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Predicting Split Decisions of Coding Units in HEVC Video Compression Using Machine Learning Techniques

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Abstract In this work, we propose to reduce the complexity of HEVC video encoding by predicting the split decisions of coding units. We use a sequence-dependent approach in which a number of frames belonging to the video being encoded are used for generating a classification model. At each coding depth of the coding units, features representing the coding unit at that particular depth are extracted from both the present and previously encoded coding units. The feature vectors are then used for generating a dimensionality reduction model and a classification model. The generated models at each coding depth are then used to predict the split decisions of subsequent coding units. Stepwise regression, random forest reduction and principal component analysis are used for dimensionality reduction; whereas, polynomial networks and random forests are utilized for classification. The proposed solution is assessed in terms of classification accuracy, BD-rate, BD-PSNR and computational time complexity. Using seventeen video sequences with four different classes of resolution, an average classification accuracy of 86.5% is reported for the proposed classification system. In comparison to regular HEVC coding, the proposed solution resulted in a BD-rate loss of 0.55 and a BD-PSNR of -0.02 dB. The average reported computational complexity reduction is found to be 39.2%.

Keywords HEVC; Pattern recognition; Video compression.

1 Introduction

The High Efficiency Video Coding (HEVC) standard is one of the successors of the well-known MPEG-4 AVC (H.264 or MPEG-4 Part 10). It is designed to target various applications, especially those dealing with Ultra High Definition (HD) content. The HEVC project was formally initiated when a joint Call for Proposals was issued by the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG) in January 2010 [1]. The prime focus was directed towards significantly improving the compression performance relative to existing standards.

After its completion in January 2013, the HEVC standard provides twice the compression capabilities as that offered by its predecessor. Given that the appropriate encoder settings are used, around 50% bit-rate reduction is possible, while maintaining minimal video quality level loss [2].

However, this coding efficiency is introduced at the cost of increasing the encoding computational complexity, which can reach up to 40% more than that of H.264/AVC [3].

Among other factors, both the enhanced compression efficiency and the increased encoding computational complexity can be attributed to HEVC's usage of flexible partitioning structures. HEVC uses quad-tree Coding Tree Units (CTUs), Prediction Units (PUs), and Residual Quad-Trees (RQTs) rather than macroblocks (MBs). In order to achieve the best configuration in terms of selecting the optimal partitioning structure, an exhaustive rate-distortion optimization (RDO) process takes place, which is the main reason behind the intensification of the computational complexity. Most of the encoding time involves recursively repeating the RDO process at each Coding Unit (CU) depth level for each structure, where every combination of encoding structure is tested and the one that minimizes the rate-distortion (RD) cost is chosen [4].

Several early termination algorithms for optimizing the encoding process in HEVC can be found in the literature, where their aim is to reduce the computational complexity while any minimizing performance degradation. Among many, some approaches utilize the textural or structural characteristics of a given CU [5]-[15], while others use machine learning techniques [16]-[25]. The optimizations are not limited to HEVC inter-coding as some also considered enhancing intra-coding [11], [12], [14], and [16]. In this field of research, utilizing machine learning techniques as a tool to minimize RD efficiency losses is limited, and most algorithms proposed do not achieve superior results in terms of computation complexity reduction without introducing significant video quality level losses.

In this work, we use a sequence-dependent approach to model the relationship between CU feature variables and split decisions. The feature variables are extracted from both the present CU and its surrounding spatial and temporal CUs. Additionally, we use dimensionality reduction techniques for

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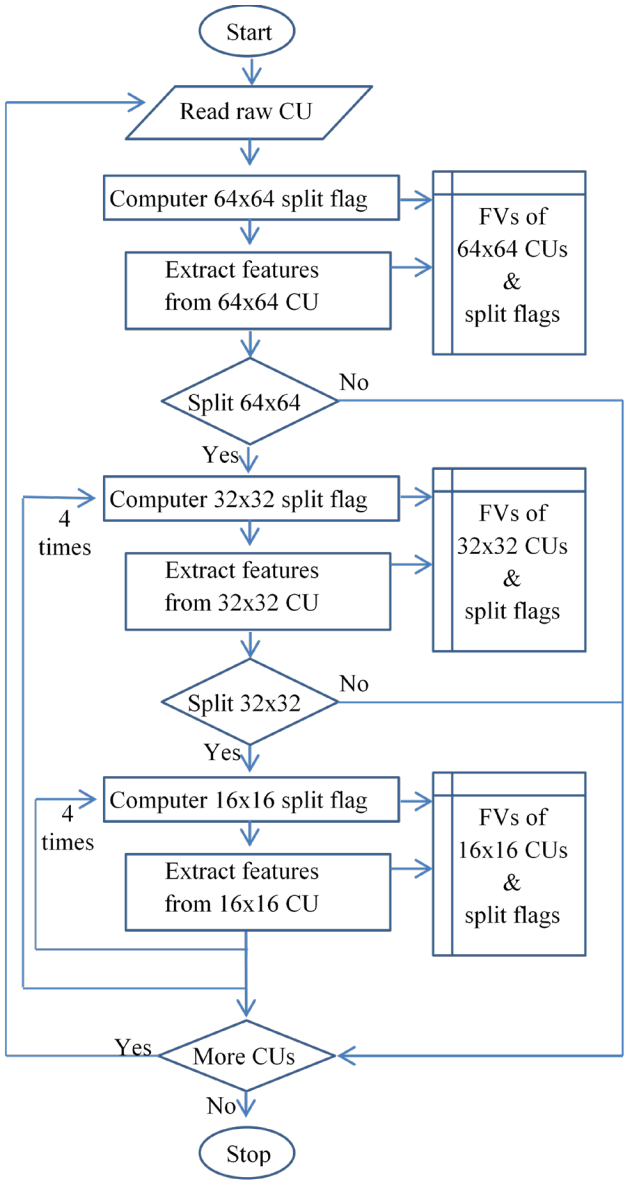

Fig. 1. Flowchart of data collection during the training phase.

the three CU depths of 64x64, 32x32 and 16x16. This is needed to reduce the number of extracted features. The feature extraction and modeling is also performed at three CU coding depths. We use stepwise regression, random forest reduction and principal component analysis (PCA) for dimensionality reduction. Moreover, we utilize polynomial networks and random forests for classification.

This paper is organized as follows. Section 2 presents a review of algorithms proposed in the literature that are reduced the encoding computational complexity. The overall CU split prediction system proposed is overviewed in Section 3. The feature extraction process and dimensionality reduction are discussed in detail in Section 4 in addition to the classification tools and arrangements used in this work. The experimental setup and experimental results are presented in Section 5. Lastly, Section 6 concludes the paper.

2 Related Work

As mentioned earlier, HEVC introduced significant coding efficiency improvements at the cost of increasing the computational complexity. Therefore, existing research work is conducted to limit this computational complexity whilst minimizing the adverse effect on compression efficiency. The work reported in [5]-[15] investigated the textural or structural characteristics of CUs at a given CU depth to optimize the HEVC encoding procedure. [5] proposed an inter-prediction optimization scheme, where the CTU structure is analyzed in a reverse order. Alternatively, a subjective-driven complexity control approach is presented in [6], which examines the relationship between visual distortion and maximum depth of all largest CUs. Another complexity control algorithm is proposed in [7], where an early termination condition is defined at each CU depth based on the content of the video sequence being encoding, the configuration files and the target complexity.

In [8], the authors present a hierarchical structure-based fast mode decision scheme. A fast CU decision algorithm is presented in [9], where the coded block flag and RD costs are checked to determine if intra- and inter- PUs can be skipped. In [10], a two-layered motion estimation based fast CU decision process is proposed, which uses the sum of absolute differences (SAD) estimation to extract the SAD costs for a CU and its sub-CUs. [11] speeds up the HEVC intra-coding process mainly by using encoded CU depths and RD costs of co-located CTU to predict both the current CU's depth search range and the RD cost for CU splitting termination. Local texture descriptors or image characteristics were used in [12]- [14] to allow faster CU size selection. A spatiotemporal based CU encoding technique is explored in [15], where sample-adaptive-offset (SAO) parameters were utilized to predict the textural complexity of the CU being encoded.

Other approaches utilized the Bayesian decision rule and other machine learning techniques to improve the time complexity of an HEVC encoder. For instance, the work in [16] and [17] uses the Bayes' rule to optimize PU and CU skip algorithms, respectively. In [18], the authors present a joint online and offline learning-based fast CU partitioning method that uses the Bayesian decision rule to optimize the CU partitioning process. The Bayesian decision theory is also utilized in [19] along with the correlation between the variances of the residual coefficients and the transform size to enhance the PU size decision process. Alternatively, a fast CU splitting and pruning algorithm is proposed in [20], which is applied at each CU depth according to a Bayes decision rule method based on low-complexity RD costs and full RD costs. A fast CU size and PU mode prediction algorithm that uses the k-means clustering method is introduced by [21].

On the other hand, [22] presents an early mode decision algorithm based on the Neyman-Pearson approach. In [23], a fast pyramid motion divergence (PMD)-based CU selection algorithm is proposed, where a k nearest neighbors (k-NN) like method is used to determine the optimal CU size. The work in

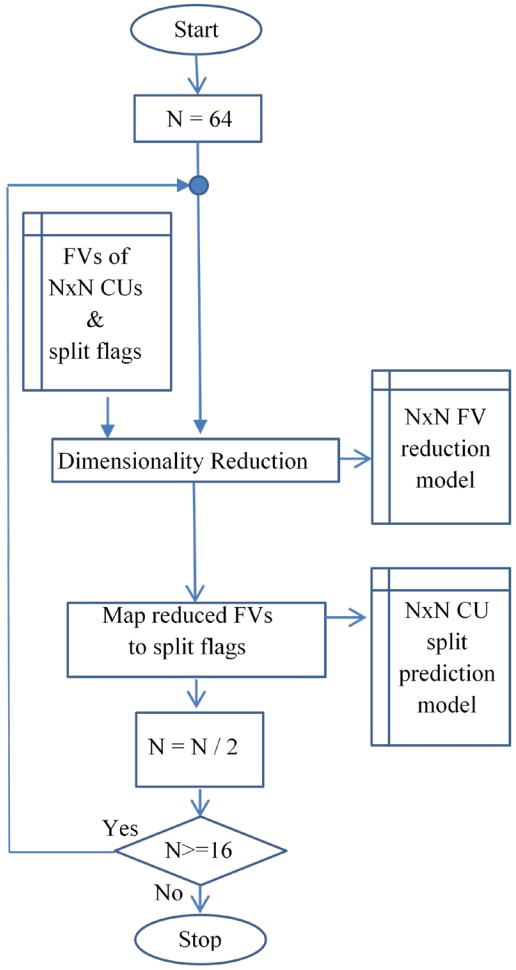

Fig. 2. Flowchart of CU split modeling in the training phase.

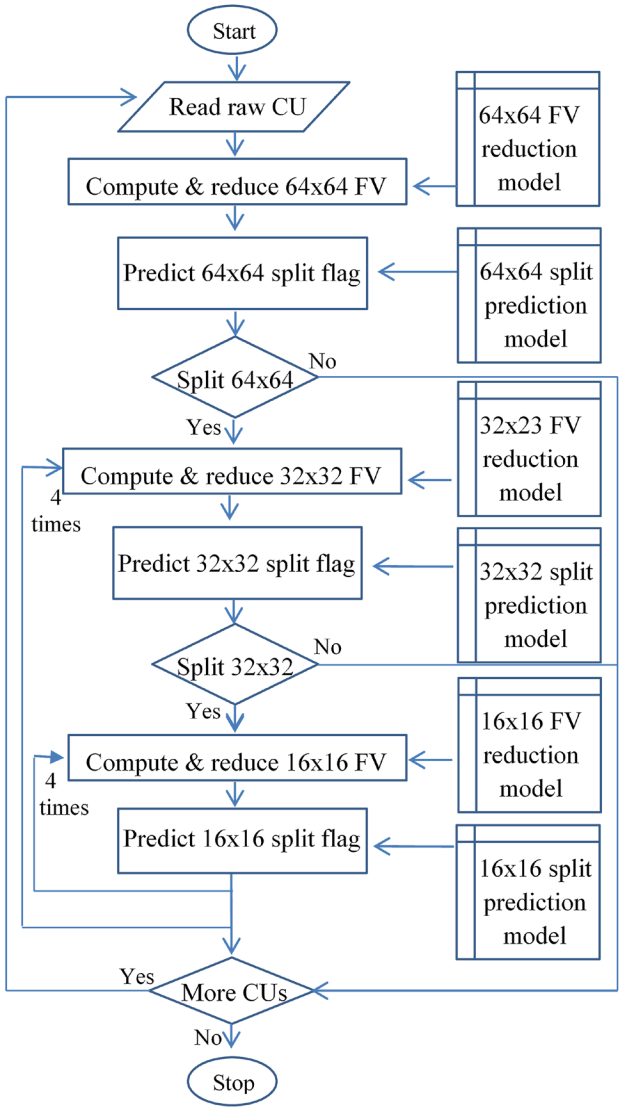

Fig. 3. Flowchart of applying the train models to predict the CU split flags.

[24] used a machine learning-based fast coding unit (CU) depth decision method, where the quad-tree CU depth levels are modeled as a three-level of hierarchical binary decision problem. The work proposed in [25] implemented early termination techniques on CUs, PUs, and TUs using a set of decision trees grown with the aid of Waikato Environment for Knowledge Analysis (WEKA) [27], an open source data mining tool.

3 System Overview

In the proposed prediction system, the first 10% of frames of a video sequence are used for training. Hence, modeling and prediction will be specific to one video as opposed to training the classification system using many video sequences. The former training approach is known as "video-dependent" modeling, while the latter is known as "video-independent" modeling. The problem with the video-independent modeling is that it follows a one-size-fits-all approach in which there is an implicit assumption that the videos used for training are suitable for predicting the CU split decisions of all other videos. Video-dependent modeling, on the other hand, makes sure that the prediction model is most suitable for predicting the CU split decisions of the remaining video content.

The concept of video-dependent modeling was previously introduced by the author in [28]-[30]. The first 10% of video frames were used for training and the prediction model is then used throughout the sequence in a video transcoding context. If needed, the training can be repeated periodically or in the case of detecting scene cuts.

Fig. 1 and 2 present the flowcharts of the proposed training system. Fig. 1 illustrates the data collection process of the training system. The video encoder will run with normal compression operations for the first 10% of the video frames during which, for each CU, features are extracted and recorded at the highest level, which is typically 64x64. The corresponding split decision is also recorded. If the encoder decides to split the CU, then the split decisions at the 32x32 and 16x16 levels will be recursively calculated during which, the training system will record the features and corresponding split decisions at 32x32 and 16x16 CU levels. The details of the selected feature variables are discussed in the next section.

The output of this data collection process is three sets of data. Each data set contains feature vectors and the corresponding

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TABLE I
FEATURE VARIABLES REPRESENTING CUS

Feature (length)	Description
CU depth (1)	Coding depth: 0=64x64, 1=32x32, 2=16x16
Prediction mode (1)	0=inter, 1=intra
PU type costs (11)	PU RD cost of (Skip, 2Nx2N, 2NxN, Nx2N, NxN, 2NxuN, 2NxdN, lNx2N, and rNx2N), and intra-PU modes (2Nx2N and NxN)
Merge flag (1)	Merge flag of current CU
Skip flag (1)	Skip flag of current CU
Total distortions of surrounding CTU (5)	Total distortion cost of each of the surrounding CTUs
Average coding depths of Surrounding CTUs (5)	Average coding depth of each CTUs of the surrounding CTUs
Variance of coding depths of surrounding CTUs (5)	Variance of coding depth of each CTUs of the surrounding CTUs
Average and variance of MVx and MVy of surrounding CTUs (40)	Average and variance of MVx and MVy of surrounding CTUs for lists List0 and List1. Normalized by frame distance.

TABLE II
RETAINED VARIABLES USING STEPWISE REGRESSION

Video sequence	Avg. # retained features		
	64x64	*32x32*	*16x16*
RaceHorses (384x192)	10	11	15
BlowingBubbles (384x192)	4	13	12
BQSquare (384x192)	7	17	17
BasketballPass (384x192)	9	15	13
RaceHorses (832x448)	7	14	19
PartyScene (832x448)	14	27	28
BQMall (832x448)	14	21	22
BasketballDrill (832x448)	13	13	16
ParkScene (1920x1024)	20	30	26
Kimono1 (1920x1024)	17	16	14
Cactus (1920x1024)	20	22	28
BQTerrace (1920x1024)	19	24	27
BasketballDrive (1920x1024)	16	18	23
Traffic (2560x1600)	22	25	26
PeopleOnStreet (2560x1600)	17	28	31
NebutaFestival (2560x1600)	16	20	24
SteamLocomotiveTrain (2560x1600)	18	20	24
Average	**14**	**19**	**21**

split flags for 64x64, 32x32 and 16x16 CU levels. The second step in the training system is to map the feature vectors to the split decisions. This is illustrated in Fig. 2. The result of this step is 3 training models that can be used for the prediction of CU split decisions at 64x64, 32x32 and 16x16 CU levels. Prior to model generation, there is an optional dimensionality reduction step. Again, this is applied at the three CU levels and the dimensionally reduced models are stored and used for reducing the dimensionality of the feature vectors during the testing phase, as shall be explained next. The system modeling and dimensionality reduction techniques used in this work are explained in the next section.

Once the system is trained, the generated models are used to predict the split decisions of the remaining CUs of the underlying video sequence. This process is illustrated in Fig. 3. Basically, feature variables are extracted at the highest CU level, which in this work it is 64x64. The corresponding train model is then used to predict the split flag. If predicted as 'no split,' then early termination is applied. Otherwise, the second train model is applied for each of the 32x32 CU levels and 4 split flags are predicted. If any of the flags are predicted as 'split', then the process is repeated at the 16x16 CU levels using the third train model. At each level, feature vectors are calculated and reduced in dimensionality if required. Again, dimensionality reduction models are calculated during the training phase.

4 System Training

This section introduces the proposed feature extraction and dimensionality reduction process. It also reviews the machine learning techniques used.

A. Feature Extraction and Dimensionality Reduction

In this work, feature extraction is applied at each of the three coding levels (i.e. 64x64, 32x32 and 16x16). Common to all levels are features extracted from surrounding CTUs. The surrounding CTUs are previously encoded and include the CTUs at the following locations relative to the current CU: left, top-left, top, top-right and co-located from the previous frame. The total number of surrounding CTUs is therefore 5. The complete list of extracted features and their description are listed in Table I. The first 15 features in Table I belong to the current CU, whereas the remaining 55 features belong to surrounding CTUs. The total number of features is therefore 70.

As illustrated in Fig. 2 above, the dimensionality of these features can be reduced prior to generating the training model. In this work, we generate experimental results with and without dimensionality reduction. We propose the use of the following dimensionality reduction techniques: stepwise regression, principle component analysis (PCA) and reduction based on random forests. In the following, we briefly summarize the use of each relative to the proposed solution. It is important to mention that all dimensionality reduction techniques are applied to the train data set as illustrated in Fig. 2. The generated model is then applied to the test data set.

Stepwise regression is a feature selection algorithm; however, it can be used as a dimensionality reduction technique as reported in [31]. In this work, we treat the feature vectors of CUs as predictors and the split decisions as response variables. As such, the problem can be formalized in a regression context. The idea of stepwise regression is to start with one feature variable and compute its correlation with the split decision. Then, another feature variable is added and the correlation is computed again. The significance of adding another feature variable is assessed by means of examining the P-value at a 0.05

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TABLE III
STEPWISE REGRESSION, EXAMPLE RETAINED VARIABLES FOR 32X32 DEPTH LEVEL WITH QP=32

Feature (length)	Retained variables
CU depth (1)	-
Prediction mode (1)	Prediction mode
PU type costs (11)	Skip RD cost, 2Nx2N-inter RD cost, 2Nx2N-intra RD cost
Merge flag (1)	-
Skip flag (1)	Skip flag status
Total distortions of surrounding CTU (5)	Total distortion in Left CTU, Total distortion in Collocated CTU
Average coding depths of Surrounding CTUs (5)	Average coding depth in Left CTU, Average coding depth in Upper CTU, Average coding depth in Collocated CTU
Variance of coding depths of surrounding CTUs (5)	Variance of coding depth in Left CTU, Variance of coding depth in Upper CTU
Average and variance of MVx and MVy of surrounding CTUs (40)	Variance of MVx (List1) in Left CTU, Average of MVy (List0) in Upper Right CTU

TABLE V
RANDOM FOREST FEATURE IMPORTANCE, EXAMPLE RETAINED VARIABLES FOR 32X32 DEPTH LEVEL WITH QP=32

Feature (length)	Retained variables
CU depth (1)	-
Prediction mode (1)	-
PU type costs (11)	Skip RD cost, 2Nx2N-inter RD cost, 2NxN RD cost, rNx2N RD cost, Nx2N RD cost, lNx2N RD cost, 2NxdN RD cost, 2NxuN RD cost, 2Nx2N-intra RD cost
Merge flag (1)	-
Skip flag (1)	Skip flag status
Total distortions of surrounding CTU (5)	Total distortion in Upper CTU, Total distortion in Upper Left CTU
Average coding depths of Surrounding CTUs (5)	Average coding depth in Upper CTU
Variance of coding depths of surrounding CTUs (5)	Variance of coding depth in Upper Right CTU, Variance of coding depth in Upper Left CTU
Average and variance of MVx and MVy of surrounding CTUs (40)	-

level of significance. If the added feature variable is found significant, then it is retained; otherwise, it is removed from the list of variables. Likewise, once a variable is retained, the stepwise regression algorithm proceeds by revisiting the previous feature variables and reassessing their significant, taking into account that a new variable has been retained. The algorithm terminates when there are no further feature variables to add or to eliminate. A full description of the algorithm can be found in [32].

Once applied to the train data set at 64x64, 32x32 and 16x16 CU levels, the result of the stepwise regression is simply 3 sets of indices of the retained feature variables, one set for each CU coding depth. These indices can be used to reduce the dimensionality of the feature vectors during the testing phase. Since we are using a video-dependent approach to learning in this work, the number of retained feature variables varies from one video sequence to the other. Full information about the experimental setup are given in the experimental results section; nonetheless, for completeness, we briefly discuss the results of applying the stepwise regression algorithm here. The number of retained variables for each video sequence is given in Table II. The table lists the average number of retained CU variables with QP values of {22, 27, 32 and 37}. Since 3 models are generated, the table lists the retained variables at 64x64, 32x32 and 16x16 CU coding levels. A full example showing specific names of retained variables for the *RaceHorses* sequence is shown in Table III.

TABLE IV
RETAINED VARIABLES USING FEATURE IMPORTANCE WITH RANDOM FORESTS

Video sequence	Avg. # retained features		
	64x64	*32x32*	*16x16*
RaceHorses (384x192)	8	13	10
BlowingBubbles (384x192)	12	14	14
BQSquare (384x192)	12	13	14
BasketballPass (384x192)	9	14	14
RaceHorses (832x448)	15	15	15
PartyScene (832x448)	13	14	14
BQMall (832x448)	14	15	13
BasketballDrill (832x448)	15	14	14
ParkScene (1920x1024)	15	14	14
Kimono1 (1920x1024)	15	15	12
Cactus (1920x1024)	15	15	14
BQTerrace (1920x1024)	15	15	14
BasketballDrive (1920x1024)	15	15	15
Traffic (2560x1600)	14	14	14
PeopleOnStreet (2560x1600)	13	13	14
NebutaFestival (2560x1600)	15	15	14
SteamLocomotiveTrain (2560x1600)	13	14	13
Average	**13.4**	**14.2**	**13.6**

In this work, we also experiment with dimensionality reduction using random forests. In this approach, we generate a large set of trees against the CU split decision. Each tree is trained on a small number of feature variables. The usage statistics of each feature variable can be used to find an informative subset of features. More specifically, if a feature variable is repeatedly selected as best split, it is consequently a good candidate to retain. More information about this algorithm can be found in [33].

Here, a random forest of 100 trees is grown, where the maximum number of decision splits or branch nodes is set to be the initial set of 70 features. The training dataset is sampled for each decision tree with replacement and the feature variables selected at random for each decision split are chosen without

TABLE VI
RETAINED VARIABLES USING PCA

Video sequence	Avg. # retained features		
	64x64	*32x32*	*16x16*
RaceHorses (384x192)	8	24	25
BlowingBubbles (384x192)	20	26	26
BQSquare (384x192)	20	22	22
BasketballPass (384x192)	19	20	21
RaceHorses (832x448)	19	30	30
PartyScene (832x448)	29	30	30
BQMall (832x448)	27	29	29
BasketballDrill (832x448)	24	24	25
ParkScene (1920x1024)	29	31	31
Kimono1 (1920x1024)	29	29	27
Cactus (1920x1024)	27	28	29
BQTerrace (1920x1024)	31	31	32
BasketballDrive (1920x1024)	29	29	29
Traffic (2560x1600)	22	23	24
PeopleOnStreet (2560x1600)	30	34	34
NebutaFestival (2560x1600)	29	30	31
SteamLocomotiveTrain (2560x1600)	28	29	30
Average	**24.7**	**27.6**	**27.9**

replacement within the same decision tree. The importance of each of these features in predicting the correct classification of a test instance from the out-of-bag data is computed and used to select the features whose raw importance score make up 80% of the total importance score. The out-of-bag data is the set of instances that were left out during the training process of a given tree in the random forest.

The number of retained variables, using random forests, for each video sequence is given in Table IV. Similar to Table II above, the table lists the average number of retained CU variables with QP values of {22, 27, 32 and 37}. Since 3 models are generated, the table lists the retained variables at 64x64, 32x32 and 16x16 CU coding levels. A full example showing specific names of retained variables for the *RaceHorses* sequence is shown in Table V.

Lastly, we also experiment with dimensionality reduction using PCA. In this approach, an orthogonal transformation is used to transfer the data from the feature domain to the principle component domain. The first principle component of the transformed data account for the highest variability in the feature data. One drawback of PCA is that it results in a reduced data set that cannot be directly interpreted. This is not the case for the other two dimensionality reduction techniques used in this paper. The number of principle components retained depends on the chosen Proportion of Variance (PoV) explained, which is 90% in this work. Again, the PCA is applied to the training dataset at 64x64, 32x32 and 16x16 CU levels. The resulting principle components are then stored and used for reducing the test data set.

The number of retained variables, using PCA, for each video sequence is given in Table VI. Similar to Tables II and IV above, the table lists the average number of retained CU variables with QP values of {22, 27, 32 and 37}. Since 3 models are generated, the table lists the retained variables at 64x64, 32x32 and 16x16 CU coding levels. Unlike stepwise regression and random forest variable selection, PCA results in a reduced data set that cannot be directly interpreted; hence, there are no specific retained variable names to list.

TABLE VII
ARRANGEMENT OF CLASSIFICATION SOLUTIONS

Solution	Classifier	Dimensionality reduction
Stepwise & Polynomial	Polynomial networks with second order expansion	Stepwise regression
PCA & Polynomial	Polynomial networks with second order expansion	PCA with PoV of 90
R.F. Select & R.F.	Random Forest	Feature importance with random forests
R.F.	Random Forest	Not used

TABLE VIII
LIST OF VIDEO SEQUENCES USED

Class	ID	Video sequence	Resolution	Frame rate	Bit depth
D	D1	RaceHorses	384x192	30	8
	D2	BlowingBubbles	384x192	50	8
	D3	BQSquare	384x192	60	8
	D4	BasketballPass	384x192	50	8
C	C1	RaceHorses	832x448	30	8
	C2	PartyScene	832x448	50	8
	C3	BQMall	832x448	60	8
	C4	BasketballDrill	832x448	50	8
B	B1	ParkScene	1920x1024	24	8
	B2	Kimono1	1920x1024	24	8
	B3	Cactus	1920x1024	50	8
	B4	BQTerrace	1920x1024	60	8
	B5	BasketballDrive	1920x1024	50	8
A	A1	Traffic	2560x1600	30	8
	A2	PeopleOnStreet	2560x1600	30	8
	A3	NebutaFestival	2560x1600	60	10
	A4	SteamLocomotiveTrain	2560x1600	60	10

A. Classification Methods

In this work, we model the relationship between the CU features and split decisions using two classification tools; namely polynomial networks [34], random forest [35] .

In the polynomial networks, we experiment with a second order polynomial classifier. In the case of random forests, 100 trees are grown, where the maximal number of branch nodes is the square root of the number of retained feature variables. This is determined based on the out-of-bag estimates of the features' importance in the tree ensemble. Based on the retained features, the training dataset is sampled for each decision tree with replacement. The variables selected at random for each decision split are chosen without replacement within the same decision tree. As the purpose of growing trees is classification, only one

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TABLE IX
OVERALL CLASSIFICATION AVERAGE OF CU SPLIT PREDICTION

Solution	64x64	32x32	16x16	**Average**
Stepwise & Polynomial	83.2	85.7	86.4	**85.1**
PCA & Polynomial	78.5	81.9	83.2	**81.2**
RF Select & RF	85.3	86.3	86.7	**86.1**
RF	86.2	86.5	86.8	**86.5**
Average	**83.3**	**85.1**	**85.8**	**84.7**

observation or class label can be seen per tree leaf. The arrangement in which we combine the classification tools with the dimensionality reduction techniques are presented in Table VII.

5 Experimental Results

We assess the performance and efficiency of the proposed solutions by implementing them in the HM reference software version 13.0 [36]. All video sequences are encoded with QPs of {22, 27, 32, and 37}. The main profile and the standard random-access temporal configuration are used. The same motion estimation parameters are used in both the original and proposed video coders. For a fair comparison with [18], we use the HEVC video test sequences. The sequence resolutions are Class A (2560x1600), Class B (1080 pixels), Class C (800 × 480), and Class D (400×240). A total of 17 video sequences are used as reported in Table VIII. We ran the experimental results on a PC with Intel Core i7-37400QM, 2.7-GHz CPU with a 16-GB DDR3 RAM. Compression efficiency is quantified in terms of BD-rate and BD-PSNR. The compression times using the proposed solutions are also computed and compared with the corresponding times obtained from running the unmodified HEVC encoder. Furthermore, the classification accuracy of the proposed classification systems is presented. We start by reporting the classification accuracy of the CU split prediction. Table IX presents the overall classification accuracies of the 4 proposed solutions. These results are the average for all video sequences coded with QPs of {22, 27, 32 and 37}. The table reports the classification results for the 3 models generated according to the CU coding depth. The results indicate that the average classification accuracy enhances slightly as the depth of the CU coding increases. The results also show that the classification solutions using random forest are the most accurate. In Table X, the average classification results for individual video sequences using the "R.F. Select & R.F." solution are shown. The resolution of the video does not seem to affect the classification accuracy. Moreover, the accuracies do not seem to vary much according to the underlying video sequence as well.

In the following experiments, we report the coding efficiency of the proposed solutions using a number of approaches; namely BD-rate, BD-PSNR [37] and Computational Complexity Reduction (CCR). CCR is computed as $(Time_{reference} - Time_{proposedSolution})/Time_{reference}$, where $Time_{reference}$ is the time needed for regular encoding and $Time_{proposedSolution}$ is the time needed to encode a sequence using the proposed fast encoder. In Table XI, the coding results of the 4 proposed solutions are listed. As mentioned earlier, all results are obtained with QPs of {22, 27, 32 and 37}. The best coding

TABLE X
CLASSIFICATION ACCURACY OF CU SPLITS FOR THE "R.F. SELECT & R.F." SOLUTION

Sequence ID	R.F. Select & R.F.			
	64x64	32x32	16x16	**Average**
D1	79.0	83.8	83.0	**81.9**
D2	85.1	84.7	83.7	**84.5**
D3	82.6	87.7	87.2	**85.8**
D4	87.1	88.1	83.6	**86.3**
C1	85.3	84.7	86.0	**84.9**
C2	89.7	88.3	87.8	**86.8**
C3	91.6	87.7	85.2	**86.9**
C4	89.1	88.9	87.7	**87.2**
B1	88.4	90.6	89.7	**87.8**
B2	80.3	77.0	82.3	**84.0**
B3	89.1	86.4	88.2	**87.1**
B4	88.1	90.1	89.6	**87.7**
B5	86.6	83.8	86.6	**86.2**
A1	89.6	91.1	91.2	**88.1**
A2	91.3	87.4	83.4	**87.3**
A3	64.0	80.5	88.3	**83.2**
A4	82.7	87.0	90.7	**86.5**
Average	**85.3**	**86.3**	**86.7**	**86.1**

results in terms of BD-rate and BD-PSNR are achieved by the "R.F. Select & RF" and "R.F." solutions. The reported results also indicate that, in general, the coding efficiency enhances as the resolution of the video increases. We report the time complexity in terms of CCR% in Table XII. We present the CCR% for two cases; the first case is the time savings without taking the training or the model generation time into account, while the second case is the CCR% with the training time being taken into account. In Table XII, it seems that without giving consideration to the training time, all solutions provide similar complexity reductions. However, because some of the training solutions are more computationally demanding, when the training time is taken into account, the range of CCR% increases from (39.1% - 37.5%) to (38.9% - 31.8%). Clearly, the most demanding training solution is the one that uses random forest. This is followed by random forest with dimensionality reduction. In this work, no attempt was taken to reduce the training time. However, one solution would be to reduce the number of train feature vectors by means of sampling, therefore reducing the model generation time. The reported results also indicate that, in general, the CCR% enhances as the resolution of the video increases. For comparison with existing work, we refer to the work reported in [9] and [18]. These results contain the BD-rate and time savings only. However, the time savings are computed as $(Time_{reference} - Time_{proposedSolution})/Time_{proposedSolution}$. This is different than the CCR reported in Table XI above, where time savings are calculated by dividing by $Time_{reference}$ instead of $Time_{proposedSolution}$. For a fair comparison, in Table XIII, we calculated the time savings of the proposed solution accordingly. In Table XIII, we compare the results of our best

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TABLE XI
CODING EFFICIENCY OF PROPOSED SOLUTIONS

Sequence ID	Stepwise & Polynomial		PCA & Polynomial		R.F. Select & R.F.		R.F.	
	BD-rate	BD-PSNR	BD-rate	BD-PSNR	BD-rate	BD-PSNR	BD-rate	BD-PSNR
D1	2.58	-0.12	1.42	-0.07	1.58	-0.08	1.48	-0.07
D2	1.84	-0.07	0.87	-0.04	0.57	-0.02	0.53	-0.02
D3	1.23	-0.06	0.75	-0.04	0.46	-0.02	0.42	-0.02
D4	4.34	-0.21	2.45	-0.11	0.33	-0.02	0.50	-0.03
Average	***2.50***	***-0.12***	***1.38***	***-0.06***	***0.74***	***-0.03***	***0.73***	***-0.03***
C1	1.74	-0.07	2.09	-0.08	0.84	-0.03	0.78	-0.03
C2	1.04	-0.05	1.45	-0.07	0.69	-0.03	0.51	-0.02
C3	1.94	-0.08	1.84	-0.08	0.48	-0.02	0.38	-0.02
C4	1.59	-0.07	1.74	-0.07	0.52	-0.02	0.58	-0.02
Average	***1.58***	***-0.07***	***1.78***	***-0.07***	***0.63***	***-0.03***	***0.56***	***-0.02***
B1	0.83	-0.03	1.29	-0.04	0.63	-0.02	0.62	-0.02
B2	0.43	-0.02	0.76	-0.03	0.47	-0.02	0.38	-0.01
B3	0.81	-0.02	1.10	-0.02	0.56	-0.01	0.52	-0.01
B4	0.75	-0.02	0.91	-0.02	0.48	-0.01	0.69	-0.01
B5	1.60	-0.04	1.17	-0.03	0.46	-0.01	0.50	-0.01
Average	***0.88***	***-0.02***	***1.05***	***-0.03***	***0.52***	***-0.01***	***0.54***	***-0.01***
A1	0.66	-0.02	1.52	-0.05	0.54	-0.02	0.45	-0.02
A2	1.35	-0.06	3.72	-0.16	1.07	-0.05	0.98	-0.04
A3	0.11	0.00	0.04	0.00	0.05	0.00	0.11	0.00
A4	-0.04	0.00	-0.1	0.00	-0.2	0.00	-0.27	0.00
Average	***0.52***	***-0.02***	***1.30***	***-0.05***	***0.36***	***-0.02***	***0.32***	***-0.02***
Overall Average	**1.34**	**-0.06**	**1.35**	**-0.05**	**0.56**	**-0.02**	**0.54**	**-0.02**

TABLE XII
COMPLEXITY REDUCTION OF PROPOSED SOLUTIONS USING CCR (%)

Sequence ID	Stepwise & Polynomial		PCA & Polynomial		R.F. Select & R.F.		R.F.	
	Without training time	With training time	Without training time	With training time	Without training time	With training time	Without training time	With training time
D1	25.2	25.2	17.8	17.8	24.8	15.4	25.3	10.4
D2	33.7	33.7	31.2	31.1	32	19.7	31.8	11.4
D3	36.8	36.7	37	36.9	35.2	20.5	35.7	13.4
D4	34.8	34.7	31.6	31.5	30.6	17.8	32	11.1
Average	***32.7***	***32.6***	***29.4***	***29.3***	***30.6***	***18.4***	***31.2***	***11.6***
C1	30.4	30.3	27.8	27.8	31.7	28.3	31	26.0
C2	32.4	32.3	31.8	31.7	33.1	28.9	33.4	27.4
C3	33.6	33.5	32.1	32.1	33	29.2	32.1	26.6
C4	39.5	39.4	38	37.9	39.2	35.6	38.4	33.1
Average	***34***	***33.9***	***32.4***	***32.4***	***34.2***	***30.5***	***33.7***	***28.3***
B1	43.2	42.7	44.5	44.4	43.9	42.0	43.6	40.9
B2	41.5	41.5	42.7	42.6	44.1	43.0	42.7	41.2
B3	46.6	46.5	41.8	41.7	41.3	39.5	38.8	36.0
B4	47.3	47.1	47.5	47.5	48.4	46.5	49.7	46.6
B5	39.7	39.7	38.1	38.0	42.6	41.4	41.3	39.7
Average	***43.7***	***43.5***	***42.9***	***42.9***	***44.1***	***42.5***	***43.2***	***40.9***
A1	47.3	46.8	47.3	44.8	48.7	46.3	48.7	46.1
A2	28.7	28.3	26.8	22.4	30.6	26.7	27.9	24.1
A3	50.2	50.2	47.3	44.1	51.7	50.9	52.9	52.1
A4	53.4	53.4	53.8	51.0	55.1	53.7	55.9	54.7
Average	***44.9***	***44.7***	***43.8***	***40.6***	***46.5***	***44.4***	***46.3***	***44.2***
Overall Average	**39.1**	**38.9**	**37.5**	**36.7**	**39.2**	**34.4**	**38.9**	**31.8**

TABLE XIII
COMPARISON WITH EXISTING WORK [9] AND [18]

Seq. ID	Stepwise & Polynomial			Kim and Park [18]		Yoo and Suh [9]	
	BD-rate	Δ1 Time (%)	Δ2 Time (%)	BD-rate	ΔTime (%)	BD-rate	ΔTime (%)
D1	1.583	-33.9	-18.6	0.9	-49.1	0.65	-26.6
D2	0.572	-49.3	-25.3	0.33	-54.7	0.52	-36.2
D3	0.460	-59.3	-27.6	0.47	-56	0.64	-43.2
D4	0.334	-45.3	-22.1	0.65	-51.2	1.02	-28.4
C1	0.835	-47.5	-40.3	0.97	-57.3	1.22	-25.7
C2	0.687	-51.4	-42.1	0.25	-56	0.41	-34.3
C3	0.484	-50.8	-42.6	0.77	-50.7	0.77	-40.7
C4	0.520	-66	-56.6	0.52	-53.3	1.06	-35.2
B1	0.630	-83.7	-77.9	0.49	-50.3	0.40	-41.6
B2	0.468	-81.5	-77.7	0.64	-61.8	0.46	-35.7
B3	0.561	-74.7	-69.6	0.57	-48	0.48	-42.7
B4	0.478	-111	-103.3	0.87	-59.9	1.13	-44
B5	0.458	-75.7	-72.2	1.33	-57.4	1.21	-46.4
A1	0.540	-101	-92.0	0.71	-55.2	0.57	-43.6
A2	1.066	-44.9	-37.4	0.79	-42.5	0.94	-42.3
A3	0.047	-109.6	-105.7	0.78	-58.8	1.01	-47.6
A4	-0.234	-128.1	-121.3	0.98	-48.7	1.43	-22.1
Avg.	**0.558**	**-71.4**	**-60.7**	**0.71**	**-53.6**	**0.82**	**-37.4**

solution against existing work.

It was not to clear to the authors if the reviewed work considered the training time when reporting the ΔTime%; hence, in Table XIII, we report our results with and without taking into account the training time. In the table, Δ1Time% refers to the time savings without training time and Δ2Time% refers to the time savings taking into consideration the training time.

As previously mentioned, it seems that the results of the proposed solution enhance with the increasing sequence resolution. This is in contrast to the results reported in [18], where the BD-rate seems to improve with decreasing sequence resolution. Moreover, the time reduction in [18] does not seem to be affected by the resolution of the video sequences.

All in all, the results in Table XIII indicate that the proposed solution has a clear advantage in terms of BD-rate and time savings. With reference to the average reported BD-rate of existing work (i.e. 0.765 dB), the proposed solution provides an enhancement of 27.1%. Additionally, this quality enhancement comes with further reduction in computational time. More specifically, with reference to the average reported time savings (i.e. -45.5%), the proposed solution provides an enhancement of 57% and 34% for Δ1Time% and Δ2Time%, respectively.

Lastly, the results in Table XIV present a comparison with the recent work reported in [23], which uses CCR% for measuring the time complexity reduction. Table XIV lists the results for 15 video sequences that are used in both [23] and the proposed solution.

The results in the table show that the BD-rate of the proposed

TABLE XIV
COMPARISON WITH EXISTING WORK [23]

Seq. ID	R.F. Select & R.F.		Xiong et al. [23]	
	BD-rate	CCR (%)	BD-rate	CCR (%)
D1	1.583	24.8	1.99	30.9
D2	0.572	32	1.67	25.6
D3	0.46	35.2	2.34	33.04
D4	0.334	30.6	1.17	44.54
C1	0.835	31.7	1.54	31.05
C2	0.687	33.1	2.53	39.83
C3	0.484	33	1.98	42.35
C4	0.52	39.2	1.72	44.19
B1	0.63	43.9	1.54	30.34
B2	0.468	44.1	2.36	36.66
B3	0.561	41.3	2.48	43.76
B4	0.478	48.4	1.62	31.91
B5	0.458	42.6	4.6	46
A1	0.54	48.7	3.25	49.7
A2	1.066	30.6	1.95	38.67
A3	0.65	51.7	2.18	37.9
A4	1.583	55.1	1.99	30.9
Avg.	**0.7**	**39.2**	**2.2**	**37.5**

solution is on average 0.7, whereas that of the proposed solution is 2.18. This noticeable enhancement in the BD-rate reduction comes at a slight advantage of increased computational complexity, where the CCR of the reviewed work is 37.5% and that of the proposed work is 39.2%.

6 Conclusion

We proposed a solution for reducing the complexity of determining the CU split decisions in HEVC video coding. The solution uses a video sequence-dependent approach to collect features that represent CUs at various coding depths. The features are extracted from both the underlaying CU and the previously encoded CUs. A classification model is then built based on these feature vectors and corresponding split decisions at various CU coding depths. Additionally, dimensionality reduction is optionality used as a preprocess to model generation. Therefore, the output of the training phase is a set of classification models for predicting split decisions and a set of dimensionality reduction models. We have used a number of dimensionality reduction and classification techniques, including stepwise regression, random forest variable selection, PCA, polynomial classifiers and random forest classifiers. Experimental results were carried out on many test video sequences with different resolutions. Comparison with existing work revealed that the proposed solution has an advantage in terms of coding efficiency and time savings. It was shown that, on average, the classification accuracy of the CU split models is 86.5%. In comparison to regular HEVC coding, the proposed solutions resulted in a BD-rate of 0.55 and a BD-PSNR of -0.02 dB. The average reported computational complexity reduction was 39.2%.

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