in Class A, B, E of CTC.

The encoding complexity for Chrominance channel only accounts for a small part comparing to Luminance channel. Thus we focus on Luminance channel in the remaining of the paper. From a high-level perspective, the encoding complexity of VTM significantly depends on the selected Quantization Parameter (QP). Particularly, larger QP values tend to have faster encoding with the VTM. Fig. 2 is obtained by measuring the encoding times of sequences of resolution 2160p, 1080p and 720p in QP 22, 27, 32 and 37. Then the average ratio is calculated between the encoding time of each QP and that of

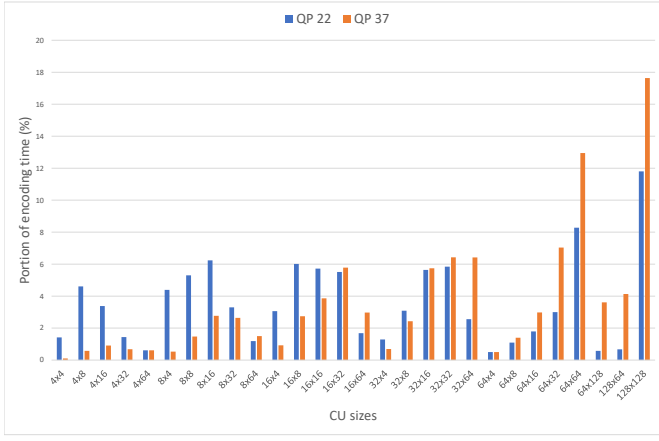


Fig. 3. Complexity distribution for CU sizes in QP22 and QP37

QP 22 is calculated. It shows that the encoding time at QP 22 could be five times as much as at QP 37.

Fig.3 shows the percentage distribution of the encoding time spent on different CU sizes in QP 22 and QP 37. In addition to the fact that the overall encoding time is higher for QP 22, it can be observed that a relatively higher portion of the time in QP 22 is passed on smaller CU sizes. This could be partly explained by the existing shortcuts in VTM disallowing excessively small CUs in QP 37. We could declare that larger CU sizes are in general more crucial to speeding up the partitioning process, especially CU 64×64 and 128×128 which take in total from 20% complexity in QP 22 to 30% in QP 37.

In another test, the selection percentages of different CU sizes are calculated. This metric is defined as the ratio between the total number of times it is selected and the total number of times a CU size is tested. Fig. 4 shows the values of this metric in QP 22 and 37. As we can see from this figure, larger CU sizes correspond to larger selection rates compared with smaller CUs. Another phenomenon worth noting is that the selection rate of 128×128 increase dramatically from 14% in QP 22 to 37% in QP 37.

QP 22							QP 37						
H\W	4	8	16	32	64	128	H\W	4	8	16	32	64	128
4	0.25	0.4	0.49	0.4	0.27	NA	4	0.25	0.29	0.42	0.38	0.14	NA
8	0.5	1	0.84	0.86	0.64	NA	8	0.35	0.61	0.7	0.8	1.35	NA
16	0.77	1.15	1.64	1.58	2.21	NA	16	0.68	0.97	1.31	1.33	4.96	NA
32	0.78	1.48	2.03	3.91	4.64	NA	32	0.73	1.47	1.67	3.11	4.24	NA
64	0.48	0.9	1.71	3.89	11	5.61	64	0.47	1.49	2.73	3.84	8.5	4.51
128	NA	NA	NA	NA	5.87	15.73	128	NA	NA	NA	NA	5.25	41.5

Fig. 4. Selection rate for different CU sizes

Combining the above figures, it is observed that CU sizes such as 16×8 , 8×16 and 16×16 are sizes with low selection rate and high complexity. For example, 16×16 CUs have the same level of complexity, while its selection rate is half of 32×32 CUs in QP 22.

To take one step further in the statistical analysis of inter coding, we present how different inter coding modes are involved in RDO search. The first experiment in Fig.5 presents

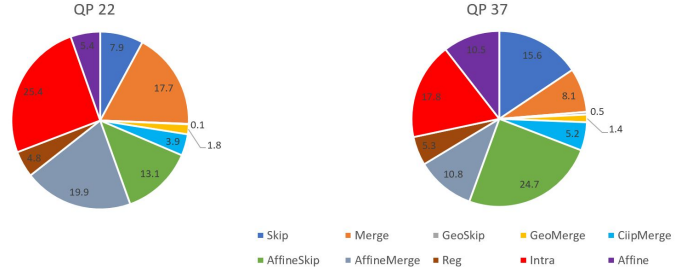


Fig. 5. Pie chart of complexities of inter coding modes

the distribution of the encoding time at inter coding mode level in QP 22 and QP 37.

In general, *Intra*, *AffineMerge*, *AffineSkip*, *Merge*, and *Skip* are main contributors to encoding time. Fig.6 provides selection rates as the ratio between the number of selected inter coding modes and number of tested modes. We could observe that the three modes, namely *AffineMerge*, *AffineSkip*, and *Merge* have relatively low selection rates, although they collectively account for nearly half of the complexity.

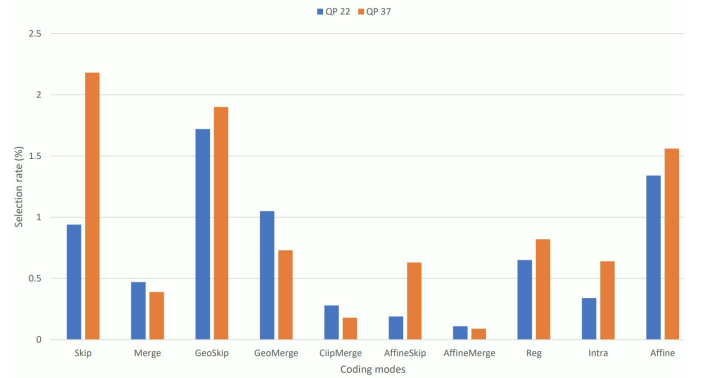


Fig. 6. Selection rate of inter coding modes

Fig.7 shows the distribution of inter modes for encoded CUs of different sizes. The fact that the aforementioned three coding modes are less chosen could also be proved by this figure. We find that the number of *Skip* is dominant for most CU sizes and that the number of these three modes is relatively small, which is consistent with Fig.6. From Fig.7 we also observe that smaller CUs tend to be encoded with intra mode. Another remark is that the skip modes (*i.e.* *Skip*, *AffineSkip*, and *GeoSkip*) are more frequently selected for larger CUs. It is probably because the residual of larger CUs is more expensive to be encoded. In addition, *Merge* mode has a higher chance to be selected in smaller QP which is in contrast to *AffineSkip* and *GeoSkip*. For some CU sizes, we could make shortcuts or conditions for early termination for RDO of inter modes which are rarely selected to speed up the encoding process, such as the *AffineMerge* mode with merely 1.9% selected for CU 128×128 .

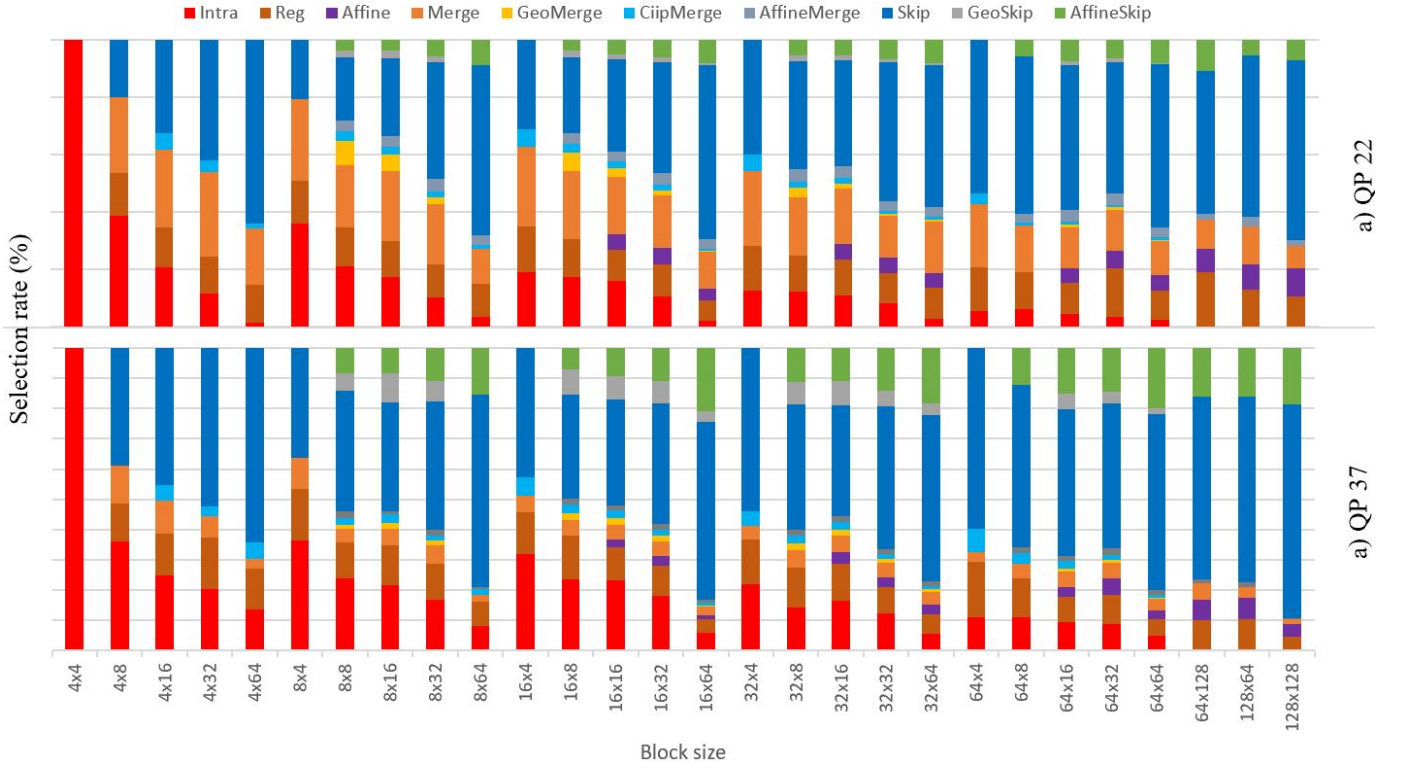


Fig. 7. Stacked chart of selected inter modes in different CU sizes

IV. ANALYSIS AND CONCLUSION

In this study, complexity analysis of CU sizes and inter coding modes has been combined with selection rate analysis. From the perspective of CU size, CU sizes with high complexity generally correspond to a high selection rate. CU sizes 128×128 and 64×64 are responsible for one-third of the complexity. In addition, CU sizes such as 16×8 , 8×16 , 16×16 exhibit relatively low selection rate while requiring a significant share of the overall complexity. Therefore, these CU sizes are relevant targets for acceleration algorithms. From a coding mode perspective, *AffineMerge*, *AffineSkip*, and *Merge* tend to be less likely to be selected. Thus, dedicated shortcuts to adaptively skip these coding modes might be promising. Shortcuts on coding modes and partitioning acceleration method are in different scopes. The former focus on reducing number of CU for RDO. The latter speeds up RDO for CU of certain sizes. The combination of these two could lead to a larger speed-up of encoding.

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