Inter-Palette Coding in Screen Content Coding

Weijia Zhu, Kai Zhang, *Member, IEEE*, Jicheng An, Han Huang, Yu-Chen Sun, Yu-Wen Huang, and Shawmin Lei, *Fellow, IEEE*

***Abstract*—The joint collaborative team on video coding has been developing an emerging standard for screen content coding (SCC) as an extension of HEVC known as HEVC-SCC. Intrablock copy (IBC) and palette coding are the two powerful coding tools adopted into HEVC-SCC. In this paper, a novel coding tool named inter-palette coding is proposed, which takes the advantages of both IBC and palette coding. With the inter-palette method, a new palette copy mode COPY_INTER can be applied, which enables the index samples to copy the pixels in the prediction block fetched by IBC or motion compensation. Experimental results show that the proposed scheme can achieve 3.15% BD-rate savings under all intra conditions on typical sequences containing "text and graphics with motion" averagely, with almost no complexity penalty.**

***Index Terms*—HEVC-SCC, screen content coding, intra block copy, palette coding, inter-palette coding.**

I. Introduction

HIGH efficiency Video Coding (HEVC) Standard [1] is an international video coding standard developed by the Joint Collaborative Team on Video Coding (JCT-VC), which is a joint group of the ITU-T Video Coding Experts Group (VCEG) and the ISO/IEC Moving Picture Experts Group (MPEG) standardization organizations. By adopting quite a number of advanced video coding techniques, HEVC provides an unprecedented compression ratio on natural video sequences [2]. In objective tests, HEVC can achieve more than 35% BD-rate saving [3] in entertainment applications compared with H.264/AVC, which is the most powerful video coding standard before HEVC. In subjective tests, HEVC can achieve approximately the same subjective quality with even 50% less bit rate than H.264/AVC [2]. With such an outstanding performance, the use of HEVC is expected to grow rapidly.

Screen contents refer to video materials that contain combinations of texts, graphics and camera-captured images. With the rapid development of computer technologies, screen content becomes more and more indispensable for applications such as wireless display, video conference and cloud computing, where high quality screen content videos need to be transmitted to the client-side. Screen contents possess many particular characteristics, such as icons, text characters, extremely sharp edges and mixed contents, which are very different from natural images. Since these contents seldom appear in natural sequences, existing coding standards such as HEVC, which are mainly designed for natural sequences, cannot fully compress screen contents efficiently. Therefore, high efficient screen content coding (SCC) has become a challenging topic.

Manuscript received December 3, 2016; revised February 26, 2017; accepted May 13, 2017. Date of publication June 15, 2017; date of current version December 8, 2017. *(Corresponding author: Kai Zhang.)*

The authors are with Mediatek Inc., Hsinchu 30078, Taiwan (e-mail: sparkjj1985@gmail.com; zhangkai@qti.qualcomm.com; anjicheng@hisilicon.com; h.huang@mediatek.com; yuchens@qti.qualcomm.com; yuwen.huang@mediatek.com; shawmin.lei@mediatek.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TBC.2017.2711144

To address this problem, JCT-VC issued a joint call for proposal for SCC [4] as an extension to HEVC in January 2014. Since then, an emerging HEVC-SCC standard has been in progress [5]. Several research works on screen contents have been adopted into HEVC-SCC, such as intra block copy (IBC) [6], palette coding [7], adaptive colour transform (ACT) [8] and adaptive motion vector resolution (AMVR) [9].

Repeated patterns and clustering colours are two of the characteristics in screen contents. Intra block copy (IBC) and palette coding are proposed to explore the redundancy behind these two characteristics respectively. Although IBC and palette coding are powerful tools, they cannot be used simultaneously for a block in HEVC-SCC. As a result, the redundancy in repeated patterns and clustering colours cannot be both removed in a single block.

In this paper, we propose a new palette coding approach named inter-palette coding. Inter-palette coding is designed to take the advantages of both IBC and palette coding. It can efficiently compress a block with clustering colours and repeated contents. In the inter-palette coding method, a new copy mode COPY_INTER is incorporated into the HEVC-SCC palette coding scheme. If a sample chooses to apply COPY_INTER, it will copy the value of the corresponding sample in the prediction block fetched by IBC or motion compensation (MC) directly. Then a run value is signaled to specify the number of subsequent samples that are coded with COPY_INTER. Experimental results show that the proposed method can improve the coding performance significantly on screen contents with almost no complexity penalty.

The rest of this paper is organized as follows. In Section II, we briefly review the IBC and palette coding in HEVC-SCC. We then describe the proposed inter-palette coding technique in Section III. Experimental results are presented and discussed in Section IV to validate the effectiveness of the proposed scheme. Finally, Section V concludes this paper.

II. IBC and Palette Coding in HEVC-SCC

In this paper, we will analyze IBC and palette coding in order to find a way to harmonize them and to take advantages of both.

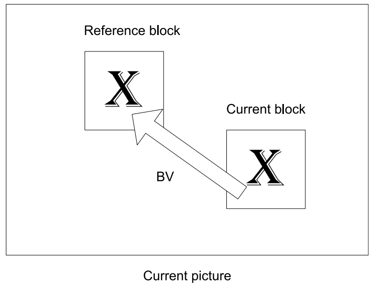


Fig. 1. Intra block copy.

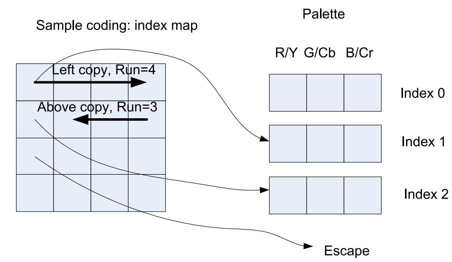


Fig. 2. Palette coding.

A. Intra Block Copy

IBC simply borrows the concept of motion compensation from inter-frame coding to intra-frame coding. As demonstrated in Fig. 1, the current block is predicted by a reference block in the same picture when IBC is applied. The samples in the reference block must have been already reconstructed before the current block is coded or decoded. The basic idea of IBC was first proposed in [10], where the signaled 'motion vector' of a block can point to a 'reference block' in the current picture.

Although IBC is not so efficient for most natural sequences, it shows a significant coding gain in SCC. The reason is that there are lots of repeated patterns, such as icons and text characters in a screen-content picture, and IBC can effectively reduce the redundancy in these repeated patterns. In HEVC-SCC, an inter-coded coding unit (CU) can apply IBC if it chooses the current picture as its 'reference picture'. The motion vector (MV) is renamed as block vector (BV) in this case.

Efforts have been made to further improve IBC by improving coding performance or reducing computational complexity. In [11], Symmetric IBC was proposed to explore the redundancy due to symmetry as well as repetition. In [12] and [13], hash based block matching scheme is proposed to rapidly find the matching block in the whole reference frame.

B. Palette Coding

Palette coding is designed to handle the clustering colours for screen contents in [14]. Palette coding employs base colours and index map to represent the input image block. Every sample will be quantized to one of the base colours in the input block and an index map is generated to indicate the corresponding base colour for each sample. Due to the sparse histogram of screen contents, the coding cost is significantly reduced by a small number of colours in each block.

As demonstrated in Fig. 2, a table named 'palette' for a CU is coded first to indicate the base colours which may appear in the current CU. The palette can be coded in a predictive way to save bits [15]. After that, the samples in the current CU will be coded. A sample is quantized to one of the base colours in the palette. Then the index corresponding to that base colour is coded. To code indices for all the samples more efficiently, the indices are put together as an index map and coded as a whole. Samples are scanned in the index map horizontally or vertically in a rotated way. A sample can choose to apply INDEX mode to signal its own index. Or it can choose COPY_ABOVE mode to copy the index of its above neighboring sample. A bit is signaled to indicate which mode is used by a sample. To further reduce bits, several consecutive samples may share the same mode. A run length is coded to represent how many consecutive samples share the same mode. If the current sample utilizes INDEX mode, then a number of consecutive samples indicated by the run length will share the same index as the current one. If the current sample utilizes COPY_ABOVE, a number of consecutive samples indicated by the run length will share the COPY_ABOVE mode, *i.e.*, all these samples will copy the indices from their above neighboring samples. In addition, a sample can also be coded directly in an ESCAPE mode to handle the outlier cases.

III. Inter-Palette Coding

We propose an inter-palette coding approach for SCC, which tries to combine the advantages of IBC and palette coding together. We will first discuss more about the motivation to invent inter-palette coding. Then we will present the design of inter-palette coding. Finally encoder optimizations specially designed for inter-palette coding is proposed.

A. Motivation

Repeated patterns can often be observed in screen videos. IBC is used to find the repeated patterns at block level. In HEVC-SCC, IBC is unified to the Inter mode by putting the reconstructed current frame into the decoding picture buffer. Although IBC and Inter mode in HEVC-SCC can efficiently remove the redundancy, they sometimes cannot find an exactly matching block for the current block. How to encode the residues between the current block and the matching block becomes an issue. In the traditional lossy coding approach, composed of transform and quantization, the quantization noise is inevitable at common bit rates in practice. As a result, IBC or Inter mode usually propagates quantization noises from reference blocks to the current block, which dramatically deteriorates the coding performance, and often causes the temporal flickering artifacts.

On the other hand, palette coding can code samples in a quasi-lossless manner with significantly improved reconstructed quality. However, it is challenging how to code the index map efficiently especially when the coding block has complex textures. Since COPY_ABOVE and INDEX modes only utilize the information inside or surrounding [16] the current CU, they cannot handle the repeated patterns.

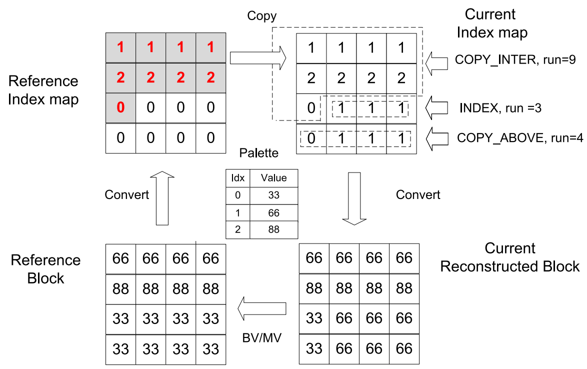


Fig. 3. An example of Inter-palette coding.

Motivated by the above analysis, we design a new coding method named inter-palette coding to take the advantages from both IBC and palette coding. In general, the concept of IBC or MC is introduced into palette coding so that samples in a CU with palette coding can also be predicted by a reference block.

B. Inter-Palette Mode

Inter-palette coding is designed as a special palette mode at CU-level, with one flag to indicate whether it is used by the current CU. Inter-palette mode works as the normal palette mode except that a new copy mode named COPY_INTER is added besides INDEX and COPY_ABOVE. As INDEX and COPY_ABOVE, a run length is signalled to specify how many subsequent samples sharing the COPY_INTER mode.

If one CU is coded with Inter-palette mode, its motion information as well as its palette and indices information needs to be transmitted. At decoder, a prediction block is fetched with the decoded motion information first. Then the samples in the prediction block are converted to reference indices in the decoded palette. In the next step, the copy mode and index for each sample in the current CU is decoded. If a sample is coded with COPY_INTER mode, it will copy the corresponding reference index. Finally, all samples are reconstructed by mapping their indices into sample values according to the current palette.

Fig. 3 shows an example how the inter-palette coding method works at the decoder side. With the transmitted MV or BV, the reference block can be attained as in inter-prediction or IBC. Then sample in the reference block can be converted to reference indices with the decoded palette for the current block. The indices in the current index map with COPY_INTER mode are copied from their reference indices (shaded area). The indices with COPY_INDEX or COPY_ABOVE are decoded as in the normal palette coding mode. Finally the current index map is converted to the reconstructed block as in the normal palette coding mode.

The samples in the prediction block need to be converted to reference indices based on the current palette. The conversion from a sample value to an index can be done by minimizing the absolute difference between the sample value and the base colour value in the palette table, formulated as:

$$Idx_i = \arg\min_{0 \le n < N} \left(\sum_{k=0}^{2} |P_i[k] - C_n[k]| \right), \quad (1)$$

where k denotes the colour component, P_i is the prediction sample value, C_n is the n^{th} base colour value in the palette. Idx_i is the obtained index after this conversion process. Table I tabulates the number of operations for the conversion where the prediction block size is $N*N$ and the current palette size is D. $8*N*N*D$ operations is required by the conversation in total, which may be a heavy burden, especially for the decoder.

TABLE I
NUMBER OF OPERATIONS IN THE CONVERSION

Operation	**+/-**	**ABS**	***Total***
Number (#)	$N*N*5*D$	$N*N*3*D$	$N*N*8*D$

To avoid the conversion process, we propose to simplify Inter-palette mode by copying sample values rather than indices at both encoder and decoder. When the current sample applies the COPY_INTER mode, the sample is directly reconstructed by copying the corresponding sample value in the prediction block. Our experiments show that there is no coding loss with this simplification. Thus the conversion can be fully removed and the complexity cost at decoder is significantly reduced in the proposed scheme. The syntax design is kept the same in the simplified solution.

C. Encoder Optimization

At encoder, there are three major tasks for the Inter-palette mode: how to conduct ME, how to find the optimal palette, and how to decide the optimal copy mode for each sample. As the encoder strategy is critical to the performance of the proposed coding tool, our design tries to get the full potential gain of inter-palette coding while not to increase the encoder complexity too much.

At the first glance, extra ME seems unavoidable for the Inter-palette mode. Fortunately, the Inter mode also requires ME, so the proposed Inter-palette mode can reuse the best motion information found by the Inter mode. To be more concrete, the best motion information including MV and reference index found for the Inter mode, will also be used by the Inter-palette mode. This ME-reuse strategy can reduce the encoding complexity significantly.

The encoder needs to find the optimal palette and corresponding index map to achieve the best coding performance. Let $X = \{x_i | i = 1,2, \ldots, N\}$ be the sample values in the input block and $Y = \{y_v | v = 1,2, \ldots, K\}$ be base colours in the palette. N denotes the number of pixels and K denotes the number of palette colours. Colour quantization can be defined as an assignment of a sample colour x_i to a base colour y_v, which can be formalized by Boolean assignment variables $M_{iv} \in \{0,1\}$. $M_{iv} = 1$ or 0 denotes x_i is quantized to y_v or not. All the assignments can be summarized in a term of Boolean

TABLE II
BD-RATE UNDER THE ALL INTRA (AI) CONFIGURATION

All Intra	G/Y	B/U	R/V
RGB, text & graphics with motion, 1080p & 720p	-2.0%	-1.9%	-2.0%
RGB, mixed content, 1440p & 1080p	-0.1%	-0.3%	-0.3%
RGB, Animation, 720p	0.0%	0.0%	0.0%
RGB, camera captured, 1080p	0.0%	0.0%	0.0%
YUV, text & graphics with motion, 1080p & 720p	-1.8%	-1.8%	-2.0%
YUV, mixed content, 1440p & 1080p	-0.3%	-0.4%	-0.6%
YUV, Animation, 720p	0.0%	0.1%	0.1%
YUV, camera captured, 1080p	0.0%	0.0%	0.0%
Enc Time[%]	104%		
Dec Time[%]	102%		

TABLE III
BD-RATE UNDER THE RANDOM ACCESS (RA) CONFIGURATION

Random access	G/Y	B/U	R/V
RGB, text & graphics with motion, 1080p & 720p	-1.3%	-1.2%	-1.3%
RGB, mixed content, 1440p & 1080p	-0.1%	-0.3%	-0.3%
RGB, Animation, 720p	0.0%	0.0%	0.0%
RGB, camera captured, 1080p	0.0%	0.0%	0.0%
YUV, text & graphics with motion, 1080p & 720p	-1.2%	-1.1%	-1.2%
YUV, mixed content, 1440p & 1080p	-0.4%	-0.5%	-0.8%
YUV, Animation, 720p	-0.1%	0.0%	0.2%
YUV, camera captured, 1080p	0.0%	-0.1%	-0.1%
Enc Time[%]	102%		
Dec Time[%]	101%		

TABLE IV
BD-RATE UNDER THE LOW DELAY B (LB) CONFIGURATION

Low delay B	G/Y	B/U	R/V
RGB, text & graphics with motion, 1080p & 720p	-0.7%	-0.6%	-0.6%
RGB, mixed content, 1440p & 1080p	0.2%	-0.1%	0.1%
RGB, Animation, 720p	-0.1%	0.0%	0.1%
RGB, camera captured, 1080p	0.0%	-0.1%	-0.1%
YUV, text & graphics with motion, 1080p & 720p	-0.6%	-0.2%	-0.1%
YUV, mixed content, 1440p & 1080p	0.1%	0.4%	0.1%
YUV, Animation, 720p	0.0%	0.2%	0.1%
YUV, camera captured, 1080p	-0.1%	0.0%	0.0%
Enc Time[%]	101%		
Dec Time[%]	101%		

TABLE V
SEQUENCE RESULTS UNDER THE AI CONFIGURATION

Sequences	G/Y	B/U	R/V
FlyingGraphics (1080p, RGB)	-1.05%	-1.24%	-1.22%
Desktop(1080p,RGB)	-5.05%	-5.17%	-5.19%
Console(1080p,RGB)	-2.87%	-2.88%	-2.97%
Web_browsing(720p, RGB)	-4.20%	-3.76%	-3.82%
FlyingGraphics (1080p, YUV)	-1.09%	-1.41%	-1.38%
Desktop(1080p,YUV)	-4.81%	-4.88%	-5.14%
Console(1080p,YUV)	-3.53%	-3.30%	-3.71%
Web_browsing(720p, YUV)	-2.61%	-2.72%	-3.00%
Average	**-3.15%**	**-3.17%**	**-3.30%**

assignment matrix M where

$$M \in \{0, 1\}^{N\times K}, \sum_{v=1}^{K} M_{iv} = 1, i \in [1, N]. \quad (2)$$

Then quantization can be formulated as matrix multiplication $M*Y$. The cost function H can be calculated as

$$H = \sum_{i=1}^{N} \left\| x_i - \sum_{v=1}^{K} M_{iv} y_v \right\|^2 = \sum_{i=1}^{N} \sum_{v=1}^{K} M_{iv} \| x_i - y_v \|^2. \quad (3)$$

The problem of finding the optimal palette and corresponding index map is equivalent to search for a parameter pair (M, Y) which minimizes H. This optimization problem can be solved using histogram based clustering method in the same way as the palette coding mode [17].

For a CU coded with the Inter-palette mode, we need to decide the mode for each sample. First, the run lengths for the three copy modes are derived by determining the longest matching index string. Then the mode for each sample is selected according to the rate distortion optimization (RDO) criterion [18]. One of the three modes (INDEX, COPY_ABOVE and COPY_INTER) with minimal RD cost is chosen as the final mode for a sample.

IV. EXPERIMENTAL RESULTS

The proposed scheme is implemented into the HEVC-SCC reference software SCM-4.0 [19] to evaluate its coding performance on screen contents video. The simulations are conducted following the JCT-VC common test conditions [20] of HEVC-SCC. Full-frame search range as suggested by CTC is used in the test. The objective coding performance comparison is evaluated by the Bjontegaard-Delta measurement [3].

Table II-IV tabulate the average bit rate saving compared with SCM-4.0 in terms of BD-Rate under different configurations. As we can observe, compared with SCM, the proposed scheme achieves 2.0%, 1.3% and 0.7% BD-rate savings under AI, RA, and LB conditions, respectively, for "RGB, text & graphics with motion, 1080p & 720p" sequences. It also achieves 1.8%, 1.2% and 0.6% BD-rate savings under AI, RA, and LB conditions respectively, for "YUV, text & graphics with motion, 1080p & 720p" sequences. In general, inter-palette coding can achieve good performance for the sequences with both repeated patterns and clustered colors. For other sequences, such as the animation or camera captured sequences, the Inter-palette mode does not work well. Since AI results are better, we can also deduce that the Inter-palette mode is more efficient in I-frames than in P/B-frames, which is reasonable since there are much less redundancy after predictions in P/B-frames usually. It should be noted that both the encoding time and decoding time go up only a little, which implies that the proposed method does not impose a heavy extra computational burden.

To further investigate the detailed results, Table V shows the AI results for four typical high definition screen contents sequences containing "text and graphics with motion". Compared with SCM-4.0, the proposed scheme achieves about 3.2% BD-rate savings in average under AI conditions on these

TABLE VI
THE PERCENTAGE OF CUS SELECTING THE INTER-PALETTE MODE

Sequences	QP=22						QP=37					
	Intra frames			Inter frames			Intra frames			Inter frames		
	8x8	16x16	32x32	8x8	16x16	32x32	8x8	16x16	32x32	8x8	16x16	32x32
FlyingGraphics (1080p, RGB)	6%	16%	4%	16%	40%	53%	5%	15%	7%	2%	8%	43%
Desktop (1080p,RGB)	27%	40%	2%	12%	31%	36%	19%	28%	1%	26%	40%	42%
Console (1080p,RGB)	13%	34%	2%	23%	38%	30%	12%	30%	2%	2%	14%	5%
Web_browsing (720p, RGB)	29%	28%	3%	1%	9%	2%	15%	21%	1%	2%	10%	4%
FlyingGraphics (1080p, YUV)	6%	17%	1%	13%	35%	46%	4%	15%	1%	1%	11%	50%
Desktop (1080p,YUV)	28%	37%	2%	29%	60%	50%	17%	26%	2%	1%	3%	3%
Console (1080p,YUV)	15%	33%	5%	16%	36%	36%	8%	21%	2%	2%	4%	11%
Web_browsing (720p, YUV)	29%	33%	1%	3%	9%	4%	10%	5%	1%	2%	7%	3%
Average	**19%**	**30%**	**3%**	**14%**	**32%**	**32%**	**11%**	**20%**	**2%**	**5%**	**12%**	**20%**

TABLE VII
BD-RATE UNDER THE ALL INTRA (AI) CONFIGURATION IN [16]

All Intra	G/Y	B/U	R/V
RGB, text & graphics with motion, 1080p & 720p	-1.5%	-1.6%	-1.6%
RGB, mixed content, 1440p & 1080p	-0.5%	-0.7%	-0.7%
RGB, Animation, 720p	0.0%	0.0%	0.0%
RGB, camera captured, 1080p	0.0%	0.0%	0.0%
YUV, text & graphics with motion, 1080p & 720p	-1.9%	-1.9%	-2.0%
YUV, mixed content, 1440p & 1080p	-0.7%	-1.2%	-1.3%
YUV, Animation, 720p	0.0%	-0.1%	-0.1%
YUV, camera captured, 1080p	0.0%	0.0%	0.0%
Enc Time[%]	130%		
Dec Time[%]	123%		

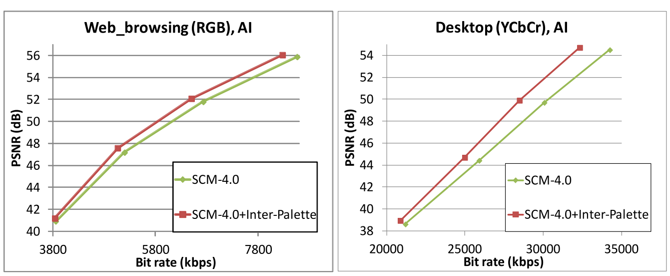


Fig. 4. The R-D curves for two exemplary sequences.

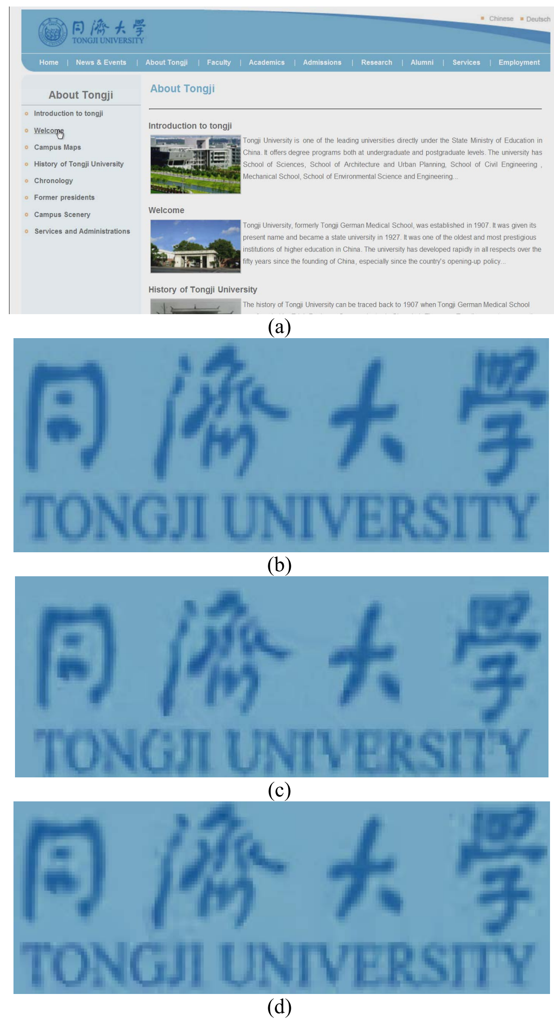


Fig. 5. An example of subjective improvement of inter-palette scheme.

sequences. In these sequences, both repeated patterns and clustering colours appear with a high frequency, such as icons in the sequence "Desktop" and characters in the sequence "Web_browsing". In addition, we make statistics on these sequences to record the percentages of CUs selecting the proposed Inter-palette mode in the RDO process with different sizes and QPs for intra and inter frames, as shown in Table VI. It can be seen that the Inter-palette mode is quite preferable in these sequences. The inter-palette mode is more popular for smaller CUs in intra frames while it is more popular for larger CUs in inter frames. That is reasonable because replicated patterns in a picture are more likely in smaller blocks. On the other hand, inter frames are more sensitive to overhead bits, and the palette overhead bits are relatively small for larger blocks. For the similar reason, we expect that the inter-palette mode should be more popular with a smaller QP, which is less sensitive to the overhead bits. Table VI verifies our expectation.

Fig. 4 depicts the RD curves under the AI conditions for the sequence 'Web_browsing' in RGB format and 'Desktop' in YCbCr format respectively. We can see that the proposed method achieves a much better coding performance compared with SCM-4.0, especially at the high bit rate. The reason is that the coding performance is less sensitive to the overhead bits at a high bit rate, as revealed in Table VI too.

As a comparison to other improvements of palette coding, we also show the AI results of the extended copy above mode proposed in [16] in Table VII. As we can see, the proposed method outperforms the extended copy above mode approach in "RGB, text & graphics with motion, 1080p & 720p" sequences. Moreover, the proposed method has a much lower encoding/decoding complexity than that in [16].

Besides objective coding gain, it is also interesting that the proposed method can improve the subjective quality. In one example, we code the 720p sequence 'Web_browsing' in YCbCr format by the SCM-4.0 encoder and the proposed encoder respectively, with QP = 32 under the AI conditions of CTC. Fig. 5 (a) shows the first picture in the original sequence, which is a typical Web page image with a lot of texts. To demonstrate the subjective improvement, a rectangle region of interest at the left top corner of the original picture is zoomed in as shown in Fig. 5 (b). Fig. 5 (c) and Fig. 5 (d) show the same region in the reconstructed pictures of the SCM-4.0 encoder and the proposed encoder respectively. We notice that texts in Fig. 5 (c) suffer annoying artifacts and noises, which are relieved obviously in Fig. 5 (d). The proposed method can provide a better visual quality because it can suppress the quantization noises introduced from the reference block of IBC.

V. Conclusion

Screen content coding becomes more and more important nowadays. Thus JCT-VC has begun to develop a video coding standard named HEVC-SCC specially designed for screen contents. In this paper, an inter-palette approach is proposed to further improve the performance of HEVC-SCC. The proposed method can compress a block with both clustering colours and duplicated contents more efficiently. Experimental results verified the effectiveness of the proposed scheme for screen content coding. Compared with SCM-4.0, 3.15% average BD-rate savings are achieved by the proposed method under AI, conditions with minor run-time increase.

References

[1] *High Efficiency Video Coding, Version 1*, document ITU-T H.265, Int. Telecomm. Union, Geneva, Switzerland, Jan. 2013.

[2] J. Ohm, G. J. Sullivan, H. Schwarz, T. K. Tan, and T. Wiegand, "Comparison of the coding efficiency of video coding standards—Including high efficiency video coding (HEVC)," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 22, no. 12, pp. 1669–1684, Dec. 2012.

[3] G. Bjøntegaard, *Calculation of Average PSNR Differences Between RD Curves*, document VCEG-M33, ITU-T SG 16/Q 6, Int. Telecomm. Union, Geneva, Switzerland, Apr. 2001.

[4] *Joint Call for Proposals for Coding of Screen Content*, document MPEG N14715, ISO/IEC JTC1/SC29/WG11 MPEG, ISO/IEC, Geneva, Switzerland, Jan. 2014.

[5] J. Xu, R. Joshi, and R. A. Cohen, "Overview of the emerging HEVC screen content coding extension," *IEEE Trans. Circuits Syst. Video Technol.*, vol. 26, no. 1, pp. 50–62, Jan. 2016.

[6] M. Budagavi and D.-K. Kwon, *AHG8: Video Coding Using Intra Motion Compensation*, document JCTVC-M0350, Joint Collaborative Team Video Coding (JCT-VC), Incheon, South Korea, Apr. 2013.

[7] X. Xiu *et al.*, "Palette-based coding in the screen content coding extension of the HEVC standard," in *Proc. Data Compression Conf. (DCC)*, Apr. 2015, pp. 253–262.

[8] L. Zhang *et al.*, "Adaptive color-space transform for HEVC screen content coding," in *Proc. Data Compression Conf. (DCC)*, Apr. 2015, pp. 233–242.

[9] B. Li, J. Xu, G. J. Sullivan, Y. Zhou, and B. Lin, *Adaptive Motion Vector Resolution for Screen Content*, document JCTVC-R0106, Joint Collaborative Team Video Coding (JCT-VC), Sapporo, Japan, Jun. 2014.

[10] S. Yu and C. Chrysafis, *New Intra Prediction Using Intra-Macroblock Motion Compensation*, document JVT-C151, Joint Video Team (JVT), Fairfax, VA, USA, May 2002.

[11] K. Zhang, J. An, X. Zhang, H. Huang, and S. Lei, "Symmetric intra block copy in video coding," in *Proc. ISCAS*, May 2015, pp. 521–524.

[12] W. Zhu, W. Ding, J. Xu, Y. Shi, and B. Yin, "Hash-based block matching for screen content coding," *IEEE Trans. Multimedia*, vol. 17, no. 7, pp. 935–944, Jul. 2015.

[13] W. Zhu, W. Ding, J. Xu, Y. Shi, and B. Yin, "2-D dictionary based video coding for screen contents," in *Proc. Data Compression Conf. (DCC)*, Apr. 2014, pp. 43–52.

[14] W. Zhu, W. Ding, J. Xu, Y. Shi, and B. Yin, "Screen content coding based on HEVC framework," *IEEE Trans. Multimedia*, vol. 16, no. 5, pp. 1316–1326, Aug. 2014.

[15] W. Pu *et al.*, "Palette mode coding in HEVC screen content coding extension," *IEEE J. Emerg. Sel. Topic Circuits Syst.*, vol. 6, no. 4, pp. 420–432, Dec. 2016.

[16] Y.-C. Sun *et al.*, *CE1: Test A.1: Extended Copy Above Mode to the First Line With Index Adjustment Bits*, document JCTVC-U0061, Joint Collaborative Team Video Coding (JCT-VC), Warsaw, Poland, Jun. 2015.

[17] R. Joshi *et al.*, *Screen Content Coding Test Model 4 Encoder Description (SCM 4)*, document JCTVC-T1014, Joint Collaborative Team Video Coding (JCT-VC), Geneva, Switzerland, Feb. 2015.

[18] G. J. Sullivan and T. Wiegand, "Rate-distortion optimization for video compression," *IEEE Signal Process. Mag.*, vol. 15, no. 6, pp. 74–90, Nov. 1998.

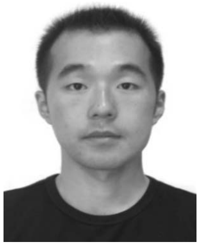
[19] (Mar. 2015). *HEVC Screen Content Extension Reference Software Version 4.0*. [Online]. Available: https://hevc.hhi.fraunhofer.de/svn/svn_HEVCSoftware/branches/HM-SCC-extensions/

[20] H. Yu, R. Cohen, K. Rapaka, and J. Xu, *Common Test Conditions for Screen Content Coding*, document JCTVC-T1015, Feb. 2015.

Weijia Zhu received the B.S. and Ph.D. degrees in computer science from the Beijing University of Technology, Beijing, China. He was a Deputy Technical Manager with Mediatek, Beijing, China. He is currently a Staff Engineer with Real Networks, Beijing. His research field includes image/video processing, compression, and communication.

Kai Zhang (M'17) received the B.S. degree in computer science and technology from Nankai University, Tianjin, China, in 2004, and the Ph.D. degree in computer science from the Institute of Computing Technology, Chinese Academy of Sciences, Beijing, China, in 2011.

From 2011 to 2012, he was a Researcher with Tencent Inc., Beijing, China. From 2012 to 2016, he was a Deputy Technical Manager, a Technical Manager, and then a Team Manager with Mediatek Inc., Beijing, China. He is currently a Staff Engineer with Qualcomm Inc., San Diego, CA, USA. Since 2006, he has contributed over 100 proposals to JVT, VCEG, JCT-VC, JCT-3V, JVET, and AVS, over 30 of which have been adopted into several video coding standards. He has authored or co-authored over 40 granted or pending U.S. patents/patent applications. His research interests include video/image coding, processing, and communication.



Jicheng An received the B.Eng. degree in automation and M.Eng. degree in control science and technology from Central South University, Hunan, China, in 2006 and 2009, respectively.

He is currently a Senior Engineer with HiSilicon Technologies Company Ltd., Beijing, China. He is an active participant at the video subgroup of the ISO/IECJTC1/SC29/WG11 Moving Picture Experts Group, the ITU-T SG16/Q6 Video Coding Experts Group, the ITU-T/ISO/IEC Joint Collaborative Team for Video Coding, the ITU-T/ISO/IEC Joint Collaborative Team on 3-D Video Coding Extensions, and the ITU-T/ISO/IEC Joint Video Exploration Team standardization activities. His research interests include image and video compression, 3-D video coding, interview motion prediction, motion estimation and compensation, and block partitioning structure.

Han Huang received the Ph.D. degree in signal and information processing from the Institute of Information Science Beijing Jiaotong University, Beijing, China, in 2014. From 2009 to 2011, he was a visiting student with the Department of Electrical, Computer, and Systems Engineering, Rensselaer Polytechnic Institute, Troy, NY, USA. He joined MediaTek Inc. in 2014, where he is currently the Deputy Technical Manager of the Video Coding and Processing Department, Multimedia Technology Development Division.

Yu-Chen Sun received the B.S. and M.S. degrees in electronic engineering and the Ph.D. degree in computer science from National Chiao Tung University, Hsinchu, Taiwan, in 2004, 2006, and 2013, respectively.

He is currently a Staff Engineer with Qualcomm, San Diego, CA, USA. From 2013 to 2016, he was a Senior Engineer with Mediatek Inc., Taiwan. He actively contributes to digital video coding standardization developed by the ITU-T Study Group 16 (VCEG) and ISO/IEC JTC 1 SC 29 / WG 11 (MPEG) such as High Efficiency Video Coding. His research interests include image/video processing, compression, and communication.

Yu-Wen Huang received the B.S. degree from the Department of Electrical Engineering, National Taiwan University (NTU) in 2000 and the Ph.D. degree from the Graduate Institute of Electronics Engineering, NTU, in 2004.

In 2004, he joined Mediatek, where he is currently a Senior Department Manager. In the first two years of his career, he developed video encoding algorithms, architectures, and related IC designs for products. Since 2007, he has been researching on future video coding technologies. Since 2010, he has been in charge of the Video Coding and Processing Department, Multimedia Technology Development Division. In 2006, he started attending international video coding standard meetings held by ISO/IEC Moving Picture Experts Group and ITU-T Video Coding Experts Group, and up to now he remains active in the standard meetings. From 2010 to 2015, he and his teammates submitted over 300 technical proposals, and many of them were adopted into the High Efficiency Video Coding/H.265 standard or the Extensions of HEVC/H.265. His current research interests include image and video coding, image and video processing, and related IC designs.

Dr. Huang was a recipient of the 2005 Student Outstanding Research Award (from GIEE, NTU), the Gold Medal of 2005 Long-Term Thesis Award (founded by Acer), the 2006 Excellent Technology Transfer Contribution Award (from Ministry of Science and Technology, Taiwan), the 2007–2011 MediaTek Best Paper Awards (MediaTek-internal), the 2013 MediaTek Innovation Award (MediaTek-internal), and the 2017 GIEE Elite Special Contribution Award (from GIEE, NTU). He has authored or co-authored over 25 international journal papers, over 40 international conference papers, over 40 granted U.S. patents, and over 40 pending U.S. patent applications. He is a member of Phi Tau Phi Scholastic Honor Society.

Shawmin Lei (S'87–M'88–SM'95–F'06) received the B.S. and M.S. degrees from National Taiwan University, Taipei, in 1980 and 1982, respectively, and the Ph.D. degree from the University of California, Los Angeles in 1988, all in electrical engineering.

From 1988 to 1995, he was with Bellcore (Bell Communications Research), Red Bank, NJ, USA, where he had worked mostly in video compression and communication areas and for a short period of time in wireless communication areas. From 1995 to 2007, he was with Sharp Laboratories of America, Camas, WA, USA, where he was a Manager of the Video Coding and Communication Group. Since 2007, he has been with Mediatek, Hsinchu, Taiwan, as a Director of Multimedia Technology Division, working in the video/image coding/processing, computer vision, acoustics/speech processing, and biomedical signal processing areas. His group has made significant contributions to the High-Efficient Video Coding (HEVC or H.265) standard. Under his direction, his group has become one of the top contributors in the video coding standard bodies, ISO MPEG and ITU-T VCEG. His research interests include video/image compression, processing and communication, picture quality enhancement, computer vision, and digital signal processing. He has published over 90 peer-reviewed technical papers and over 600 contributions to MPEG4, JPEG2000, H.263+, H.264, and HEVC international standard meetings. He has been awarded over 100 patents.