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RESEARCH ARTICLE

Enhancing HEVC Efficiency: A Novel Approach to Intra-Mode Estimation Through Hadamard Cost Analysis

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ABSTRACT In the realm of video coding, the quest for enhanced efficiency is unending. This study introduces a novel optimization in High Efficiency Video Coding (HEVC) by refining intra-mode estimation through Hadamard cost analysis. With the rapid evolution of codecs, real-time applications demand more than ever from the complexity of intra-mode selection. Here we show how by employing a refined approach to the rate distortion optimization (RDO) module, we achieve a 5.8% reduction in HEVC complexity and a minor yet notable −0.02% improvement in Bjontegaard Delta Bit Rate (BD-BR). Our method stands out by not only reducing computational load but also by improving bit-rate, a rare feat in the literature. By integrating this approach, future versions of HEVC could witness a significant leap in performance. We believe our findings contribute to the broader context of video compression technologies, inviting further exploration and development. Code is available at https://github.com/drjunaidtariq/ImprovedHEVC/.

INDEX TERMS Rough mode decision, rate distortion optimization, intra mode, fast algorithm.

I. INTRODUCTION

The most visited social media website, Facebook, uses the H.264 codec to handle videos [1]. Facebook allows users to upload videos up to 10GB in size, which is why this codec is utilized. This article discusses the successor of the H.264 codec, known as H.265 or High Efficiency Video Coding (HEVC) [2]. The first frame of these codecs employs the intra-mode procedure for encoding. The intra-frame is divided into blocks called coding units (CUs), and the content of each CU is predicted using neighboring pixels. Neighboring pixels are copied into the CU's area in 35 different ways, referred to as intra-modes. These intra-modes have slight angle deviations for copying neighboring pixels into the CU to predict its content. The angles of 33 intra-modes are visually represented in Fig. 1 (a). The remaining two intra-modes are specifically designed to handle smooth content. Figure 1 (b-c) provide examples of intra-mode prediction using neighboring pixels. In Fig. 1 (b), the horizontal intra-mode applied to a block of size 4 × 4, where neighboring pixels are copied horizontally into the block area. This horizontal angle is indicated in Fig. 1 (a) by the 10^{th} dotted line. Similarly, Fig. 1 (c) demonstrates the vertical intra-mode applied to the same block, where upper neighboring pixels are copied vertically into the block area. This vertical angle is highlighted in Fig. 1 (a) by the 26^{th} dotted line.

The RMD module of HEVC applies 35 intra-modes to each CU, and then selects the best intra-modes that result in the least rate distortion (RD) cost. This brute-force mechanism for intra-mode selection is highly inefficient. Additionally, there are various sizes of CUs, which further complicate the

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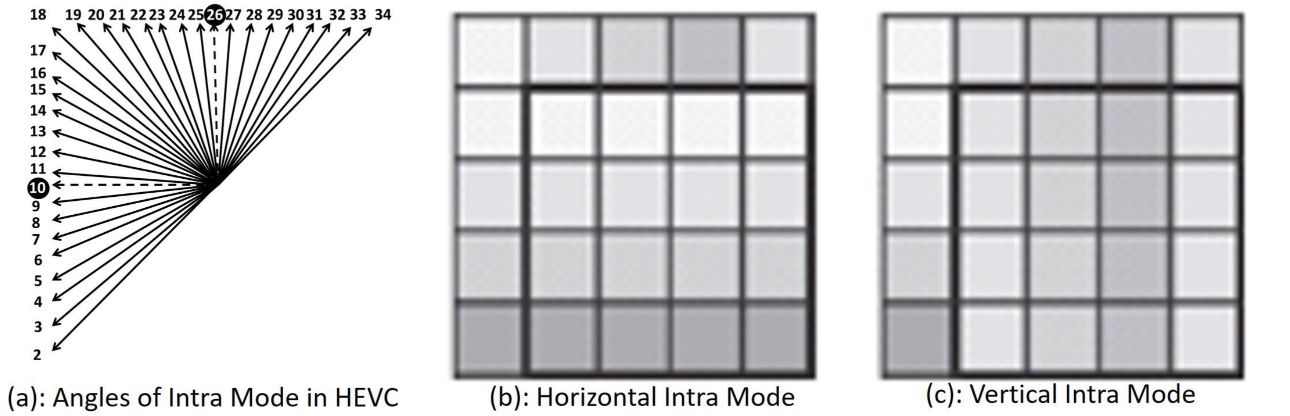


FIGURE 1. Intra-modes in HEVC. (a) Angles of intra-modes (angular) in HEVC. (b) Visual output of horizontal (angle 10 in Fig. 1 (a)) intra-mode in HEVC. (c) Visual output of vertical (angle 26 in Fig. 1 (a)) intra-mode in HEVC.

intra-frame process. Initially, the intra-frame is divided into 64×64 size blocks, followed by the application of 35 intra-modes. Subsequently, each of these 64×64 blocks is further divided into four 32×32 size blocks, followed by the same 35 intra-mode application for each. This division process continues until the block size reduces to 8×8. The RMD module shortlists up to 8 intra-modes, which are then forwarded to the next module of HEVC, the RDO module. The RDO module performs computationally intensive operations such as transform, quantization, inverse-transform, inverse-quantization, entropy encoding, etc., on each of the shortlisted RMD modes. The intra-mode that yields the lowest RDO cost is chosen as the optimal intra-mode for that specific block.

The intra-mode selection process involving RMD's and RDO's operations makes it a very complex process. Moreover, skipping steps of the intra-mode selection process without any rationale increases the BD-BR overhead too high. Hence, it is a hot research topic these days. As artificial intelligence (AI) algorithms are making history, their application in the video compression field is inevitable. The application of such intelligent algorithms can help achieve the best tradeoff between complexity reduction and bit-rate overhead. Furthermore, there are a number of inefficiencies in HEVC that have been highlighted by many researchers. For example, Ammar in [3] found out that intra-modes are producing the same RD cost. The reason behind this same RD cost issue can be the closeness among the angles of the intra-modes. These angles are already graphically presented in Fig. 1 (a). Additionally, in order to reduce the complexity of HEVC, the bit-rate always increases due to the early termination of the selection process. However, the proposed strategy not only reduces the complexity of HEVC but also improves the bit-rate. Thus, the following constitute the primary contribution of this article:

(i) The first proposed optimization reduced the complexity of HEVC by 5.8% and improved the BD-BR by −0.02% on average.
(ii) Both proposed optimizations achieved a strong mapping between the RMD and RDO modules, surpassing the original HEVC platform, namely HM (HEVC test model).
(iii) The subjective results of the first optimization clearly showed an improvement in BD-PSNR, despite 5.8% less coding time than standard HEVC.

Usually, the complexity reduction methods described in the literature aim to reduce the complexity of HEVC, but at the cost of an increased bit rate. However, the proposed method (the first proposed optimization) in this article not only reduced the complexity (by 5.8%) of HEVC but also decreased the BD-BR (by −0.02%). These values may not be significant, but this achievement is unique to only one or two methods in the literature. The format of this article is as follows: Sections II, III, IV, and V present the relevant studies, motivation, proposed model, and coding results, respectively. A very useful discussion is also presented in section VI of the article. Finally, section VII serves as the conclusion of the article.

II. RELATED WORKS

Video compression [4], [5], [6] and image compression [7], [8], [9] are perennially popular topics in research. Because, not only can quick analysis be easily performed on the compressed data, but effective compression [10] can also be achieved. Therefore, many interesting works exist that address the challenges associated with compression. The time complexity of video compression poses a significant challenge. Time reduction is typically achieved at the expense of an increased bit rate. This increased bit rate results from the suboptimal selection of the compression element, such as the intra-mode in our case. Consequently, researchers have endeavored to strike a balance between the rise in bit rate and the reduction in time complexity. To achieve this tradeoff, some researchers have utilized statistical approaches [11], and some have employed AI techniques [12]. All of these studies have aimed to utilize technologies to extract valuable information that could facilitate early intra-mode selection, thus avoiding the brute-force selection methodology. Lots of work has been done in this field; however, there is still room for improvement in managing intra-modes through the latest technologies [13]. One global health challenge has been solved in [14] with the help of such advanced technology.

Nair et al. in [11] utilized Support Vector Machines (SVM) to perform fast intra-mode selection. Nair extracted statistical data, known as Hu moments, from the block to acquire local information. These Hu moments were then inputted into SVM to determine the intra-mode for the current block. This approach reduced the complexity of the RDO module by an average of 47.23%, although the overall complexity reduction was not specified. Additionally, the BD-BR increased by an average of 3.35%. In [12], the intra-mode selection problem is treated as an optimization problem, and the spiral optimization technique is utilized to reduce the complexity of HEVC. This method evaluates an intra-mode (i) and then completes a single spiral cycle. Then another intra-mode (j) is evaluated, and if the i^{th} mode is still the best, then the spiral completes the second cycle; otherwise, the spiral shifts to the new intra-mode, i.e., the j^{th} intra-mode and tries to complete three spirals. This process continues until three spiral cycles are completed for an intra-mode. The mode that completes three spiral cycles is considered the optimal intra-mode. This spiral work reduced the overall time complexity of HEVC by 34.09% on average. The BD-BR increase of this work is 1.56% on average.

In [15], the partition map technique is proposed. This work reported multiple results by varying the configuration or setting of the Convolutional Neural Network (CNN). For example, the reported L0 result will be used for comparison here because the bit rate of the other configurations is too high to be considered a contribution. This L0 setting reduced the overall complexity of the HEVC by 1.6% on average. The BD-BR increase of this L0 configuration is 0.52% on average. Another fast intra-mode study is documented in [16], which utilized a multi-task-based learning algorithm. This study employs a deep neural network to extract appropriate features from the block. This automated feature detection can enhance prediction accuracy. The study decreased the overall complexity of HEVC by an average of 32.08%. On average, this study resulted in a 1.84% increase in BD-BR.

In [17], smooth CUs are identified for early planer mode selection. Because planer mode is mostly selected for smooth regions. These smooth areas within the frame are intelligently identified by examining the neighboring pixels of the CU. If these neighboring pixels are identical, the planer mode is selected. This reduces the number of modes from the current CU from eight to one, which is a significant improvement. However, such CUs are limited in number. Consequently, this approach only manages to save 14% of the time. The work presented in [18] attempts to select the best intra-mode by evaluating various modes. The reward decreases with each new evaluation, encouraging an early intra-mode selection. This study is inspired by the classical secretary problem, where no recalls were permitted. However, in the computing domain, recall can be incorporated for more effective selection. Therefore, the optimal secretary selection is linked to the best intra-mode selection.

The RMD module is optimized in [19]. This work does not evaluate all 35 intra-modes but evaluates intra-modes by skipping a few modes in between. Only those missing intra-modes that are close to the best intra-mode of the first phase are evaluated. This work consists of three phases, and on average, it reduces the time by 28%. In [20], a threshold is proposed based on the RD costs of the current frame. If the RD cost of the intra-mode is less than or equal to this threshold, the intra-mode decision process stops. This approach saves approximately 38% of the encoding time. Hung's threshold in [21] is based on the RD cost of the previous frame. Groups are formed in [22] based on the complexity of the CU. Subsets of intra-modes are then evaluated according to the complexity of the CU.

The gradient-based approach is the most well-known method for fat intra-mode selection. This approach predicts the pixel direction within the CU. This directional information is believed to aid in fast intra-mode selection. Therefore, a gradient-base fast intra-mode selection is proposed for all the codes [23]. In [23], intra modes are reduced for the current CU by computing the gradient.

The information from the CU is extracted by applying the planer intra-mode in [24]. Then the sub-set of intra-modes is selected based on the aforementioned information, thus reducing the time requirement for the encoder. In [25], a classifier is trained to perform fast intra-mode selection. This work reduces the encoding time by 31.54% on average. The uncertainty is modeled in [26] to facilitate fast intra-mode selection. This uncertainty arises because the selected intra-mode does not adhere to any specific rules. The intra-mode selection is determined by the RD cost, which includes the rate required to transmit the mode information. The nature-inspired AI algorithm is applied in [27] for fast intra-mode selection. This study represents intra-modes as fireflies, with the brightest firefly being considered the best intra-mode. The convergence of fireflies at the brightest firefly is interpreted as fast intra-mode selection. In [28], the intra-mode of the parent CU is used to predict the intra-mode of the child CUs. There is a significant correlation between parent and child CUs because the parent CU is recursively divided into smaller CUs. Similarly, the algorithm proposed in [3] achieved a 34% average time reduction.

All the aforementioned works have reduced the coding time but at the cost of increased bit-rate. This bit-rate increase is due to sub-optimal intra-mode selection. In the following sections, an algorithm is presented that reduces the coding time and bit-rate simultaneously. Due to this exceptional performance, the proposed study may be integrated into future coding standards.

III. MOTIVATION AND FINDINGS

In the previous section, various distinctive works were summarized, each with its own strengths and weaknesses.

This section will address the same issue but in a unique and different way compared to the aforementioned state-of-the-art (SOTA) works. The inspiration for this study stems from the experimental findings depicted in Fig. 2. The latest *HEVC test Model*, HM 18.0, was acquired from [29] for all the experiments to be discussed in this article. Moreover, the *All_Intra_Main* configuration is used, which is specially created for intra-mode. Lastly, Table 1 presents a summary of the software and hardware on which these experiments are conducted.

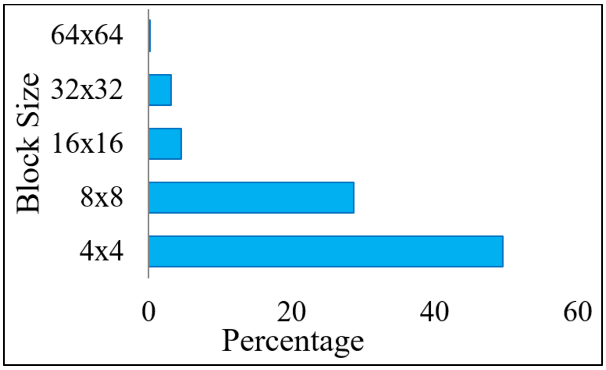


FIGURE 2. Blocks having the same rate distortion (RD) cost among their intra-modes.

Figure 2 shows that up to 50% of the blocks have the same RD cost among their intra-modes. The reason behind this same RD cost is the closeness of the angles of the intra-modes, hence producing the same RD cost for different intra-modes. The statistics in Fig. 2 are obtained by encoding the first 50 frames of two HEVC test videos, namely *Johnny* and *Basketballdrill*. *Johnny* is considered a slow-motion test video, while *basketballdrill* is considered a fast-motion test video. The percentages in Fig. 2 are obtained by first counting the blocks that have the same RD cost among their intra modes, with respect to the total number of blocks present in the 100 frames (50 frames for each test video). Fig. 2 shows that approximately 50% of the blocks exhibit this inefficiency of producing the same RD cost; hence, it is worth investigating.

An effort is made to identify those intra-modes that produce the same RD cost. However, there is no pattern as to when and which intra-modes will yield the same RD cost. The RD cost of intra-modes is illustrated in Fig. 3. In Fig. 3, the x-axis represents the intra-modes of HEVC, while the y-axis represents the RD cost of these intra-modes. The data in Fig. 3 presented in a scatter plot, but it appears similar to a bar chart. This bar-chart-like appearance indicates that the adjacent intra-mode may or may not result in the same RD cost. At times, the neighboring intra-mode of any given intra-mode may produce a similar RD cost, while at other times, it may yield a significantly different RD cost. Therefore, an alternative mechanism is needed to address this issue.

Another experiment was conducted in which the RD cost differences between every two consecutive intra-modes were computed. Subsequently, groups were formed based on the

TABLE 1. Hardware/software settings.

Hardware	Software
Core i5	Windows 10
8 GB Ram	Visual Studio 19
500 GB Hard Disk	Direct X
64 Bit System	CMake

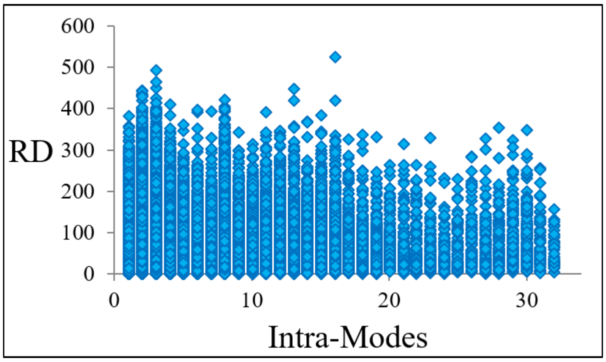


FIGURE 3. Comparison of RD-cost of intra-modes with its neighboring intra-modes.

number of pairs with differences less than 10, less than 50, less than 100, and less than 1000. The statistical data related to these groups is shown in Fig. 4. This statistical data was obtained using *Basketballdrill* and another slow-motion video named *Slideshow*. In Fig. 4, the x-axis represents the groups, while the y-axis represents the count. Figure 4 clearly illustrates that when the content is simple (Slideshow), there are numerous intra-modes with fewer differences among them. Even fast-motion video like *Basketballdrill* has some intra-modes that have less variation among them. Therefore, an early termination based on such information can only be achieved using a static threshold, such as 10. For instance, if the difference between two intra-modes is less than 10, early termination is feasible. This early termination aligns with HEVC's existing early termination, where HEVC terminates the process if the sum of transform coefficients reaches zero. However, this termination mechanism consistently raises the bit-rate overhead.

To efficiently perform early intra-mode decision, it is necessary to establish a connection between the RMD and RDO modules. The computation complexity of the RDO module is significantly higher compared to that of the RMD module. The RMD module is computationally efficient because it utilizes Hadamard cost to early predict potential intra modes for the current block, without the need to fully encode each intra mode. This approach reduces the complexity of HEVC, as fully encoding all 35 intra modes is extremely time-consuming. The Hadamard cost is effective because it employs the Hadamard transform, which is faster than the discrete cosine transform (DCT). In summary, the Hadamard transform provides a quick approximation of the DCT. Therefore, intra-modes that give the same Hadamard costs in the RMD module are chosen, and their RD costs in the RDO module are monitored. The findings are illustrated

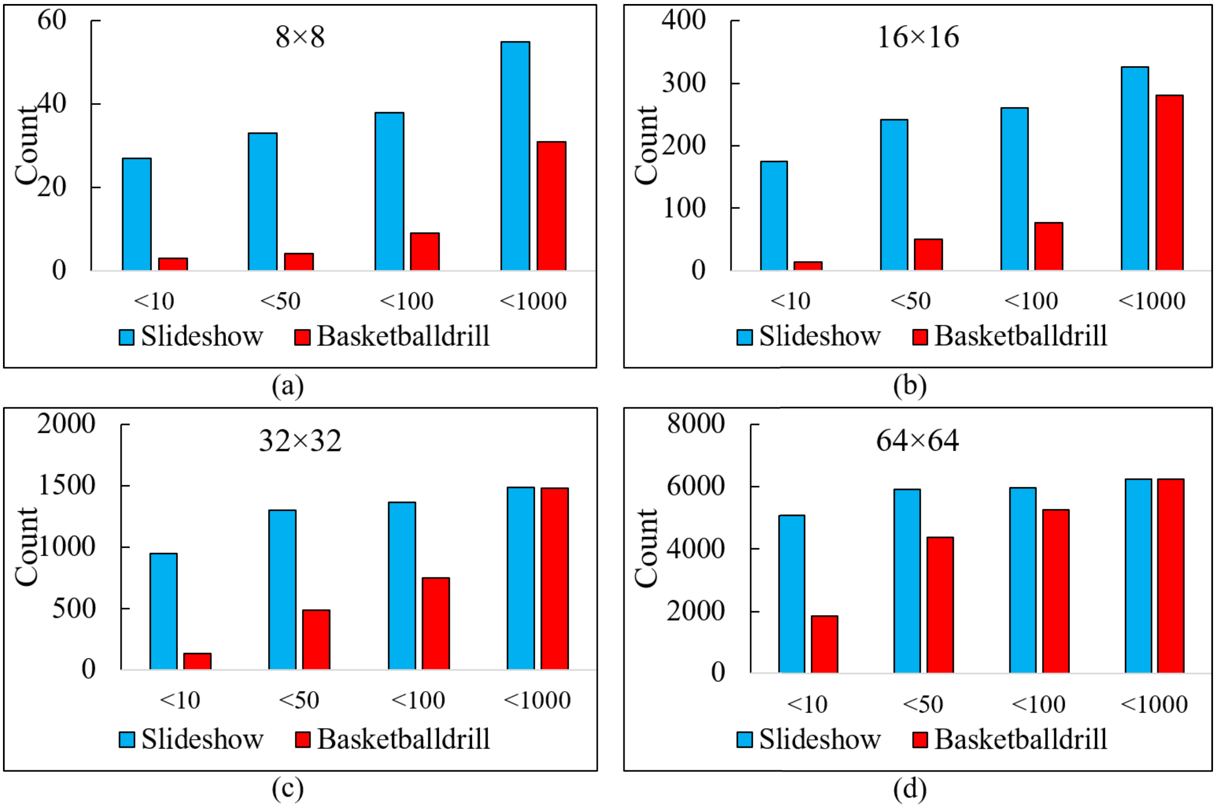


FIGURE 4. CU size-wise data is presented, which counts the blocks having a difference of Γ between their consecutive intra-modes, where $\Gamma \in \{10, 50, 100, 1000\}$.

in Fig. 5 (a-c). In Fig. 5 (a-c), the *x*-axis represents block sizes, while the *y*-axis represents the percentage of modes with identical RD costs or zero differences in their RD costs. Figure 5 (a-c) demonstrates that intra-modes with the same Hadamard cost in the RMD module also exhibit the same RD cost in the RDO module. The maximum accuracy of this similarity prediction is up to 81%, which is achieved for the test video named *Slideshow* for the block size of 16×16. Therefore, the Hadamard cost in the RMD module reflects the same properties as the RD cost in the RDO module. However, this prediction/mapping is less accurate for fast-motion videos, such as in the case of *Basketballdrill*. While this prediction may vary, there is a high likelihood that intra-modes with the same Hadamard cost in the RMD module will also have the same RD cost in the RDO module. Consequently, intra-modes with identical Hadamard costs will be chosen, and one of them will be excluded from RDO computation to save encoding time. This exclusion will not impact efficiency as both modes yield the same results. Since this discovery is based on slow-motion (*Slideshow*) and fast-motion (*Basketballdrill*) videos, it can be extended to other test videos and will be utilized in the upcoming section to propose an effective early mode decision method for HEVC.

IV. PROPOSED MODELS

The findings from the motivation section will be expanded here to propose a fast intra-mode decision algorithm. This decision will utilize the relationship between RMD and RDO modules. Such early-mode decisions are devoid of the issues associated with pre-computed or global thresholds. Since each block possesses unique content, texture, and color intensities, utilizing the RMD values of the same block will facilitate an effective mode decision. This section will introduce two early-mode decisions based on the aforementioned relationship.

A. SKIP RDO OPERATIONS FOR INTRA-MODES

The findings of the previous section will be extended here. For example, if two RMD modes have the same Hadamard cost, and these modes are also expected to have the same RDO cost, then which intra-mode should be dropped from the pair to save the RDO computation? In simple words, if (i, j) are expected to have the same RD cost in the RDO module, then either i should be dropped or j should be dropped? To answer this question, the selection percentages for such scenarios are obtained from standard HEVC for both i and j, and shown in Fig. 5 (d-f). The percentage results of Fig. 5 (d-f) are obtained from three different test videos, which clearly show that the second mode, i.e., j^{th} mode, is selected more often compared to the first mode, i.e., i^{th} mode. The rationale behind this could be that the more options one evaluates, the better selection can be made. The maximum accuracy of this second mode prediction is up to 98%, achieved for the test video named *Slideshow* for the block size of 64×64.

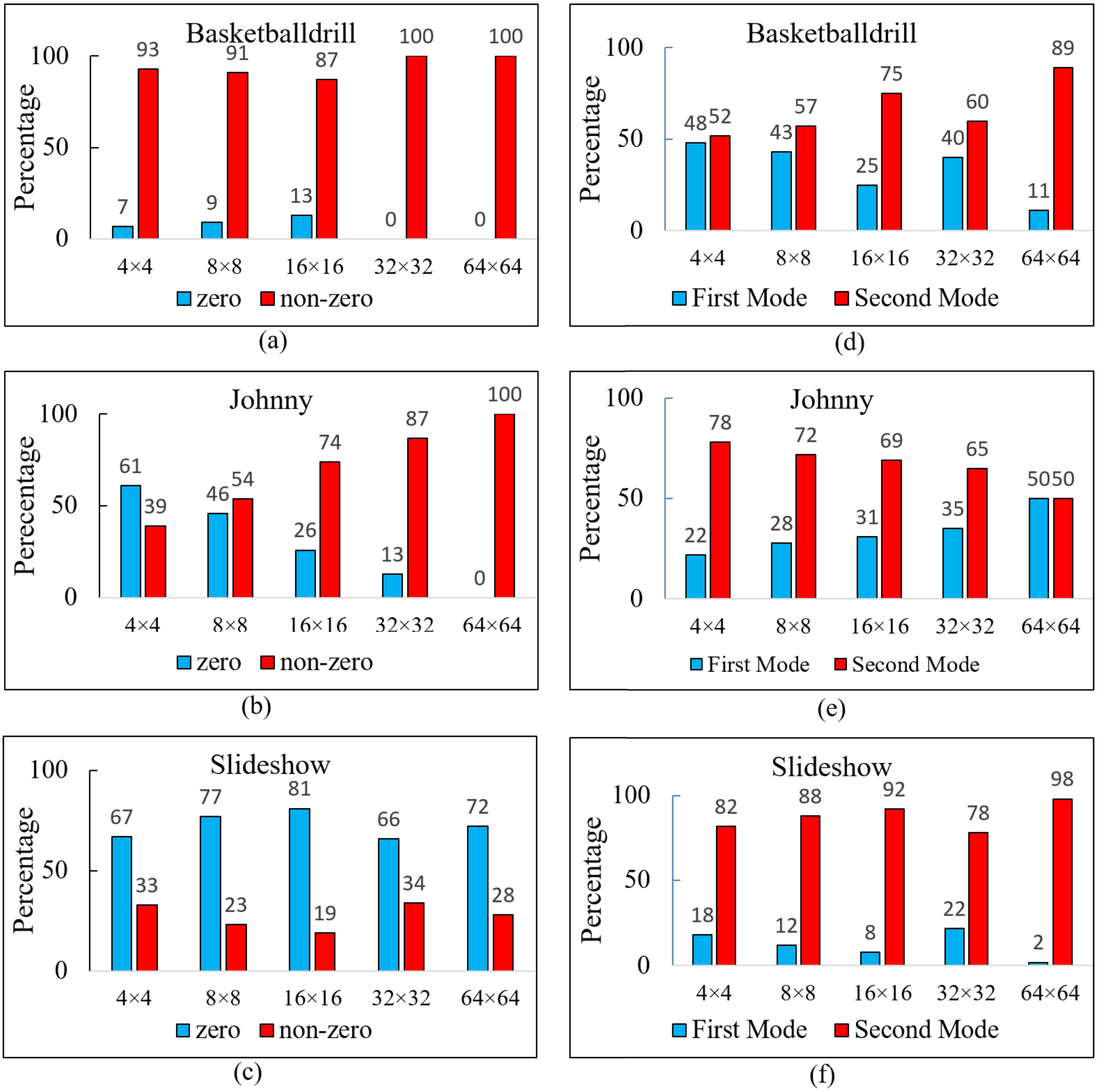


FIGURE 5. In (a-c): Percentages of intra-modes that have zero difference between their Hadamard cost in the RMD module and also have zero difference between their RD cost in the RDO module; (d-f): Mode selection percentages of the RDO module for the pair (first mode, second mode) that have the same Hadamard cost in the RMD module.

Hence, dropping the i^{th} intra-modes for RDO is not expected to increase the bit rate overhead. Therefore, the proposed early termination of RDO operations can be given as:

$$L[m++] = \begin{cases} I_j, & \text{if } H(i) = H(j), \\ I_i, & \text{otherwise.} \end{cases}$$

where

$$\{i, j, m\} \leq N, \quad i <> j. \tag{1}$$

Here $L[]$ is the updated list after adding either mode i or mode j, the post-increment $m{+}{+}$ term moves to the next location after saving a value, $H()$ represents the Hadamard cost, N is the total number of modes shortlisted for the RDO module, and $i <> j$ means i is not equal to j. The model given in (1) will save intra-mode I_j in the list $L[m++]$ only if the Hadamard costs of intra-modes i and j are the same. Otherwise, (1) will save intra-mode I_i in the list $L[m++]$.

B. STANDARD DEVIATION BASED EARLY MODE DECISION

The early termination mechanism modeled in (1) is very efficient but saves a limited amount of time. To achieve greater time savings, another early termination model will be presented here that also aims to address the similarity

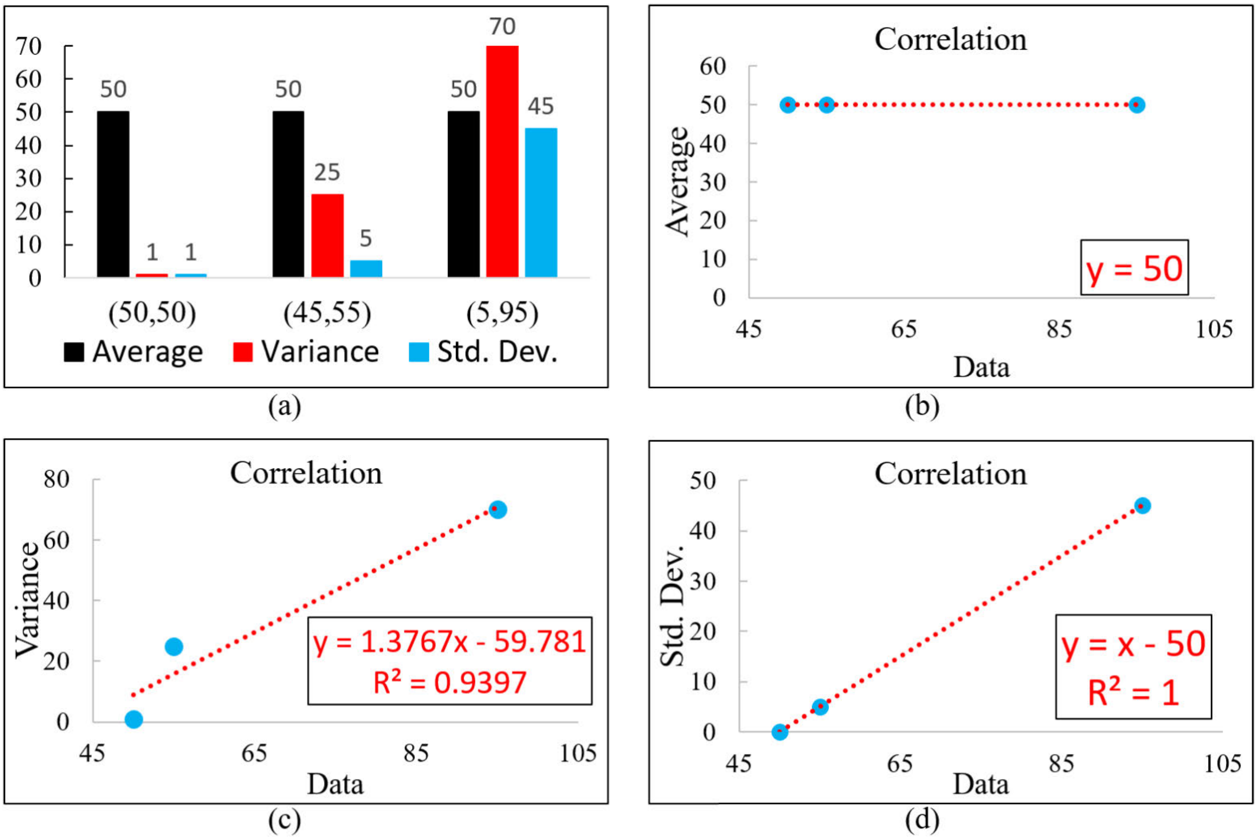


FIGURE 6. Correlation (R^2) between the three examples and (average, variance, standard deviation).

issue. Additionally, the model presented in (1) is quite restrictive as it only monitors intra-modes with identical Hadamard costs. Clearly, such instances will be rare in fast-motion videos. Hence, the intra-modes shortlisted by the RMD module will be analyzed to identify a distinct pattern among them. Hence, making it a distinct work from other existing works that extract the same features from all the blocks or use a single global threshold. In this subsection, the intra-modes shortlisted by the RMD module will be considered as input, and statistical information will be extracted from these shortlisted intra-modes to determine similarity and dissimilarity. The statistical data presented in Fig. 4 and Fig. 5 clearly indicate that as we transition from fast-motion video (*BasketballDrill*) to slow-motion video (*Slideshow*), the similarity between the RD costs of modes increases. This rise in similarity is attributed to the content similarity, as fast motion alters the block's contents, resulting in significantly different RD costs for each intra-mode. In contrast, slow-motion video does not introduce substantial changes to the block, leading to similar RD costs for intra-modes. This observed *similarity* or *dissimilarity* among Hadamard costs of intra-modes can aid in bypassing computationally intensive RDO operations.

Suppose there are N intra-modes that are shortlisted by the RMD module:

$$m_1, m_2, m_3, \ldots, m_N \tag{2}$$

The Hadamard cost (H) of these modes can also be obtained from the RMD module:

$$H(m_1), H(m_2), H(m_3), \ldots, H(m_N) \tag{3}$$

Then *similarity* or *dissimilarity* among these Hadamard costs can be computed as:

$$\frac{1}{N}\left\{[H(m_1)-\mu]+[H(m_2)-\mu]+\ldots+[H(m_N)-\mu]\right\} \tag{4}$$

Here, μ is the average of N Hadamard costs. To deal with negative values, the above equation can be expressed as:

$$\sigma = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(H(m_i)-\mu)^2} \tag{5}$$

If σ is zero, then all the $H(m_i)$ are the same; if σ is a small number, then $H(m_i)$ are similar; and if σ is a big number, then $H(m_i)$ are dissimilar. This σ is also known as the *standard deviation*. The importance of σ is presented here with the help of three examples in Fig. 6. Figure 6 (a) presents the *average*, *variance*, and *standard deviation* (Std. Dev.) of three examples (50, 50), (45, 55), and (5, 95). Each of these examples has two values that have an increasing difference between them. Figure 6 (a) shows that the average is 50 for the three examples, the variance is (1, 25, and 70), and the standard deviation is (1, 5, 45). These values clearly show that the standard deviation is modeling these examples very well. The standard deviation is '1' for the (50, 50) example, '5' for the (45, 55) example, and '45' for the (5, 95) example. The *variance* also produces a similar kind of output. Therefore, the *correlations* between the three examples and (average, variance, standard deviation) are computed and are shown in Fig. 6 (b-d). Figure 6 (b-d) clearly shows that the standard deviation has the highest correlation with the data. This means that if the data is closely related, then the standard deviation is small. Whereas, if data is dispersed, then the standard deviation is large. Hence, the standard deviation of the Hadamard cost of the RMD's intra-modes will be computed, and then this standard deviation will be used to make early mode decisions to save valuable time. Therefore, the proposed early termination for RDO operations using the standard deviation can be given as follows:

$$S = min\Big\{j : [H(m_j) - H(m_i)] \leq \sigma\Big\},$$

where,

$$\sigma = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(H(m_t) - \mu)^2},$$
$$\mu = \frac{1}{N}\sum_{t=1}^{N}H(m_t),$$
$$i < j \leq N. \tag{6}$$

Here, σ represents the standard deviation of the Hadamard costs of RMD modes, j denotes the stopping point or mode, $H(m_i)$ represents the Hadamard cost of mode m_i, N indicates the total number of modes shortlisted for the RDO module, and $j > i$ represents two consecutive intra modes. The model presented in (6) will initially calculate the σ of the Hadamard costs of all the intra-modes shortlisted by the RMD module. Subsequently, the condition ($[H(m_j) - H(m_i)] \leq \sigma$) will be assessed between every two consecutive intra-modes. If the aforementioned condition holds true, then the RDO module will conclude at intra-mode j. Otherwise, the RDO module will continue until all the N intra-modes are assessed.

C. COMBINING SKIP-RDO & STANDARD-DEVIATION ALGORITHMS

The two proposed algorithms have the capability to be combined, but (1) will always execute first. Because the model in (1) updates the mode list by dropping a few modes. Now (6) can be applied to this updated list. Therefore, the combined model (C) after combining (1) and (6) can be given as:

$$C = min\Big\{j : H(L[j]) - H(L[j-1]) \leq \sigma\Big\},$$

where,

$$L[m++] = \begin{cases} I_j, & \text{if } H(i) = H(j), \\ I_i, & \text{otherwise.} \end{cases} \tag{7}$$

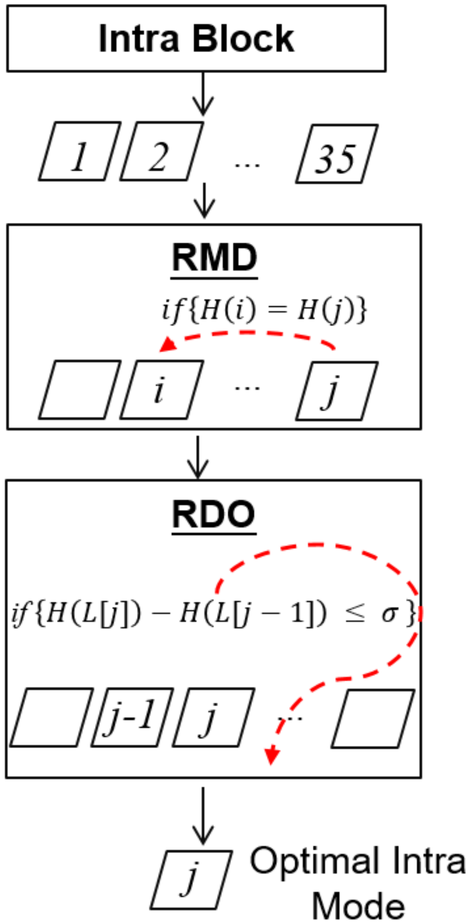


FIGURE 7. Flowchart of the proposed combine algorithm.

Here, $L[]$ is the updated list after adding either mode i or mode j, σ represents the standard deviation of the Hadamard costs of this updated list, $H()$ denotes the Hadamard cost, and j signifies the stopping point or mode. The $L[j]$ will return the mode at the j^{th} index, while $H(L[j])$ will return the Hadamard cost of this mode. The first mode that fulfills the condition $\{H(L[j]) - H(L[j-1]) \leq \sigma\}$ will be considered as the stopping point.

The flowchart of the proposed combined algorithm is shown in Fig. 7. Figure 7 illustrates that the current block and 35 intra-modes are passed to the RMD module. The RMD module updates the mode list using (1), highlighted by a red dotted line. This updated list is then forwarded to the RDO module, which examins for the early termination condition between every two consecutive intra-modes using (7). If (7) is satisfied, the RDO module is stops. This termination point in the RDO module is also marked with a red dotted line.

V. EXPERIMENTAL RESULTS

The early terminations proposed for HEVC in (1), (6), and (7) are implemented in HEVC test model (HM) 18.0 [29], which is the latest version. The *all-intra-main* configuration is used to encode the videos because this configuration codes each frame as an intra-frame. In order to make a fair comparison,

TABLE 2. Results of proposed early termination algorithms.

Classes	Sequences	Frames Encoded	Skip-RDO/ Eq. (1)			Std. Dev./ Eq. (6)			Combine/ Eq. (7)		
		Count	BD-P	BD-B	ΔT	BD-P	BD-B	ΔT	BD-P	BD-B	ΔT
A 2560×1600	Nebuta	300	0.000	-0.03	2.04	-0.048	0.65	36.53	-0.045	0.61	36.70
	Traffic	150	0.000	-0.02	4.34	-0.109	2.04	34.39	-0.104	1.94	34.94
	PeopleOnStreet	150	0.000	0.03	4.57	-0.127	2.25	35.77	-0.123	2.17	36.15
B 1920×1080	BQTerrace	600	0.000	0.00	4.11	-0.105	1.66	35.51	-0.096	1.52	35.87
	Cactus	500	0.000	-0.04	4.86	-0.069	1.86	34.81	-0.070	1.88	35.42
	Kimono	240	0.000	-0.10	4.84	-0.067	1.92	34.01	-0.062	1.75	34.62
C 832×480	BasketballDrill	500	-0.010	0.31	3.21	-0.070	1.47	33.85	-0.084	1.82	34.33
	RaceHorses	300	-0.010	0.10	4.66	-0.114	1.72	35.66	-0.106	1.61	39.88
	PartyScene	500	0.000	0.09	2.00	-0.191	2.43	35.63	-0.178	2.27	35.63
D 416×720	BlowingBubbles	500	0.000	-0.02	3.64	-0.128	2.16	36.38	-0.148	2.47	36.88
	BQSquare	600	0.000	0.04	4.37	-0.212	2.50	36.65	-0.209	2.44	37.03
	BasketballPass	500	0.040	-0.79	3.03	-0.092	1.37	35.29	-0.092	1.46	35.46
E 1280×720	KristenAndSara	600	0.000	0.09	8.66	-0.108	2.09	34.55	-0.106	2.06	34.98
	FourPeople	600	-0.010	0.17	6.81	-0.121	2.06	35.00	-0.136	2.33	35.86
	Johnny	600	-0.010	0.28	9.02	-0.086	2.18	34.13	-0.085	2.12	34.71
F 1280×720	SlideShow	500	0.010	-0.06	22.80	-0.321	1.41	32.48	-0.156	0.66	34.15
	ChinaSpeed	500	-0.020	0.23	6.57	-0.212	2.50	33.86	-0.209	2.44	34.33
	BasketballDrillText	500	0.040	-0.70	4.80	-0.071	1.33	34.12	-0.082	1.54	34.65
Avg.		-	0.001	-0.02	5.80	-0.125	1.87	34.92	-0.116	1.84	35.64

the same four quantization parameters { 22, 27, 32, 37} are used to encode each test video. The test videos are used as suggested by HEVC in [30]. The coding efficiency is measured using the metrics provided by HEVC in [31], such as BD-PSNR, BD-BR, and ΔT. This ΔT is computed as:

$$\Delta T = \left(\frac{HEVC\_Time - Prop\_Time}{HEVC\_Time} \right) \cdot 100 \qquad (8)$$

where *Prop_Time* is the time taken by the proposed algorithm to encode the video, and *HEVC_Time* is the time taken by the original HM of HEVC to encode the same video.

A. DATASET

The dataset includes test videos [30] recommended by HEVC. This dataset comprises six classes (A to F), each containing videos with various resolutions ranging from 416 × 720 to 2560 × 1600. Moreover, these videos exhibit different frame rates, ranging from 24 frames per second (FPS) to 60 FPS. There are also variations in the motion of the videos, with some in slow-motion and others in fast-motion. In order to assess the effectiveness of the algorithm, it must deliver satisfactory performance for both slow-motion and fast-motion videos. In the proposed study, three videos are randomly selected from each class to ensure that all motion types and resolutions are adequately represented.

B. IMPLEMENTATION DETAILS

The HM 18.0 is developed in Visual Studio and is freely available online in multiple locations. In HM 18.0, the encoding project (TAppEncoder) uses various encoding libraries placed in TLibEncoder. TLibEncoder contains several C++ files, each dedicated to a specific encoding task. One of these files is TEncSearch.cpp, which is responsible for searching intra-mode for the current block. Within TEncSearch.cpp, the RMD process is implemented in a function called *estIntraPredLumaQT()*. The current study focuses on updating the *estIntraPredLumaQT()* function by modifying the variable numModesForFullRD, which tracks the count of intra-modes shortlisted for the RDO module. The modification of variable numModesForFullRD is carried out using (1). Finally, the function named *xRecurIntraCodingLumaQT()* performs the task of RDO on each of the modes provided by the RMD module. The current study monitors the stopping condition (7) after *xRecurIntraCodingLumaQT()* computes the Rate-Distortion (RD) cost for the current intra-mode. If the condition is true, the current study stops the *xRecurIntraCodingLumaQT()* function to save time by skipping the operations for the remaining intra-modes.

C. RESULTS OF THE PROPOSED EARLY TERMINATION ALGORITHMS

Table 2 presents the performance of the proposed algorithms. In Table 2, 'BD-P' and 'BD-B' are the abbreviations for 'BD-PSNR' and 'BD-BR', respectively. The values in Table 2 under the column 'Skip-RDO/Eq. (1)' demonstrate that the proposed algorithm reduced the complexity of HEVC for each test video. All the values in this column are greater than zero, as computed using (8). In Table 2, under the BD-B column, negative values indicate a reduction in bit-rate compared to the original HM software. This is the primary contribution of the proposed algorithm, as it not only decreases complexity but also enhances bit-rate. In contrast, existing early termination algorithms lead to increased bit-rate overhead. For some videos, the proposed algorithm did not reduce the bit-rate, as shown by the positive values under the BD-B column. On average, the proposed algorithm decreased the complexity of HEVC by 5.8% and BD-BR by −0.02%.

Similarly, the values in Table 2 under the column 'Std. Dev./ Eq. (6)' show that the standard deviation based proposed algorithm also reduced the complexity of HEVC for each test video. All the values in the ΔT column are greater than zero, indicating significant savings. On average, the standard deviation based proposed algorithm reduced the complexity of HEVC by 34.92% and increased the BD-BR by 1.87%. This time-saving is essential for a fair comparison with existing algorithms. The combined result of the proposed algorithms (7) is also presented in Table 2 under the column 'Combine/Eq. (7)'. The values in the ΔT column demonstrate that the time-saving is further accelerated to 35.64% on average.

The subjective or visual quality of the proposed 'Skip-RDO' algorithm for BD-BR improved test videos is shown in Fig. 8. This algorithm enhanced the BD-BR of HEVC, necessitating the presentation of its subjective quality. In Fig. 8, two test videos from Table 2 are selected that exhibited a decrease in BD-BR, i.e., negative values. Figure 8 shows that the proposed algorithm has enhanced the quality of the videos. The improvement is emphasized with the help of dotted rectangles in Fig. 8. A direct comparison between the outputs of HEVC and the proposed algorithm reveals that HEVC's output appears blurry or dim in contrast to the output of the proposed algorithm.

Similarly, Fig. 9 presents the subjective quality of the proposed 'Skip-RDO' algorithm for the *PeopleOnStreet* test video, which was unable to improve BD-BR. The details regarding this test video can be obtained from Table 2. Figure 9 shows that the proposed algorithm's output creates a staircase-like quality degradation. This staircase is also called blocky-effect, which is an indication of low quality. However, these issues only occur in certain areas of the video. Hence, the overall performance of the proposed algorithm is satisfactory. 'Std. Dev.' and 'Combine' algorithms also give similar subjective qualities, as shown in Fig. 9.

D. COMPARISON WITH THE LATEST ALGORITHMS

An attempt was made to find an existing fast intra-mode algorithm that had improved the BD-BR, but there was no such algorithm. Therefore, the latest fast intra-mode selection works are summarized in Table 3. The works mentioned in Table 3 are pure fast intra-mode selection algorithms. By *pure*, we mean only those articles that reported time savings for the intra-mode selection process. Some articles combine the time savings of fast CU size selection with the time savings of fast intra-mode selection. Hence, it results in significant time savings. Four of the latest articles were selected, and their results are summarized in Table 3. The abbreviations for BD-BR and time-saving are chosen as ΔB and ΔT, respectively. These abbreviations are selected to incorporate the four articles in a single table for easy comparison. The proposed combined algorithm is presented in the last column of Table 3.

As the aim of this article is to efficiently reduce the complexity of the encoder, the four latest works are arranged in Table 3 from left to right based on the reporting year. The proposed algorithm is listed at the end of the table, following the traditional way of presenting the proposed algorithm in an article. Before delving into details, it is worth mentioning that all the works in Table 3 employ different methodologies to address the same issue. The encoding results of [15] in Table 3 show that this algorithm saves the least amount of time, i.e., only 1.6% on average, but it also incurs the least bit-rate overhead, i.e., only 0.52% on average. This makes it the most suitable benchmark for comparison with the proposed algorithm due to its minimal bit-rate overhead. Similarly, the results of [16] show that it saves 32.08% indicate a time savings of 32.08% in encoding, with a bit-rate overhead of only 1.84% on average. No doubt, it costs more bit-rate compared to [15], but it saves a significant amount of encoding time. In comparison to the proposed algorithm, this work incurs a 0.0% higher bit-rate overhead but saves 11.09% less time. These percentage values clearly demonstrate that the proposed algorithm achieves a satisfactory balance between the increase in bit-rate and the decrease in complexity. The aforementioned percentage increase/decrease is calculated using (9). The latest work [11] incurs a 3.35% bit-rate overhead, while simultaneously saving 47.23% of RDO's time. Kindly note that this is not the overall encoding time of HEVC, but rather the time saved by the RDO module. This is highlighted as it represents the latest advancement in the field of intra-mode decision. In comparison to another recent study [12], the proposed method saves an additional 4.5% in time but incurs a 17.94% increase in bit-rate overhead. In this scenario, the proposed algorithm fails to strike a balance between the rise in bit-rate overhead and the reduction in computational complexity.

$$Change\% = \left(\frac{Value_2 - Value_1}{Value_1}\right) \cdot 100 \tag{9}$$

The comparison among the five aforementioned works is graphically presented in Fig. 10 to facilitate easy comparison. Figure 10 (a) arranges the works based on ΔB. The work [15] secured first place in this comparison by costing only 0.52% more bit rate compared to the standard HEVC work. Similarly, Fig. 10 (b) arranges the works based on ΔT. The work [11] secured first place in this comparison by saving up to 47.23% of the RDO's time. Please note that all other works in Fig. 10 have mentioned overall HEVC time savings except [11], which only mentioned the time saving of the RDO module. As the works are arranged in ascending and descending orders, respectively, it is easy to determine which work offers a better tradeoff between the increase in the bit rate overhead and the decrease in the encoding time. Although [15] achieved first place in the bit rate overhead challenge, it ranked last in time saving (refer to Fig. 10

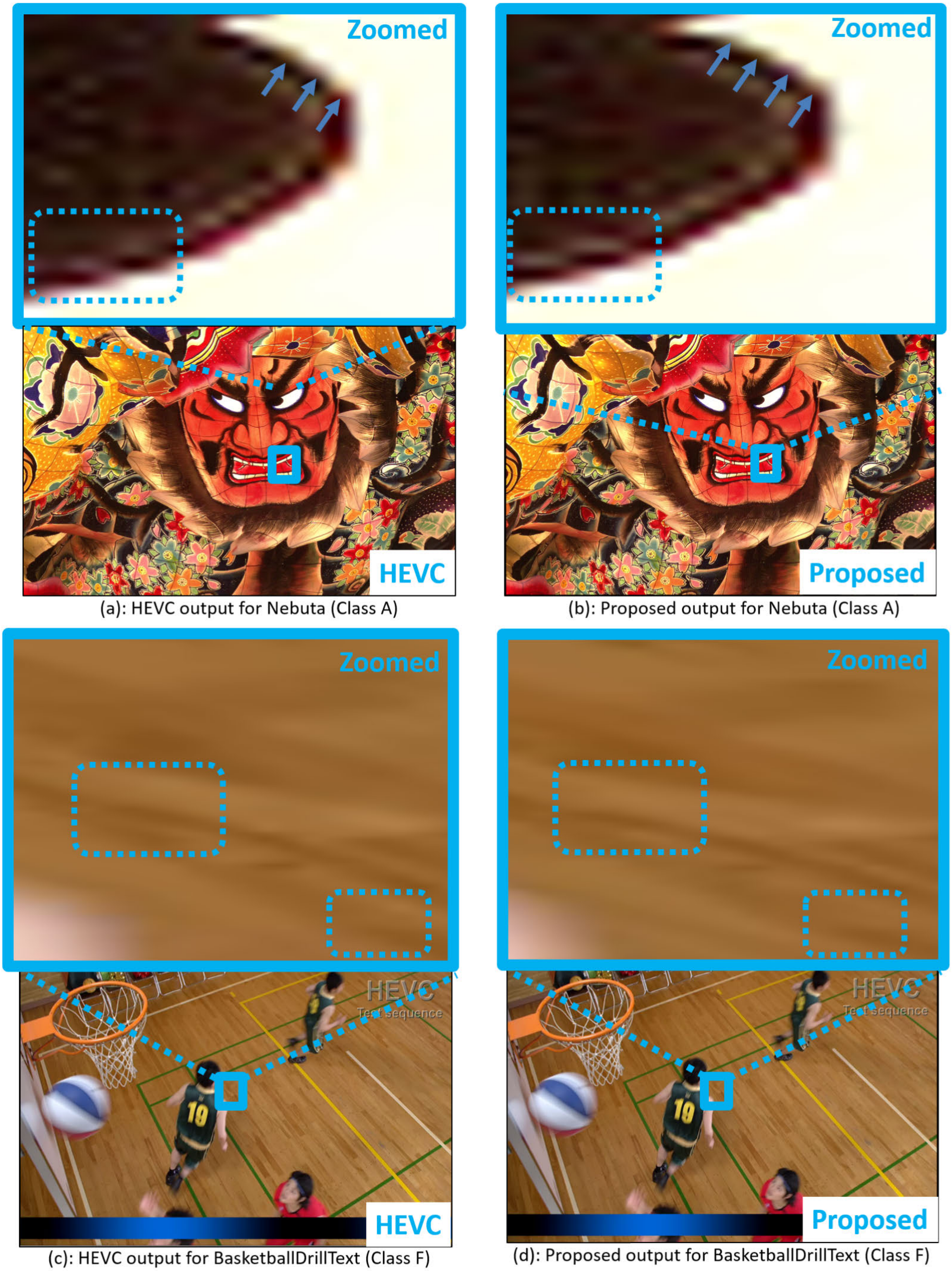
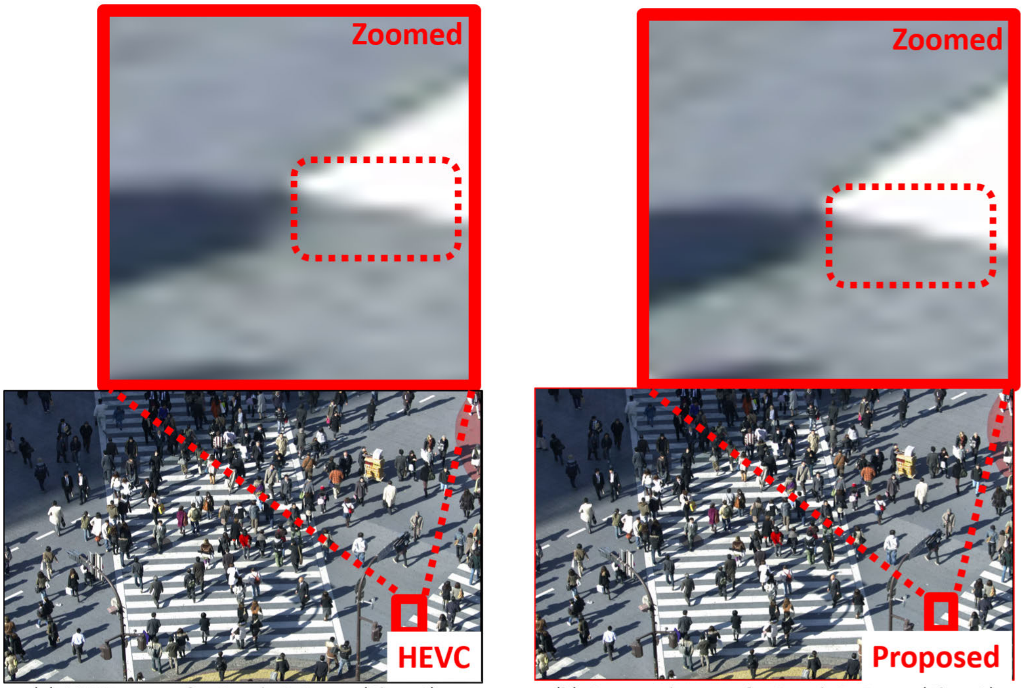


FIGURE 8. Subjective (Visual) quality of the proposed 'Skip-RDO' algorithm for BD-BR improved test videos.



(a): HEVC output for PeopleOnStreet (Class A) (b): Proposed output for PeopleOnStreet (Class A)

FIGURE 9. **Subjective quality of the proposed 'Skip-RDO' algorithm for test video whose BD-BR is not improved.**

TABLE 3. **Comparison with latest fast intra mode algorithms.**

Sequences	[15](2023)		[16] (2023)		[11] (2024)		[12] (2024)		Combine	
	ΔB	ΔT	ΔB	ΔT	ΔB	ΔT	ΔB	ΔT	ΔB	ΔT
Nebuta	-	-	-	-	1.32	37.86	0.53	35.13	0.61	36.70
Traffic	-	-	-	-	-	-	1.67	33.96	1.94	34.94
PeopleOnStreet	-	-	-	-	-	-	1.86	35.06	2.17	36.15
BQTerrace	0.71	1.51	1.53	33.44	-	-	1.34	34.44	1.52	35.87
Cactus	0.51	1.76	1.33	33.25	2.53	49.91	1.51	34.38	1.88	35.42
Kimono	-	-	-	-	-	-	1.38	33.69	1.75	34.62
BasketballDrill	0.71	1.55	2.27	28.26	-	-	1.67	32.85	1.82	34.33
RaceHorses	0.44	1.63	1.29	32.84	-	-	1.30	33.56	1.61	39.88
PartyScene	0.26	1.64	1.38	36.11	3.39	50.52	2.06	34.46	2.27	35.63
BlowingBubbles	0.19	1.46	1.19	32.16	5.96	51.41	2.03	34.31	2.47	36.88
BQSquare	0.3	1.41	2.24	33.9	-	-	1.99	34.66	2.44	37.03
BasketballPass	0.49	1.48	2.26	30.5	-	-	0.88	34.05	1.46	35.46
KristenAndSara	0.61	1.81	1.45	31.84	-	-	1.53	34.09	2.06	34.98
FourPeople	0.66	1.7	1.57	32.12	5.61	49.53	1.87	34.18	2.33	35.86
Johnny	0.89	1.71	1.68	29.58	-	-	2.03	34.13	2.12	34.71
SlideShow	-	-	3.46	33.03	-	-	1.17	33.76	0.66	34.15
ChinaSpeed	-	-	-	-	-	-	1.99	33.45	2.44	34.33
BasketballDrillText	-	-	2.29	29.96	-	-	1.14	33.43	1.54	34.65
Avg.	0.52	1.6	1.84	32.08	3.35	47.23	1.56	34.09	1.84	35.64

(b)). Similarly, [11] secured first place in the time-saving challenge, but it is the most expensive option when it comes to bit rate overhead. The proposed work secured third place in the bit rate overhead challenge, but it came in second

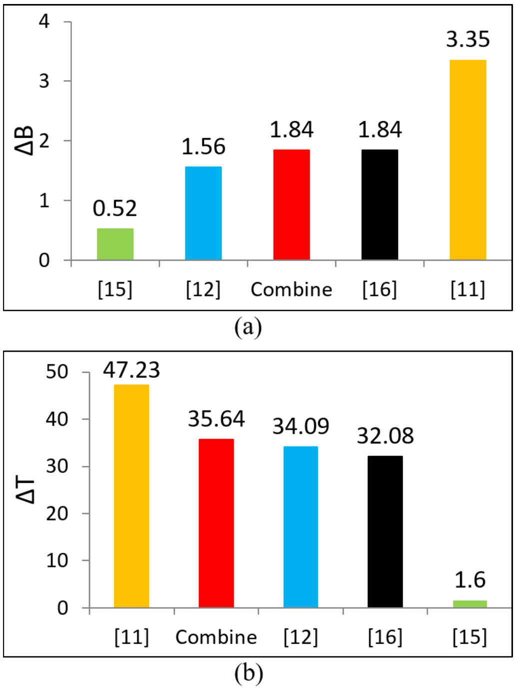


FIGURE 10. Comparison with the latest algorithms: (a) ΔB comparison, the lower the better; (b) ΔT comparison, the higher the better.

in the time-saving challenge. It might be possible that the proposed work would have secured first place in time-saving if [11] had reported the overall HEVC time-saving. The [16] secured fourth place in both comparisons. If we place it in the third place in the ΔB comparison (due to the same ΔB), it will still be in the fourth place in the ΔT comparison due to less time-saving than the proposed algorithm (*Combine*). This demonstrates that the proposed algorithm effectively strikes a sensible balance between the bit-rate overhead and the complexity reduction.

VI. DISCUSSION

The proposed algorithm presented in sub-section (IV-A), *Skip-RDO*, will be discussed here because its performance is very unique. It not only reduces the complexity of HEVC but also decreases the bit rate. Typically, the complexity reduction methods in the literature reduce the complexity of HEVC but at the expense of an increased bit rate. To comprehend this exceptional performance, we need to understand how RMD computes the Hadamard cost. The RMD module of HEVC calculates the Hadamard cost of each intra mode as [32]:

$$RMD_{pred} = SATD + \lambda_{pred} \cdot R_{pred} \tag{10}$$

where λ_{pred} is Lagrangian multiplier, SATD represents sum of absolute Hadamard transformed coefficients, and R_{pred} represents the number of bits required to represent the intra mode.

The R_{pred} is assigned using variable-length coding (VLC) scheme in HEVC to code each intra mode and differentiate between them. Since there are 35 intra modes, 6 bits will be needed to assign a unique code to each intra mode, as $log_2(5.12) = 35$. A simple example of encoding 35 intra modes using VLC (a simplified version of VLC) is shown in Table 4. In Table 4, the column named *Intra Modes* lists all the 35 intra modes in HEVC, the column named *VLC Code* assigns a unique code to each intra mode for identification, and the column named *Bits Required* indicates the number of bits the VLC Code contains or the bits needed to transmit each specific intra mode. Table 4 shows that each intra mode has an associated sending cost mentioned in the form of *Bits Required*. Table 4 also indicates that some modes have a 4-bit cost, some have a 5-bit cost, and some have a 6-bit cost. Therefore, it is possible that HEVC selects the early intra mode i from the mode list simply because it requires fewer sending bits (cost) than the j^{th} (later intra mode in the mode list) mode. This problem is addressed by the proposed model using (1), in which the j^{th} mode is given preference. As a result, BD-PSNR is improved by 0.001%. This proposed model also achieved a 5.8% time saving, indicating that the RMD module shortlists both the *i* and *j* intra modes for the computationally extensive module, i.e., RDO. The proposed model achieved time savings by selecting one intra mode between *i* and *j*, as they both have the same RMD cost.

TABLE 4. Bits requirement of intra modes.

Intra Mode	VLC Code	Bits Required
0	0000	4 bits
1	0001	4 bits
2	0010	4 bits
3	0011	4 bits
4	0100	4 bits
5	0101	4 bits
6	0110	4 bits
7	0111	4 bits
8	1000	4 bits
9	1001	4 bits
10	1010	4 bits
11	1011	4 bits
12	1100	4 bits
13	1101	4 bits
14	1110	4 bits
15	1111	4 bits
16	00000	5 bits
17	00001	5 bits
18	00010	5 bits
19	00011	5 bits
20	00100	5 bits
21	00101	5 bits
22	00110	5 bits
23	00111	5 bits
24	01000	5 bits
25	01001	5 bits
26	01010	5 bits
27	01011	5 bits
28	01100	5 bits
29	01101	5 bits
30	01110	5 bits
31	01111	5 bits
32	100000	6 bits
33	100001	6 bits
34	100010	6 bits

Consequently, not only is PSNR improved, but a 5.8% time saving is also achieved.

The limitation of this algorithm is that it cannot be further extended; that is, the maximum time saving cannot exceed 5.8%. This is because the modes with the same RMD costs are already identified, and one of them is dropped from the RDO list to save time.

VII. CONCLUSION

A novel optimization algorithm for High Efficiency Video Coding (HEVC) has been successfully developed by refining intra-mode estimation through Hadamard cost analysis. This in-depth analysis has helped uncover hidden patterns between the RMD and RDO modules to achieve efficient estimation. The proposed algorithm has shown exceptional performance by reducing the complexity of HEVC by 5.8% and improving the Bjontegaard Delta Bit Rate (BD-BR) by -0.02%. This innovative concept in fast intra-mode selection simultaneously enhances both bit rate and coding efficiency. Subjective results have also demonstrated a 0.001% improvement in BD-PSNR. Therefore, it can be integrated into future versions of HEVC as an early termination mechanism to enhance coding performance. This study is expected to contribute to the development of advanced coders with an increased number of intra-modes. Additionally, a robust mapping between the RMD and RDO modules has been established, surpassing the original HEVC platform, HM (HEVC Test Model). Similarity or dissimilarity is determined by computing the standard deviation (σ) of the Hadamard costs of the intra-modes. Early termination based on this σ is practical as it utilizes the current block's data, leading to a 35.64% reduction in HEVC complexity and an average increase of 1.84% in BD-BR.

COMPLIANCE WITH ETHICAL STANDARDS

Data Availability Statement Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Conflict of interest The author declares that there is no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by the author.

REFERENCES

[1] (2024). *Requirements for Facebook Videos*. [Online]. Available: https://www.facebook.com/business/help/1692533511105458

[2] K. Ugur, K. Andersson, A. Fuldseth, G. Bjontegaard, L. P. Endresen, J. Lainema, A. Hallapuro, J. Ridge, D. Rusanovskyy, C. Zhang, A. Norkin, C. Priddle, T. Rusert, J. Samuelsson, R. Sjoberg, and Z. Wu, "High performance, low complexity video coding and the emerging HEVC standard," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 20, no. 12, pp. 1688–1697, Dec. 2010.

[3] J. Tariq, A. Armghan, A. Ijaz, and I. Ashraf, "Light weight model for intra mode selection in HEVC," *Multimedia Tools Appl.*, vol. 80, no. 14, pp. 21449–21464, Jun. 2021.

[4] S. Yadav, P. Gulia, N. S. Gill, M. Yahya, P. K. Shukla, P. K. Pareek, and P. K. Shukla, "A video compression-cum-classification network for classification from compressed video streams," *Vis. Comput.*, vol. 40, no. 11, pp. 7539–7558, Nov. 2024.

[5] M. Yang, X. Zhou, F. Yang, M. Zhou, and H. Wang, "PIMnet: A quality enhancement network for compressed videos with prior information modulation," *Signal Process., Image Commun.*, vol. 117, Sep. 2023, Art. no. 117005.

[6] Y. Hu, C. Jung, Q. Qin, J. Han, Y. Liu, and M. Li, "HDVC: Deep video compression with hyperprior-based entropy coding," *IEEE Access*, vol. 12, pp. 17541–17551, 2024.

[7] B. Bondžulić, B. Pavlović, N. Stojanovic, V. Petrović, and D. Bujaković, "A simple and reliable approach to providing a visually lossless image compression," *Vis. Comput.*, vol. 40, no. 5, pp. 3747–3763, May 2024.

[8] Y. Jiang, R. Cui, and F. Liu, "Multi-resolutional human visual perception optimized pathology image progressive coding based on JPEG2000," *Signal Process., Image Commun.*, vol. 115, Jul. 2023, Art. no. 116960.

[9] C. Peñaranda, C. Reaño, and F. Silla, "Hybrid-smash: A heterogeneous CPU-GPU compression library," *IEEE Access*, vol. 12, pp. 32706–32723, 2024.

[10] F. Artuser and F. Özkaynak, "Chaotic quantization based JPEG for effective compression of whole slide images," *Vis. Comput.*, vol. 39, no. 11, pp. 5609–5623, Nov. 2023.

[11] P. S. Nair and M. S. Nair, "KSVM-based fast intra mode prediction in HEVC using statistical features and sparse autoencoder," *IEEE Access*, vol. 12, pp. 48846–48852, 2024.

[12] J. Tariq, M. Javed, H. Rahman, A. Armghan, and A. Ijaz, "AI application in video: Spiral optimizer based fast intra mode selection in HEVC," *Multimedia Tools Appl.*, vol. 83, no. 25, pp. 66463–66478, Jan. 2024.

[13] S. G. Ali, C. Zhang, Z. Guan, T. Chen, Q. Wu, P. Li, P. Yang, Z. Ghazanfar, Y. Jung, Y. Chen, B. Sheng, Y.-C. Tham, X. Wang, and Y. Wen, "AI-enhanced digital technologies for myopia management: Advancements, challenges, and future prospects," *Vis. Comput.*, vol. 40, no. 6, pp. 3871–3887, Jun. 2024.

[14] B. Qian, H. Chen, Y. Xu, Y. Wen, H. Li, Y. Xie, D. D. Feng, J. Kim, L. Bi, X. Xu, X. He, and B. Sheng, "Deep contour attention learning for scleral deformation from OCT images," *Vis. Comput.*, vol. 2, pp. 1–16, May 2024.

[15] A. Feng, K. Liu, D. Liu, L. Li, and F. Wu, "Partition map prediction for fast block partitioning in VVC intra-frame coding," *IEEE Trans. Image Process.*, vol. 32, pp. 2237–2251, 2023.

[16] Z. Liu, T. Li, Y. Chen, K. Wei, M. Xu, and H. Qi, "Deep multi-task learning based fast intra-mode decision for versatile video coding," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 1, no. 1, pp. 1–19, Apr. 2023.

[17] L.-L. Wang and W.-C. Siu, "Novel adaptive algorithm for intra prediction with compromised modes skipping and signaling processes in HEVC," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 23, no. 10, pp. 1686–1694, Oct. 2013.

[18] J. Tariq, "Intra mode selection using classical secretary problem (CSP) in high efficiency video coding (HEVC)," *Multimedia Tools Appl.*, vol. 78, no. 22, pp. 31533–31555, Nov. 2019.

[19] Z. Liang, L. Zhang, S. Ma, and D. Zhao, "Fast mode decision algorithm for intra prediction in HEVC," *Visual Communications Image Processing*, vol. 1, pp. 1–4, Apr. 2011.

[20] K.-Y. Liao, J.-F. Yang, and M.-T. Sun, "Rate-distortion cost estimation for H.264/AVC," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 20, no. 1, pp. 38–49, Jan. 2010.

[21] C.-H. Yeh, M.-F. Li, M.-J. Chen, M.-C. Chi, X.-X. Huang, and H.-W. Chi, "Fast mode decision algorithm through inter-view rate-distortion prediction for multiview video coding system," *IEEE Trans. Ind. Informat.*, vol. 10, no. 1, pp. 594–603, Feb. 2014.

[22] P. Wang, C. Ni, G. Zhang, and K. Li, "R-lambda model based CTU-level rate control for intra frames in HEVC," *Multimedia Tools Appl.*, vol. 78, no. 1, pp. 125–139, Jan. 2019.

[23] T. Zhang, M.-T. Sun, D. Zhao, and W. Gao, "Fast intra-mode and CU size decision for HEVC," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 27, no. 8, pp. 1714–1726, Aug. 2017.

[24] E. Hosseini, F. Pakdaman, M. R. Hashemi, and M. Ghanbari, "A computationally scalable fast intra coding scheme for HEVC video encoder," *Multimedia Tools Appl.*, vol. 78, no. 9, pp. 11607–11630, May 2019.

[25] G. Daehyeok and H. Choi, "Relative SATD based minimum risk Bayesian framework for fast intra decision of HEVC," *KSII Trans. Internet Inf. Syst.*, vol. 13, no. 1, pp. 1–20, 2019.

[26] J. Tariq, "High-performance intra-mode accelerator for HEVC," *Vis. Comput.*, vol. 36, no. 8, pp. 1603–1617, Aug. 2020.

[27] J. Tariq, A. Armghan, A. Ijaz, and I. Ashraf, "Pure intra mode decision in HEVC using optimized firefly algorithm," *J. Vis. Commun. Image Represent.*, vol. 68, Apr. 2020, Art. no. 102766.
[28] Y. Wang and Z. Su, "An efficient intra prediction algorithm for HEVC intra-coding," in *Proc. 13th Int. Congr. Image Signal Process., Biomed. Eng. Informat. (CISP-BMEI)*, Oct. 2020, pp. 407–412.
[29] (2023). *HEVC Test Model*. [Online]. Available: https://hevc.hhi.fraunhofer.de/Accessed
[30] B. Frank, *Common Test Conditions and Software Reference Configurations*, document JCTVC-F900, 2011.
[31] B. Gisle, *Calculation of Average PSNR Differences Between RD-curves*, document VCEG-M33, 2001.
[32] C. Rosewarne, B. Bross, M. Naccari, K. Sharman, and G. Sullivan, *High Efficiency Video Coding (HEVC) Test Model 16 (HM 16) Improved Encoder Description Update 5*, Standard ISO/IEC JTC1/SC29/WG11 N16048, 2016.

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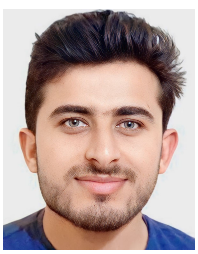

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