FAST LOSSLESS COMPRESSION OF WHOLE SLIDE PATHOLOGY IMAGES USING HEVC INTRA-PREDICTION

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ABSTRACT

The lossless compression of Whole Slide pathology Images (WSIs) using HEVC is investigated in this paper. Recently proposed intra-prediction algorithms based on differential pulse-code modulation (DPCM) and edge prediction provide significant bitrate improvements for a wide range of natural and screen content sequences, including WSIs. However, coding times remain relatively high due to the high number (35) of modes to be tested. In this paper, FastIntra, a novel method that requires testing only four modes is proposed. Among these four modes, FastIntra introduces a novel median edge predictor designed to accurately predict edges in different directionalities. Performance evaluations on various WSIs show average compression time reductions of 23.5% with important lossless coding improvements as compared to current block-wise intra-prediction and DPCM-based methods.

Index Terms— HEVC, lossless compression, intra coding, whole slide pathology images.

1. INTRODUCTION

High-throughput slide scanners allow the use of digital pathology images of microscope glass slides in clinical and research settings [1]. In order to create digital pathology images that resemble real microscopy viewing experiences, specimens must be scanned at high optical resolutions. For example, a typical microscope specimen of 20×30 mm in size usually produces up to 50 GB of uncoded data using a scanning resolution of 0.2–0.5 μm per pixel [2]. Consequently, the digitized versions of microscope glass slides, which are called whole-slide images (WSIs), are characterized by their large file sizes. Currently, lossless compression methods are used to reduce the amount of data needed to represent WSIs. The most frequently used compression techniques for WSIs are JPEG and JPEG2000 [3].

Recently, the use of the High Efficiency Video Coding (HEVC) standard is investigated for lossless compression of WSIs. Specifically, the works in [4] and [5] propose important improvements to the lossless intra-prediction coding modality of HEVC. In particular, differential pulse code modulation (DPCM) is employed on a sample-by-sample basis, in all angular and planar intra-prediction modes, and an edge predictor is introduced. These improvements have been shown to reduce bitrate in WSIs by an average of 7.82% and of 6.64% compared to current block-wise intra-prediction and the Sample-based Angular Prediction (SAP) method, respectively [4].

Despite the important improvements achieved by DPCM-based intra-prediction in WSIs, the coding times remain relatively high due to the large number of intra-prediction modes to be tested. HEVC intra-prediction employs spatial prediction with a total of 35 predefined modes. The best mode among these predefined modes is selected by rate-distortion optimization (RDO) for each prediction block, which can be very time-consuming.

A number of strategies have been proposed to reduce coding times of intra-prediction in HEVC. These strategies, which mainly focus on the lossy coding case, aim at reducing the number of modes to be tested by RDO [6, 7, 8]. [6] proposes exploiting the information about modes selected for neighboring blocks to speed up the mode decision process. [7] calculates gradient-mode histograms and selects a reduced set of candidate modes to be tested by RDO. [8] also selects a reduced set of candidate modes, but uses edge information of neighboring blocks. All of these methods reduce coding times by up to 35%; however, they usually sacrifice coding performance.

Recently, we proposed a method to reduce coding times for lossless intra-prediction coding in HEVC [9]. This proposal, which employs DPCM-based intra-prediction, drastically reduces the number of modes to be tested. Although that proposal can reduce coding times up to 53.84%, the lossless coding performance is sacrificed compared to other recent improvements based on DPCM.

In this paper, we propose a strategy to reduce lossless coding complexity, in terms of coding times, for WSIs in HEVC intra-prediction. The strategy employs DPCM-based intra-prediction due to its very good performance for lossless compression. The strategy reduces the number of modes to be tested without sacrificing lossless coding performance. The employed modes are well-suited for WSIs and are capable of predicting smooth regions and strong edges in different directions. Among these modes, we introduce a novel median edge predictor to accurately predict edges in different directionalities. The proposed strategy also reduces the overhead associated with signalling the employed modes to the decoder.

The rest of the paper is organized as follows. Section 2 presents a brief overview of current intra-prediction and the associated coding complexity. Section 3 details the DPCM-based intra-prediction modes for WSIs used in this work. Section 4 presents the performance evaluation and Section 5 concludes this paper.

2. INTRA-PREDICTION IN HEVC

Intra-prediction coding in HEVC follows a block-wise approach. Specifically, HEVC partitions each frame hierarchically into non-overlapping coding units (CUs) and further into prediction units

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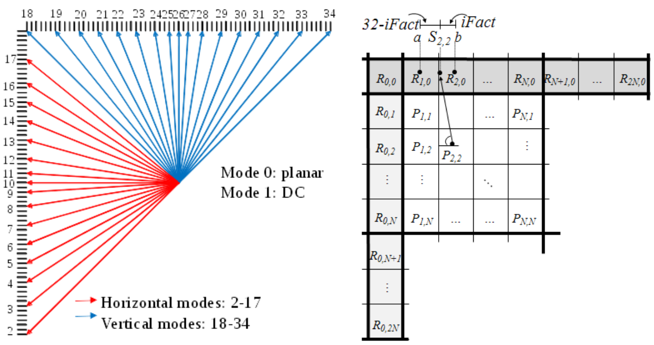

(a) (b)

Fig. 1: (a) Current HEVC intra prediction modes. (b) Prediction principle for all angular modes for an $N \times N$ block. Reference samples a and b are linearly interpolated to compute prediction sample $P_{x,y}$ at position (x, y), where $x = 1$, $y = 1$ is the position of the sample located in the top-left corner. $iFact$ is the distance between original sample $S_{x,y}$ and reference sample b at 1/32 pixel accuracy. Possible samples used as reference are: $\{R_{0,1}, R_{0,2}, \ldots, R_{0,2N}\}$ and $\{R_{0,0}, R_{1,0}, \ldots, R_{2N,0}\}$, located to the left and above of the current block, respectively.

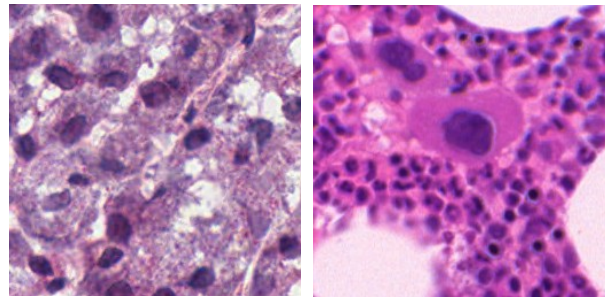

Fig. 2: Sample region of two different WSIs. Note the smooth texture of the depicted tissues and cellular structures and the high number of edges.

(PUs) [10]. It then predicts each PU by using spatial data prediction within the same frame. For each PU to be coded, prediction blocks for the luma and chroma components are created by extrapolating previously coded and reconstructed pixels surrounding the target block. In the case of lossless coding, HEVC bypasses the transform, quantization, and any other processing that affects the decoded sequence. The residual signal, which is the difference between the original block and its prediction, is thus directly fed to the entropy coding process.

The complexity of the HEVC intra-prediction process is considerably high mainly due to the large number of available intra-prediction modes. HEVC uses a set of 35 modes, which include 33 angular modes that propagate surrounding pixels along different directions and model different directional patterns (see Fig. 1), and a DC and PLANAR mode that generate smooth surfaces [11]. Encoding times are then considerably high when RDO is employed to select the best mode for each PU in the hierarchical block structure. This means that a full RDO process requires testing each of the 35 available modes for each PU.

In order to reduce the complexity associated with RDO-based mode selection, HEVC includes a two-step fast encoding algorithm [12]. In the first step, a rough mode decision is performed to select $N < 35$ candidate modes based on an approximation of the coding cost of each mode. In the case of lossless coding, the selection is based on the coding cost of the residual signal and estimated mode bits. The N selected candidate modes are then used by RDO to select the best mode for each PU. This fast encoding algorithm partly reduces encoding times with a minimal sacrifice in encoding performance. However, the complexity is still high due to extensive mode search performed in the first step.

3. PROPOSED COMPRESSION METHOD

DPCM-based intra-prediction has been shown to provide important coding improvements for lossless compression of a great variety of natural and screen content sequences [13, 14]. This is mainly due to the fact that an adjacent pixel to that to be predicted is usually a more accurate predictor than a pixel that is several pixels apart in a neighboring block [13]. In [4], we showed that DPCM-based intra-prediction also improves lossless coding performance for WSIs.

WSIs of biopsy tissues usually portray a great variety of cellular structures and tissues, which results in a combination of smooth regions and regions depicting edges in various directions. Smooth regions in WSIs usually resemble many smooth textures commonly found in natural imagery. However, differently from natural imagery, WSIs feature a very limited number of directional patterns. Fig. 2 shows a small section of two different WSIs. Note the relatively high amount of edges. Also note the smooth regions exhibiting different cellular structures.

Based on the previous observations, WSIs can then be effectively intra-coded by using prediction modes that specifically approximate smooth regions and predict edges in different directionalities. Indeed, in [4] we showed that the introduction of a simple edge predictor, implemented on a sample-wise manner, considerably improves lossless coding performance in these images when combined with DPCM-based angular intra-prediction. In this work, we build upon these improvements and propose a method that uses a small number of DPCM-based modes. The proposed method is hereinafter referred to as *FastIntra*.

The modes in FastIntra are aimed at effectively predicting smooth regions and edges in WSIs, while still being capable of predicting directional patterns. Our objective is twofold. First, we are interested in maintaining the coding improvements gained by combining edge prediction with DPCM-based angular intra-prediction. Second, we are also interested in reducing coding times. Based on this objective, FastIntra reduces the number of available modes for intra-prediction to four DPCM-based modes. Among these four modes, FastIntra introduces a novel median edge predictor. These modes use as reference the previously encoded and reconstructed samples surrounding the target sample (see Fig. 3). When these previously encoded and reconstructed samples are not available, e.g., along some block boundaries, we pad the missing reference samples with the nearest available encoded and reconstructed samples. By reducing the number of modes available, FastIntra also reduces the associated overhead needed to signal them to the decoder. In the following, we explain in detail the four modes used in this work.

Mode 0 – horizontal and vertical edge predictor. The first mode is an edge predictor that considers the value of three neighboring samples when computing the predicted value for the target sample. Let $S_{x,y}$ denote the target sample at position (x, y) within an $N \times N$ block, where $x = 1$, $y = 1$ is the top-left corner. Prediction sample $P_{x,y}$ is then computed based on neighboring pixels located at positions a, b and c as follows [4, 15]:

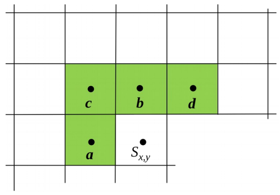

Fig. 3: Position of reference samples used by all modes in FastIntra.

$$P_{x,y} = \begin{cases} \min(a,b) & \text{if } c \geq \max(a,b) \\ \max(a,b) & \text{if } c \leq \min(a,b) \\ a+b-c & \text{otherwise} \end{cases} \quad (1)$$

This edge predictor is capable of accurately detecting vertical or horizontal edges, a major difference with current modes in HEVC, which are not designed to predict strong edges. If an edge is not detected, then $P_{x,y} = a + b - c$, which represents the expected smoothness of the image in the absence of edges. Mode 0 then allows modeling smooth surfaces in WSIs if no edges are present. Another important aspect of this edge predictor is that it is also capable of effectively modeling pure horizontal and vertical patterns. This is illustrated in the sample 4×4 block in Fig. 4. Note that for this sample block, a pure horizontal DPCM-based mode is well suited for prediction, as the original block depicts a strong horizontal pattern. By applying Mode 0 as proposed here, the resulting prediction block effectively models the horizontal pattern.

Mode 1 – median edge predictor. We propose as Mode 1 a median edge predictor (MEP) that considers the median value of n different edge predictors. The main objective of our proposed MEP is to improve prediction in regions depicting several edges by making several predictions, and then choosing the one that is closest to the actual value. Specifically, Mode 1 uses the median of a set of five edge predictors for $S_{x,y}$. More specifically, $P_{x,y} = \text{median}(p_1, p_2, p_3, p_4, p_5)$, where

$$\begin{array}{ll} p_1 = a + d - b & \\ p_2 = a + ((b - c) \gg 1) & p_4 = (a + b) \gg 1 \\ p_3 = b + ((a - c) \gg 1) & p_5 = (a + d) \gg 1. \end{array} \quad (2)$$

Here, $\gg$ denotes a bit-shift operation to the right. Predictor p_1 aims at predicting diagonal edges ($\nearrow\!\!\!\swarrow$) by using the gradient between neighboring samples at positions d and b. Predictor p_2 aims at predicting vertical edges by using the gradient between neighboring samples at positions b and c. Predictor p_3 aims at predicting horizontal edges by using the gradient between neighboring samples at positions a and c. The last two predictors, p_4 and p_5, are aimed at exploiting the correlations between $S_{x,y}$ and the neighboring samples located at positions a, b and d under the assumption that a strong diagonal edge ($\nearrow\!\!\!\swarrow$) crosses $S_{x,y}$.

Mode 2 – average predictor. Mode 2 is an average predictor that uses the average of neighboring samples at positions $\{a, b, c\}$ to make the prediction $P_{x,y} = (a + b + 2c) \gg 2$. Mode 2 is then expected to be effective in modeling smooth surfaces.

Mode 3 – cross-residual predictor. The last mode implements a sample-wise cross-residual prediction in the pure horizontal and vertical directions. The residuals obtained following one direction are predicted using its orthogonal direction. This is based on the observation that the difference between adjacent pixels is linearly increased or decreased according to the direction of the prediction mode [16]. If horizontal DPCM is used on the original block S to obtain the residual block r, then vertical DPCM is used on r to obtain the cross-residual prediction. Conversely, if vertical DPCM is used on S, then horizontal DPCM is used on r. Both cases result in

(a)

91	90	89	89	87
85	83	83	81	80
60	61	63	62	60
57	52	50	49	51
27	28	24	20	19

(b)

85	83	83	81
60	61	63	62
57	52	50	49
27	28	24	20

(c)

85	83	83	81
60	61	63	62
58	**54**	50	49
27	28	24	**22**

Fig. 4: (a) A sample 4×4 block depicting a strong horizontal pattern. Reference samples from adjacent blocks are shown in grey. Corresponding prediction block computed by (b) a pure horizontal DPCM-based mode and by (c) Mode 0 as proposed in this work. Residual values in bold in (c) denote values that are not predicted using the horizontally adjacent sample.

the same mathematical expression for the cross-residual prediction, $P_{x,y} = a + b - c$. Note that this operation also corresponds to the case of absence of edges in Mode 0, *i.e.*, $\min(a,b) < c < \max(a,b)$.

Due to the reduced number of available intra-prediction modes in our proposed strategy, the two-step fast encoding algorithm described in [12] is not necessary. All four modes are tested for each PU in the hierarchical structure of HEVC, in all color components. The reduced number of modes also reduces considerably the associated overhead. With the current 35 modes available in HEVC, 6 bits are needed to represent each mode. This number of bits is reduced to five by signaling the three most probable modes using up to two bits. In the proposed strategy, only 2 bits are needed to represent each mode, which represents a reduction of over 66% in overhead, before entropy coding. In our proposed strategy, each of the two bits of the mode's index binary representation is entropy encoded using a binary arithmetic coder. For simplicity, equal probability is assumed for these two bits.

4. PERFORMANCE EVALUATION

FastIntra is evaluated on 12 different color WSIs from the Center for Biomedical Informatics and Information Technology of the US National Cancer Institute. Test images are acquired in RGB format at 24 bpp (8 bpp per color component) and have dimensions between 13943×11727 and 17408×25600. They are grouped into three different datasets. The first dataset (images 1–6) depicts lymphatic tissues of different sizes; the second dataset (images 7–9) consists of kidney tissues, while the third dataset (images 10–12) depicts pancreatic tissues. All test WSIs are acquired after staining the tissue with Hematoxylin and Eosin (H&E) stain.

The four modes described in Section 3 are implemented in all PUs sizes available in the hierarchical block structure, with a maximum size of 64×64 and minimum size of 4×4. In order to improve lossless coding performance, the reversible YUV transform employed in JPEG2000 is used on all RGB images [17]. This transform allows for a numerically lossless transformation of the red (R), green (G) and blue (B) channels into and from the luma (Y) and chroma (C_b, C_r) representation using the following equations:

$$\begin{array}{lcl} Y = \lfloor (R + 2G + B)/4 \rfloor & & G = Y - \lfloor (C_b + C_r)/4 \rfloor \\ C_b = B - G & \iff & B = C_b + G \\ C_r = R - G & & R = C_r + G. \end{array} \quad (3)$$

Two sets of evaluation experiments are performed using the HEVC reference software HM-16.6+SCM5.1 in 4:4:4 lossless mode [18]. The first set is aimed at evaluating the effectiveness of the reversible YUV transform. Lossless compression bitrate R and coding time t for current block-wise intra-prediction coding

Table 1: Average compression bitrate and execution time for 12 WSI images. Bitrate and time results under the *$HEVC_{Orig}$* column are in bpp per component and seconds, respectively. All other results are expressed as the percentual difference with $\mathrm{HEVC_{Orig}}$. Best results are highlighted in bold font.

Image	$\mathrm{HEVC_{Orig}}$		$\mathrm{HEVC_{YUV}}$		SAP-HV		SAP		SAP+ SWP2+DTM		SAP-E		SAP-E+ IntraBC		FastIntra (Proposed)	
	R	t	$\%R$	$\%t$	$\%R$	$\%t$	$\%R$	$\%t$	$\%R$	$\%t$	$\%R$	$\%t$	$\%R$	$\%t$	$\%R$	$\%t$
1	4.10	1371	-26.9	-5.8	-32.9	-4.8	-33.3	-1.4	-35.2	+137.5	-37.1	-2.6	-37.1	+2937.2	**-38.0**	**-25.4**
2	4.47	1765	-25.4	-4.9	-31.4	-4.1	-31.9	+0.0	-34.9	+133.6	-37.3	-3.0	-37.4	+5819.5	**-38.5**	**-23.9**
3	4.37	3255	-23.6	-8.1	-29.0	-6.8	-29.5	-3.7	-31.5	+124.0	-33.4	-5.1	-33.5	+7727.1	**-34.1**	**-23.9**
4	2.53	1148	-20.6	-7.0	-25.6	-6.7	-26.4	-2.5	-25.2	+134.0	-27.4	-0.6	**-32.9**	+395.2	-26.4	**-24.5**
5	4.10	1507	-19.6	-5.2	-26.0	-3.5	-26.5	+0.0	-29.3	+134.0	-31.1	-1.3	-31.1	+4265.5	**-31.8**	**-23.8**
6	4.25	3363	-26.7	-6.8	-31.4	-5.3	-31.8	+0.0	-33.7	+117.3	-35.5	-2.3	-35.8	+3725.9	**-36.2**	**-22.4**
7	2.46	2408	+5.5	+1.4	-6.6	+0.5	-6.8	+5.4	-12.1	+108.6	-15.9	+1.3	-16.1	+775.3	**-16.6**	**-19.6**
8	0.57	731	+39.0	+6.5	-10.0	+3.7	-8.6	+7.4	-24.6	+127.9	-27.9	+3.0	**-28.4**	+32.6	-28.1	**-29.2**
9	2.20	1898	+3.2	+3.9	-9.7	+3.0	-10.2	+7.9	-14.1	+134.9	-16.7	+4.9	**-16.9**	+1417.1	-16.6	**-19.2**
10	1.62	796	-0.4	+1.7	-12.8	+0.5	-12.8	+7.0	-17.1	+139.8	-20.3	+9.6	**-20.5**	+669.1	-20.3	**-24.5**
11	3.43	841	-3.2	+0.5	-11.7	-1.3	-12.2	+5.0	-15.4	+145.5	-18.8	+3.2	-18.9	+1355.5	**-19.5**	**-23.1**
12	2.07	1557	+18.0	+2.6	-8.9	+0.1	-7.0	+5.2	-12.8	+142.9	-17.4	+2.0	-17.5	+58.7	**-17.9**	**-21.8**
Average	3.01	1720	-6.7	-1.8	-19.7	-2.1	-19.7	+2.5	-23.8	+131.7	-26.6	+0.8	**-27.2**	+2394.1	-27.0	**-23.4**

in HEVC (without the YUV transform) are provided in column $\mathrm{HEVC_{Orig}}$ of Table 1. These results are used as anchor for all following evaluations. Results using the YUV transform are expressed as percentual differences in column $\mathrm{HEVC_{YUV}}$, negative values meaning improvements over anchor. Thanks to the YUV transform, average bitrate improvements of 6.7% are obtained. It can be observed that average compression times are reduced by 1.8%. This is mainly due to the increase of zero-valued residuals, which reduces the load of the context-adaptive binary arithmetic coder (CABAC). Therefore, the YUV transform is used in all following experiments. Note that the YUV transform decreases compression performance for images 7, 8, 9 and 12. All these images have in common a large background region, depicting no stained tissue. In particular, image 8 contains almost only background, which explains the exceptionally low bitrate (0.57 bpp per component) required to code it. This suggests that the YUV transform is most effective for regions depicting stained tissue.

The second set of experiments evaluates the coding improvements of various DPCM-based intra-prediction methods, IntraBC and FastIntra. The reversible YUV transform is used in all methods. The methods evaluated are:

- SAP-HV: DPCM-based intra-prediction applied only to mode 10 and mode 26 [10].
- SAP: DPCM-based intra-prediction applied exclusively to angular modes [13].
- SAP+SWP2+DTM: SAP in conjunction with SWP2 (in lieu of PLANAR mode), and DTM (in lieu of DC mode). SWP2 computes a weighted average of surrounding pixels, while DTM uses the most similar surrounding pixel [19].
- SAP-E: SAP in conjunction with a DPCM-based DC mode and the edge predictor in (1) (in lieu of PLANAR mode) [4].
- SAP-E+IntraBC: SAP-E in conjunction with IntraBC [18], which allows predicting blocks by using any previously encoded block within the same frame. In this evaluation, the search range for IntraBC is set to 16 CUs.

Table 1 tabulates results for all these methods. As mentioned in Section 2, our objective is to maintain the coding gains attained by DPCM-based intra-prediction when applied to all 35 modes (SAP-E), while reducing coding times. It can be seen that the FastIntra algorithm attains the coding gain goal. Interestingly, FastIntra slightly improves upon SAP-E on average and individually for all images except for images 4, 9 and 10, albeit the number of available intra-prediction modes is reduced to four. The SAP-HV, SAP and SAP+SWP2+DTM methods yield results worse than SAP-E for all tested images, and are all consistently outperformed by the proposed FastIntra algorithm. Combining IntraBC with SAP-E improves its average coding gain (27.2% versus 26.6% without IntraBC), surpassing FastIntra's gains (27.0%) by only 0.2%. Larger improvements are not observed due to the fact that the tested WSIs do not depict a high number of repeating patterns that can be exploited by IntraBC. However, these small coding improvements come at the cost of greatly increasing the execution time, even though the number of explored CUs is limited. As obvious from the table, the coding time reduction goal for FastIntra is successfully reached. Indeed, this algorithm is able to compress all images significantly faster than any other tested method, with average time reductions of 23.4% over anchor. This is to be compared with an average 0.8% time requirement *increment* of SAP-E over anchor.

For completeness, JPEG-LS with default parameters and lossless JPEG2000 with 5 spatial discrete wavelet transform (DWT) decomposition levels are tested. Notwithstanding, these results are not shown in Table 1 for the sake of brevity. The coding gains of these algorithms are 11.5% and 22.6%, respectively. Therefore, the FastIntra algorithm significantly outperforms JPEG-LS in terms of coding performance and attains gains slightly better than those of JPEG2000.

5. CONCLUSIONS

This paper proposed FastIntra, a method for fast lossless compression of WSIs using DPCM-based intra-prediction coding in HEVC. DPCM-based strategies are known to be efficient for compressing a great variety of sequences and images, specially when simple edge predictors are incorporated. However, the time complexity of these strategies is relatively high due to the high number of modes to be tested. FastIntra employs only four modes aimed at predicting smooth regions and edges, which are commonly depicted in WSIs. Among these four modes, FastIntra introduces a novel median edge predictor to effectively predict edges in different directionalities. Performance evaluations indicate that FastIntra reduces the average coding time by over 23% while improving upon the compression bitrates attained by both current block-wise intra-prediction and DPCM-based strategies.

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