An Efficient HDR Video Compression Scheme based on a Modified Lab Color Space

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***Abstract*— With recent developments in both High Dynamic Range (HDR) capturing and display technologies, consumer distribution of HDR videos is now possible. The current distribution pipeline, however, is based on Standard Dynamic Range (SDR) signal characteristics. To accommodate HDR in the current pipeline infrastructure, some adjustments are necessary. One element of the pipeline that needs to be addressed is compression scheme. Current compression standards, such as HEVC, rely on YC_bC_r as their color encoding. However, this color encoding cannot represent the HDR signal without introducing visual artifacts. Two approaches exist for compensating for these visual errors: re-adjustment of the HDR signal in YC_bC_r as a pre-processing step to compression, or employing a color encoding that better meets the HDR signal requirements. In this paper, we propose to use the perceptually uniform CIELAB color space for HDR video color encoding following the latter approach. To make CIELAB suitable for HDR video color encoding, we change the transfer function and the scaling of the a* and b* channels. The performance of this approach is compared to YC_bC_r color encoding in our study via compressing these signals based on High Efficiency Video Coding (HEVC) standard and comparing the bitrate of these signals at the same quality level. An average bit-rate saving of 12.9% in terms of Overall Signal to Noise Ratio (OSNR), and 41.3% in terms of DE100 are reported for our proposed color encoding scheme compared to the conventional YC_bC_r. A negligible average loss of 0.6% is reported in terms of perceptually transformed Peak Signal to Noise Ratio (tPSNR).**

Keywords- High Dynamic Range (HDR); color encoding; perceptual quantizer; color difference, CIELAB.

I. INTRODUCTION

Recent advances in capturing and displaying technologies have made consumer distribution of HDR content possible. However, the current video distribution pipeline elements, including compression standards, are designed based on Standard Dynamic Range (SDR) videos characteristics. Given the distinct characteristics of HDR [1], special considerations in terms of both processing and compression need to be taken into account for efficient and true-to-original quality HDR distribution.

High Efficiency Video Coding (HEVC) is the latest compression standard used in video distribution pipelines [2]. HEVC and its predecessors rely on YC_bC_r as their color encoding, where Y represents luminance as a weighted combination of relative light Red (R), Green (G), and Blue (B). This relative light information is obtained by applying a perceptual transfer function known as gamma encoding (standardized as BT.1886 [3]). C_b and C_r are the blue and red differences from the luminance channel, respectively. For the limited brightness range (0.01 to 100 cd/m^2) and color gamut (BT.709 [4]) of SDR, 8-bit YC_bC_r represents SDR signal without visible artifacts or color differences.

On the other hand, HDR content is characterized by a higher range of brightness (usually 0.005 to 10000 cd/m^2) and mainly wider color gamut of BT.2020 [5]. For signals with this wide range of brightness and color, gamma encoding and 8-bit quantization cannot perceptually representative. Thus, a new perceptual transfer function, known as Perceptual Quantizer (PQ) was designed specifically for HDR and later was standardized as SMPTE ST 2084, [6]. Although by changing the transfer function and increasing the bit-depth the quality of the HDR signal is improved by precluding most of the quantization artifacts, still a 10-bit PQ YC_bC_r HDR signal has color differences with the original HDR signal [7]. These color errors are even present before compressing the signal and are intensified even more after applying the chroma 4:2:0 subsampling process as showed in [8]. The causes of these errors are the perceptual non-uniformity of the YC_bC_r signal and the existing correlation between luma (Y) and chroma (C_b and C_r) channels in YC_bC_r [9].

Two general approaches try to address the issues related to 10-bit PQ YC_bC_r 4:2:0 HDR color encoding: re-adjusting the YC_bC_r signal, or using a different color encoding which does not carry the known problems of YC_bC_r. The former approach requires additional pre-processing steps before video coding. On the other hand, the latter approach may need some adjustments during video coding to optimize the process for the new color encoding.

In this work, we study the performance of a modified CIELAB color space for HDR compression [10]. To make CIELAB suitable for HDR compression, we propose some changes to its original form. The modified CIELAB signals are then quantized to 10 bits followed by chroma down-sampling and then compressed using the HEVC codec. The performance of the proposed CIELAB color space for compressing HDR videos is compared with existing color encodings including YC_bC_r, in terms of the common HDR objective metrics.

The rest of this paper is organized as follows. Section II provides overview of existing color encodings. Section III provides details on the suggested modifications of CIELAB. Section IV presents and discusses the results and conclusions are drawn in Section V.

II. Overview of Existing Color Encoding Schemes for HDR Video Compresson

The existing HDR video coding system is based on 10-bit $Y'C_bC_r$. This signal is derived from the relative light R'G'B' signal. The prime on the representations of the signals denotes relative light, i.e., perceptually quantized instead of the linear light. It has been shown in [8] that two original linear RGB colors with similar luminance values transformed to 10-bit 4:2:0 $Y'C_bC_r$ using the conventional way followed by chroma subsampling, may result in two very different luminance (Y) values. That is why deriving Y' from relative light R'G'B' is referred to as Non-Constant Luminance (NCL) approach. Since even small changes in luminance values are quite apparent to human eyes, visible artifacts appear on 10-bit 4:2:0 NCL $Y'C_bC_r$ HDR signal.

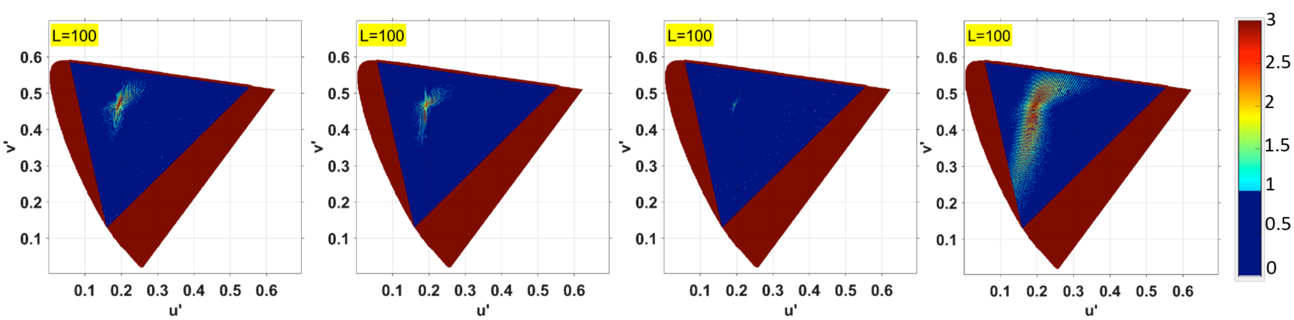
To overcome the non-constant luminance issue, Constant Luminance (CL) derivation of $Y'C_bC_r$ that is based on linear light RGB content can be utilized. However, to put it in practice, the entire infrastructure of the current video transmission system needs to be updated to support CL approach. To avoid such a costly update, a recursive re-adjustment algorithm of the Y' channel (luma) in the 10-bit NCL Y'CbCr to the Y' channel in the 10-bit CL Y'CbCr was proposed in [11]. It is reported in [11] that the visible artifacts of the 10-bit NCL Y'CbCr disappear in the re-adjusted version of the signal. These pre-processing luma adjustments are part of Supplement 15 to ITU-T H-series Recommendations [12] document which offers a description of processing steps and guidelines for converting from 4:4:4 RGB linear light representation video signals into adjusted 10-bit PQ $Y'C_bC_r$ 4:2:0 signal for HDR video transmission. A faster version of this algorithm is proposed in [13] and an approximation of this algorithm was proposed in [14] without the required pre-processing.

To avoid the necessary pre-processing steps associated with using $Y'C_bC_r$, another approach for transmitting HDR is to replace $Y'C_bC_r$ color encoding with a color encoding approach with more de-correlated color and brightness channels. One of such encoding is IC_tC_p [15]. The brightness (I) and color (C_t and C_p) channels information are highly de-correlated. Hence, IC_tC_p does not bear the chroma errors reported with $Y'C_bC_r$. IC_tC_p is designed based on SMPTE ST 2084 as the transfer function.

Another color encoding for HDR video compression is $Y'D'_zD'_x$ [16] that is based on XYZ colors space and SMPTE ST 2084 as the transfer function. This color space was investigated by Moving Picture Experts Group (MPEG) in the early exploration stages of HDR video compression and its requirements. Due to some artifacts seen on some of the HDR videos compressed with $Y'D'_zD'_x$, which in fact were clipping errors, this color encoding was no longer explored by MPEG.

Another proposed color encoding for HDR video compression is Yu"v" [17] that is based on Yu'v' [18]. A transfer function is proposed for this color space in [17]. For dark areas (with luminance value smaller than 5 cd/m^2), u" and v" represent the attenuated u' and v' by Y. Although this introduces dependency on Y for u" and v" channels, it is shown to reduce the noise in dark areas and hence results in better compression efficiency compared to Yu'v'[17].

Figure 1 (a), (b), (c), and (d) show how NCL $Y'C_bC_r$, CL $Y'C_bC_r$, IC_tC_p, and $Y'D'_zD'_x$, respectively represent the whole color gamut of BT.2020 at luminance level of 100cd/m^2 in terms of CIE DE2000 error [19]. Please note to provide fair comparisons of the color encoding schemes rather than transfer functions, we did not include Yu"v" results as it uses a different transfer function from the SMPTE ST 2084. CIE DE2000 is a color difference metric. Errors smaller than one, i.e., invisible errors are represented with dark blue in Figure 1. The visible color differences (with error value larger than 1) are represented with light



(a) (b) (c) (d)

Figure 1. Color encoding error in terms of CIE DE2000 for (a) NCL $Y'C_bC_r$, (b) CL $Y'C_bC_r$, (c) IC_tC_p, and (d) $Y'D'_zD'_x$ shown using an error bar (right) at luminance level of 100 cd/m^2

blue to red. Note that these errors are only the quantization errors and chroma sub-sampling is not yet applied. Figure 1 shows that except for IC_tC_p (c), even before compression the colors of an HDR signal are visibly distorted.

In this paper, yet another perceptually uniform color encoding, CIELAB, and its performance for HDR video compression is investigated. As CIELAB is designed for SDR brightness values up to of 100 cd/m^2, some adjustments are made to its original form to accommodate HDR signal, which are presented in details in what follows.

III. PROPOSED MODIFICATIONS TO CIELAB FOR HDR COMPRESSION

CIELAB consists of one brightness channel (L*) which goes up to 100 cd/m^2 and two color channels a* and b* which cover colors from green to red, and from blue to yellow, respectively. Each of these channels is constructed as follows:

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16 \quad , \tag{1}$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right] \quad , \tag{2}$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right] \quad , \tag{3}$$

$$f(w) = \begin{cases} w^{1/3}, & w > 0.008856 \\ 7.787\,w + 16/116, & w \le 0.008856 \end{cases} \tag{4}$$

where X_n, Y_n, and Z_n are the XYZ components of the white point. Since HDR luminance values can go up to 10000 cd/m^2, the current CIELAB cannot efficiently handle an HDR signal. To address this issue, an hdr-CIELAB is proposed in [20]. The only change in hdr-CIELAB is the transfer function to have better performance for shadows and highlights compared to conventional CIELAB; otherwise all the other derivations are the same as in CIELAB. Still, the encoded L* in hdr-CIELAB goes only up to 245 cd/m^2.

In this work, we propose to use SMPTE ST 2084 as the transfer function for HDR luminance values in CIELAB. Therefore, the proposed L*, a* and b* channels will be calculated as follows:

$$L^* = Y' \quad , \tag{5}$$

$$a^* = \begin{cases} \dfrac{X' - Y'}{0.1441 \times 2}, & -0.1441 \le x \le 0 \\ \dfrac{X' - Y'}{0.1083 \times 2}, & 0 < x \le 0.1083 \end{cases} \tag{6}$$

$$b^* = \begin{cases} \dfrac{Y' - Z'}{0.2338 \times 2}, & -0.2338 \le x \le 0 \\ \dfrac{Y' - Z'}{0.6208 \times 2}, & 0 < x \le 0.6208 \end{cases} \tag{7}$$

where X', Y', and Z' are the perceptually quantized X, Y and Z signals using SMPTE ST 2084. In (6) and (7), a* and b* channels are scaled to fall within [-0.5 0.5] so that BT.1361 quantization [21] can be applied to them.

The proposed CIELAB for HDR signals is somewhat similar to $Y'D'_zD'_x$ [16]. However, in the proposed modified CIELAB, color difference channels are scaled differently for positive and negative differences so that codewords are utilized more efficiently.

IV. EXPERIMENTAL SETUP

To evaluate the proposed modified CIELAB color encoding for HDR video compression, we use four HDR video sequences from MPEG HDR video dataset: FireEater2, Market3, BalloonFestival, and SunRise. All of these videos are 1920x1080p, and are in the BT.2020 container although their actual colors fall inside the BT.709 gamut. Figure 2 shows tone mapped snapshots of the first frame of each video sequence.

Figure 3 shows how the original linear light HDR content is encoded to the modified CIELAB, followed by quantization and chroma down-sampling. It is worth noting that our modified CIELAB-based method uses the original sampling filters designed specifically for $Y'C_bC_r$ and as such they are not optimized for our proposed scheme. For compression, we used the HEVC encoder reference software HM 16.15, Main10 profile. We coded the tested videos at four bit-rate levels using four QPs, as suggested in [22]. To compare them with the original ones in terms of quality, the color encoded and compressed signals are then de-compressed and converted back to the linear light domain as shown in Figure 3.

(a) (b) (c) (d)

Figure 2. Snapshots of the first frames of HDR test video sequences (tone-mapped version): (a) FireEater2, (b) Market3, (c) BalloonFestival, and (d) SunRise

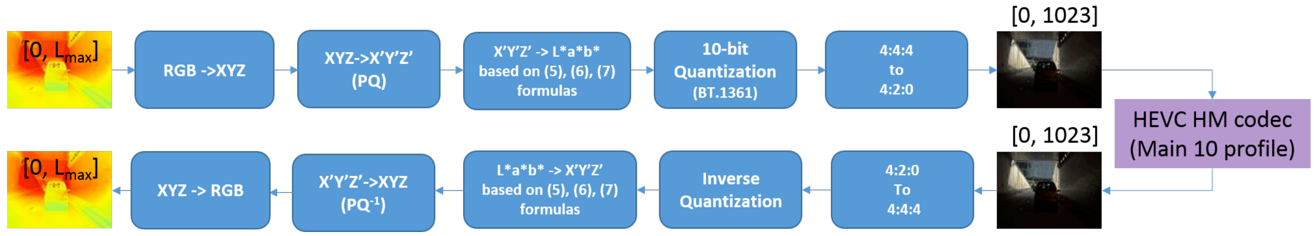


Figure 3. Pre/post processing steps of the proposed modified CIELAB for HDR video compression

V. RESULTS AND DISCUSSIONS

Figure 4 (a), (b), (c) and (d) shows the bit-rate versus DE100, Overall Signal to Noise Ratio (OSNR) and perceptually Transformed Peak Signal to Noise Ratio (tPSNR) in terms of (db) for the proposed modified CIELAB, the NCL YC_bC_r, luma-adjusted NCL $Y'C_bC_r$, IC_tC_p and $Y'D'_zD'_x$ for FireEater2, Market3, SunRise and BalloonFestival, respectively. tPSNR is the average of the PSNR X', Y' and Z'. OSNR is the overall SNR of X', Y' and Z' with calculation of the error for each pixel and then averaging the errors. DE100 is the PSNR based value of the average error in terms of CIE DE2000 metric [22]. Table I also shows the bit-rate savings in terms of the same metrics for the proposed color encoding over NCL $Y'C_bC_r$.

As can be seen from Figure 4, the proposed modified CIELAB clearly outperforms the NCL $Y'C_bC_r$, luma-adjusted NCL $Y'C_bC_r$ and $Y'D'_zD'_x$ in terms of DE100. This shows that the proposed method can maintain the original colors better at any given bit-rate. The proposed method performs almost identical to IC_tC_p in terms of DE100.

Moreover, it can be seen form Figure 4 that the proposed method also outperforms NCL $Y'C_bC_r$, luma-adjusted NCL $Y'C_bC_r$, and $Y'D'_zD'_x$ in terms of OSNR, especially at higher bit-rates. All the tested color encoding schemes seem to be performing similarly in terms of tPSNR.

Please note that the chroma down-sampling filter used for the proposed CIELAB is the same as the one in $Y'C_bC_r$. However, a better performance may be achieved in terms of tPSNR and OSNR if a new sampling filter is designed that better matches the a* and b* characteristics. Although this is not in the scope of this paper, it is part of our future work.

Moreover, the rate-distortion optimization (RDO) setting inside the encoder was maintained the same in all these experiments. Since the current RDO is customized for $Y'C_bC_r$ characteristics, it is expected that further improvements may be obtained by modifying the RDO process according to the proposed modified CIELAB color encoding. This step as well is in the scope of future work.

Another note-worthy observation from Figure 4 is how $Y'D'_zD'_x$ underperforms all the tested color encodings, although its derivation is very similar to what is proposed in this paper. However, as the proposed scaling of a* and b* employs the available codewords more efficiently, it achieves better compression performance compared to $Y'D'_zD'_x$ as observed in Figure 4.

Overall, it is shown that the proposed color encoding results in better performance in terms of DE100 compared to conventional NCL $Y'C_bC_r$, by an average of 41% over the four videos, hence better maintaining the original HDR colors. By using a chroma down-sampling filter that is designed for the proposed space and changing the encoder rate-distortion optimization process, it is expected to improve the performance of the tested color in terms of tPSNR and OSNR.

TABLE I. BIT-RATE SAVINGS OF THE PROPOSED CIELAB COMPARED TO NCL Y'CBCR

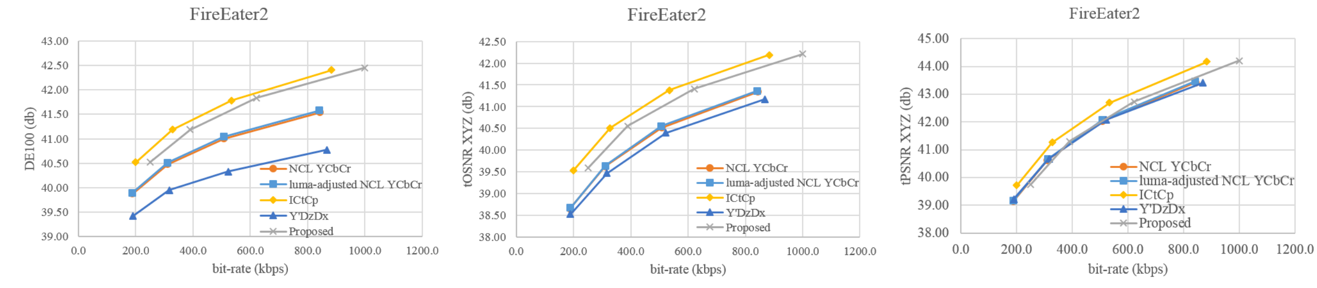
Metric / Video	tPSNR X (%)	tPSNR Y (%)	tPSNR Z (%)	tPSNR XYZ (%)	tOSNR XYZ (%)	DE 100 (%)
FireEater 2	-7.4	8.0	-3.0	-1.0	-24.0	-32.6
Market3	13.1	17.4	2.7	10.5	6.2	-63.6
SunRise	0.2	9.9	-23.0	-6.3	-19.5	0.0
BalloonF estival	5.4	21.5	-17.7	-0.7	-14.3	-69.2
Average	2.9	14.2	-10.2	0.6	-12.9	-41.3

VI. CONCLUSIONS

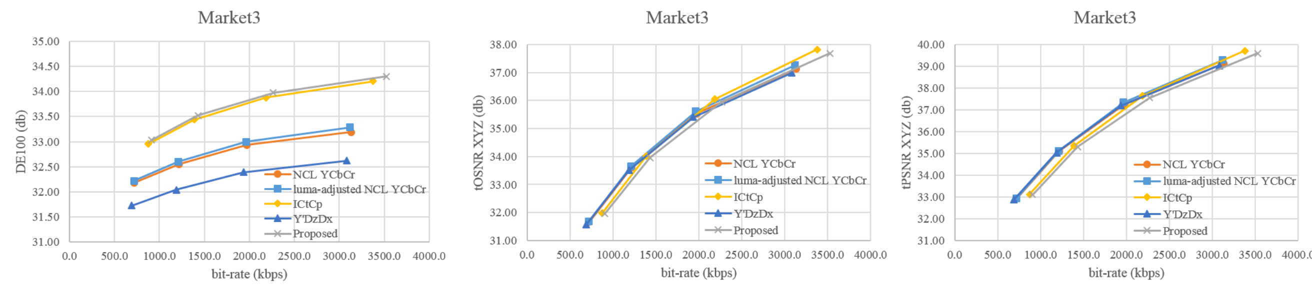
In this paper, we presented a modified CIELAB color encoding scheme for efficiently compressing HDR content.

Performance evaluations show that the proposed adjusted CIELAB space, even using the chroma down-sampling designed for $Y'C_bC_r$, maintains the original HDR colors better than other existing color spaces and results in an average of 41% bit-rate savings over four videos in terms of DE100 (db). The performance of the proposed modified color space even without changing the chroma sub-sampling filters of $Y'C_bC_r$ is almost similar to that of IC_tC_p.

The slight underperformance of the proposed approach in terms of tPSNR can be improved by changing the chroma down-sampling filter to a more tailored one to the a* and b*



(a)



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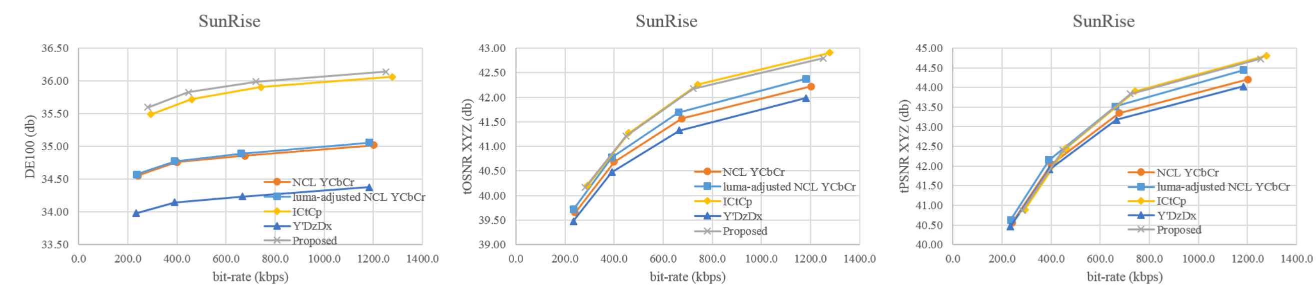
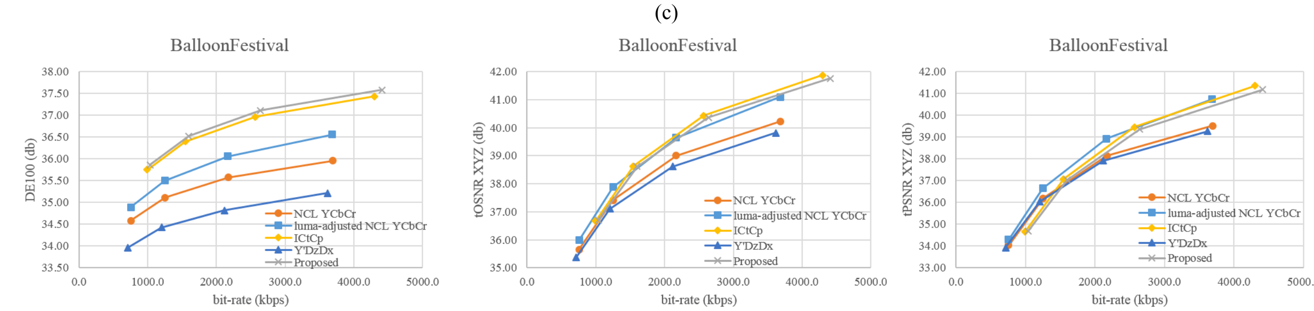


(c)



(d)

Figure 4. R-D curves of the proposed color encoding compared to NCL YC_bC_r, luma-adjuste YC_bC_r, $Y'D'_zD'_x$ and IC_tC_p in terms of DE100 (db), OSNR (db) and tPSNR (db) for (a) FireEater2, (b) Market3, (c) SunRise, and (d) BalloonFestival

characteristics. Furthermore, changing the RDO process to be performed in the proposed space instead of $Y'C_bC_r$ may also result in further performance improvement in terms of tPSNR.

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