RESIDUAL DPCM FOR LOSSLESS CODING IN HEVC

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ABSTRACT

Incorporating sample-based prediction during lossless coding can significantly improve coding performance. However, its use within a codec designed for lossy coding requires a modification of the available prediction scheme. When implementing the codec, two different prediction processes will have to be implemented. This paper describes a lossless coding scheme that delays the sample-based prediction till the residue coding stage of the codec and carries out prediction in the residual domain. In this way, the prediction scheme of the lossy coder can be retained while realizing the coding gains associated with sample-based prediction. The proposed scheme improves lossless intra coding performance in HEVC Main Profile by an average of 6.5%.

***Index Terms*—** intra coding, HEVC, lossless coding, coding gains analysis

1. INTRODUCTION

Lossless image compression has long been used for applications such as archival, medical imaging, screen content and mask lithography. Recently, the practical relevance of lossless coding of multimedia data has also been evident from the inclusion of lossless coding tools in several image and video coding standards. Often a new set of tools, significantly different from those already available for the purpose of lossy coding, have to be designed as the requirement of lossless coding renders available tools unsuitable. For example, in the High 4:4:4 Predictive Profile of the H.264/AVC standard, the intra coding process has to be modified to include a lossless coding method based on a sample-by-sample differential pulse code modulation (DPCM).

While lossless coding has been widely studied, almost all previous works are focused on improving prediction performance in the pixel domain. While removing redundancy through pixel-wise prediction can significantly improve coding performance, including it in a codec designed for lossy coding is not straightforward. Since hybrid lossy coding schemes are designed to accommodate the use of block transforms, intra prediction within each transform block is carried out with pixels that lie outside the block. Modifying available prediction methods to include pixel-wise prediction means incurring extra implementation cost when lossless modes are incorporated into available codec design.

ISO/IEC MPEG and ITU-T VCEG have been working together on a new video coding standard, known as High Efficiency Video Coding (HEVC), as the Joint Collaborative Team - Video Coding (JCTVC). HEVC includes many new coding tools, in part to address the different statistics of videos with higher resolutions, and significantly improves the compression performance of H.264/AVC. In this paper, we describe a lossless coding method which improves the lossless coding performance of the HEVC standard.

1.1. Background on HEVC

Here, we briefly describe the partition structure used in HEVC [1]. In the current design of HEVC, each picture is divided into "largest coding units" (LCU) and each LCU can be further divided into sub-CUs through a recursive quad-tree structure. Leaf CUs can also be further partitioned into prediction units (PU) each of which may carry distinct information (e.g. motion vectors or intra-prediction mode) required for generating its prediction. The definition of transform units (TU), nested within CUs, allows TU size to vary independent of the size of the CU in which it resides [2]. During the encoding of an N x N CU, the encoder can signal the use of a transform that is of the same size as the CU. Alternatively, the CU can be coded with 4 transforms, each of size N/2 x N/2. It is possible for this transform quad-tree to grow further; the maximum depth of a transform tree is dependent on a sequence level residual quad-tree depth signal.

1.2. Lossless coding in HEVC

In the current design of HEVC Main profile [1], lossless coding can be signalled at CU level, i.e., individual CUs can be flagged as losslessly coded. Lossless coding is achieved by bypassing transform, quantization and in-loop filters [3]. This mechanism enables lossless coding without additional burden on encoder and decoder implementation. A flag in the picture parameter set signals whether lossless coding is used. If lossless coding is not used for a particular picture, CU-level lossless signalling is disabled for CUs in that picture.

1.3. Contribution

In this paper, we first analyze the use of DPCM and transforms for lossless coding. Next, we propose a lossless coding scheme that performs DPCM on the the prediction residues so that the existing prediction process can be retained while realizing the gains associated with sample-based prediction. We implemented the scheme in the HEVC [1] reference software (HM) and compare the proposed lossless coding scheme to what is available in the current design of HEVC.

2. CODING GAINS ANALYSIS

2.1. Background on intra-predictive transform

In order to analyze the coding gains of the intra coding process, the work in [4] formulated the intra prediction process with the accompanying transform as an "intra-predictive transform". Consider the case of 1-D signals in blocks of length $n-k$. Let $x_1, \cdots, x_{n-k}$ denote the signals within the current block and $\tilde{x_1}, ..., \tilde{x_k}$ denote signals from the previous blocks which are available to predict the current block. Let the input and output vector of the transform be $\mathbf{x} = [\tilde{x_1}, \cdots, \tilde{x_k}, x_1, \cdots, x_{n-k}]^T$ and $\mathbf{y} = [\tilde{y_1}, \cdots, \tilde{y_k}, y_1, \cdots, y_{n-k}]^T$ respectively. Then, the intra-predictive transform takes the form:

$$\mathbf{y} = \mathbf{Tx} = \begin{bmatrix} \mathbf{I}_{k\times k} & \mathbf{0}_{k\times(n-k)} \\ \multicolumn{2}{c}{\mathbf{T}_{(n-k)\times n}} \end{bmatrix} \mathbf{x}, \tag{1}$$

where $\mathbf{I}_{k\times k}$ is an $k \times k$ identity matrix. Consistent with the nature of intra prediction, the predictors, $\tilde{x_1}, ..., \tilde{x_k}$, remains unchanged after the transform.

We illustrate the intra-predictive transform for a conventional intra coding process where intra prediction is followed by a DCT transform. Consider a 1-D predicted block of length 4 that uses the pixel value $\tilde{x}$ for prediction, i.e., k=1 and n=5. After prediction, a 1-D 4-point DCT is applied to the prediction residues:

$$\begin{aligned} &DCT(x_1-\tilde{x}, x_2-\tilde{x}, x_3-\tilde{x}, x_4-\tilde{x}) \\ &= DCT(x_1, x_2, x_3, x_4) - DCT(\tilde{x}, \tilde{x}, \tilde{x}, \tilde{x}), \end{aligned} \tag{2}$$

where $DCT()$ denotes the 1-D 4-point DCT. This leads to the intra-predictive transform:

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -2 & & & & \\ 0 & & & & \\ 0 & & \mathbf{DCT} & & \\ 0 & & & & \end{bmatrix}, \tag{3}$$

[1] This is used by the JCT-VC to investigate new video coding tools and is updated to reflect the status of HEVC standardization. This is available at https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/.

where $\mathbf{DCT}$ is the 4-point DCT matrix:

$$\begin{bmatrix} 0.5 & 0.5 & 0.5 & 0.5 \\ 0.6533 & 0.2706 & -0.2706 & -0.6533 \\ 0.5 & -0.5 & -0.5 & 0.5 \\ 0.2706 & -0.6533 & 0.6533 & -0.2706 \end{bmatrix}. \tag{4}$$

The coding gain of a transform quantifies the advantage in using it over the direct quantization of the variables to be coded [5] and is defined as the ratio of the arithmetic mean of the variances of input variables to the geometric mean of the variances of the output variables. If $\mathbf{C_x}$ and $\mathbf{C_y}$ denote the covariance matrices of the input to the transform, $\mathbf{x}$, and the output of the transform, $\mathbf{y}$, respectively, then

$$\mathbf{C_y} = \mathbf{TC_xT^T}. \tag{5}$$

Assuming that the input vector x is a block of samples from a weakly stationary Gaussian process, each x_i has the common variance σ_x. Since only $n-k$ output coefficients are coded, the coding gain of the intra-predictive transform is:

$$G = \frac{\sigma_x^2}{(\prod_{i=1}^{n-k} c_{k+i,k+i})^{\frac{1}{n-k}}}. \tag{6}$$

In our analysis, $\mathbf{C_x}$ is generated with the following correlation model:

$$covariance(x_i, x_j) = \rho^{|j-i|}. \tag{7}$$

That is, the covariance of two pixel values depends on the distance between the pixels.

2.2. Performance of DPCM and lossless transforms

An alternative to using DPCM for lossless coding is to design lossless transforms. Even though the prediction residues are losslessly coded, the lossless coding process should still benefit from transforms that achieve both energy compaction and decorrelation. However, the use of block transform means that not all pixels can be predicted from reconstructed pixels that are close to themselves. For these pixels, prediction performance may suffer as they are less correlated with their predictors. We use the coding gains analysis described earlier to study the relative performance of DPCM and variable size lossless transform.

Written as an intra-predictive transform, the process of coding length-8 data with 2 4-point transforms can be expressed as:

$$\mathbf{T_{DCT4}} = \begin{bmatrix} 1 & \mathbf{0_{1\times4}} & \mathbf{0_{1\times4}} \\ \mathbf{0_{4\times1}} & \mathbf{DCT_{4x4}} & \mathbf{0_{4\times4}} \\ \mathbf{0_{4\times1}} & \mathbf{0_{4\times4}} & \mathbf{DCT_{4x4}} \end{bmatrix}. \tag{8}$$

$\mathbf{T_{DCT4}}$, however, does not code the source data with intra prediction. Coding both the first and the second length-4 data with intra prediction is possible as the reconstruction of the first length-4 data is available during the coding of the second

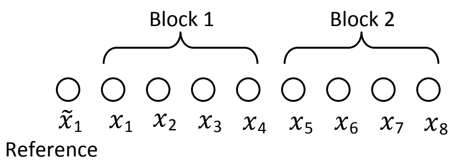

Fig. 1. 1D intra prediction: Pixels in Block 1 can be coded with $\tilde{x_1}$ as predictor while pixels in Block 2 can be predicted against x_4.

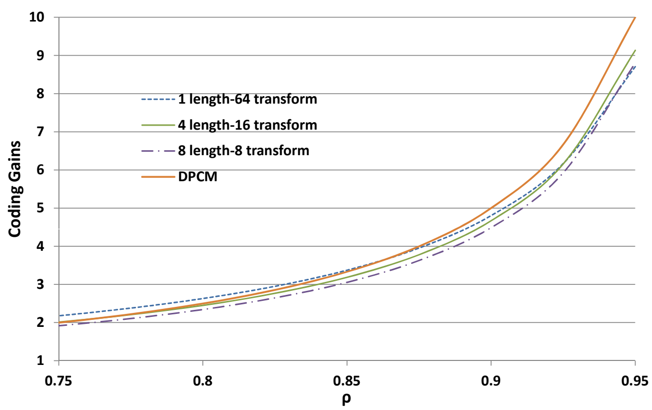

Fig. 2. Coding gains vs image correlation model parameter, ρ, of various intra-predictive transforms for a block of length 64.

(see Fig. 1). This process can also be written as an intra-predictive transform:

$$\mathbf{T_{conventional}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -2 & & & & & & & & \\ 0 & & & & & & & & \\ 0 & & \mathbf{DCT_{4x4}} & & & & \mathbf{0_{4x4}} & & \\ 0 & & & & & & & & \\ 0 & 0 & 0 & 0 & -2 & & & & \\ 0 & 0 & 0 & 0 & 0 & & & & \\ 0 & 0 & 0 & 0 & 0 & & \mathbf{DCT_{4x4}} & & \\ 0 & 0 & 0 & 0 & 0 & & & & \end{bmatrix}. \tag{9}$$

Similarly, the DPCM process for a block of length 8 can be written as:

$$\mathbf{P_{DPCM}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix}. \tag{10}$$

Fig. 2 shows how the coding gains of the different intra-predictive transforms vary with ρ, the correlation coefficient that captures the correlation characteristic of the 1-D signal. The results presented in Fig. 2 reveal that DPCM outperforms lossless transform of various sizes when used for lossless coding of intra prediction residues when the correlation between pixels is high. This analysis motivates the use of DPCM rather than lossless transform for lossless coding.

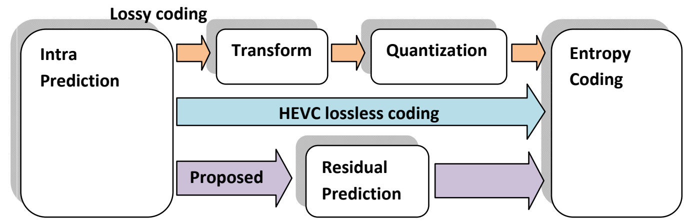

Fig. 3. Lossless coding in HEVC Main profile achieved with a transform and quantization bypass. DPCM predictor is added as a separate component to complement an existing lossy coding scheme.

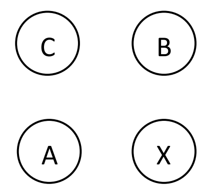

Fig. 4. Residue being predicted, X, and its neighbours

3. PROPOSED METHOD

We introduce a new lossless coding method that can be easily incorporated into a hybrid image/video coding standard. The goal is to realize the gains of sample-wise DPCM-like prediction with minimal modification to the current design of an intra prediction scheme.

The prediction performance during residual prediction can be improved by considering the characteristics of neighbours when determining the predictor. For example, if the position of prediction lies on an edge, better prediction performance can be achieved if the prediction is done along the edge than across it. This can be done using a simple edge prediction procedure [6] on the neighbouring residues A, B and C as shown in Fig. 4:

$$X = \begin{cases} \min(A,B), & if\ C \geq \max(A,B) \\ \max(A,B), & if\ C \leq \min(A,B) \\ A+B-C, & otherwise. \end{cases} \tag{11}$$

This predictor is also used in LOCO-I, the algorithm at the core of JPEG-LS [7]. Unlike LOCO-I, where the prediction is done in the pixel domain, the proposed scheme applies the prediction in the residual domain. In this way, the DPCM predictor can be easily implemented as a separate component to complement an existing lossy coding scheme (e.g., HEVC intra coding) by imparting improved lossless coding capabilities.

To handle boundary conditions, where all or some of the boundary residue, A, B and C, may not be available, we use the following to ensure a consistent treatment. If any of the boundary residue is not available, we will simply set it to 0. For example, alone the above-most row of residue, where the pixels above, i.e., B and C, are not available, we will set them to 0. If we work this out, we find that for all the pixels along the top row except the first, A would be used as the prediction, as is reasonably expected. Similarly, for the left-most column of residue, where the pixels to the left, i.e., A and C, are not available, we will set them to 0. In this case, for all pixels along the left column except the first, B would be used as the prediction. Finally, for the top-left residue pixel, all of A, B and C are not available, and are all set to 0. In this case, the prediction used is 0, and the residue is coded as is.

Compared to the work in [8], there is no dependence on the intra prediction type, and this residual pixel-based prediction can be applied to all intra coded blocks.

3.1. Inclusion of proposed method in HEVC

In the current design of the Main Profile of HEVC, lossless coding can be enabled by bypassing the transform and quantization stage of the encoding process. Though this requires only a few modifications to the originally lossy codec, it underperforms a scheme that incorporated sample-based prediction during intra coding [3].

To incorporate the proposed scheme into the HEVC coding framework, as illustrated in Fig. 3, the only modification required is to the residual coding stage, while the prediction process can be retained.

4. EXPERIMENTAL RESULTS

The proposed scheme was implemented in HM8.0 and comparisons were made against HM8.0 in the transform bypass mode. `TransquantBypassEnableFlag` and `CUTransquantBypassFlagValue` were set to 1 and QP was set to 0 (for Main Profile experiments) and -12 (for HE10 experiments) in the configuration file. Table 1 shows the coding performance results for the All-Intra Main and the All-Intra HE10 configurations.

Despite being independent of the chosen intra coding modes, the proposed method significantly improves the coding performance of the current HEVC design. It is also able to achieve most of the gains associated with a method, known as sample-based angular prediction (SAP), that modifies the intra coding process by implementing a mode specific sample-wise DPCM predictor for each intra coding mode [3]; the coding performance of SAP is also shown in Table 1.

Table 1. Rate reduction (%) (negative numbers imply coding gains)

	Proposed		SAP [3]	
	Main	HE-10	Main	HE-10
PeopleOnStreet	-13.2	-12.8	-9.5	-9.4
Traffic	-11.9	-11.9	-10.6	-10.8
Nebuta	-11.5	-9.3	-6.5	-5.2
SteamLocomotive	-9.5	-7.2	-5.0	-3.6
Average for Class A	-11.5	-10.3	-7.9	-7.3
BasketballDrive	1.0	-0.9	-3.3	-3.1
BQTerrace	-0.5	-1.8	-3.6	–3.6
Cactus	0.0	-1.1	-3.2	-2.8
Kimono1	-5.6	-6.7	-5.7	-5.8
ParkScene	-6.8	-7.0	-5.8	-5.8
Average for Class B	-2.4	-3.5	-4.3	-4.2
BasketballDrill	0.5	-0.1	-6.9	-5.8
BQMall	-2.9	-3.6	-6.0	-5.6
PartyScene	-2.8	-2.8	-5.3	-5.1
RaceHorses	-8.2	-8.7	-6.9	-7.4
Average for Class C	-3.4	-3.8	-6.3	-6.0
BasketballPass	-12.3	-12.0	-12.3	-12.6
BlowingBubbles	-3.4	-3.4	-6.7	-6.2
BQSquare	-0.9	-1.4	-4.3	-4.3
RaceHorses	-10.6	-10.7	-9.4	-9.4
Average for Class D	-6.8	-6.9	-8.2	-8.1
FourPeople	-10.8	-11.0	-10.2	-11.0
Johnny	-7.4	-8.4	-8.7	-9.9
KristenAndSara	-8.1	-9.3	-9.2	-10.6
Average for Class E	-8.8	-9.6	-9.4	-10.5

5. CONCLUSION

In this paper, we first analyze the relative performance of DPCM and lossless transform before introducing a lossless coding scheme that delays the sample-based prediction till the residue coding stage of the codec and carries out prediction in the residual domain. In this way, the prediction scheme of the lossy coder can be retained and remain unchanged while realizing the coding gains associated with sample-based prediction. Experimental results show that the proposed scheme improves lossless intra coding performance of HEVC Main Profile by an average of 6.5%.

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