Transactions Letters

HEVC Lossless Coding and Improvements

Minhua Zhou, Wen Gao, Minqiang Jiang, and Haoping Yu

***Abstract*—The lossless coding mode of the High Efficiency Video Coding (HEVC) main profile that bypasses transform, quantization, and in-loop filters is described. Compared to the HEVC nonlossless coding mode with the smallest quantization parameter value (i.e., 0 for 8-b video and −12 for 10-b video), the HEVC lossless coding mode provides perfect fidelity and an average bit-rate reduction of 3.2%–13.2%. It also significantly outperforms the existing lossless compression solutions, such as JPEG2000 and JPEG-LS for images as well as 7-Zip and WinRAR for data archiving. To further improve the coding efficiency of the HEVC lossless mode, a sample-based angular intra prediction (SAP) method is presented. The SAP employs the same prediction mode signaling method and the sample interpolation method as the HEVC block-based angular prediction, but uses adjacent neighbors for better intra prediction accuracy and performs prediction sample by sample. The experimental results reveal that the SAP provides an additional bit-rate reduction of 1.8%–11.8% on top of the HEVC lossless coding mode.**

***Index Terms*—Block-based angular intra prediction, High Efficiency Video Coding (HEVC), lossless coding, sample-based angular intra prediction (SAP).**

I. Introduction

High Efficiency Video Coding (HEVC) [1] is the next-generation video compression standard being jointly developed by the Joint Collaborative Team on Video Coding (JCT-VC) of ITU-T WP3/16 and ISO/IEC JTC 1/SC 29/WG 11. HEVC provides 50% more bit-rate reduction and a higher degree of parallelism when compared to H.264/AVC by adopting a variety of coding efficiency enhancement and parallel processing tools. In HEVC, a picture is divided into the largest coding units (LCUs) of equal size, and each LCU is further decomposed into coding units (CUs). One unique feature of HEVC is that it enables the lossless coding mode at the CU level even for 8-b video 4:2:0 chroma format.

There is an increasing demand for lossless video coding in real-world applications. In the automotive vision application, video captured from cameras of a vehicle may need to be transmitted to the center processors in a lossless manner for video analytics purposes. In web collaboration and remote desktop sharing applications where hybrid natural and syntactic video coding might be required, part of the video scene may contain synthetic contents such as presentation slides as well as graphical representations of function keys in GUI that need to be coded with the lossless mode. In content creation and post production, JPEG2000 [11] has recently seen a resurgence for content distribution; HEVC with the lossless mode can help penetrate this market. In those application scenarios, a lossless coding mode that provides certain level of compression is in high demand.

However, mainstream applications of the HEVC standard, such as set-top boxes, video surveillance, video conferencing, and video streaming, require high efficiency coding, which usually comes with quality degradation to the original video content. HEVC represents the state-of-the-art tradeoff among coding efficiency and implementation complexity. It would be unpractical to develop a separate set of tools, such as JPEG2000 [11], in HEVC to support a lossless mode with the best possible lossless coding efficiency. Therefore, the design principle of the HEVC lossless mode is to leverage the existing HEVC lossy coding structure and to maximize logic sharing with the existing HEVC coding tools. Tools proposed to the HEVC lossless coding are subject to this special constraint in addition to common complexity and coding efficiency tradeoff consideration.

The remainder of this paper is organized as follows. Section II describes the lossless coding mode currently adopted in the HEVC main profile. Section III presents a sample-based angular intra prediction method (SAP) aimed to improve the intra prediction efficiency of the lossless mode. The experimental results are provided in Section IV followed by conclusions in Section V.

II. Lossless Coding in HEVC Main Profile

The lossless coding mode in the HEVC main profile [1] is achieved by simply bypassing transform, quantization, and in-loop filters (de-blocking filter, sample adaptive offset, and adaptive loop filter). The design is aimed to enable the lossless coding without burdening the HEVC main profile encoder and decoder implementation for mainstream applications.

Fig. 1 illustrates the diagram of the HEVC lossless coding encoder in which transform, quantization, and in-loop filters are bypassed. The intra prediction, inter prediction, and en-

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M. Zhou is with Texas Instruments, Inc., Dallas, TX 75093 USA (e-mail: zhou@ti.com).

W. Gao, M. Jiang, and H. Yu are with Huawei Technologies, Santa Clara, CA 95050 USA (e-mail: wen.gao@huawei.com; jiang@huawei.com; haoping.yu@huawei.com).

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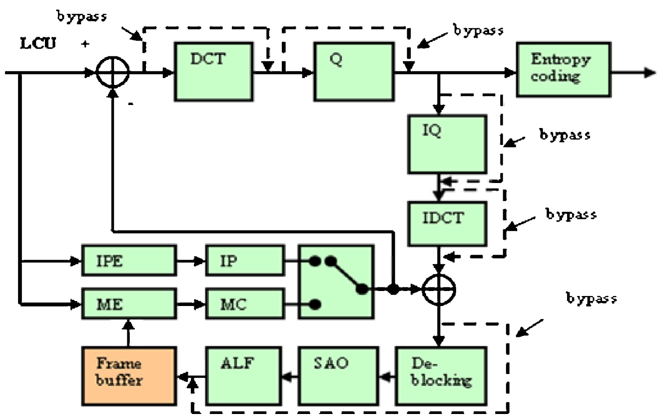

Fig. 1. Diagram of the HEVC encoder with the lossless coding mode.

tropy coding are used as is in the lossless coding mode to exploit spatial, temporal, and statistical redundancy.

Similar to H.264/AVC [2], in HEVC the lossless coding mode can be turned on or off either for the entire picture or at the individual CU level. However, the signaling method is different. In the picture parameter set (PPS) there is a high-level flag to indicate whether the lossless coding mode is turned on or off for the picture referring to the PPS. If this flag is set equal to 1, an additional flag is sent at the CU level to signal whether the current CU is coded with the lossless mode or not. If this flag is set equal to 0 in the PPS, the CU-level flag is not sent, and all the CUs in the picture are encoded with transform, quantization, and loop filters in the process, which will always result in a certain level of video quality degradation. To encode an entire picture in the lossless coding mode, one can set the flag in the PPS to 1 and set the CU-level flag equal to 1 for every CU in the picture.

III. Sample-Based Angular Intra Prediction (SAP)

The current HEVC lossless coding mode can be further improved by introducing more advanced tools. One area that can be further investigated for lossless coding efficiency improvement is the intra prediction. Intra prediction becomes more important in the lossless coding, as statistics show that there is a significant percentage of intra coded CUs even when P- and/or B-slices are used.

A. Review of HEVC Block-Based Angular Intra Prediction

In HEVC [1] a block-based angular intra prediction is defined to exploit spatial sample redundancy in intra coded CUs. As shown in Fig. 2, a total of 33 angles are defined for the angular prediction, which can be categorized into two classes: vertical and horizontal angular predictions.

As shown in Fig. 3, for an N × N prediction unit (PU) the block-based angular intra prediction involves a total of 4N + 1 reference samples from neighboring PUs and all the samples inside the PU share the same prediction angle. The prediction samples are generated by using the reference samples from the left and upper neighboring PUs only. The prediction angle is signaled in the bitstream so that the decoder can perform exactly the same operations to reconstruct the prediction samples.

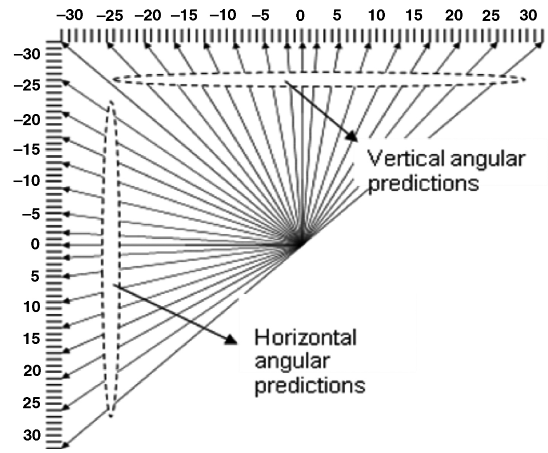

Fig. 2. Angular intra prediction angle definition in HEVC.

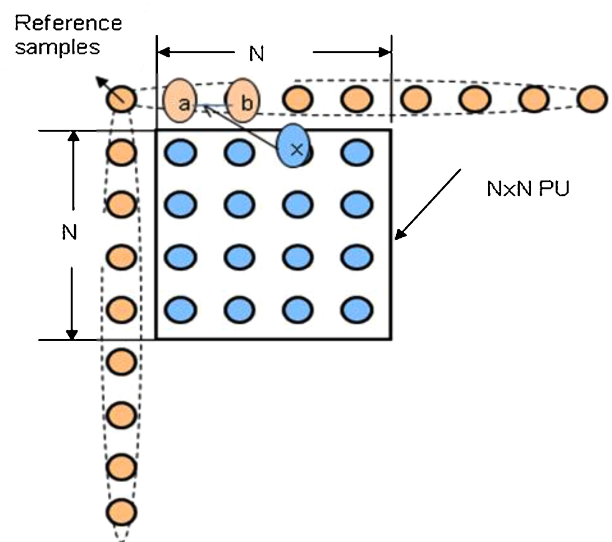

Fig. 3. Block-based angular intra prediction in HEVC.

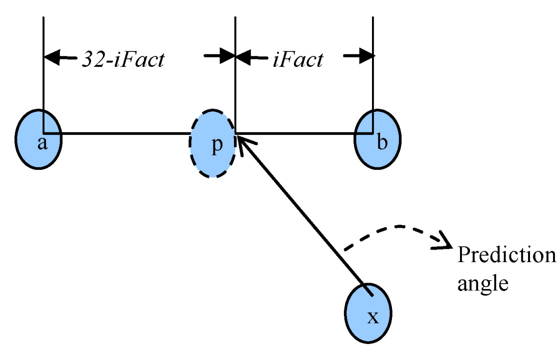

Fig. 4. Linear interpolation of the angular prediction.

For each sample in a PU, two reference samples are selected based on the location of the current sample in the PU and the prediction angle. Once the reference samples are determined, the prediction sample is generated by using linear interpolation defined as

$$p = ((32 - iFact) * a + iFact * b + 16) >> 5 \qquad (1)$$

where a, b are reference samples for the current sample x, p is the prediction sample, and *iFact* is the distance between p and b as depicted in Fig. 4.

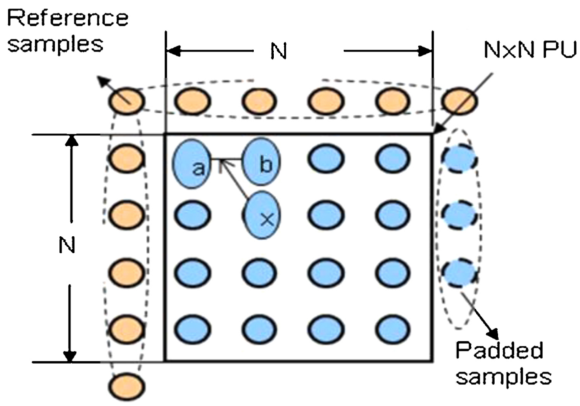

Fig. 5. Reference sample selection of SAP for vertical prediction angles.

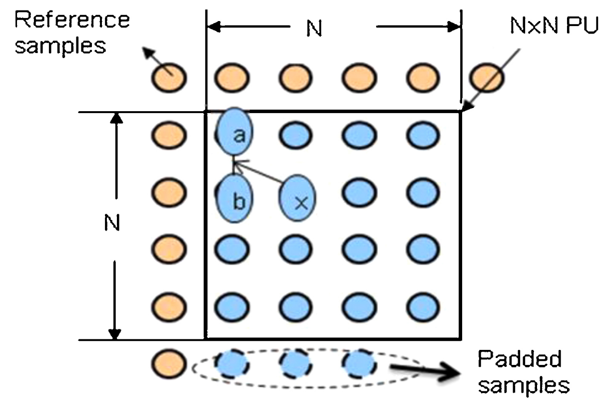

Fig. 6. Reference sample selection of SAP for horizontal prediction angles.

For lossless coding, the reference samples are available not only around the upper and left PU boundaries of the current PU, but also inside the current PU. Therefore, for better intra prediction accuracy of the lossless coding, the angular prediction can be extended to the sample level.

B. Algorithm Description of Sample-Based Angular Intra Prediction (SAP)

The SAP is designed to better exploit the spatial redundancy in the lossless coding mode by generating intra prediction samples from adjacent neighbors. The design principle here is very similar to the sample-based DPCM presented in [4] for the H.264/MPEG-4 AVC [2] lossless coding, but SAP is fully harmonized with the HEVC block-based angular intra prediction, and can be applied to all the angular intra prediction modes specified in HEVC.

As shown in Figs. 5 and 6, in the proposed SAP [5], [8], [9] the angular prediction is performed sample by sample. The adjacent neighboring samples a, b of the current sample x in the current PU are used for prediction. That is, the reference samples used for prediction are not limited to those boundary reference samples from the left and upper neighboring PUs. The SAP has to be processed in a predefined order to ensure the availability of these adjacent neighbors for prediction. For vertical prediction angles (Fig. 5), the SAP is processed row by row within a PU, while for horizontal prediction angles (Fig. 6) the SAP is processed column by column within a PU. If a reference sample is outside the current PU, it is simply padded with boundary samples of the current PU as shown in Figs. 5 and 6.

Once the reference samples *a, b* are selected based on prediction angle and the location of the current sample x, the same linear interpolation defined in (1) is carried out to generate the prediction sample p. After prediction sample p is generated, a different operation is performed on the encoder and decoder side: on the encoder side residual sample value, i.e., $x - p$, is generated for the current sample x; on the decoder side, the current sample x is reconstructed by adding the decoded residual to prediction sample p, the reconstructed sample x serves as a reference sample for the SAP prediction of the next sample in the PU.

The same SAP algorithm is applied to the luminance and chrominance components of an intra coded PU. The SAP can be fully parallelized on the encoder side because all the sample values of the current PU are known. However, in the decoder the SAP can only be processed in one row or one column in parallel due to the interdependency between the sample reconstruction and prediction.

The remaining part of SAP specification remains the same as the block-based angular prediction, i.e., all the samples inside a PU share the same prediction angle, the same definition and signaling of the prediction angles, and the same processing for the reference samples from left and upper neighboring PUs. Therefore, the SAP does not require changes in syntax and semantics, and is a simple extension of the existing block-based angular prediction mode to support more efficient lossless coding.

TABLE I
HEVC HM6.0 COMMON TEST CONDITION SEQUENCES

Seq. Class	Picture Size	Category
A	2500 × 1600 (cropped)	4K×2K ultra-HD at 30 and 60 f/s
B	1920 × 1080	1080p HD at 24, 50, and 60 f/s
C	832 × 480	WVGA at 30, 50, and 60 f/s
D	416 × 240	WQVGA at 30, 50, and 60 f/s
E	1280 × 720	720p video conferencing at 60 f/s

IV. EXPERIMENTAL RESULTS

The HM6.0 software has been used for the simulation. The common test conditions and reference configurations specified in [3] are followed, except that only the lowest quantization parameter (QP) (QP = 0 for Main and QP = −12 for HE10) is tested because larger QP does not play a role in the lossless coding. In HM6.0 common test conditions, there are six categories of sequences; two test settings, i.e., main (8-b) and high-efficiency (HE, 10-b); and each setting has four configurations, namely, all I-frame (AI), random access (RA), low-delay B (LB), and low-delay P (LP). Table I provides an overview of the HM6.0 common test condition sequences. To ensure a fair comparison against other lossless coding schemes, all the class A to E sequences are used across the configurations.

A. Performance of the Current HEVC Lossless Mode

Table II summarizes the coding efficiency difference between the HM6.0 with the smallest QP in the nonlossless mode

TABLE II

BIT-RATE INCREASE (%) OF THE HM6.0 NONLOSSLESS CODING USING THE LOWEST QP WHEN COMPARED TO THE HM6.0 LOSSLESS CODING

Seq. Class	Bit-Rate Difference (%)							
	AI-Main	RA-Main	LB-Main	LP-Main	AI-HE10	RA-HE10	LB-HE10	LP-HE10
A	0.0	4.6	5.8	5.3	−3.5	2.3	3.0	3.7
B	6.9	13.2	14.0	12.6	4.4	8.9	9.2	9.9
C	7.6	14.5	15.3	14.8	6.9	11.1	11.6	13.2
D	5.2	14.3	15.6	14.9	6.0	12.5	13.2	14.5
E	7.0	14.9	15.5	14.6	2.4	12.8	14.3	16.6
Avg.	5.3	12.3	13.2	12.4	3.2	9.5	10.3	11.6

TABLE III

COMPRESSION RATIO OF THE HM6.0 LOSSLESS CODING

Seq. Class	Compression Ratio							
	AI-Main	RA-Main	LB-Main	LP-Main	AI-HE10	RA-HE10	LB-HE10	LP-HE10
A	2.05	2.40	2.41	2.35	1.21	1.40	1.41	1.39
B	2.03	2.35	2.36	2.29	1.21	1.39	1.39	1.37
C	1.92	2.51	2.52	2.43	1.13	1.45	1.46	1.44
D	1.79	2.63	2.64	2.55	1.06	1.50	1.50	1.49
E	2.65	3.23	3.19	3.11	1.47	1.80	1.81	1.81
Avg.	2.09	2.62	2.62	2.55	1.22	1.51	1.51	1.50

TABLE IV

COMPRESSION RATIO ACHIEVED BY RUNNING ARCHIVAL TOOLS

Seq. Class	Compression Ratio				
	ZIP	7-Zip	WinRAR	JPEG-LS	JPEG2K
A	1.63	1.92	2.14	2.48	2.41
B	1.59	1.81	1.97	2.14	2.14
C	1.47	1.69	1.76	1.96	1.93
D	1.45	1.70	1.69	1.88	1.83
E	1.90	2.21	2.30	2.69	2.72
Avg.	1.61	1.87	1.97	2.23	2.21

TABLE V

BIT-RATE REDUCTION (%) OF THE SAP WHEN COMPARED TO THE HM6.0 LOSSLESS CODING

Seq. Class	Bit-Rate Difference (%)							
	AI-Main	RA-Main	LB-Main	LP-Main	AI-HE10	RA-HE10	LB-HE10	LP-HE10
A	−8.8	−2.8	−2.3	−3.0	−12.3	−4.1	−3.7	−4.6
B	−5.1	−1.0	−0.7	−1.1	−8.5	−1.9	−1.4	−1.9
C	−6.9	−1.8	−1.4	−1.5	−10.4	−3.0	−2.3	−2.5
D	−8.4	−2.0	−1.5	−1.6	−12.0	−2.9	−1.9	−2.0
E	−10.6	−3.1	−3.3	−4.3	−15.7	−4.8	−4.2	−4.2
Avg.	−8.0	−2.1	−1.8	−2.3	−11.8	−3.3	−2.7	−3.0

TABLE VI

DISTRIBUTION OF INTRA CODED CU AND INTRA PREDICTION MODE (%) OF THE SAP WHEN COMPARED TO THE HM6.0 LOSSLESS CODING IN AI-MAIN CONFIGURATION

Seq. Class	Intra Coded CU and Intra Prediction Mode Distribution (%)							
	HM6.0				SAP			
	Intra CU	Planar pred.	DC pred.	Ang. pred.	Intra CU	Planar pred.	DC pred.	Ang. pred.
A	100	11.7	9.3	79.0	100	1.6	0.9	97.5
B	100	13.3	9.5	77.2	100	7.4	9.1	83.5
C	100	10.4	6.9	82.6	100	4.3	3.6	92.1
D	100	9.4	6.8	83.8	100	3.3	3.0	93.7
E	100	12.7	10.0	77.2	100	2.9	2.9	94.2
Avg.	100	11.5	8.5	80.0	100	3.9	3.9	92.2

and HM6.0 in the lossless coding mode, where the quantization parameter was set to zero for main profile configurations (i.e., AI-Main, RA-Main, LB-Main, and LP-Main), and to −12 for high-efficiency 10-b configurations (i.e., AI-HE10, RA-HE10, LB-HE10, LP-HE10). As shown in Table II, the HM6.0 lossless coding provides, on average, a 3.2% to 13.2% bit-rate reduction when compared to the HM6.0 nonlossless coding with the smallest QP that also comes with quantization noise.

Table III summarizes the actual compression ratio of the HM6.0 lossless coding while using various coding configurations defined in the common test conditions [3]. As shown in the table, the HEVC lossless coding is most effective in LB-Main and LB-HE10 configurations in which unidirectional B-slices are used.

Table IV presents the compression ratio obtained by running JPEG-LS [10], JPEG2K [11] (lossless), and the archive software, e.g., ZIP, WinRAR, and 7-Zip (version 4.65) [12]. Note that the two 10-b class A sequences *NebutaFestival* and *SteamLocomotive* are coded as 8-b video in Table IV, the same as in the HM6.0 Main configurations.

Comparing Table IV with the Main configurations of Table III clearly shows that the HEVC lossless coding mode significantly outperforms the existing lossless compression formats as well as the existing archive tools available when the compression target is video content. In particular, the all intra(AI-Main) configuration of HEVC lossless coding is better than ZIP, and similar to JPEG-LS and JPEG2K in average compression ratio, while the low-delay (LB-Main and LP-Main) configurations of HEVC lossless coding achieve a significantly higher compression ratio than the general purpose archive tools. Table III also reveals that the lossless compression efficiency provided by the current HEVC Main profile lossless coding mode is still relatively low for 10-b video, a clear sign that the lossless quality enhancement tools are needed for the future lossless profile specification that supports high-fidelity video.

B. Performance of SAP

Table V summarizes the coding efficiency difference between the SAP and the HM6.0 lossless coding mode. On average the SAP provides a 1.8% to 11.8% additional bit-rate reduction for the same compression ratio. In addition, the SAP provides more gain in HE10 configurations than in main configurations. This is due to the fact the HEVC CABAC binarization for DCT transform coefficient levels (i.e., prediction residuals in the lossless case as transform is skipped) is most efficient for small values [6], which works well for 8-b video because the prediction residual is already relatively small, but not for 10-b video (see Table III). In contrast, the SAP is capable of reducing prediction residuals and converting originally large prediction residuals (without SAP) into small ones that can be more efficiently coded with the CABAC scheme. Since there are more blocks with large prediction residuals in the 10-b video, the SAP, in general, can better improve lossless coding efficiency in 10-b video than in 8-b video.

TABLE VII
DISTRIBUTION OF INTRA CODED CU AND INTRA PREDICTION MODE (%) OF THE SAP WHEN COMPARED TO THE HM6.0 LOSSLESS CODING IN RA-MAIN CONFIGURATION

Seq. Class	Intra Coded CU and Intra Prediction Mode Distribution (%)							
	HM6.0				SAP			
	Intra CU	Planar pred.	DC pred.	Ang. pred.	Intra CU	Planar pred.	DC pred.	Ang. pred.
A	30.4	15.0	14.5	70.5	50.8	2.1	1.8	96.1
B	34.1	18.4	16.6	64.9	36.3	13.9	19.3	66.8
C	30.1	14.5	7.9	77.6	30.4	4.5	3.3	92.2
D	19.0	11.3	5.7	83.0	23.4	2.6	1.2	96.2
E	46.2	20.1	28.9	51.0	45.4	7.4	11.7	80.9
Average	32.0	15.9	14.7	69.4	37.3	6.1	7.5	86.4

The SAP improves coding efficiency by increasing the angular intra prediction usage and number of intra coded CUs. As shown in Table VI, in the AI-Main configuration the percentage of PUs using angular prediction has been increased from 80% in HM6.0 to about 92% when the SAP is enabled, and PUs using the planar and DC modes have been decreased to 3.9%, respectively. A similar trend is observed across all the configurations. The test data also reveals that the additional coding gain from the sample-based planar and DC intra prediction modes for lossless coding can be fairly limited due to the extremely low usage, and may not justify changes required in both reference sample access and interpolation logic. Furthermore, the sample-based planar and DC intra prediction modes may cause a decoder throughput issue because the prediction depends on more adjacent neighbors.

The increased prediction efficiency from the SAP also leads to an increase in the intra coded CUs usage in the configurations using P- and B-slices. As shown in Table VII, in the RA-Main configuration for example, the percentage of intra coded CUs has been increased from 32% in HM6.0 to 37% after applying the SAP. The intra prediction becomes more important in lossless coding after the SAP is enabled.

V. CONCLUSION

The lossless coding currently supported in the HEVC main profile provides an efficient and superior compression solution for video content when compared to the existing lossless compression solutions. By simply bypassing transform, quantization, and in-loop-filters, the HEVC main profile provides a unique feature of lossless video representation that significantly outperforms the HEVC nonlossless coding with the smallest QP but imposes no additional burden on both the encoder and decoder implementation. The proposed SAP further improves the coding efficiency significantly on top of the HEVC lossless mode. The SAP as well as other quality enhancement tools such as CABAC for lossless compression [6], [7] can be considered in a potential future specification of a lossless HEVC profile, which supports high-fidelity video and other color sampling formats and representations.

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Minhua Zhou received the B.E. degree in electronic engineering and the M.E. degree in communication and electronic systems from Shanghai Jiao Tong University, Shanghai, China, in 1987 and 1990, respectively, and the Ph.D. degree in electronic engineering from the Technical University of Braunschweig, Braunschweig, Germany, in 1997.

From 1993 to 1998, he was a Researcher with the Heinrich-Hertz Institute, Berlin, Germany. Since 1998, he has been with Texas Instruments, Inc., Dallas, TX, where he is currently a Research Manager of video coding technology. His current research interests include video compression, video pre- and postprocessing, 3-D video, and joint algorithm and architecture optimization.

Wen Gao received the B.S. degree in electrical engineering from the University of Science and Technology of China, Hefei, China, in 1993, the M.S. degree in electrical engineering from Peking University, Beijing, China, in 1996, and the Ph.D. degree in electrical engineering from Purdue University, West Lafayette, IN, in 2001.

From 2001 to 2010, he was a member, a Senior Member, and a Principal Member of the Technical Staff of Corporate Research with Thomson Multimedia and Thomson—Technicolor. Since 2010, he has been with the Video Technology Research Laboratory, Huawei Technologies/Futurewei Technologies, Santa Clara, CA. His current research interests include video compression, digital signal processing, and multimedia data transmission.

Minqiang Jiang received the B.E. degree in electronic engineering from Xidian University, Xian, China, in 1984, the M.E. degree in communication and electronic systems from Tsinghua University, Beijing, China, in 1987, and the Ph.D. degree in computer engineering from Santa Clara University, Santa Clara, CA, in 2006.

From 2006 to 2011, he was a member and Senior Member of the Technical Staff with VWEB, IntellaSys, and Droplet Technologies. Since 2011, he has been with the Huawei Technologies/Futurewei Technologies, Video Technology Research Laboratory, Santa Clara. His current research interests include video compression, video pre- and postprocessing, and algorithm optimization.

Haoping Yu received the B.S. and M.S. degrees in electrical engineering from the University of Science and Technology of China, Hefei, China, in 1984 and 1987, respectively, and the Ph.D. degree in electrical engineering from the University of Central Florida, Orlando, in 1995.

From 1995 to 2008, he was a member, a Senior Member, and a Principal Member of the Technical staff of Corporate Research, Thomson Consumer Electronics and Thomson Multimedia. Since 2008, he has been with Huawei Technologies/Futurewei Technologies, as the Head of the Video Technology Research Laboratory, Santa Clara, CA. His current research interests include video compression, processing, and delivery for both consumer and professional applications.