TWO LAYER LOSSLESS CODING OF HDR IMAGES

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ABSTRACT

This report proposes a two layer lossless coding system for high dynamic range (HDR) images expressed in a floating point data format. Its encoder outputs compressed image data in two layers. From the base layer, a standard low dynamic range (LDR) image is decoded. Merging with the enhancement layer, the original HDR image is decoded without any loss. We introduce a reversible logarithmic mapping to reduce bit depth of pixel values. We also introduce bit plane classification to divide data into two layers. It was confirmed that our method has better coding performance than existing methods especially at high bit rate coding of LDR images.

Index Terms— image, lossles, coding, HDR, scalable

1. INTRODUCTION

The concern with high dynamic range (HDR) images has been growing in advanced image technologies for the last several years [1-2]. It can express wider dynamic range of its pixel values than currently standard low dynamic range (LDR) images. This report focuses on how to compress data volume of an HDR image, having backward compatibility to displaying an LDR image generated from the original HDR image with tone mapping.

So far, various types of two layer coding systems have been proposed [3-9]. Its encoder outputs compressed HDR image data in two layers - the base layer and the enhancement layer. From the bit stream in the former layer, an LDR image is decoded with a standard decoder. It can be displayed with standard imaging devices. Merging with the bit stream in the latter layer, the original HDR image is decoded. Those systems are referred to the bit depth scalable coding.

G. Ward, et. al. proposed a backward compatible two layer coding system [3]. In the base layer, the original HDR color image is tone mapped to produce an LDR image, and compressed with the JPEG internationally standard encoder. In the enhancement layer, the ratio of luminance of LDR and that of HDR is embedded. The original HDR color image is decoded by multiplying the luminance ratio image in the enhancement layer and the LDR color image in the base layer.

Their method was extended to video signals [4], and this topic has been attracting researchers' attention as the bit depth scalable video coding [5-7]. For still images, I. R. Khan improved existing methods introducing piecewise linear modeling of a tone mapping [8]. T. Jinno, et. al. improved coding efficiency in the enhancement layer, replacing the ratio image by the low passed HDR image [9].

Unlike those existing reports dealt with 'lossy' coding of HDR images, this report discusses on 'lossless' coding of HDR images under constrain that the system has backward compatibility with 'lossy' coding of LDR images. In addition, it focuses on HDR images expressed in a floating point data format, which has wider range of pixel values than a fixed point format [10].

Introducing a one to one mapping from a floating point value to an integer, an existing approach can be simply extended to 'lossless' for HDR images (existing method 1). However, its integer pixel value requires so long bit depth, making compression of the enhancement layer quite difficult. To cope with this problem, we have already applied a reversible logarithmic mapping (Rev.Log) to pixel values of the HDR image (existing method 2), and confirmed its effectiveness on reducing bit rate of the enhancement layer [11].

In this report, we furthermore reduce bit rate of the enhancement layer for 'lossless' coding of HDR images, combining with a bit plane classification and the JPEG 2000 lossless encoder [14]. In our method, pixel values are classified into upper bit planes and the lower ones after the Rev.Log mapping. The former is encoded to produce a bit stream in the base layer. It is decoded and compensated so that a properly tone mapped LDR image can be displayed. The latter, whose bit depth does not exceed a designated value, is encoded as a bit stream in the enhancement layer. Quality and bit rates of the LDR image can be controlled by users. The HDR image is always decoded without any loss.

In our experiments, we confirm that the proposed method reduces bit depth and bit rate of the enhancement layer comparing to the existing methods. We also show superiority of our method in the base layer at high bit rate and high quality coding of LDR images.

2. EXISTING METHODS

Two existing methods and their problems are summarized as below. We assume that a pixel value of an input HDR image is given as an exponent x_E and a mantissa x_M. These are integers in D_E and D_M bit depth, respectively. A pixel value x_H of each color component of the HDR image is calculated as

$$x_H = (1 + x_M \cdot 2^{-D_M}) \cdot 2^{x_E - E_0} = f_{Flt}(x_M, x_E) \qquad (1)$$

for

$$x_M \in [0, 2^{D_M} - 1], \quad x_E \in [0, 2^{D_E} - 1].$$

For example, D_M=10 and D_E=5 and E_0=15 for $1 \le x_E \le 30$ in 'Open EXR' format [10]. It also defines negative value, zero, infinite and not a number. However those are omitted below without loss of generality.

2.1. Existing Method 1

Fig.1 illustrates the existing method 1. It is based on the 'lossy' coding in [8] and simply extended to 'lossless' coding. A set of floating point value (x_M, x_E) is converted to an integer by 'Float to Integer' in the figure as

$$
\begin{aligned}
x_I &= (x_M + 2^{D_M}) \cdot 2^{x_E - E_1} = f_{Int}(x_M, x_E) \\
&= x_H \cdot c_I, \quad c_I = 2^{E_0 - E_1 + D_M}
\end{aligned}
\qquad (2)
$$

which is equivalent to multiplying c_I to x_H in (1). To make it integer, 'x_E-E_1' must be greater than or equal to zero. We set E_1 to the minimum of x_E in the image. Note that inverse of (2) reconstructs the original (x_M, x_E) without any loss, namely this mapping is 'reversible'.

The integer HDR image x_I is converted to the LDR image x_{L1} with a tone mapping function. In this report, we use the Hill function

$$y = \frac{255}{\bar{x}/x + 1} = f_{Hill}(x), \quad \bar{x} = \exp\left(\underset{x>0}{E}[\log_e x]\right), \qquad (3)$$

where $E[\ ]$ denotes arithmetic mean over all the positive values of x. Based on this function, each of the color component x_{LC} of the LDR image x_L is generated as

$$
\begin{cases}
x_{LC} = \dfrac{f_{Hill}(x_{IY})}{x_{IY}} \cdot x_{IC}, & C \in \{R, G, B\} \\
x_{IY} = 0.27 x_{IR} + 0.67 x_{IG} + 0.06 x_{IB}
\end{cases}
\qquad (4)
$$

where x_{IC} and x_{IY} denote color component and luminance of the integer HDR image x_I, respectively. We denote the tone mapping operation defined by (4) as

$$x_L = f_{Tmo}(x_I) \qquad (5)$$

for $x_L = (x_{LR}, x_{LG}, x_{LB})$ and $x_I = (x_{IR}, x_{IG}, x_{IB})$.

In Fig.1, the LDR image x_{L1} is generated from the integer HDR image x_I as

$$x_{L1} = R[f_{Tmo}(x_I)] \qquad (6)$$

where $R[\ ]$ denotes rounding to integer. Its data volume is compressed with JPEG 2000 'lossy' encoder to produce bit stream in the base layer. In the enhancement layer, the difference

$$x_{D1} = x_I - y_I \qquad (7)$$

for

$$y_I = R[f_{Tmo}^{-1}(y_{L1})] \qquad (8)$$

is coded with JPEG 2000 'lossless' encoder. A problem in this existing method 1 is that the difference x_{D1} has too long bit depth, and has weak correlation among pixels. It makes compression quite difficult.
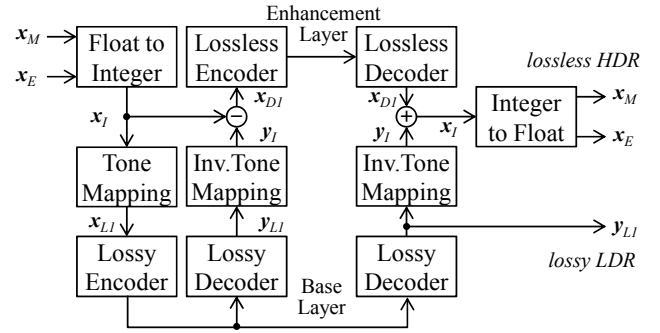

Fig.1 Existing method 1. The original HDR is decoded without any loss. Mantissa x_M and exponent x_E are converted to an integer x_I. However, it's bit depth is too long to be compressed.

2.2. Existing Method 2

Fig.2 illustrates the existing method 2. It was reported in [11]. It applies a reversible logarithmic mapping 'Rev.Log'

$$x_P = x_M + 2^{D_M} \cdot x_E = f_{Log}(x_M, x_E) \qquad (9)$$

to generate an integer image x_P. Note that this mapping is 'reversible'. This procedure itself can be found in previous reports such as [12]. In this report, we demonstrate that it can be treated as an approximation of logarithmic mapping of x_H in (1). Substituting x_E in (1) into (9), x_P becomes

$$x_P = (\log_2 x_H + E_0 - \delta) \cdot 2^{D_M} = f_{Log}(f_{Flt}^{-1}(x_H)) \quad (10)$$

for

$$\delta = \log_2 \frac{1 + \varepsilon}{2^{\varepsilon}} \in [0, 0.086], \quad \varepsilon = x_M \cdot 2^{-D_M} \in [0, 1)$$

where δ depends on x_M. It indicates that 'Rev.Log' can be treated as a logarithmic function of x_H as δ is negligible. It also contributes to reduce bit depth of x_P without any loss

[11]. Since the histogram of x_H is 'sparse', the mapping makes it 'dense' without any input-dependent table [13].

To produce a properly tone mapped LDR image, the compensation 'Cmp' is applied. It is defined as

$$x_{L2} = R[f_{Cmp}(x_P)] = R[f_{Tmo}(f_{Int}(f_{Log}^{-1}(x_P)))] . \quad (11)$$

Note that the mapping f_{Cmp} is not reversible. After this compensation, the LDR image x_{L2} is coded with JPEG 2000 'lossy' encoder. Also note that $x_{L1} = x_{L2}$ since (11) becomes

$$x_{L2} = R[f_{Tmo}(x_I)] \quad (12)$$

from (2), (9). In the enhancement layer, the difference

$$y_{D2} = x_P - y_{P2} \quad (13)$$

for

$$y_{P2} = R[f_{Cmp}^{-1}(y_{L2})] = R[f_{Log}(f_{Int}^{-1}(f_{Tmo}^{-1}(y_{L2})))] \quad (14)$$

is coded with JPEG 2000 'lossless' encoder.

The existing method 2 has a merit that only a standard lossy decoder is required in decoding the LDR image y_{L2}. However, the inverse compensation in (14) degrades coding performance in the enhancement layer. This is because it magnifies the noise $y_{L2} - x_{L2}$ added by the lossy coding in the base layer.
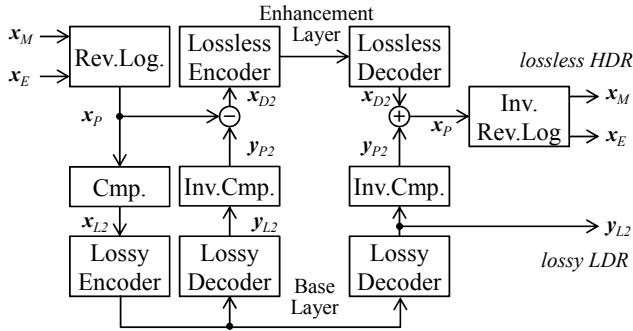

Fig.2 Existing method 2. Reversible logarithmic mapping (Rev.Log.) reduces bit depth of x_P. Compensation (Cmp.) produces a tone mapped LDR image x_{L2}. However its inverse magnifies coding noise.

3. PROPOSED METHOD

Fig.3 illustrates the proposed method. It also utilizes the 'Rev.Log'. Unlike the existing method 2, the upper bit plane

$$x_U = \lfloor x_P \cdot 2^{-D} \rfloor \quad (15)$$

of the image x_P is encoded in the base layer. The parameter D is set to be a positive integer. As it increases, bit rate of the base layer is reduced, that of the enhancement layer is increased, and quality of the LDR image is degraded. Unlike the existing methods, it is coded with 'lossless' encoder to produce the base layer bit stream.

In the base layer, coding performance is expected to be superior to the existing methods at high bit rates, since the LDR image is encoded with spatial quantization followed by a lossless encoder [15,16]. On the contrary, it can be demerit that the compensation

$$y_{L3} = R[f_{Cmp}(y_{P3})] = R[f_{Tmo}(f_{Int}(f_{Log}^{-1}(y_{P3})))] \quad (16)$$

for

$$y_{P3} = x_U \cdot 2^D \quad (17)$$

is necessary in decoding the LDR image y_{L3}. In the enhancement layer, the difference

$$x_{D3} = x_P - y_{P3} \quad (18)$$

is coded with JPEG 2000 'lossless' encoder. It guarantees that the maximum bit depth of x_{D3} in this layer can be controlled by the parameter D. Coding performance in both of the base layer and the enhancement layer is experimentally investigated in **4.**.
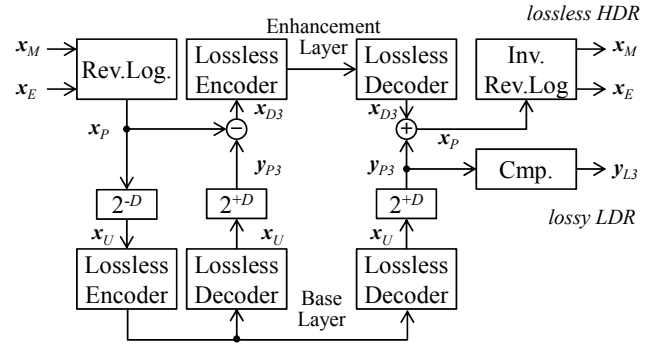

Fig.3 Proposed method. Upper bit plane image x_U is encoded without any loss. It is encoded, scaled and compensated to produce a tone mapped LDR image y_{L3}.

4. EXPERIMENTAL RESULTS

Fig.4(a) illustrate a tone mapped LDR image x_L in (5) for 'Cannon' in the OpenEXR format. Its image size is clipped to 544×768 pixels so that 5 stage octave decomposition wavelet transform can be applied. Fig.4(b) illustrates another tone mapped LDR image 'Mt.TamWest' in the size of 704×1184 pixels. These are tested in our experiments.

(a) 'Cannon'   (b) 'Mt.TamWest'

Fig.4 Results of the tone mapping.

4.1. Base Layer

Fig.5 summarizes rate-distortion curves in the base layer. Distortion of the decoded LDR image

$$e_{Lm} = y_{Lm} - x_L, \quad m \in \{1,2,3\} \qquad (19)$$

was measured with the peak-signal to noise ratio (PSNR) in [dB]. Bit rate was calculated as the total data volume in [bit] of the base layer divided by the total number of pixels.

It was observed that there is no significant difference between the existing method 1 and the existing method 2. It was also observed that the proposed method is superior to the existing methods at bit rates higher than 3.5 and 5.2 [bpp] for 'Cannon' and 'Mt.TamWest', respectively. Performance in the base layer could be improved introducing an optimum non-uniform quantization.

4.2. Enhancement Layer

Fig.6 summarizes bit depth of the difference x_{D1}, x_{D2} and x_{D3} in Fig.1, Fig.2 and Fig.3 respectively at various quality of the LDR image in the base layer. Note that SNR of the HDR image is infinite since it is lossless. It indicates that the existing method 2 reduces bit depth by approximately 4 and 12 [bit] for 'Cannon' and 'Mt.TamWest' respectively comparing to the existing method 1. It also indicates that the proposed method reduces more than 1 and 3 [bit] for each image comparing to the existing method 2.

Fig.7 illustrates bit rate of the enhancement layer. Similarly to Fig.6, superiority of the proposed method to both of the existing methods was observed especially at high bit rates.

Fig.8 illustrates total bit rate of all the layers. Fig.9 magnifies a part of Fig.8 to focus on comparison between the proposed method and the existing method 2. The labels 'one layer (x_I)' and 'one layer (x_P)' indicate a result of lossless coding of x_I in (2) and x_P in (9) respectively without dividing into two layers. It was observed that the proposed method can't exceed 'one layer (x_P)', however very close to it for 'Mt.TamWest'. Note that the one layer method does not have functionality of the two layer method.
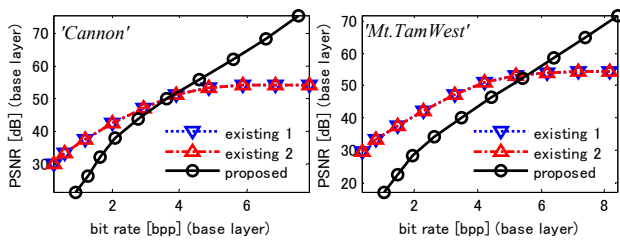

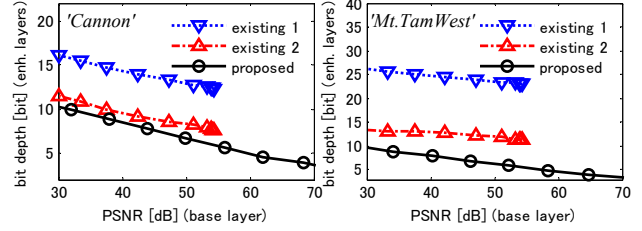Fig.5 Rate distortion curves in the base layer.
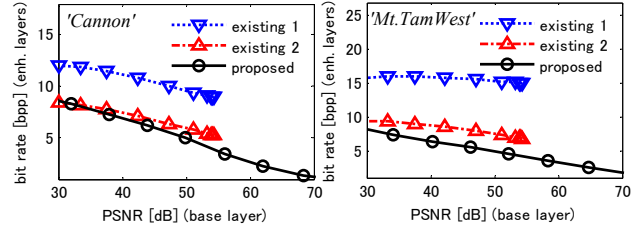

Fig.6 Bit depth in the enhancement layer.

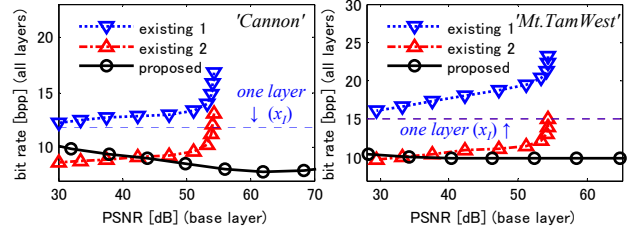Fig.7 Bit rate in the enhancement layer.
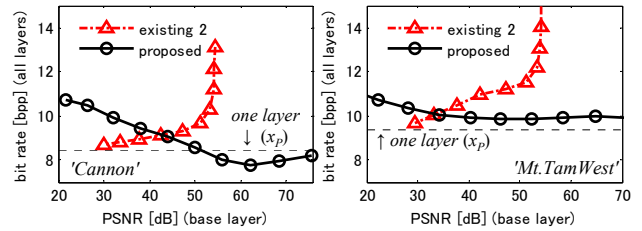

Fig.8 Bit rate of all the layers.

Fig.9 Bit rate of all the layers. A part of Fig.8 is magnified.

5. CONCLUSIONS

A two layer lossless coding of HDR images was proposed. It was designed especially for pixel values expressed in a floating point data format. Utilizing sparseness of the HDR pixel values in its histogram, a reversible logarithmic mapping was utilized to pack its histogram. Furthermore, its upper bit plane image was encoded in the base layer. As a result, it was confirmed that the proposed method reduces bit depth and bit rate at high SNR and high bit rate LDR image coding mode.

Further discussions are necessary to improve coding performance in the base layer at low bit rates.

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