Recurrent Intra Prediction Mode for Future Video Coding

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Abstract

Intra prediction is a crucial component of hybrid video coding framework due to its remarkable ability to reduce spatial redundancy in video signals. Unlike the single-mode based intra prediction in HEVC and VVC, intra fusion prediction methods, that combine the results of multiple angular prediction modes, were newly adopted by Enhanced Compression Model (ECM). However, intra fusion prediction over-relies on local spatial correlations and neglects potential texture similarities in non-adjacent regions. To overcome these limitations and elevate the accuracy of luma intra prediction, a Recurrent Intra Prediction Mode (RIPM) is proposed in this paper, which is composed of two sub-modules, i.e., Recurrent Intra Merge Mode (RIMM) and Recurrent Block Vector Substitution Module (RBVSM). RIMM utilizes the recurrent spatial texture information of the adjacent and non-adjacent spaces for adaptive mode derivation and prediction within the intra fusion prediction framework. RBVSM is a sophisticated mechanism for adaptive prediction mode selection and weight assignment during intra fusion prediction, resulting in enhanced coding performance with minimal impact on computational complexity. The proposed method, implemented on top of ECM-12.0, demonstrates a 0.095% BD-rate gain for the luma component under All Intra configuration, with negligible complexity increase. Currently, RIPM is under study in Exploration Experiments (EE) for ECM in JVET.

1 Introduction

Versatile Video Coding (VVC) [1], finalized in June 2020, is the latest video coding standard developed by the Joint Video Experts Team (JVET), which comprises the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG). VVC significantly improves upon its predecessor, High Efficiency Video Coding (HEVC), by reducing the bit rate by over 50% with the comparative subjective video quality [2]. To further push the boundaries of video compression, JVET introduced the Enhanced Compression Model (ECM) in 2021. The initial version, ECM-1.0, achieved a 12% Bjøntegaard delta rate (BD-rate) [3] saving under Random Access (RA) configuration. As of February 2024, the latest ECM version, ECM-12.0, boasts an even more impressive 24% BD-rate saving compared to the VVC reference software, i.e., VTM-11.0 [4].

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Intra prediction is a crucial component in the conventional video coding framework which aims at reducing spatial redundancy within a frame. The luma intra prediction in ECM builds upon that in VVC, such as the 65 intra angular modes, Wide Angular Intra Prediction (WAIP) [5], Intra Sub-Partition (ISP) [6], and Matrix-based Intra Prediction (MIP) [7]. ECM enhances these existing tools and brings in new intra coding methods. Notably, ECM expands the Most Probable Modes (MPMs) list from 6 to 23 angular modes [8]. Additionally, ECM refines the Multiple Reference Line (MRL) [9], enabling more precise prediction based on multiple reference samples. It also introduces novel methods such as the Extrapolation Filter-based Intra Prediction Mode (EIP) [10] for improved prediction accuracy, along with Intra Template Matching Prediction (IntraTMP) [11] which reuses similar recontructed area within a frame for more efficient prediction.

Moreover, ECM adopts several intra fusion prediction-based methods that combine multiple angle prediction results into a final prediction, contrasting with the single-mode based intra prediction mentioned above. Intra fusion prediction plays an important role in ECM, improving the compression efficiency of both luma and chroma components. Decoder-side Intra Mode Derivation (DIMD) [12] and Template-based Intra Mode Derivation (TIMD) [13] are representative intra fusion tools. DIMD models the gradient directions in the reconstructed areas adjacent to the current block and maps these gradients to intra angular modes. The most likely modes are selected, and the prediction process fuses results from multiple modes to obtain the final prediction result. TIMD follows a similar approach, deriving optimal intra angular modes for neighboring areas based on template loss analysis and predicting the coding block using intra fusion prediction. However, both DIMD and TIMD rely heavily on texture similarity in neighboring spatial regions, overlooking valuable spatial information from non-neighboring regions. This significantly limits the potential for improvement of these coding tools. While new tools offer potential benefits, the increased number of intra coding tools introduces additional coding overhead, which offsets the accuracy gains they provide.

To overcome the limitations of existing intra prediction methods, this paper proposes the Recurrent Intra Prediction Mode (RIPM) [14], inspired by both IntraTMP and intra fusion prediction techniques. The proposed method includes two submodules: Recurrent Intra Merge Mode (RIMM) and Recurrent Block Vector Substitution Module (RBVSM). RIMM reuses the intra modes that have been derived from the reconstruction blocks using DIMD and TIMD through a wide-area sampling strategy combined with template loss analysis to enable reference-based prediction of recurrent textures in the spatial domain. In conjunction with RIMM, RBVSM further enhances RIMM by replicating block vector modes and adaptively substituting intra-angular modes, leveraging non-adjacent spatial information without introducing additional coding overhead. Implemented on top of ECM-12.0 [15], the proposed method achieves 0.095% BD-rate gain on the Y-component under All Intra configuration, with minor complexity change. Currently, RIPM is under study in Exploration Experiment (EE) for ECM in JVET.

This paper is organized as follows: Section 2 reviews DIMD, TIMD, and IntraTMP in ECM. Section 3 details RIMM and RBVSM. Section 4 discusses experimental

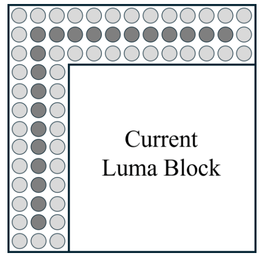

Figure 1: Illustration of DIMD. The 3×3 sobel filter is applied to the second adjacent row and column of the current luma block.

results, and Section 5 concludes the paper.

2 Related Coding Tools in ECM

This section provides an overview of the existing intra coding tools in ECM that are related to the proposed method. Specifically, we will introduce and discuss DIMD, TIMD, and IntraTMP.

2.1 Decoder-side Intra Mode Derivation

The DIMD is conducted based on the gradient information extracted from a predefined template area with Sobel gradient operator [16]. As shown in Fig. 1, the template area comprises 3 adjacent rows and columns surrounding the current block. Gradient information within the template area is extracted using a 3×3 sliding window. Within each window, the horizontal gradient G_{hor} and the vertical gradient G_{ver} are calculated using a 3×3 horizontal Sobel filter F_{hor} and a 3×3 vertical Sobel filter F_{ver}, respectively. The F_{hor} and F_{ver} are shown as follows,

$$F_{hor} = \begin{bmatrix} 1 & 0 & -1 \\ 2 & 0 & -2 \\ 1 & 0 & -1 \end{bmatrix}, \tag{1}$$

$$F_{ver} = \begin{bmatrix} -1 & -2 & -1 \\ 0 & 0 & 0 \\ 1 & 2 & 1 \end{bmatrix}. \tag{2}$$

The gradient angle θ of each sliding window is then computed by,

$$\theta = \arctan\left(\frac{G_{ver}}{G_{hor}}\right). \tag{3}$$

The gradient amplitude G is calculated as follows,

$$G = |G_{hor}| + |G_{ver}|. \tag{4}$$

To derive the most probable intra angular modes for each coding block, a Histogram of Gradients (HoG) is maintained. To construct the HoG, an angular mode, i.e., x-axis of the HoG, is first derived for each sliding window based on the predefined relationship between θ and 65 angular modes in ECM. If both G_{hor} and G_{ver} are 0, the angle θ is mapped to the planar mode. The y-axis is the accumulated amplitude G corresponding to the angular mode. For the angular mode a, we can use G_a to

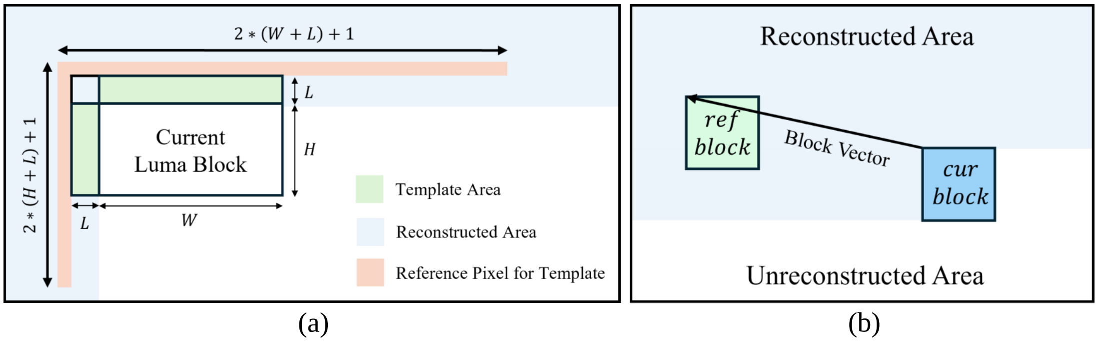

Figure 2: Illustration of (a) TIMD; (b) IntraTMP.

represent its accumulated amplitude. After the HoG is built, up to five intra angular modes with the highest amplitudes are selected for the intra-fusion prediction phase in DIMD.

The final prediction for the luma block is obtained by the weighted fusion of predicted luma blocks using the selected intra modes, which is calculated by,

$$p(x,y) = \sum_{m \in \mathcal{M}} p_m(x,y) \times w_m, \tag{5}$$

where $p(x,y)$ is the ultimate prediction result located at (x,y) of the current block, $\mathcal{M}$ is the set of selected intra modes, $p_m(x,y)$ is the prediction result of intra angular mode m, and w_m is the calculated weight for intra angular mode m. The weight of planar mode is fixed to $1/4$. For other intra angular modes in $\mathcal{M}$, the weight w_m for mode m is proportional to the corresponding amplitude in the histogram of gradient, which can be calculated by,

$$w_m = \frac{3}{4} \times \frac{G_m}{\sum_{r \in \mathcal{R}} G_r}, \tag{6}$$

where $\sum_{r \in \mathcal{R}} G_r$ is the sum of the amplitude of the selected intra angular modes in $\mathcal{M}$ except for planar mode.

2.2 Template-based Intra Mode Derivation

In ECM, when a coding block selects TIMD as the prediction method, the template area is first predicted using the intra angular mode in the MPMs list, as illustrated in Fig. 2(a). Subsequently, the loss between predicted and reconstructed pixel values within the template region is calculated by the Sum of Absolute Transform Differences (SATD), a process referred to as template loss analysis. The intra angular mode with the lowest template loss is then selected for prediction. If the loss associated with the second-best intra angular mode is less than twice that of the best mode, both modes are utilized for TIMD prediction; otherwise, only the mode with the smallest loss is chosen. Furthermore, template loss analysis is performed to determine whether Planar or DC modes should be included as extra intra modes for TIMD. The weight w_σ assigned to the intra mode σ involved in TIMD is inversely proportional to their corresponding template losses, which can be calculated by,

$$w_\sigma = \frac{\sum_{t\in\mathcal{T}} L_t}{(\mathcal{N}_\mathcal{S} - 1) \times \sum_{s\in S} L_s}, \tag{7}$$

where S is the set of selected intra modes, $\mathcal{T}$ is the set $\mathcal{S}$ without intra mode σ, L_t and L_s represent the template loss of corresponding intra angular mode, and $\mathcal{N}_S$ is the number of intra angular mode in set S. Finally, the prediction for the current coding block is calculated using Eqn. (5), after obtaining each prediction result of the selected intra modes.

2.3 Intra Template Matching Prediction

IntraTMP extends the concept of template matching from inter prediction to intra prediction. It operates by first establishing a designated search area within the reconstructed region. The luma block, employing a Γ-shaped template, scans the area to identify a reference block whose template exhibits the highest similarity. The displacement coordinates of the optimal reference block are then stored for later use. During the prediction phase, the pixel values of the luma block are reconstructed by replicating those from the reference block, as determined by the stored block vectors.. This process effectively leverages the spatial correlations to achieve a high-quality prediction of the luma block, as demonstrated in Fig. 2(b).

3 The Proposed Recurrent Intra Prediction Mode

In this section, we provide the details of the proposed RIPM, which has two submodules, i.e., RIMM and RBVSM. The RIMM module improves prediction accuracy by incorporating the spatial textual information from both neighboring and non-neighboring area. RBVSM further refines the prediction by adaptively substituting intra angular modes with block vector modes based on a comprehensive analysis of template loss.

3.1 Recurrent Intra Merge Mode

Inspired by the existing intra fusion prediction techniques and the IntraTMP method, we introduce RIMM as a novel solution to address the underutilization of non-adjacent spatial information in luma intra prediction. Similar to DIMD and TIMD, RIMM employs a template-based approach for intra angular mode derivation, designed to mitigate the computational overhead associated with the explicit coding of individual intra modes. Unlike the DIMD and TIMD based solely on texture similarity between the coded block and its adjacent neighbors, the RIMM extends this approach by recognizing that similar reference blocks with high texture correlation may also reside in non-adjacent spaces. By traversing both adjacent and non-adjacent spatial areas, RIMM leverages block-level texture similarity to identify and reuse an optimal set of angular modes.

In the RIMM framework, a sampling operation is performed to obtain the intra mode group z from both proximity and non-proximity spatial regions. Suppose the reconstructed coding blocks at a sampling point utilize DIMD, TIMD, or RIMM as the prediction mode. In that case, the RIMM records the intra mode group z

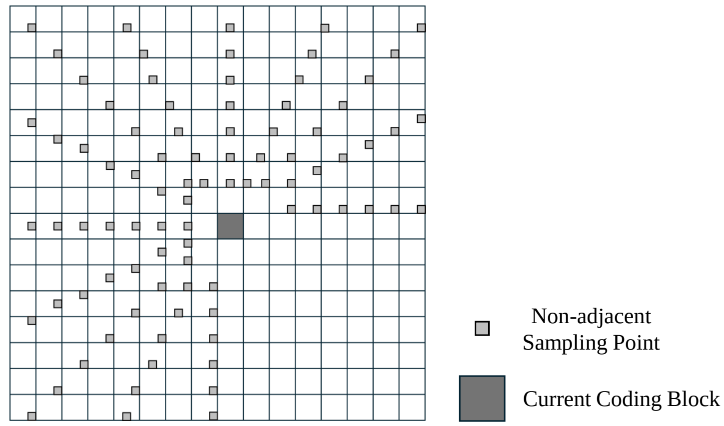

Figure 3: Enhanced sampling strategy of RIMM in non-adjacent area.

derived from those blocks, along with their corresponding weights, into a designated intra merge list $\mathcal{Z}$. The sampling points consist of 13 adjacent and 87 non-adjacent locations, as illustrated in Fig. 3. Moreover, dereplication strategies are applied to ensure that each intra mode group z in the intra merge list $\mathcal{Z}$ is distinct.

With the derived intra merge list $\mathcal{Z}$, the template loss of each intra angular mode in each z is calculated using the same method in TIMD. Subsequently, the overall loss $\mathcal{L}$ of each intra mode group z in the list $\mathcal{Z}$ is systematically calculated by,

$$\mathcal{L}_z = \sum_{i \in z} L_i \times w_i, \tag{8}$$

where L_i represents the template loss of intra angular mode i in the intra mode group z, and w_i denotes the corresponding weight. The intra mode group with the lowest total template loss is then strategically selected for use in RIMM. It is crucial to note that this selected intra mode group encapsulates not only the intra angular modes but also their associated weight values. Additionally, for luma block prediction, RIMM follows the intra fusion prediction strategy previously implemented in DIMD and TIMD. Moreover, a coding unit level flag is utilized to denote whether RIPM is used.

3.2 Recurrent Block Vector Substitution Module

While the RIMM technique effectively leverages the high texture similarity in both proximal and non-proximal spatial domains to enhance coded block prediction, the direct reuse of intra angular modes can lead to suboptimal prediction accuracy. This limitation stems from the potential misalignment between certain block gradients and the intra-angular modes used during prediction. To address this issue, we introduce an RBVSM mechanism, built upon RIMM module, to refine the intra angular modes utilized in prediction, thereby enhancing overall prediction performance.

Once RIMM determines an intra mode group, RBVSM initially samples from both proximity and non-proximity spatial regions. If the coding block at a sampling point utilizes Intra Block Copy (IBC) [17] or IntraTMP for prediction, the corresponding block vector is extracted and added to the list. The distribution of sampling points follows the same pattern used by RIMM for intra mode group extraction, as shown

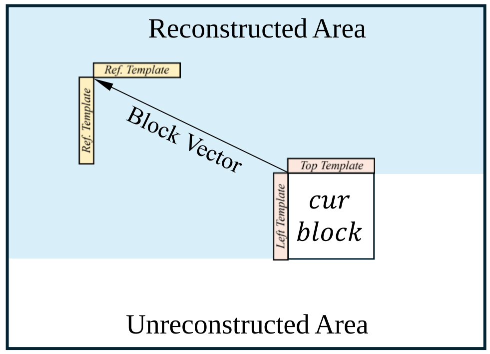

Figure 4: Illustration of template prediction. The template of the current coding block is predicted by the reference template.

in Fig. 3. After sampling is completed, each block vector mode in the list undergoes individual template prediction, with the SATD computed between the predicted and reconstructed values. Block vector based template prediction, illustrated in Fig. 4, primarily involves copying the pixels from the reference block template region to the current block template region for prediction.

As shown in Section 3.1, the RIMM calculates the template loss for all included intra angular modes within the selected intra mode group. Based on the template loss analysis, RBVSM replaces the intra angular modes with recurrent block vector modes, while preserving the mode weights within the intra mode group during the substitution process. Subsequent to the RBVSM's mode replacement, the novel intra fusion method proceeds as follows: In instances where intra angular modes are substituted with block vector modes, the prediction results for these block vector modes are derived utilizing a methodology similar to that of IntraTMP, as illustrated in Section 2.3. The intra fusion prediction is then performed according to the approach outlined in Eqn. (5).

3.3 Implementation Study and Fast Algorithm

The increasing complexity of ECM is becoming a significant concern. In this paper, we propose a comprehensive encoder-side optimization method that effectively limits the complexity increase without compromising the performance of RIPM. Since intra angular mode predictions are utilized by multiple intra fusion prediction based coding tools like DIMD, TIMD, and RIPM, RIPM utilizes a cache buffer to store each intra angular prediction result. During intra fusion stage, the encoder retrieves the corresponding prediction results from the cache buffer, significantly reducing encoder-side complexity.

Furthermore, multiple Rate-Distortion Optimization (RDO) processes are required for a single prediction mode to determine the optimal transform and quantization methods in the current ECM. To address this redundancy, the proposed method introduces an additional cache to store the predicted results of the intra coding tools, significantly reducing the time overhead caused by repeated predictions at the encoder. Moreover, by implementing a threshold, RDO can be automatically bypassed for modes yielding suboptimal predictions in the current block, effectively mitigating the complexity increases associated with the incorporation of additional intra coding

Table 1: Experimantal results of the proposed method, Anchor: ECM-12.0

Class	Sequence	RIPM			RIPM w/o RBVSM		
		Y	U	V	Y	U	V
A1 3840×2160	Tango2	-0.11%	-0.08%	0.11%	-0.13%	0.03%	-0.12%
	FoodMarket4	-0.17%	-0.23%	-0.10%	-0.16%	-0.16%	-0.08%
	Campfire	-0.06%	-0.06%	0.16%	-0.08%	0.03%	0.13%
A2 3840×2160	CatRobot	-0.07%	0.03%	-0.03%	-0.08%	0.03%	0.09%
	DaylightRoad2	-0.20%	-0.09%	0.04%	-0.14%	0.07%	-0.06%
	ParkRunning3	-0.17%	-0.11%	-0.16%	-0.15%	-0.15%	-0.16%
B 1920×1080	MarketPlace	-0.13%	-0.11%	0.08%	-0.14%	-0.13%	0.03%
	RitualDance	-0.16%	0.08%	-0.22%	-0.14%	0.16%	-0.01%
	Cactus	-0.06%	-0.11%	-0.08%	-0.05%	-0.01%	0.14%
	BasketballDrive	-0.11%	0.16%	0.11%	-0.09%	0.22%	0.18%
	BQTerrace	-0.09%	-0.19%	-0.12%	-0.07%	-0.01%	0.01%
C 832×480	BasketballDrill	-0.02%	-0.05%	-0.05%	-0.03%	-0.05%	0.12%
	BQMall	-0.05%	-0.14%	-0.18%	-0.07%	-0.08%	0.00%
	PartyScene	-0.03%	-0.04%	0.00%	-0.04%	0.02%	0.03%
	RaceHorses	-0.03%	0.03%	0.05%	-0.02%	0.04%	0.32%
E 1280×720	FourPeople	-0.13%	-0.17%	0.02%	-0.14%	-0.15%	-0.24%
	Johnny	-0.05%	-0.03%	0.08%	-0.04%	-0.09%	-0.05%
	KristenAndSara	-0.08%	-0.07%	-0.18%	-0.03%	-0.08%	-0.17%
Class Summary	Class A1	-0.11%	-0.12%	0.06%	-0.13%	-0.03%	-0.03%
	Class A2	-0.15%	-0.06%	-0.05%	-0.12%	-0.02%	-0.04%
	Class B	-0.11%	-0.04%	-0.05%	-0.10%	0.05%	0.07%
	Class C	-0.03%	-0.05%	-0.05%	-0.04%	-0.02%	0.10%
	Class E	-0.08%	-0.09%	-0.03%	-0.07%	-0.11%	-0.16%
Overall Summary	Average	-0.095%	-0.067%	-0.027%	-0.089%	-0.017%	0.005%
	$\Delta EncT_{opt}$		100.3%			102.8%	
	$\Delta DecT_{opt}$		99.2%			101.6%	
w/o Fast Algorithm	$\Delta EncT_{ori}$		102.6%			-	
	$\Delta DecT_{ori}$		100.5%			-	

tools.

4 Experimental Results

To evaluate the performance of the proposed RIPM, we integrate it to the ECM-12.0. Simulations are conducted conforming to the JVET common test condition and evaluation procedures for enhanced compression tool testing [18]. The test results are obtained under All Intra configuration, and the test Quantization Parameters (QP) are 22, 27, 32, and 37. The BD-rate is used for evaluating the coding performance. The negative BD-rate results denote the performance gain. The encoding and decoding complexity denoted by $\triangle EncT$ and $\triangle DecT$ are calculated as follows,

$$\triangle EncT = \frac{TEnc_{Proposed}}{TEnc_{Anchor}} \times 100\%, \tag{9}$$

$$\triangle DecT = \frac{TDec_{Proposed}}{TDec_{Anchor}} \times 100\%, \tag{10}$$

where $TEnc_{Proposed}$ and $TDec_{Proposed}$ are the encoding and decoding time of the anchor with the proposed method, and $TEnc_{Anchor}$ and $TDec_{Anchor}$ represent the encoding and decoding time of the anchor, i.e., ECM-12.0.

As shown in Table 1, compared with ECM-12.0, the proposed RIPM achieves 0.095%, 0.067%, and 0.027% BD-rate savings for Y, Cb, and Cr components, respectively. Notably, RIPM exhibits superior performance for higher resolution videos, particularly in Classes A1, A2, and B. When the RBVSM module is disabled, the BD-rate savings for the Y component decrease slightly to 0.089%. Moreover, the incorporation of fast algorithms reduces the encoding time of RIPM by approximately 2%, ensuring that the implementation imposes no additional computational burden on either the encoder or decoder. This efficiency may also be attributed to RBVSM influencing other stages of prediction, such as partitioning.

5 Conclusion

In this paper, a recurrent intra prediction mode is proposed for luma intra prediction. RIPM has two submodules: RIMM and RBVSM. RIMM derives an optimal intra mode group through a predefined sampling strategy and template loss analysis at both encoder and decoder side. RBVSM then adaptively substitutes intra angular modes in the optimal intra mode group with block vector modes. Since the intra mode group derivation and mode substitution rely solely on the reconstructed area, explicit signaling of specific intra modes is unnecessary. With the inclusion of RIPM, the luma intra prediction accuracy is enhanced and the intra mode signaling overhead is reduced. Experimental results demonstrate that the proposed RIPM can achieve 0.095% BD-rate saving compared to the ECM-12.0 with neglected complexity increase. The analysis and observation presented in this paper contribute valuable insights for further improving the prediction accuracy of intra prediction. As one of the first attempts to combine local and non-local mode/content information in intra prediction, the proposed method could be improved in the future by incorporating more intra coding tools, including not only the conventional coding tools but also the neural network based methods.

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