

# Intra Coding of the HEVC Standard

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**Abstract**—This paper provides an overview of the intra coding techniques in the High Efficiency Video Coding (HEVC) standard being developed by the Joint Collaborative Team on Video Coding (JCT-VC). The intra coding framework of HEVC follows that of traditional hybrid codecs and is built on spatial sample prediction followed by transform coding and postprocessing steps. Novel features contributing to the increased compression efficiency include a quadtree-based variable block size coding structure, block-size agnostic angular and planar prediction, adaptive pre- and postfiltering, and prediction direction-based transform coefficient scanning. This paper discusses the design principles applied during the development of the new intra coding methods and analyzes the compression performance of the individual tools. Computational complexity of the introduced intra prediction algorithms is analyzed both by deriving operational cycle counts and benchmarking an optimized implementation. Using objective metrics, the bitrate reduction provided by the HEVC intra coding over the H.264/advanced video coding reference is reported to be 22% on average and up to 36%. Significant subjective picture quality improvements are also reported when comparing the resulting pictures at fixed bitrate.

**Index Terms**—High Efficiency Video Coding (HEVC), image coding, intra prediction, Joint Collaborative Team on Video Coding (JCT-VC), video coding.

## I. INTRODUCTION

THE TWO prominent international organizations specifying video coding standards, namely ITU-T Video Coding Experts Group (VCEG) and ISO/IEC Moving Picture Experts Group (MPEG), formed the Joint Collaborative Team on Video Coding (JCT-VC) in April 2010. Since then, JCT-VC has been working toward defining a next-generation video coding standard called High Efficiency Video Coding (HEVC). There are two major goals for this standard. First, it is targeted to achieve significant improvements in coding efficiency compared to H.264/Advanced Video Coding (AVC) [1], especially when operating on high-resolution video content. Second, the standard should have low enough complexity to enable high-resolution high-quality video applications in various use cases,

including operation in mobile environments with tablets and mobile phones.

This paper analyzes different aspects of the HEVC intra coding process and discusses the motivation leading to the selected design. The analysis includes assessing coding efficiency of the individual tools contributing to the overall performance as well as studying complexity of the introduced new algorithms in detail. This paper also describes the methods HEVC utilizes to indicate the selected intra coding modes and further explains how the tools are integrated with the HEVC coding block architecture.

Intra coding in HEVC can be considered as an extension of H.264/AVC, as both approaches are based on spatial sample prediction followed by transform coding. The basic elements in the HEVC intra coding design include:

- 1) quadtree-based coding structure following the HEVC block coding architecture;
- 2) angular prediction with 33 prediction directions;
- 3) planar prediction to generate smooth sample surfaces;
- 4) adaptive smoothing of the reference samples;
- 5) filtering of the prediction block boundary samples;
- 6) prediction mode-dependent residual transform and coefficient scanning;
- 7) intra mode coding based on contextual information.

In addition, the HEVC intra coding process shares several processing steps with HEVC inter coding. This processing, including, e.g., transformation, quantization, entropy coding, reduction of blocking effects, and applying sample adaptive offsets (SAO), is outside of the scope of this paper.

This paper is organized as follows. Section II explains the motivation leading to the selected design for HEVC intra coding. It also describes the overall HEVC coding architecture and the new intra prediction tools introduced in the HEVC standard. Section III presents the intra mode coding and the residual coding approaches of the standard. Section IV provides complexity analysis of the introduced intra prediction processes with detailed information about the contribution of different intra prediction modes. Section V summarizes the compression efficiency gains provided by the proposed design and Section VI concludes this paper.

## II. HEVC INTRA CODING ARCHITECTURE

In H.264/AVC, intra coding is based on spatial extrapolation of samples from previously decoded image blocks, followed by discrete cosine transform (DCT)-based transform coding [2]. HEVC utilizes the same principle, but further extends it to be able to efficiently represent wider range of textural and

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structural information in images. The following aspects were considered during the course of HEVC project leading to the selected intra coding design.

- 1) *Range of supported coding block sizes:* H.264/AVC supports intra coded blocks up to the size of  $16 \times 16$  pixels. This represents a very small area in a high-definition picture and is not large enough to efficiently represent certain textures.
- 2) *Prediction of directional structures:* H.264/AVC supports up to eight directional intra prediction modes for a given block. This number is not adequate to predict accurately directional structures present in typical video and image content, especially when larger block sizes are used.
- 3) *Prediction of homogeneous regions:* The plane mode of H.264/AVC was designed to code homogeneous image regions. However, this mode does not guarantee continuity at block boundaries, which can create visible artifacts. Thus, a mode that guarantees continuous prediction sample surfaces would be desired.
- 4) *Consistency across block sizes:* H.264/AVC uses different methods to predict a block depending on the size of the block and the color component the block represents. A more consistent design is preferred, especially as HEVC supports a large variety of block sizes.
- 5) *Transforms for intra coding:* H.264/AVC utilizes a fixed DCT transform for a given block size. This design does not take into consideration different statistics of the prediction error along the horizontal and vertical directions depending on the directionality of the prediction.
- 6) *Intra mode coding:* Due to the substantially increased number of intra modes, more efficient coding techniques are required for mode coding.

The coding structure utilized for intra coding in HEVC follows closely the overall architecture of the codec. Images are split into segments called coding units (CU), prediction units (PU), and transform units (TU). CU represent quadtree split regions that are used to separate the intra and inter coded blocks. Inside a CU, multiple nonoverlapping PU can be defined, each of which specifies a region with individual prediction parameters. CU are further split into a quadtree of transform units, each TU having a possibility of applying residual coding with a transform of the size of the TU.

HEVC contains several elements improving the efficiency of intra prediction over earlier solutions. The introduced methods can model accurately different directional structures as well as smooth regions with **gradually changing sample values**. There is also emphasis on **avoiding introduction of artificial edges with potential blocking effects**. This is achieved by **adaptive smoothing of the reference samples and smoothing the generated prediction boundary samples for DC and directly horizontal and vertical modes**.

All the prediction modes utilize the same basic set of reference samples from above and to the left of the image block to be predicted. In the following sections, we denote the reference samples by  $R_{x,y}$  with  $(x, y)$  having its origin one pixel above and to the left of the block's top-left corner.

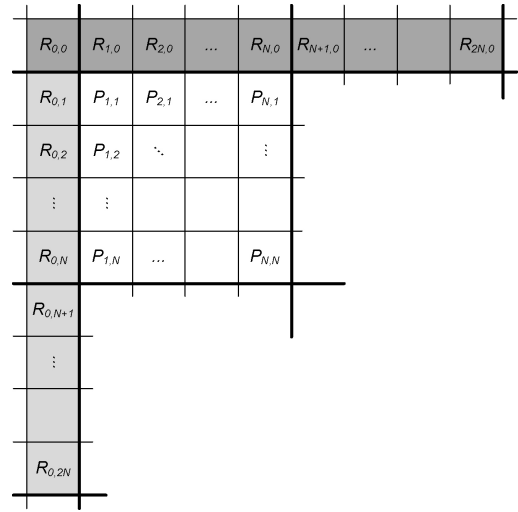


Fig. 1. Reference samples  $R_{x,y}$  used in prediction to obtain predicted samples  $P_{x,y}$  for a block of size  $N \times N$  samples.

TABLE I  
SPECIFICATION OF INTRA PREDICTION MODES AND ASSOCIATED NAMES

Intra Prediction Mode	Associated Names
0	Planar
1	DC
2..34	Angular ( $N$ ), $N = 2...34$

Similarly,  $P_{x,y}$  is used to denote a predicted sample value at a position  $(x, y)$ . Fig. 1 illustrates the notation used.

Neighboring reference samples may be unavailable for intra prediction, for example, at picture or slice boundaries, or **at CU boundaries when constrained intra prediction is enabled**. Missing reference samples on the left boundary are generated by repetition from the closest available reference samples below (or from above if no samples below are available). Similarly, the missing reference samples on the top boundary are obtained by copying the closest available reference sample from the left. If no reference sample is available for intra prediction, all the samples are assigned a nominal average sample value for a given bit depth (e.g., 128 for 8-b data).

It should be noted that in addition to left, above, and above-right reconstructed samples used for H.264/AVC intra prediction, below-left side of samples ( $R_{0,N+1}.. R_{0,2N}$ ) are also used for HEVC. These samples were excluded from the H.264/AVC process as they were rarely available in the traditional macroblock-based coding structure [2], but the hierarchical HEVC coding architecture makes these candidates available more frequently.

HEVC design supports a total of 35 intra prediction modes. Table I specifies the numbers and names associated with each mode. In this paper, intra prediction mode 0 refers to the planar intra prediction, mode 1 to DC prediction, and modes 2 to 34 to angular prediction modes with different directionalities. Fig. 2 further illustrates the prediction directions associated with the angular modes.

#### A. Angular Intra Prediction

Angular intra prediction in HEVC is designed to be able to efficiently model different **directional structures** typically

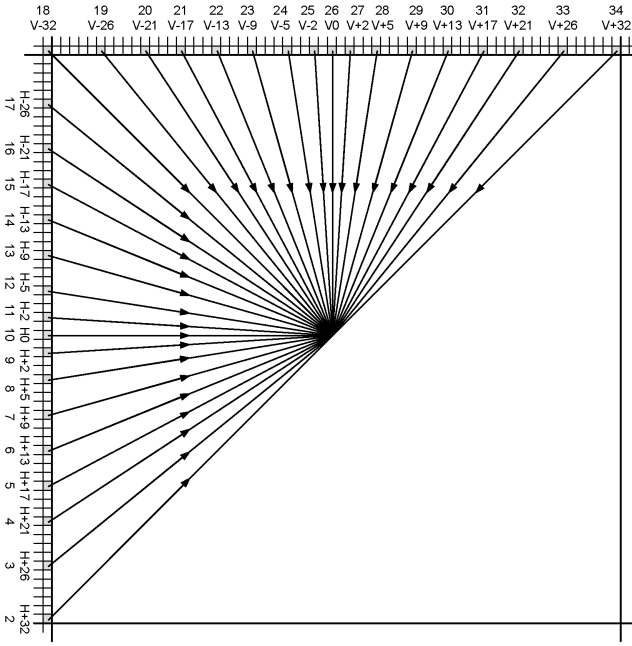


Fig. 2. HEVC angular intra prediction modes numbered from 2 to 34 and the associated displacement parameters. H and V are used to indicate the horizontal and vertical directionalities, respectively, while the numeric part of the identifier refers to the pixels' displacement as 1/32 pixel fractions.

present in video and image contents. The number and angularity of prediction directions are selected to provide a good tradeoff between encoding complexity and coding efficiency for typical video material. The sample prediction process itself is designed to have low computational requirements and to be consistent across block sizes and prediction directions. The latter aims at minimizing the silicon area in hardware and the amount of code in software implementations. It is also intended to make it easier to optimize the implementation for high performance and throughput in various environments. This is especially important as the number of block sizes and prediction directions supported by HEVC intra coding far exceeds those of previous video codecs, such as H.264/AVC. In HEVC, there are four effective intra prediction block sizes ranging from  $4 \times 4$  to  $32 \times 32$  samples, each of which supports 33 distinct prediction directions. A decoder must thus support 132 combinations of block size and prediction direction.

The following sections discuss in further detail different aspects contributing to the coding performance and implementation complexity of the HEVC angular intra prediction.

1) *Angle Definitions*: In natural imagery, horizontal and vertical patterns typically occur more frequently than patterns with other directionalities. The set of 33 prediction angles is defined to optimize the prediction accuracy based on this observation [7]. Eight angles are defined for each octant with associated displacement parameters, as shown in Fig. 2.

Small displacement parameters for modes close to horizontal and vertical directions provide more accurate prediction for nearly horizontal and vertical patterns. The displacement parameter differences become larger when getting closer to diagonal directions to reduce the density of prediction modes for less frequently occurring patterns.

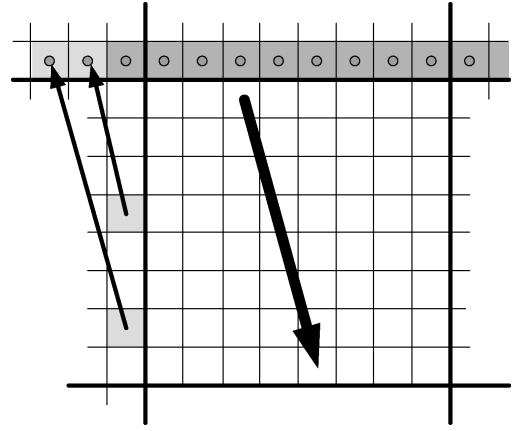


Fig. 3. Example of projecting left reference samples to extend the top reference row. The bold arrow represents the prediction direction and the thin arrows the reference sample projections in the case of intra mode 23 (vertical prediction with a displacement of  $-9/32$  pixels per row).

2) *Reference Pixel Handling*: The intra sample prediction process in HEVC is performed by extrapolating sample values from the reconstructed reference samples utilizing a given directionality. In order to simplify the process, all sample locations within one prediction block are projected to a single reference row or column depending on the directionality of the selected prediction mode (utilizing the left reference column for angular modes 2 to 17 and the above reference row for angular modes 18 to 34).

In some cases, the projected pixel locations would have negative indexes. In these cases, the reference row or column is extended by projecting the left reference column to extend the top reference row toward left, or projecting the top reference row to extend the left reference column upward in the case of vertical and horizontal predictions, respectively. This approach was found to have a negligible effect on compression performance, and has lower complexity than an alternative approach of utilizing both top and left references selectively during the prediction sample generation process [5]. Fig. 3 depicts the process for extending the top reference row with samples from the left reference columns for an  $8 \times 8$  block of pixels.

3) *Sample Prediction for Arbitrary Number of Directions*: Each predicted sample  $P_{x,y}$  is obtained by projecting its location to a reference row of pixels applying the selected prediction direction and interpolating a value for the sample at 1/32 pixel accuracy. Interpolation is performed linearly utilizing the two closest reference samples

$$P_{x,y} = ((32 - w_y) \cdot R_{i,0} + w_y \cdot R_{i+1,0} + 16) >> 5 \quad (1)$$

where  $w_y$  is the weighting between the two reference samples corresponding to the projected subpixel location in between  $R_{i,0}$  and  $R_{i+1,0}$ , and  $>>$  denotes a bit shift operation to the right. Reference sample index  $i$  and weighting parameter  $w_y$  are calculated based on the projection displacement  $d$  associated with the selected prediction direction (describing the tangent of the prediction direction in units of 1/32 samples

and having a value from  $-32$  to  $+32$  as shown in Fig. 2) as

$$\begin{aligned} c_y &= (y \cdot d) \gg 5 \\ w_y &= (y \cdot d) \& 31 \\ i &= x + c_y \end{aligned} \quad (2)$$

where  $\&$  denotes a bitwise AND operation. It should be noted that parameters  $c_y$  and  $w_y$  depend only on the coordinate  $y$  and the selected prediction displacement  $d$ . Thus, both parameters remain constant when calculating predictions for one line of samples and only (1) needs to be evaluated per sample basis. When the projection points to integer samples (i.e., when  $w_y$  equals zero), the process is even simpler and consists of only copying integer reference samples from the reference row.

Equations (1) and (2) define how the predicted sample values are obtained in the case of vertical prediction (modes 18 to 34) when the reference row above the block is used to derive the prediction. Prediction from the left reference column (modes 2 to 17) is derived identically by swapping the  $x$  and  $y$  coordinates in (1) and (2).

### B. Planar Prediction

While providing good prediction in the presence of edges is important, not all image content fits an edge model. The DC prediction provides an alternative but is only a coarse approximation as the prediction is of order 0. H.264/AVC features an order-1 plane prediction mode that derives a bilinear model for a block using the reference samples and generates the prediction using this model. One disadvantage of this method is that it may introduce discontinuities along the block boundaries. The planar prediction mode defined in HEVC aims to replicate the benefits of the plane mode while preserving continuities along block boundaries. It is essentially defined as an average of two linear predictions (see [8, Fig. 2] for a graphical representation)

$$\begin{aligned} P_{x,y}^V &= (N - y) \cdot R_{x,0} + y \cdot R_{0,N+1} \\ P_{x,y}^H &= (N - x) \cdot R_{0,y} + x \cdot R_{N+1,0} \\ P_{x,y} &= (P_{x,y}^V + P_{x,y}^H) \gg (\log_2(N) + 1). \end{aligned} \quad (3)$$

### C. Reference Sample Smoothing

H.264/AVC applies a three-tap smoothing filter to the reference samples when predicting  $8 \times 8$  luma blocks. HEVC uses the same smoothing filter  $([1 \ 2 \ 1]/4)$  for blocks of size  $8 \times 8$  and larger. The filtering operation is applied for each reference sample using neighboring reference samples. The first reference sample  $R_{0,2N}$  and  $R_{2N,0}$  are not filtered. For  $32 \times 32$  blocks, all angular modes except horizontal and vertical use a filtered reference. In  $16 \times 16$  blocks, the modes not using a filtered reference are extended to the four modes (9, 11, 25, 27) closest to horizontal and vertical. Smoothing is also applied where the planar mode is used, for block sizes  $8 \times 8$  and larger. However, HEVC is more discerning in the use of this smoothing filter for smaller blocks. For  $8 \times 8$  blocks, only the diagonal modes (2, 18, 34) use a filtered reference. Applying the reference sample smoothing selectively based on the block size and directionality of the prediction is reported to reduce contouring artifacts caused by edges in the reference sample arrays [23].

### D. Boundary Smoothing

As noted above in the case of the H.264/AVC plane prediction mode, DC and angular prediction modes may introduce discontinuities along block boundaries. To remedy this problem, the first prediction row and column are filtered in the case of DC prediction with a two-tap finite impulse response filter (corner sample with a three-tap filter). Similarly, the first prediction column for directly vertical prediction and the first prediction row for directly horizontal prediction are filtered utilizing a gradient-based smoothing [9]. For a more complete description of the filtering process, please refer to [25].

As the prediction for chroma components tends to be very smooth, the benefits of the boundary smoothing would be limited. Thus, in order to avoid extra processing with marginal quality improvements, the prediction boundary smoothing is only applied to luma component. The average coding efficiency improvement provided by the boundary smoothing is measured to be 0.4% in HM 6.0 environment [14].

### E. I – PCM Mode and Transform Skipping Mode

HEVC supports two special coding modes for intra coding denoted as I-PCM and transform skipping mode. In I-PCM mode, prediction, transform, quantization, and entropy coding are bypassed while the prediction samples are coded by a predefined number of bits. The main purpose of the I-PCM mode is to handle the situation when the signal cannot be efficiently coded by other modes.

On the contrary, only transform is bypassed in transform skipping mode. It was adopted to improve the coding efficiency for specific video contents such as computer-generated graphics. HEVC restricts the use of this mode when the block size is equal to  $4 \times 4$  to avoid the significant design change due to this mode while this choice was proven to have most of coding efficiency benefits.

### F. Restrictions for Partitioning Types

HEVC intra coding supports two types of PU division,  $PART_{2N} \times 2N$  and  $PART_N \times N$ , splitting a CU into one or four equal-size PUs, respectively. However, the four regions specified by the partitioning type  $PART_N \times N$  can be also represented by four smaller CU with the partitioning type  $PART_{2N} \times 2N$ . Due to this, HEVC allows an intra CU to be split into four PU only at the minimum CU size. It has been demonstrated that this restriction is associated with minimal impact in coding efficiency, but it reduces the encoding complexity significantly [3].

Another way to achieve the same purpose would be reducing the CU size to  $4 \times 4$  with the partitioning mode  $PART_{2N} \times 2N$ . However, this approach would result in a chroma intra prediction block size of  $2 \times 2$  pixels, which can be critical to the throughput of the entire intra prediction process. For this reason, the minimum allowed CU size is restricted to  $8 \times 8$  pixels while allowing the partitioning type  $PART_N \times N$  only in the smallest CU.

### G. TU-Based Prediction

When a CU is split into multiple TU, the intra prediction is applied for each TU sequentially instead of applying the



intra prediction at the PU level. One obvious advantage for this approach is the possibility of always utilizing the nearest neighboring reference samples from the already reconstructed TU. It has been shown that this property improves the intra picture coding efficiency by about 1.2% [4] compared to the case of using PU border reference samples for the PU. It should be noted that all the intra prediction information is indicated per PU and the TUs inside the same PU share the same intra prediction mode.

### III. MODE AND RESIDUAL CODING

#### A. Mode Coding for Luma

HEVC supports total 33 angular prediction modes as well as planar and DC prediction for luma intra prediction for all the PU sizes. Due to the large number of intra prediction modes, H.264/AVC-like mode coding approach based on a single most probable mode was not found effective in HEVC [8]. Instead, HEVC defines three most probable modes for each PU based on the modes of the neighboring PUs. The selected number of most probable modes makes it also possible to indicate one of the 32 remaining modes by a fixed length code, as the distribution of the mode probabilities outside of the set of most probable modes is found to be relatively uniform.

The selection of the set of three most probable modes is based on modes of two neighboring PUs, one above and one to the left of the current PU. By default, modes of both candidate PUs are included in the set. Possible duplicates and the third mode in the set are assigned with modes planar, DC, or angular (26) in this order. In the case that both top and left PU has the same directional mode, that mode and two closest directional modes are used to construct the set of most probable modes instead.

In the case current intra prediction mode is equal to one of the elements in the set of most probable modes, only the index in the set is transmitted to the decoder. Otherwise, a 5-b fixed length code is used to determine the selected mode outside of the set of most probable modes.

#### B. Derived Mode for Chroma Intra Prediction

Quite often structures in the chroma signal follow those of the luma. Taking advantage of this behavior, HEVC introduces a mechanism to indicate the cases when chroma PU utilizes the same prediction mode as the corresponding luma PU. Table II specifies the mode arrangement used in signaling the chroma mode.

In the case that derived mode is indicated for a PU, the prediction is performed by using the corresponding luma PU mode. In order to remove the possible redundancy in the signaling arising when derived refers to one of the modes always present, angular (34) mode is used to substitute the duplicate mode as shown in Table II.

#### C. Syntax Design for the Intra Mode Coding

HEVC uses three syntax elements to represent the luma intra prediction mode. The syntax element *prev\_intra\_luma\_pred\_flag* specifies whether the luma intra

TABLE II  
SPECIFICATION OF CHROMA INTRA PREDICTION  
MODES AND ASSOCIATED NAMES

Chroma intra prediction mode	Primary mode	Alternative mode, if primary mode is equal to the derived mode
0	Planar	Angular (34)
1	Angular (26)	Angular (34)
2	Angular (10)	Angular (34)
3	DC	Angular (34)
4	Derived	N/A

prediction mode is matched with one of three most probable modes. When the flag is equal to 1, the syntax element *mpm\_idx* is parsed, indicating which element of the most probable mode array specifies the luma intra prediction mode. When the flag is equal to 0, the syntax element *rem\_intra\_luma\_pred\_mode* is parsed, specifying the luma intra prediction mode as *rem\_intra\_luma\_pred\_mode* + *N*, where *N* is the number of elements in the most probable mode array having a mode index greater than or equal to the syntax element *rem\_intra\_luma\_pred\_mode*.

In chroma mode coding, a 1-b syntax element (0) is assigned to the most often occurring derived mode, while 3-b syntax elements (100, 101, 110, 111) are assigned to the remaining four modes.

#### D. Intra Mode Residual Coding

HEVC utilizes intra mode dependent transforms and co-efficient scanning for coding the residual information. The following sections describe the selected approaches in more detail.

1) *Block Size-Dependent Transform Selection*: Integer transforms derived from DCT and discrete sine transform (DST) are applied to the intra residual blocks. A DST-based transform is selected for  $4 \times 4$  luma blocks and DCT-based transforms for the rest. For more details on the specification of the transforms, the reader is referred to [10] and [11].

Different approaches to select the transforms were studied during the course of the HEVC development. For example, an early HEVC draft utilized a method that selected the horizontal and vertical transforms separately for  $4 \times 4$  luma blocks based on the intra prediction mode. This approach provided an average coding efficiency improvement of 0.8% [10]. However, it was found that the simple block size depended approach now adopted in the standard provides very similar coding efficiency [26]. Also larger size alternative transforms were studied, but it was reported that the additional coding efficiency improvements were marginal compared to the complexity impact [27]. Thus, only DCT-based transforms are utilized for block sizes larger than  $4 \times 4$ .

2) *Intra Prediction Mode-Dependent Coefficient Scanning*: HEVC applies adaptive scanning of transform coefficients to the transform block sizes of  $4 \times 4$  and  $8 \times 8$  in order to take advantage of the statistical distribution of the active coefficients in 2-D transform blocks. The scan is selected based on directionality of the intra prediction mode as shown

TABLE III  
MAPPING TABLE BETWEEN INTRA PREDICTION MODES AND  
COEFFICIENT SCANNING ORDER

Intra prediction mode	Coefficient scanning for $4 \times 4$ and $8 \times 8$	Coefficient scanning for $16 \times 16$ and $32 \times 32$
Angular (6–14)	Vertical	Diagonal
Angular (22–30)	Horizontal	Diagonal
All other modes	Diagonal	Diagonal

in Table III. Vertical and horizontal scans refer to the corresponding raster scan orders, while the diagonal scan refers to a diagonal scan from down-left to up-right direction. The average coding gain from the intra mode dependent scans is reportedly around 1.2% [12].

#### IV. COMPLEXITY OF INTRA PREDICTION TOOLS

##### A. Complexity Analysis of Decoding Process

1) *Analysis of Operational Cycle Counts*: Defining a proper metric for theoretical analysis of complexity can be difficult as various aspects come into play. For example, if relying on counting operations, defining what constitutes one operation largely depends on the underlying architecture. The bit width of each data element being processed also plays an important role in determining a number of gates in hardware and the amount of parallelism achievable in software. How an algorithm is implemented can also have a significant impact. A lower number of operations is not always better. Executing four operations in parallel may be faster and considered less complex than executing three in sequence. In this section, we thus limit ourselves to a more superficial comparison of HEVC prediction modes with the H.264/AVC ones.

The DC, directly horizontal, and directly vertical prediction modes are the ones most similar to those defined in H.264/AVC. HEVC simply defines an additional postfiltering operation where one row and/or column of samples is filtered. The overhead of such filtering becomes less with larger block sizes, as the fraction of filtered samples becomes smaller.

For predicting a block of size  $N \times N$ , angular prediction requires the computation of  $p = (u \cdot a + v \cdot b + 16) \gg 5$  for each sample, which involves two multiplications (8-b unsigned operands, 16-b result), two 16-b additions, and one 16-b shift per predicted sample, for a total of five operations. In the H.264/AVC case, directional prediction may take the form  $p = (a + 2b + c + 2) \gg 2$ , which may be considered to be five operations as well. However, on some architectures, this can be implemented using two 8-b halving add operations:  $d = (a + c) \gg 1$  and  $p = (d + b + 1) \gg 1$ . The H.264/AVC directional prediction process is thus less complex as it requires no multiplication and no intermediate value wider than 9 b.

In the case of the plane and planar modes, considering the generating equations is probably not adequate, as the prediction values can be efficiently computed incrementally. For the H.264/AVC plane mode, it is expected that one 16-b addition, one 16-b shift, and one clip to 8-b range are required

TABLE IV  
DECODING TIME COMPARISON BETWEEN HM 6.0 DECODER AND ITS  
OPTIMIZED DECODER USED FOR FURTHER ANALYSIS

Setting	Bitrate (Mbit/s)	HM 6.0 (s)	Optimized (s)
<i>BasketballDrive</i> , QP = 22	71.1	104.47	21.97
<i>BasketballDrive</i> , QP = 37	8.4	61.60	6.98
<i>BQTerrace</i> , QP = 22	179.2	163.94	41.42
<i>BQTerrace</i> , QP = 37	21.6	91.00	12.03
<i>Cactus</i> , QP = 22	105.7	120.46	28.84
<i>Cactus</i> , QP = 37	14.2	69.59	8.78
<i>Kimono</i> , QP = 22	22.3	37.11	7.02
<i>Kimono</i> , QP = 37	3.8	26.94	2.88
<i>ParkScene</i> , QP = 22	52.7	60.53	14.02
<i>ParkScene</i> , QP = 37	7.3	33.90	4.35
Geometric mean	25.4	66.34	10.91

Sequences are each 10-s long and are coded in intra-only mode. Optimized decoder is about four to nine times faster than HM.

per sample. For the HEVC planar mode, three 16-b additions and one 16-b shift are expected per sample.

The partial analysis provided here is indicative. It suggests that the HEVC intra prediction modes are more complex than the AVC modes, but not necessarily by a large amount. In the following, focus is shifted to complexity investigation based on actual implementations.

2) *Decoding Time of Intra Prediction in Relation to Overall Decoding Time*: In a first experiment, the percentage of decoding time spent on intra prediction is measured. Reference encodings for the main profile of HM 6.0 [14] are used in the all-intra configuration [15]. The experiment is focused on high-definition sequences from the JCT-VC class B test set (five  $1920 \times 1080$  sequences). MD5 checksum computation and file output of the reconstructed pictures are disabled such that decoding times more accurately reflect time spent on actually decoding pictures. Measurements are obtained on a laptop featuring an Intel Core i5 processor clocked at 2.53 GHz. Software was compiled using gcc 4.6.3. In addition to the HM software, an optimized decoder, based on [16], is also considered. Table IV summarizes decoding times and gives an indication of the level of optimization. For the comparative results between HEVC HM decoder and H.264/AVC JM decoder, please refer to [24], which reported that they are comparable. The fraction of decoding time used for intra prediction is further summarized in Table V.

While the results obtained with HM and optimized software show some differences, they do not diverge significantly: on average roughly 12%–15% of decoding time is consumed by intra prediction. The results may however be somewhat surprising in the sense that generating the reference arrays used for prediction takes more time than generating the prediction from those reference arrays. Part of this observation may be caused by the fact that in both of the tested software implementations, full reference arrays are constructed, including  $2N + 1$  samples for a row above and  $2N + 1$  samples for a left column. Most prediction modes do not require all these samples, and constructing only the required ones may reduce the amount of time by up to 50%.

TABLE V  
DECODING TIME FRACTION FOR INTRA PREDICTION

Setting	Reference (%)	Prediction (%)	Total (%)
<i>BasketballDrive</i> , QP=22	11.0/5.7	5.0/3.8	15.0/9.5
<i>BasketballDrive</i> , QP=37	9.9/8.0	5.7/9.4	15.6/17.4
<i>BQTerrace</i> , QP=22	10.2/4.6	4.2/2.5	14.4/7.1
<i>BQTerrace</i> , QP=37	11.6/8.3	6.3/7.1	17.9/15.4
<i>Cactus</i> , QP=22	10.6/5.4	4.5/3.2	15.1/8.6
<i>Cactus</i> , QP=37	11.1/8.8	5.5/8.0	16.6/ 16.8
<i>Kimono</i> , QP=22	8.3/4.5	4.3/4.9	12.6/9.4
<i>Kimono</i> , QP=37	8.0/6.6	5.0/8.8	13.0/15.4
<i>ParkScene</i> , QP=22	10.1/5.4	4.3/2.9	14.4/8.3
<i>ParkScene</i> , QP=37	10.8/8.2	5.0/7.1	15.8/15.3
Average	10.2/6.6	5.0/5.8	15.2/12.4

*Reference* represents construction of the reference samples array and *Prediction* represents the actual prediction process. For the HM6 software, functions in the TComPattern class are considered part of reference, functions in the TComPrediction class part of prediction. In each pair of numbers, the left one represents HM6 and the right one the optimized decoder

TABLE VI  
CYCLES PER SAMPLE FOR INTRA PREDICTION MODES (IN A SPECIFIC SOFTWARE IMPLEMENTATION BASED ON [16])

Mode	Luma				Chroma		
	4	8	16	32	4	8	16
DC	1.50	0.75	0.44	0.22	0.28	0.14	0.08
Planar	1.13	0.66	0.65	0.64	0.56	0.45	0.50
Horizontal	0.94	0.42	0.19	0.12	0.38	0.23	0.20
Vertical	0.94	0.52	0.32	0.26	0.28	0.12	0.10
Angular (2–9)	1.31	1.23	0.82	0.68	1.13	0.73	0.67
Angular (11–17)	1.50	1.23	0.89	0.69	1.41	0.83	0.67
Angular (18–25)	1.50	1.14	0.76	0.56	1.31	0.71	0.63
Angular (27–34)	1.31	1.14	0.78	0.55	1.13	0.73	0.61

3) *Cycles for Each Prediction Mode*: Using optimized software based on [16], the decoding time associated with each prediction mode is further studied. Table VI shows numbers of computed cycles, normalized by the number of predicted samples. Numbers for chroma are reported separately for two reasons: postfiltering is not applied to chroma components (DC, horizontal, and vertical modes) and predictions for both chroma components can be generated concurrently. Note that the number of cycles may vary for different angular prediction modes. Angular modes are thus split into four categories (positive/negative angle, main direction is hor/ver).

Note that the cost of DC postsmoothing is significant. For blocks of size  $4 \times 4$ , the DC mode even is the most time-consuming prediction mode. It should be further noted that the postsmoothing is not optimized by SIMD operations (at least not manually). While the number of cycles per sample decreases as the size of the blocks increase, this does not always seem to be the case. The differences between the various angular ranges are due to two factors: for modes 2–9 and 11–17, the result is transposed, leading to a higher cycle count; and for modes 11–17 and 18–25, samples from the second reference array are projected onto the first one.

TABLE VII  
RESULTS OF THE TESTS ON DIFFERENT INTRA CODING TOOLS

	Test 1	Test 2	Test 3	Test 4	Test 5
Class	$\Delta$ BDR	$\Delta$ BDR	$\Delta$ BDR	$\Delta$ BDR	$\Delta$ BDR
Class A	6.1%	5.7%	2.6%	9.6%	1.1%
Class B	6.5%	8.5%	1.5%	5.7%	1.0%
Class C	6.9%	3.7%	0.3%	1.6%	1.1%
Class D	4.8%	2.5%	0.3%	1.4%	0.8%
Class E	9.5%	12.3%	1.9%	6.9%	1.6%
Class F	5.6%	4.8%	0.3%	1.5%	1.2%
Maximum	14.8%	19.2%	4.7%	16.3%	1.6%
All	6.5%	6.1%	1.1%	4.4%	1.1%

### B. Fast Encoding Algorithm

While an increase in the number of intra prediction modes can provide substantial performance gains, it also makes the rate-distortion (RD) optimization process more complex. In this section, we introduce the new encoding algorithm utilized by the official HM 6.0 reference software and describe how it is optimized for large sets of prediction candidates [17].

The fast encoding algorithm of HM software includes two phases. In the first phase, the  $N$  most promising candidate modes are selected by the rough mode decision process. In this process, all candidates (35 modes) are evaluated with respect to the following cost function:

$$C = D_{Had} + \lambda \cdot R_{mode} \quad (4)$$

where the  $D_{Had}$  represents the absolute sum of Hadamard transformed residual signal for a PU and  $R_{mode}$  represents the number of bits for the prediction mode.

In the second stage, the full RD costs with reconstructed residual signal used for actual encoding process are compared among the  $N$  best candidates. The prediction mode with the minimum RD cost is selected as the final prediction mode. The number  $N$  is varied depending on the PU size. The  $N$  is set to  $\{8, 8, 3, 3, 3\}$  for  $4 \times 4$ ,  $8 \times 8$ ,  $16 \times 16$ ,  $32 \times 32$ , and  $64 \times 64$  PU, respectively, to allow more thorough search for the small block sizes most critical to the joint optimization of prediction and residual data. It should be noted that the size of TU is assumed to be equal to the maximum possible value rather than allowing the TU splitting in this stage for minimizing the complexity. RD optimized TU structure is determined after the second stage by using the best prediction mode.

Results marked as Test 6 in Table VIII indicate that the design of the described fast algorithm is well optimized for the large number of prediction modes.

## V. EXPERIMENTAL RESULTS

### A. Test Conditions

The JCT-VC common test conditions [20] were used to evaluate the performance of different aspects of the intra picture coding of HEVC. These conditions define a set of 24 video sequences in six classes (A to F) covering a wide range of resolutions and use cases. In addition to natural camera captured material, the Class F sequences also include computer screen content and computer graphics content, as well as

TABLE VIII  
RESULTS OF THE TESTS ON FAST INTRA ENCODING AND SAO

Class	Test 6		Test 7
	$\Delta$ BDR	t (enc)	$\Delta$ BDR
Class A	−0.4%	294%	0.8%
Class B	−0.3%	296%	0.7%
Class C	−0.3%	297%	0.9%
Class D	−0.4%	296%	0.6%
Class E	−0.4%	286%	0.9%
Class F	−0.4%	303%	2.9%
Maximum	−0.2%	333%	4.3%
All	−0.4%	296%	1.1%

content mixing natural video and graphics. In order to assess the objective quality differences, Bjøntegaard delta bitrates are computed using piece-wise cubic interpolation [18], [19]. The 10-b *Nebuta* and *SteamLocomotive* sequences were not included in the experimental results since the HEVC Main profile only specifies operation for 8-b 4:2:0 video.

HM6.0 reference software [14] with the Main profile settings were used to evaluate the HEVC intra coding performance. The four rate points required to calculate the Bjøntegaard delta bitrates were generated by using quantization parameters 22, 27, 32, and 37.

Performance of the H.264/AVC intra coding was investigated using JM 18.2 reference software [22] with its high-profile settings (RD optimizations,  $8 \times 8$  DCT and CABAC enabled). In order to operate approximately at the same bitrates with HEVC, quantization parameters of 24, 29, 34, and 39 were used for H.264/AVC.

## B. Experimental Results

2) *Performance Analysis of the HEVC Intra Coding Tools:* In order to analyze how different aspects contribute to the total performance of HEVC intra coding, the following experiments were carried out.

- 1) *Test 1:* Restricting HM 6.0 intra modes to the eight H.264/AVC directional modes, DC, and planar mode, utilizing a 1-MPM approach for mode coding.
- 2) *Test 2:* Restricting the HM 6.0 maximum CU size to  $16 \times 16$  and the maximum TU size to  $8 \times 8$ .
- 3) *Test 3:* Restricting the maximum TU size to  $16 \times 16$ .
- 4) *Test 4:* Restricting the maximum TU size to  $8 \times 8$ .
- 5) *Test 5:* Substituting the HM 6.0 3-MPM intra mode coding with a 1-MPM approach.
- 6) *Test 6:* Utilizing full RD optimizations for selecting the intra mode as described in Section IV-B.
- 7) *Test 7:* Switching off SAO.

The relevant syntax changes due to the differences of the number of intra modes and MPMs were applied in Tests 1 and 5 for the fair comparison. Tables VII and VIII summarize the performance for each test. Positive numbers indicate the increase in bitrate associated with restricting the codec according to the test descriptions. In addition to the average and per class results, the maximum difference for a single test sequence is also reported. According to Test 1, the average impact provided by the HEVC angular prediction is 6.5%

TABLE IX  
PERFORMANCE OF HM6.0 COMPARED WITH JM18.2

Class	Sequence	Bit-saving (%)
Class A ( $2560 \times 1600$ )	<i>Traffic</i>	−21.9
	<i>PeopleOnStreet</i>	−22.2
Class B ( $1920 \times 1080$ )	<i>Kimono</i>	−27.8
	<i>ParkScene</i>	−16.5
	<i>Cactus</i>	−23.6
	<i>BasketballDrive</i>	−29.0
	<i>BQTerrace</i>	−20.8
Class C ( $832 \times 480$ )	<i>BasketballDrill</i>	−31.7
	<i>BQMall</i>	−20.3
	<i>PartyScene</i>	−12.6
	<i>RaceHorses</i>	−18.3
Class D ( $416 \times 240$ )	<i>BasketballPass</i>	−22.6
	<i>BQSquare</i>	−13.3
	<i>BlowingBubbles</i>	−13.8
	<i>RaceHorses</i>	−19.3
Class E ( $1280 \times 720$ )	<i>FourPeople</i>	−23.3
	<i>Johnny</i>	−35.5
	<i>KristenAndSara</i>	−28.8
Class F ( $1024 \times 768$ )	<i>BasketballDrillText</i>	−27.9
	<i>ChinaSpeed</i>	−18.8
	<i>SlideEditing</i>	−15.7
	<i>SlideShow</i>	−27.6
Averages	Class A	−22.1
	Class B	−23.6
	Class C	−20.7
	Class D	−17.2
	Class E	−29.2
	Class F	−22.5
	Maximum	−35.5
	All	−22.3

while more differences up to 14.8% are noticed for sequences with strong directional patterns such as *BasketballDrive* and *BasketballDrill*. In addition, the coding efficiency benefits are rather uniform across difference classes while Class E, which consists of the video conferencing sequences having large objects and steady background, provides more benefits.

Allowing larger CU, PU, and TU with more flexibility in both predicting and transforming the picture content provides an average bitrate impact of 6.1% according to Test 2. To clarify further, Tests 3 and 4 study the effects provided by utilization of transform sizes larger than  $8 \times 8$  while keeping the maximum CU size to  $64 \times 64$ . Test 3 indicates that switching of the  $32 \times 32$  transform affects the coding efficiency by 1.1% on average and Test 4 indicates that switching off both  $32 \times 32$  and  $16 \times 16$  transforms has an average impact of 4.4%. It can be observed that the coding efficiency benefits from the large size transform become more significant when the spatial resolution of the video sequence is increased. Test 5 shows that using one most probable mode instead of three would result in 1.1% average coding efficiency difference.

Test 6 illustrates the performance of the HM 6.0 encoding algorithm for intra coding. A full RD optimized codec would be able to achieve a −0.4% coding gain on average, but with almost three times the encoding time of HM 6.0. Thus, the current HM 6.0 encoder design seems to provide a very interesting compromise between coding efficiency and complexity.



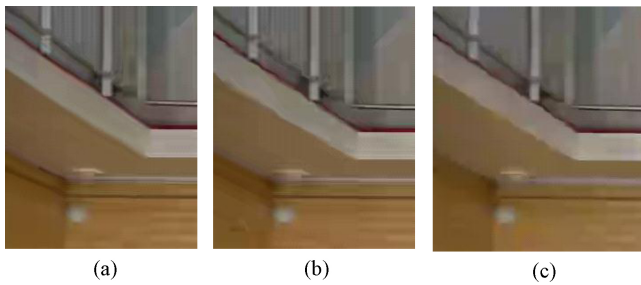


Fig. 4. Example of visual quality improvements in 50 f/s *BasketballDrive*  $1920 \times 1080$  sequence. (a) HM 6.0 (8.4 Mb/s). (b) AVC 10 modes (8.5 Mb/s). (c) JM 18.2 (9.1 Mb/s).



Fig. 5. Example of visual quality improvements in the first frame of 60 f/s *KristenAndSara*  $1280 \times 720$  sequence. Above: an extract of HM 6.0 coded frame at 4.8 Mb/s. Below: JM 18.2 at 4.9 Mb/s.

Finally, Test 7 provides the results showing that the switching off SAO results in the 1.1% coding efficiency loss on average.

2) *Performance Compared to H.264/AVC Intra Coding*: Table IX compares the intra picture coding performance of HEVC with that of H.264/AVC using the test conditions described above. The experiment indicates that in order to achieve similar objective quality, HEVC needs 22.3% lower bitrate on average. Although the average bit-saving of HEVC intra coding seems less than that of HEVC inter coding, which was typically reported over 30%, the benefits are still substantial.

The advantages over H.264/AVC intra coding tend to be larger when the video resolution becomes higher and the strong directionalities exist. Differences close to 30% were observed for seven of the sequences: *Kimono*, *BasketballDrive*, *BasketballDrill*, *Johnny*, *KristenAndSara*, *BasketballDrillText*, and *SlideShow*. The highest difference of 35.5% is obtained in the case of *Johnny*. These sequences are characterized by strong directional textures. In addition, *Kimono*, *Johnny*, and *KristenAndSara* feature also large homogenous regions. The flexible coding structure of HEVC supporting blocks up to  $64 \times 64$  with accurate prediction means appears to be especially effective for this kind of content. The large transform block size also plays a role in performance improvement by

providing strong energy compaction and smaller quantization errors. Especially for regions that cannot be properly predicted by angular prediction (e.g., diverse textures), a large transform is successfully applied for residual coding. Sample-adaptive offset filtering also provides additional gains in intra pictures by compensating distortions between reconstructed and original signals.

3) *Subjective Quality Evaluation*: Comparison of visual quality provided by HM 6.0 implementation of HEVC, HM 6.0 restricted to 10 intra prediction modes as described for Test 1 above, and JM 18.2 implementation of H.264/AVC is presented in Fig. 4. It shows that directional patterns are much more clear and distinctive in the image produced by HM 6.0 while blurred lines are observed in other cases. In the image from the JM, several lines are completely missing. Very similar effects are noticeable also in Fig. 5, comparing decoded picture quality of HM 6.0 with that of JM 18.2 in the case of the *KristenAndSara* test sequence. It appears that the angular prediction with accurate prediction directions contribute positively to the reconstruction of edge structures. As can be observed from these results, the angular prediction and other intra tools adopted in HM 6.0 have potential to provide significant improvements in visual quality in addition to the objective performance gains.

## VI. CONCLUSION

The intra coding methods described in this paper can provide significant improvements in both objective and subjective quality of compressed video and still pictures. While demonstrating compression efficiency superior to previous solutions, computational requirements and different aspects affecting implementation in various environments were thoroughly considered. The proposed methods passed stringent evaluation by the JCT-VC community and now form the intra coding toolset of the HEVC standard. Potential future work in the area includes, e.g., extending and tuning the tools for multiview/scalable coding, higher dynamic range operation, and 4:4:4 sampling formats.

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