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Spatial-Temporal Correlation Based Fast Intra Mode Decision for HEVC

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Abstract. *In high efficiency video coding (HEVC), up to 35 intra prediction modes are adopted to improve encoding performance. However, large numbers of modes lead to increased coding complexity inevitably, which hinders the promotion of HEVC in real-time environment. To reduce the encoding complexity, a spatial-temporal correlation based fast intra mode decision algorithm is proposed in this paper. Herein, the rough mode decision (RMD) candidate list and the rate distortion optimization (RDO) candidate list are narrowed respectively by strong spatial correlation and temporal correlation between prediction units (PUs). For RMD, the proposed algorithm early determines the impossible range of the PU optimal mode in line with spatial correlation, which would narrow RMD candidate list and speed up RMD process. For RDO, the proposed algorithm tries to combine temporal correlation with intra coding to simplify RDO candidate list and save RDO time consuming. Experimental results demonstrate that the proposed algorithm yields average 28.64% encoding time reduction with 1.19% BDBR gain or 0.06dB BDPSNR loss compared with HM16.9. The proposed algorithm drives HEVC coding efficiency under real-time environments.*
Keywords: HEVC; Video coding; Spatial-temporal correlation; Mode decision

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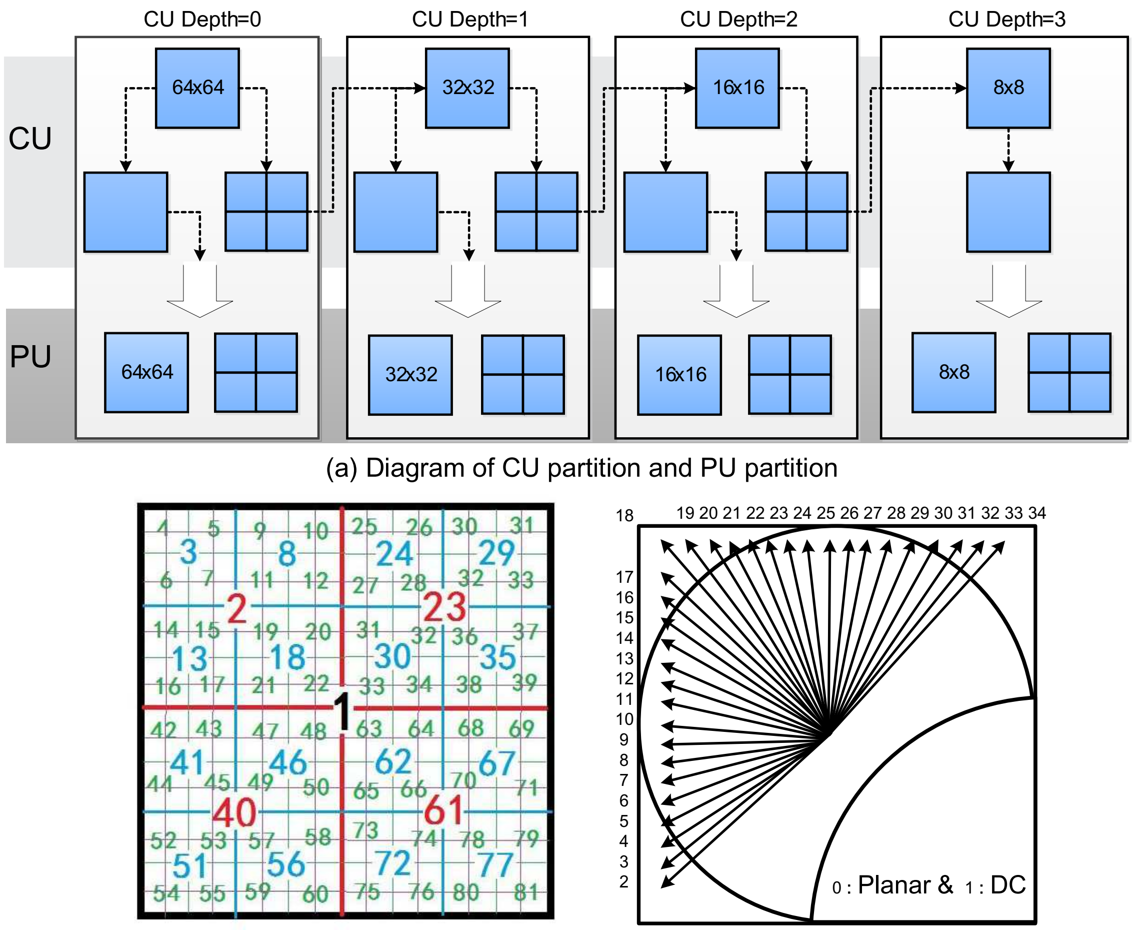
1. **Introduction.** Since the popularity of video application, high-definition and ultra-high-definition video technologies have rapidly evolved in recent years. The amount of video data has explosively increased, which has brought serious challenge for video storage. Therefore, with the condition of limited storage resources, the high efficiency video coding (HEVC) standard [1] has been developed by the Joint Collaborative Team on Video Coding (JCT-VC). As an upgrade for H.264/AVC [2], HEVC achieves 50% bitrate reduction [3] under the equivalent visual quality. For intra coding, the excellent advances in coding performance mainly profit from the employment of flexible quad-tree coding partitioning structure and fine multi-angle prediction mode. It allows coding unit (CU) to be adaptively selected with depth from 0 to 3 in each coding tree unit (CTU), corresponding to CU size of 64×64, 32×32, 16×16, 8×8 as shown in Figure 1. Especially, the smallest CU can be further divided into four prediction units (PUs) for intra prediction. In order to get the best CTU partition, all quad-tree nodes will be traversed. For each

node, 35 intra prediction modes will also be traversed to get optimal prediction mode erenow.



(a) Diagram of CU partition and PU partition

(b) Orderof CU partitionin each CTU

(c) Intra prediction modes

FIGURE 1. A complete CTU partition

However, it is accompanied by greatly increased coding complexity. To reduce coding complexity, rough mode decision (RMD) is introduced to intra prediction before rate distortion optimization (RDO) process for HEVC. In RMD process, 35 intra prediction modes are checked to get M candidate modes based on sum of absolute transformed differences (SATD) cost. M is defined by PU size, which is set to {8, 8, 3, 3, 3} for 4×4, 8×8, 16×16, 32×32 and 64×64 respectively. Furthermore, most probable modes (MPMs) are composed by prediction modes of left and above PUs to optimize RDO process. The RDO candidate list consists of M candidate modes and MPMs, which avoids the rate distortion (RD) cost computation of all 35 intra prediction modes. But all 35 intra prediction modes will be traversed with SATD. And it still needs to be calculated at least 2623 (1×3+4×3+16×3+64×8+256×8=2623) RD costs for each CTU, where the RD cost calculations of small size (4×4, 8×8) PUs up to 2560, accounting for 95.8% of the total RD operation at least. This process takes over 90% complexity of the entire encoding, which hinders the promotion of HEVC in real-time environment.

Therefore, various fast intra mode decision algorithms have been carried out to reduce coding computation in RMD and RDO respectively.

The fast intra mode decision algorithms for RMD can be classified into two categories. First, some researchers focus on fast mode decision guided by image analysis techniques

[4-11]. Shi et al. [4-9] analyze PU texture direction by calculating its gradient characteristic. Based on this, the RMD candidate modes are reduced and then RMD process is accelerated. Zhu [10] and Ramezanpour [11] delve into the relationship between sum of absolute difference (SAD) and SATD. Further, they take advantage of SAD to limit the number of candidate modes in RMD, thereby alleviating PU mode decision complexity. Although the above algorithms shorten time for intra mode decision, the analysis of gradient or SAD inevitably consumes additional time in encoding. Second, other researchers make full use of the spatial correlation between PUs to accelerate RMD process in intra mode decision [12-16]. Kumar et al. [12-15] narrow the search scope of PU modes in line with the optimal mode of space adjacent (left and above) PUs. Lu [16] finds that there is a stronger correlation between the current PU and its parent PU. And they utilize the optimal and suboptimal modes of the parent PU to accelerate RMD process of the current PU. Experimental results show that this algorithm achieves better performance than the algorithm based on left and above PUs. However, the fast algorithms based on parent PU have not been sufficiently explored. Thus how to utilize parent PU efficiently for speeding up current PU mode decision remains to be further studied.

Based RDO acceleration fast intra mode decision algorithms can also be divided into two categories. On the one hand, various research studies center on distortion cost function [17-20]. Saurty et al. [17-19] take full account of the correlation between SATD cost and RD cost, further compare SATD cost with the corresponding threshold. Based on this, the larger SATD modes are removed and the RDO candidate list is simplified. Tian [20] sets the threshold according to RD cost of the encoded modes, which is compared with the RD cost of the current mode to decide whether to early terminate PU mode decision. The key to the above algorithms lies in the threshold. For diverse video sequences and variable quantization parameter (QP), the threshold must be inconsistent. However, these algorithms only consider single factor to set threshold. The robustness of these algorithms is weak, which leads to reduce mode decision complexity at the expense of huge RD performance loss. On the other hand, some researchers accelerate RDO process based on data statistics. According to the data statistics, Yao et al. [5] [8] [20] directly add the N ($N<M$) modes of minimum SATD to the RDO list for speeding up RDO process. However, the above algorithms only focus on statistic information and neglect other relevant information such as temporal correlation between frames. The preliminary experimental results show that the similarity between the current PU optimal mode and co-located optimal mode of the previous frame is larger. The RD performance may be improved if the co-located optimal mode of the previous frame is added to the RDO candidate list. But there are few studies in this area.

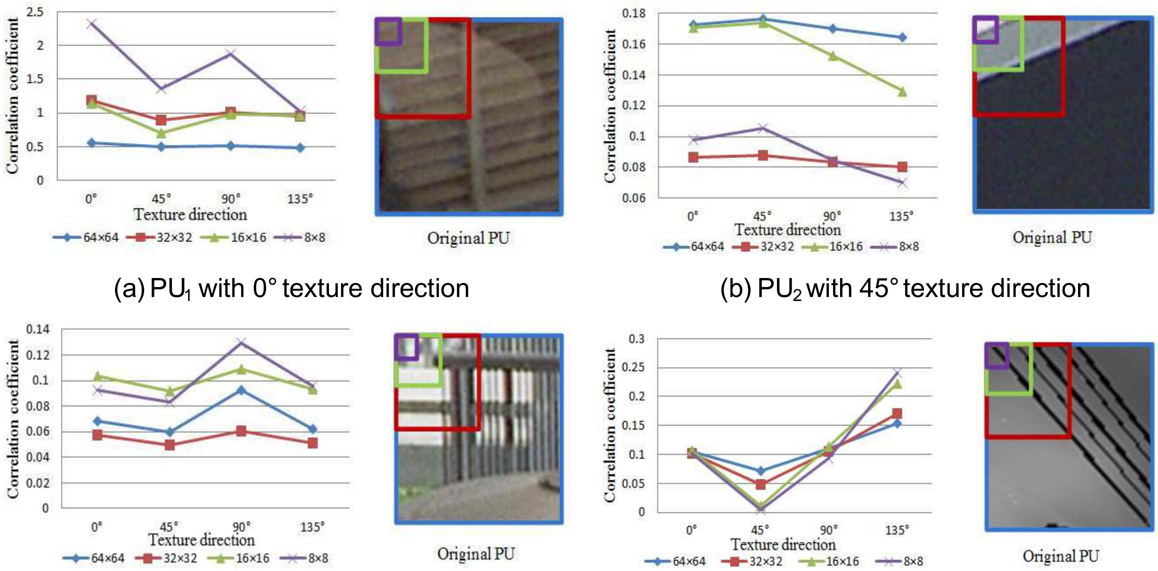
To sum up, spatial correlation and temporal correlation between PUs are introduced to intra mode decision based on the above analysis in this paper. A spatial-temporal correlation based fast intra mode decision algorithm is proposed. For RMD and RDO, the proposed algorithm starts with spatial correlation and temporal correlation between PUs to speed up intra mode decision.

The remainder of the paper is organized as follows. Section 2 further analyzes spatial-temporal correlation of video sequences and the principle of the proposed algorithm is clarified in Section 3. Section 3 also provides the proposed algorithm in detail. Extensive experimental results are presented and illustrated in Section 4, followed by the conclusion in Section 5.

2. **Spatial-Temporal Correlation Analysis of Video Sequences.** To get the optimal prediction mode for each PU, 35 intra prediction modes are traversed in RMD and

3 RD costs are calculated at least in RDO. But it is unnecessary to traverse all prediction modes due to strong spatial-temporal correlation in video sequences. Based on the correlation, the optimal prediction mode could be fast decided by narrowing the RMD candidate list and the RDO candidate list.

2.1. **Spatial Correlation Analysis.** Previous studies have shown that there is a correlation between spatial neighboring PUs (the current PU and its parent PU) in texture [16]. Herein the correlation is further proved. The texture similarity between the current PU and its parent PU is measured by gray level co-occurrence matrix. As shown in Figure 2, 4 typical PUs are adopted for the experiment, where the y-axis and the x-axis represent the texture correlation coefficient and the texture direction respectively. The larger the texture correlation coefficient, the closer the texture direction is to the texture direction corresponding to the correlation coefficient. Experimental results show that the texture directions of the current PU and its parent PU are basically consistent, which being a strong theoretical support for fast mode decision algorithm based on spatial correlation. Then how to utilize the spatial correlation becomes the key of the fast mode decision algorithm.



(a) PU_1 with 0° texture direction

(b) PU_2 with 45° texture direction

(c) PU_3 with 90° texture direction

(d) PU_4 with 135° texture direction

Figure 2. Texture correlation between spatial neighboring PUs

2.2. **Temporal Correlation Analysis.** For inter coding, the temporal correlation is exploited to improve video compression performance due to temporal continuity of the video sequences [1]. The temporal continuity is an inherent characteristic of video sequences, without being considered by intra coding. Therefore, the temporal correlation is prone to be introduced into intra coding. According to the above knowledge, there is the following conjecture: the similarity between the current PU optimal mode and co-located optimal mode of the previous frame would be high. Preliminary experimental results just confirm this conjecture by setting HEVC test video sequence "BasketballPass" as an example, as shown in Figure 3. For the best CTU partition, PUs with same optimal prediction modes in adjacent frames take up large parts of the entire frame, which are covered with red. Further, extensive HEVC test video sequences (Class A-Class F) are tested for data statistics. Statistics show that the probability is up to 31.4%, which the current PU optimal mode is the same as co-located optimal mode of the previous frame in CTU partition process. Thus how to effectively utilize co-located optimal mode of the previous frame becomes another key to the fast mode decision algorithm.

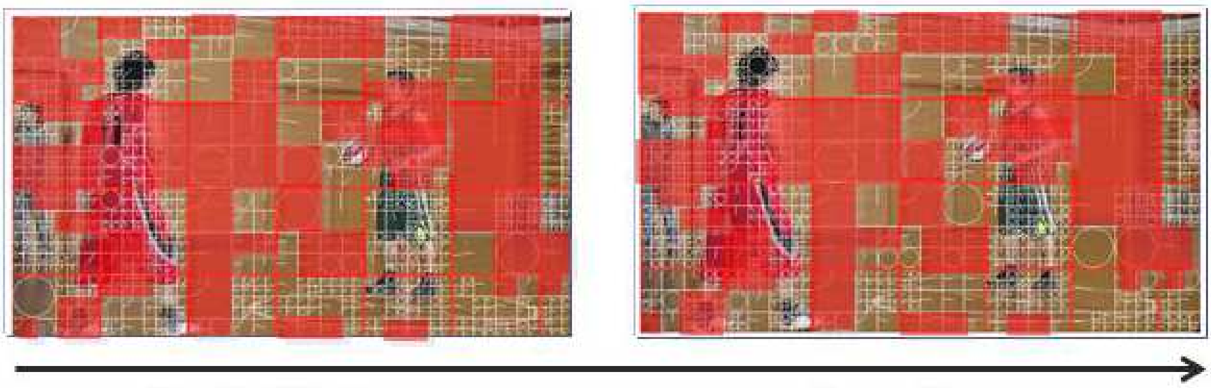


FIGURE 3. Adjacent frames of "BasketballPass" sequence

3. **Spatial-Temporal Correlation Based Fast Intra Mode Decision.** In view of strong spatial correlation and temporal correlation in video sequences, the spatial-temporal correlation based fast intra mode decision is proposed to early narrow RMD or RDO candidate list and improve intra coding performance herein. The principle and main-process stream for proposed algorithm are as following.

3.1. **Principle for Proposed Algorithm.**

- **Principle 1.** For RMD, the proposed algorithm early determines the impossible range of the PU optimal mode in line with spatial statistical analysis theory [21], which the correlation is related to the distance for data and the correlation among remote data is weak. It would narrow RMD candidate list and speed up RMD process. First, 33 directional prediction modes are divided into 4 subsets (Sb1, Sb2, Sb3 and Sb4) as shown in Figure 4. Sb1 and Sb3 (Sb2 and Sb4) are the farthest away from each other. And then, on the basis of spatial statistical analysis theory, the impossible range of the parent PU optimal mode would be judged by its known optimal mode. Further, low probability subsets of current PU are removed based on spatial correlation between the current PU and its parent PU. Last candidate subsets are determined for current PU. Specific principles are as follows, where $\text{Mode}_{ParBest}$ and $\text{Mode}_{CurBest}$ are the parent PU optimal mode and the current PU optimal mode respectively.
  1. If $\text{Mode}_{ParBest} \in$Sb1, $\text{Mode}_{CurBest} \in$Sb1, Sb2 or Sb4;
  2. If $\text{Mode}_{ParBest} \in$Sb2, $\text{Mode}_{CurBest} \in$Sb1, Sb2 or Sb3;
  3. If $\text{Mode}_{ParBest} \in$Sb3, $\text{Mode}_{CurBest} \in$Sb2, Sb3 or Sb4;
  4. If $\text{Mode}_{ParBest} \in$Sb4, $\text{Mode}_{CurBest} \in$Sb1, Sb3 or Sb4;

  To validate the feasibility of the above rule, 6 class HEVC test video sequences are adopted to count the probability that the optimal mode belongs to different mode sets. Experimental results are shown in TABLE 1, where S= {Mode sets based on the above rule, MPMs, Planar, DC}, S1= {MPMs, Planar, DC}, S2= {MPMs}, S3= {Planar, DC}. P, P1, P2, and P3 denote the probability of the optimal prediction mode belonging to S, S1, S2 and S3 respectively. As shown in TABLE 1, P is

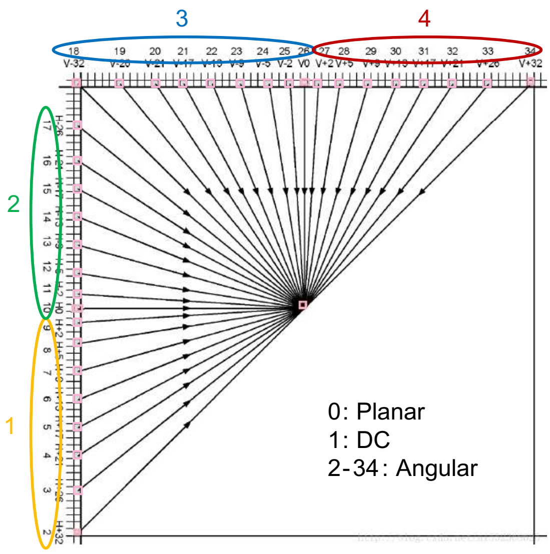


Figure 4. Candidate modes of RMD and subset method

the maximum, which is up to 97.96%. Besides, preliminary experimental results show that this method yields average 15.4% encoding time reduction for RMD. The experimental results powerfully support the above rule and the algorithm of spatial correlation based fast intra mode decision in theory.

Table 1. Prpbabilty of the optimal mode belonging to different mode sets

Class	P (%)	P1 (%)	P2 (%)	P3 (%)
ClassA	97.21	79.18	68.26	41.55
ClassB	99.26	89.95	83.48	40.82
ClassC	95.72	77.24	64.75	44.12
ClassD	97.62	80.43	71.23	32.26
ClassE	98.27	85.01	77.78	34.67
ClassF	99.68	97.70	96.83	55.52
Average	97.96	84.92	77.06	41.49

- **Principle 2.** For RDO, some algorithms [5] [8] [20] directly add the N modes of minimum SATD to the RDO list for speeding up RDO process, without considering temporal correlation in frames. Based on this, the proposed algorithm tries to combine temporal correlation with intra coding, which adds co-located optimal mode of the previous frame into the RDO list of the current PU. At the same time, the modes in RDO list are decreased focusing on most time-consuming PUs (4×4 PUs, 8×8 PUs). To ensure mode number in RDO list, the following statistics is made. TABLE 2 and TABLE 3 respectively summarize the probability that the current

PU optimal mode belongs to S_t (N) = {N modes of minimum SATD, MPMs} and S_t' (N) = {Co-located optimal mode of the previous frame, N modes of minimum SATD, MPMs}, where Pt1 to Pt4 and Pt1' to Pt4' corresponding to S_t (N) and S_t' (N), N=1, 2, 3, 4.

Table 2. The probability that the current PU optimal mode belongs to S_t

Class	Pt1 (%)	Pt2 (%)	Pt3 (%)	Pt4 (%)
ClassA	86.55	92.48	95.33	96.63
ClassB	93.92	96.99	98.52	98.96
ClassC	83.16	89.66	93.02	94.93
ClassD	86.13	92.62	95.62	96.85
ClassE	88.66	95.15	97.03	97.81
ClassF	99.98	99.99	100.00	100.00
Average	89.73	94.48	96.59	97.53

Table 3. The probability that the current PU optimal mode belongs to S_t'

Class	Pt1' (%)	Pt2' (%)	Pt3' (%)	Pt4' (%)
ClassA	88.75	93.55	95.97	97.08
ClassB	94.85	97.37	98.70	99.08
ClassC	85.08	90.62	93.65	95.40
ClassD	89.40	93.98	96.34	97.36
ClassE	93.55	96.28	97.69	98.30
ClassF	99.98	100.00	100.00	100.00
Average	91.94	95.30	97.06	97.87

As shown in TABLE 2 and TABLE 3, the average probability could be over 97% for St (4) and St' (3). Furthermore, another experimental result show that the latter achieves average 8.29% time reduction with little difference in probability compared with the former, because co-located optimal mode of the previous frame may be in N modes of minimum SATD or MPMs, and the same mode is not calculated repeatedly. Therefore, the latter get better performance than the former. And St' (3) will be adopted in the proposed algorithm.

3.2. **The Flow Char.** Figure 5 draws the flow chart that the algorithm of spatial-temporal correlation based fast intra mode decision. In the first stage, the possible sets of the current PU optimal mode are determined based on corresponding rules. Then, the narrowed RMD list is achieved. Further, SATD cost of the modes in the narrowed RMD list is calculated preparing for RDO stage. In the second stage, RDO list is narrowed in line with temporal correlation and data statistics. Last, the optimal prediction mode is got by RDO cost calculation.

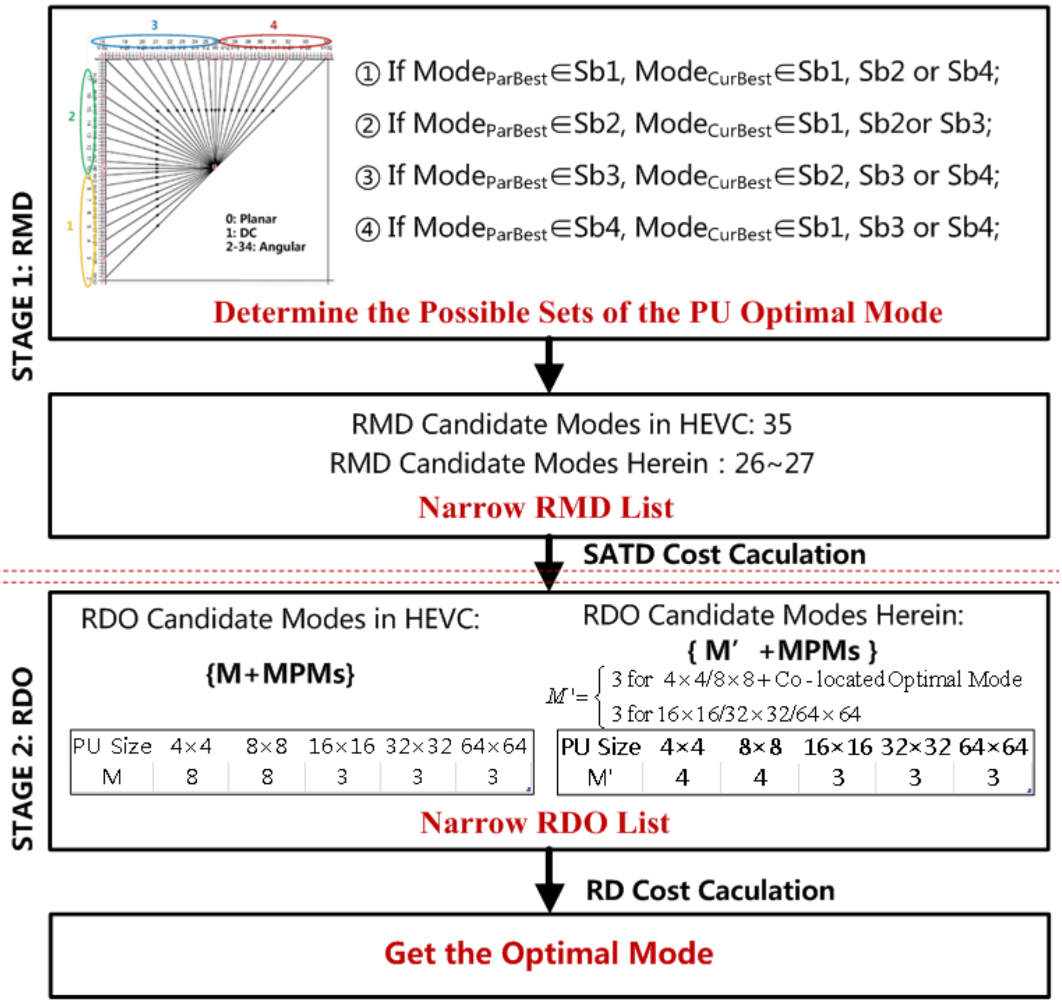


FIGURE 5. The flow chart of the proposed method

4. **Performance Evaluation.** The proposed algorithm is implemented in HEVC test model version 16.9 (HM 16.9) under all intra coding mode. To evaluate the performance of the proposed algorithm, extensive test video sequences are adopted from 416×240 to 2560×1600 with varying QPs at 22, 27, 32 and 37. Other encoder parameters are configured as the HEVC common test conditions by JCT-VC.

In order to validate gain or loss of the proposed algorithm, BDBR and BDPSNR [22] are calculated to testify the RD performance. Meanwhile, the saving time is measured by formula (1).

$$\Delta T(\%) = \frac{EncodingTime_{proposed} - EncodingTime_{HM16.9}}{EncodingTime_{HM16.9}} \tag{1}$$

The experimental results are as shown in TABLE 4. Compared with HM 16.9, the proposed algorithm yields average 28.64% encoding time reduction with 1.19% BDBR gain or 0.06dB BDPSNR loss. For most video sequences, the encoding performance is equivalent. The experimental results prove that the algorithm is suitable for most video sequences, which has strong universality.

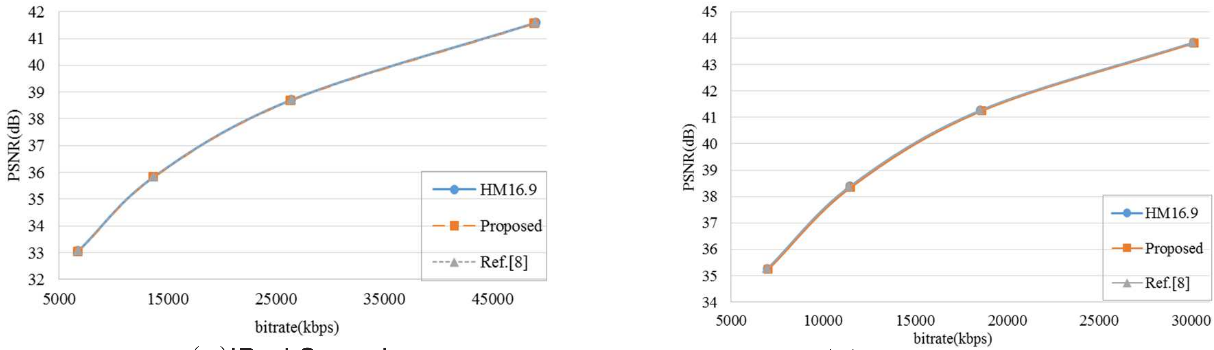
To further assess the performance of the proposed algorithm, reference [8] is tested for comparison. As shown in TABLE 4, the proposed algorithm achieves 13.14% time reduction with little RD performance loss. Figure 6 intuitively demonstrates the RD curves under different algorithms for ParkScene sequence and "FourPeople"' sequence. As shown in Figure 6, the RD curves of different algorithms are basically coincident, which further testifies that RD performance loss is negligible. What's more, comparison of the time saving between different algorithms is revealed in Figure 7. The proposed algorithm achieves more time reduction, because the fast algorithm based on spatial-temporal correlation avoids additional computation compared with the algorithm guided by image analysis techniques.

In brief, the proposed fast intra mode decision algorithm effectively reduces encoding time by narrowing RMD list and RDO list with spatial-temporal correlation between PUs, which makes HEVC convenient to real-time application.

Table 4. Performance of proposed algorithm compared with similar algorithms under HM16.9

Class (Resolution)	Sequence	Proposed			Ref. [8]		
		BDBR (%)	BDPSNR (dB)	ΔT (%)	BDBR (%)	BDPSNR (dB)	ΔT (%)
Class A (2560 1600)	PeopleOnStreet	1.11	-0.06	-28.00	0.03	-0.01	-15.50
	Traffic	0.90	-0.05	-30.30	0.01	-0.02	-18.46
Class B (1920 1080)	ParkScene	0.53	-0.02	-30.81	0.01	-0.01	-17.18
	BasketballDrive	0.98	-0.02	-26.60	0.02	-0.08	-11.88
Class C (832 480)	BasketballDrill	2.30	-0.11	-28.21	0.02	-0.01	-18.85
	RaceHorses	1.34	-0.09	-27.99	0.05	-0.02	-12.08
Class D (416 240)	BasketballPass	0.90	-0.05	-27.12	0.01	-0.01	-13.36
	RaceHorses	1.87	-0.12	-28.45	0.17	-0.01	-12.54
Class E (1280 720)	Johnny	0.93	-0.04	-28.10	0.03	-0.08	-15.87
	FourPeople	1.02	-0.06	-29.18	0.02	-0.05	-16.40
Class F (1280 720)	SlideShow	1.25	-0.07	-30.22	0.06	-0.01	-18.33
Average		1.19	-0.06	-28.64	0.04	-0.03	-15.50

5. **Conclusions.** In view of strong spatial correlation and temporal correlation in video sequences, the spatial-temporal correlation based fast intra mode decision is proposed by narrowing the RMD candidate list and the RDO candidate list respectively. Herein, spatial statistical analysis theory and inter coding idea are originally introduced to intra coding, from which the spatial-temporal correlation between PUs is refined. For RMD, the proposed algorithm early determines the impossible range of the PU optimal mode in line with spatial correlation, which would narrow RMD candidate list and speed up RMD process. For RDO, the proposed algorithm tries to combine temporal correlation with intra coding to simplify RDO candidate list and save RDO time consuming. Experimental results demonstrate that the proposed algorithm yields average 28.64% encoding time reduction with 1.19% BDBR gain or 0.06dB BDPSNR loss compared with HM16.9. Further



(a)'ParkScene' (b)'FourPeopl'

FIGURE 6. Comparison of the R-D performance

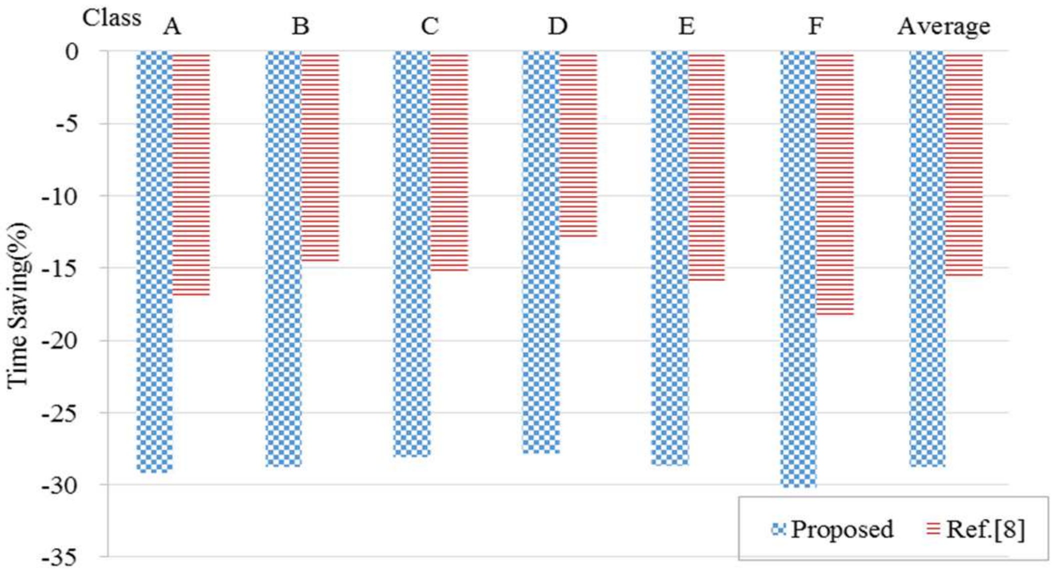


FIGURE 7. Comparison of the time saving

compared with another advanced algorithm, the proposed algorithm achieves 13.14% time reduction with little RD performance loss. In a word, the proposed algorithm promotes HEVC to be used in real-time video communication systems.

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