# Efficient Lossless Bit Depth Scalable Coding for HDR Images

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*Abstract*— **This report proposes two layered bit depth scalable coding methods for high dynamic range (HDR) images expressed in floating point data format. From the base layer bit stream, low dynamic range (LDR) images are decoded. They are tone mapped appropriately for human eye sensitivity, and shortened to a standard bit depth, e.g. 8 [bit]. From the enhance layer bit stream, HDR images are decoded. However the bit depth of this layer has been huge in the existing method. To reduce it, we divide the tone mapping into a reversible logarithmic mapping and its compensation. It was confirmed that the proposed methods significantly reduce the bit depth of the enhance layer, even though the compensation slightly increases coding noise.**

## I. INTRODUCTION

Owing to the current state-of-the-art compression technologies such as JPEG 2000 international standard [1], huge data volume of high quality and high resolution images have become feasible to be transmitted via digital networks. Recently, high dynamic range (HDR) images have been attracting researchers' attention for advanced technologies. To fully utilize its huge dynamic range, their pixel values are stored in the floating point format, i.e. RGBE format and Open EXR format [2]. However, most of conventional encoders are designed for fixed point integer pixel values.

One of straightforward approaches to utilize a conventional encoder is to reduce dynamic range of pixel values in HDR images before encoding. R.Xu et.al applied a logarithmic function prior to a JPEG 2000 encoder [3]. However, the original HDR image can't be recovered from its bit stream without any loss. It also ignores backward compatibility to conventional low dynamic range (LDR) images.

So far, various types of two layered bit depth scalable coding have been proposed [4-7]. Its encoder outputs bit streams in two different layers. From the base layer, an LDR image is decoded. It is tone mapped appropriately for human eye sensitivity. Its bit depth is shortened to conventional length, e.g. 8 [bit]. From the enhance layer, an HDR image is decoded combining with the base layer bit stream. However the bit depth of the enhance layer becomes so huge. It is necessary to shorten its bit depth, since some current encoder does not support such a long bit depth. It is also crucial to reduce its data volume because the image in this layer is residual, and pixels have weak correlation with neighboring pixels. It makes data compression quite difficult.

This report aims at reducing the bit depth of the enhance layer. For this purpose, quantization in spatial domain followed by a wavelet transform in encoding procedure was proposed in [8]. However, total data amount of both of the layers was not reduced due to the spatial domain quantization. Unlike most of those existing methods, we deal with a floating point data format of HDR images to be encoded by the bit depth scalable coding.

In this report, we divide the tone mapping into two stages. One is a reversible logarithmic mapping (Rev.Log) [9], and the other is its compensation (Cmp). Since the HDR image is given in a floating point format, its range can be reduced by 'Rev.Log', and also its inverse procedure reconstructs the original HDR image without any loss. It essentially contributes to reduce bit depth of the enhance layer. For the base layer, we utilize a conventional lossy encoder, e.g. JPEG 2000 [1], so that coding performance in the base layer is maintained as the same level of the existing method.

This report introduces two types of proposed methods. One has the compensation in encoding side, and the other has it in the decoding side. They outputs the base layer bit stream for decoding the tone mapped LDR image, and the enhance layer bit stream for decoding the original HDR image without any loss. In our experiments, we confirm that both of the proposed methods significantly reduce the bit depth of the enhance layer, maintaining coding performance in the base layer.

## II. EXISTING METHOD

An example of the floating point data format of the HDR image is briefly explained. An existing method extended for lossless coding of the HDR image is described.

### A. Floating Point Data Format

This report deals with HDR images in a floating point data format in which a pixel value is given by an exponent in integer $x_E$ and a mantissa in integer $x_M$ as

$$x_F = (1 + x_M \cdot 2^{-D_M}) \cdot 2^{x_E - E_0} \tag{1}$$

for

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

In the 'Open EXR' [2], e.g., $x_M$ and $x_E$ are given as $D_M$=10 and $D_E$=5 bit depth integer data, respectively. A constant $E_0$ is set to 15 for $1 \le x_E \le 30$. It also has a sign bit, however it is omitted in the discussion below due to lack of space.

Since this report aims at lossless coding of HDR images, we need a reversible mapping between ($x_M$, $x_E$) and an integer. Therefore, we modify (1) to

$$x_I = (x_M + 2^{D_M}) \cdot 2^{x_E - E_1} = f_{Int}(x_M, x_E)\,. \qquad (2)$$

It is necessary for ($x_E$ -$E_1$) to be zero or a positive integer so that $x_I$ becomes integer. To minimize bit depth of $x_I$ under this condition, $E_1$ is set to the minimum of $x_E$ in an input image. Defining the bit depth of pixels $x_X$ in an image by

$$B_{dp}(x_X) = \log_2\left(Max_X - Min_X + 1\right) \quad \text{[bit]} \qquad (3)$$

for the maximum and the minimum in an image

$$Max_X = \max\{x_X\}, \quad Min_X = \min\{x_X\}\,,$$

the bit depth of $x_I$ becomes

$$\begin{aligned} B_{dp}(x_I) &= \log_2\left((-1 + 2^{1+D_M})2^{Max_E - Min_E} - 2^{D_M} + 1\right) \\ &< Max_E - Min_E + 1 + D_M \\ &< 2^{D_E} + D_M\,. \end{aligned} \qquad (4)$$

Note that $Min_M$ and $Max_M$ of $x_M$ tend to be 0 and $2^{D_M}$ -1, respectively. However, $Min_E$ and $Max_E$ of $x_E$ tend to be greater than 0 and less than $2^{D_E}$ -1, respectively in practice.

### *B. Existing Method*

Fig.1 illustrates a lossless bit depth scalable coding referred to an 'existing method' hereinafter. The reversible mapping in (2) labeled as 'Float to Integer' is added to the conventional bit depth scalable coding approach in a dotted box in the figure. It produces an LDR image $x_W$ from $x_I$ with a tone mapping (Irrev.Tmp). It is encoded by a lossy encoder composed of an irreversible 9/7 wavelet transform (Irrev.Dwt), quantization (Qnt) and the EBCOT encoder ($E_0$) defined by the JPEG 2000 standard [1]. In this report, we use the Hill function

$$y = \frac{x^a}{x^a + b^a} \cdot (1 + b^a) = g_{Tmp}(x), \quad x, y \in [0,1] \qquad (5)$$

as a tone mapping. Parameters *a* and *b* are appropriately set by an user [2]. We applied it to luminance of $x_I$, e.g. as

$$x_W = R\left[ g_{Tmp}\left( \frac{x_I - Min_I}{Max_I - Min_I} \right) \cdot 255 \right] := f_{Tmp}(x_I) \qquad (6)$$

where $R[x]$ denotes the integer nearest to $x$. It reduces the bit depth to conventional 8 [bit], and a tone mapped LDR image $x_W$ is generated. Note that it is irreversible, namely it holds

$$x_I - f_{Tmp}^{-1}(f_{Tmp}(x_I)) \neq 0\,. \qquad (7)$$

A problem of the existing method discussed here is that the residual image $x_I$ - $y_I$, to be encoded with a lossless encoder ($E_1$) in the enhance layer, has too long bit depth. In addition, it is quite difficult to compress its data volume since the residual image tends to have weak correlation among pixels.

## III. PROPOSED METHOD

Dividing the tone mapping in (6) into two stages: reversible logarithmic mapping and its compensation, we propose two methods which reduce bit depth of the enhance layer. One has the compensation in encoding, the other has it in decoding.

### *A. Proposed Method 1*

Fig.2 illustrates the proposed method 1. Firstly, we apply the reversible logarithmic mapping (Rev.Log) [9]

$$x_L = x_M + 2^{D_M} \cdot x_E = f_{Log}(x_M, x_E) \qquad (8)$$

to $x_M$ and $x_E$ to generate an integer $x_L$. Note that this mapping is reversible, and also the bit depth of $x_L$

$$\begin{aligned} B_{dp}(x_L) &= \log_2\left(2^{D_M} - 1 + 2^{D_M} Max_E - 2^{D_M} Min_E + 1\right) \\ &= \log_2\left(Max_E - Min_E + 1\right) + D_M \\ &< D_E + D_M \end{aligned} \qquad (9)$$

is reduced comparing to that of $x_I$ in (4). It means that the histogram sparseness [10] of $x_I$ is utilized and redundancy in the range of pixel values is deleted. The property peculiar to the floating point data format is appropriately considered.

Secondly, we introduce compensation (Cmp) so that the LDR image becomes the same as that of the existing method. We define the compensation $f_{Cmp}$ by

$$f_{Cmp}(x_L) = f_{Tmp}(f_{Int}(f_{Log}^{-1}(x_L))) \qquad (10)$$

for $x_L$ in (8). Note that this procedure is irreversible.

The proposed method 1 has a merit that there is no need to use the compensation for LDR-only users. Just a conventional lossy decoder is enough for displaying the LDR image. On the other hand, in encoding, the inverse of the compensation ($\text{Cmp}^{-1}$) slightly degrades coding performance in the enhance layer, since it magnifies the noise $y_W'$-$x_W'$.

### *B. Proposed Method 2*

Fig.3 illustrates the proposed method 2. We introduce the compensation in decoding side. The normalization (*Nrm*) and its inverse defined by

$$\begin{cases} f_{Nrm}(x_L) = R\left[ \dfrac{x_L - Min_L}{Max_L - Min_L} \cdot 255 \right] \\ f_{Nrm}^{-1}(y_L') = R\left[ \dfrac{y_L'(Max_L - Min_L)}{255} \right] + Min_L \end{cases} \qquad (11)$$

are applied to $x_L$ and $y_L'$, respectively in the figure. Note that the minimum $Min_L$ and the maximum $Max_L$ of $x_L$ are included into the bit stream as overhead data.

The proposed method 2 has a merit that the noise $y_L'$-$x_L'$ is not magnified unlike the proposed method 1 in the enhance layer in encoding. However the compensation magnifies the noise $y_L$ - $x_L$ in decoding and slightly degrade quality of the LDR image.

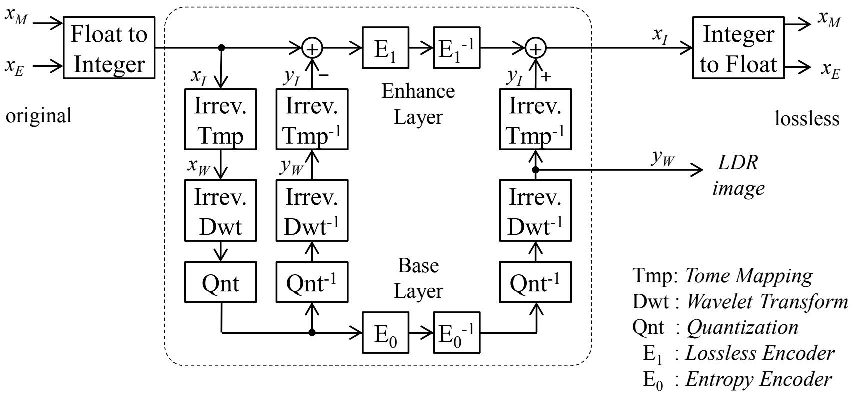

Fig.1 Existing Method

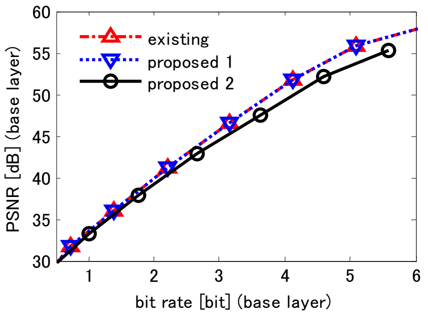

Fig.5 Rate distortion curves of the base layer.

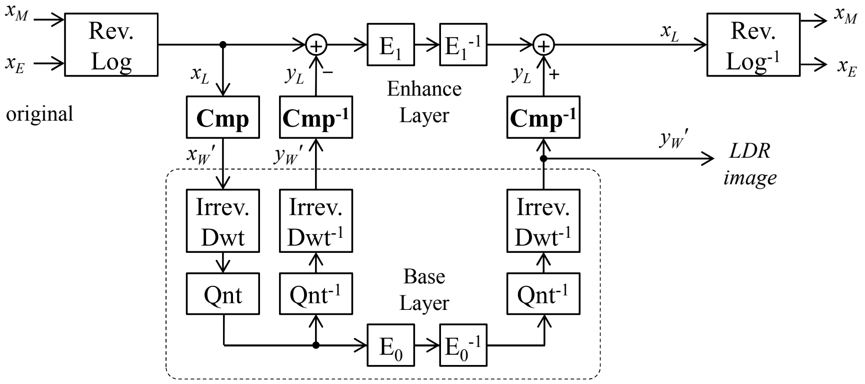

Fig.2 Proposed Method 1

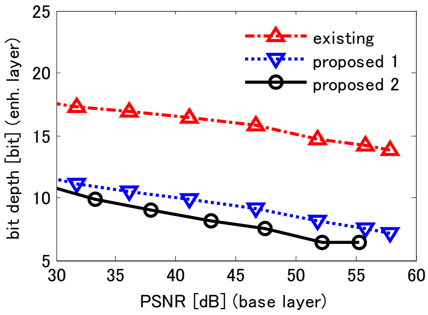

Fig.6 Bit depth of the enhance layer.

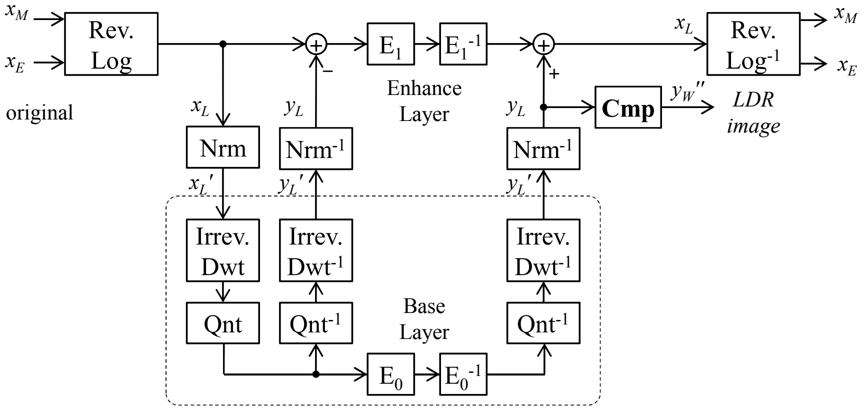

Fig.3 Proposed Method 2

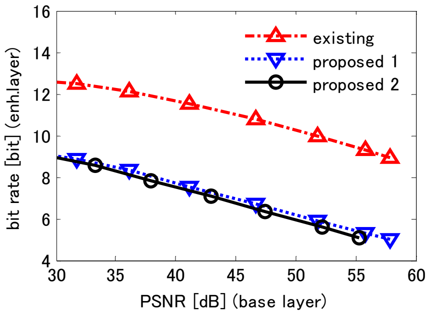

Fig.7 Bit rate of the enhance layer.

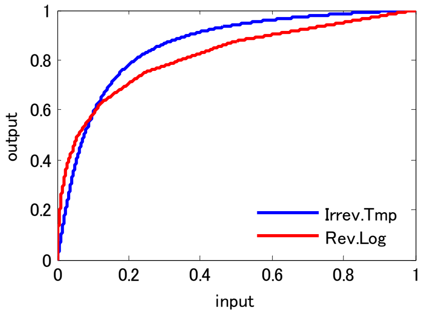

Fig.8 Tone mapping curves.

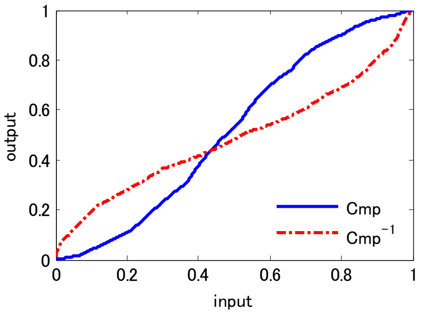

Fig.9 Mapping of the compensation.

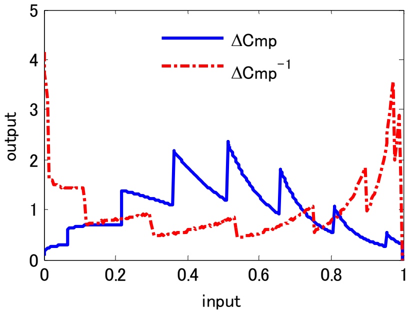

Fig.10 Compensation magnifies coding noise.

## IV. EXPERIMENTS

Fig.4(a) illustrates a tone mapped image $x_W$ of Red component of 'Cannon' in the Open EXR format ($544\times 768$ pixels). Parameters in (5) are set to $a$=1.2 and $b$=1/12 as an example. Fig.4(b) illustrates an image $x_L$ mapped by 'Rev.Log' in (8). Note that it is normalized to [0,255] for demonstration.


(a) 'Irrev.Tmp' (b) 'Rev.Log'

Fig.4 Results of the tone mappings.

### A. Base layer

Fig.5 illustrates rate-distortion curves in the base layer. The distortion was measured with the PSNR defined by

$$PSNR = 10\log_{10}\frac{255^2}{E[(y_W - x_W)^2]} \quad [dB] \qquad (12)$$

where $E$[ ] denotes ensemble average of all the pixels in the image. It was observed that there is no significant difference between the existing method and the proposed method 1. However, it was found that the proposed method 2 is $0.9\times 1.8$ [dB] slightly worse than the proposed method 1 at 2 to 4 [bpp] middle bit rate. This is because 'Cmp' in decoding magnifies coding noise in the LDR image.

### B. Enhance Layer

Fig.6 illustrates bit depth of the residual image $x_I - y_I$ in the existing method, and $x_L - y_L$ in the proposed methods. Before the lossy encoding, $B_{dp}(x_I)$= 17.37 [bit] was reduced to $B_{dp}(x_L)$= 12.76 [bit] by 'Rev.Log'. Comparing to the existing method at the same PSNR of the LDR image, the proposed method 2 reduces the bit rate by 7.1 to 8.6 [bit]. On the other hand, the proposed method 1 reduces it by 6.0 to 7.1 [bit]. It is slightly worse than the proposed method 2. This is due to magnification of noise by 'Cmp$^{-1}$' in the enhance layer.

Fig.7 illustrates the bit rate in the enhance layer. The JPEG 2000 lossless encoder composed of the reversible 5/3 discrete wavelet transform (5 stage) and the EBCOT [1] is applied as a lossless encoder ($E_1$) in Fig.1 to 3. It was observed that the bit rate was reduced by 3.6 to 4.0 [bit] and 3.6 to 4.3 [bit] by the proposed method 1 and the proposed method 2, respectively.

### C. Mapping and Compensation

Fig.8 illustrates mapping curves of 'Irrev.Tmp' in Fig.1 and 'Rev.Log' in Fig.2 and Fig.3. Both of input and output are normalized to the range [0,1]. Fig.9 illustrates the mapping curves of 'Cmp' and 'Cmp$^{-1}$' in the proposed methods. The red line in Fig.8 is compensated with the blue line in Fig.9. The result is the same as the blue line in Fig.8 for signals. However we should pay attention to the fact that it contains coding noise due to 'Qnt', 'Irrev.Dwt' and 'Nrm'.

Fig.10 illustrates how the noise is magnified by 'Cmp' and 'Cmp$^{-1}$' in the proposed methods. For example, '$\Delta$Cmp' is defined for a normalized input $x \in [0,1]$ by

$$\Delta Cmp = \frac{f_{Cmp}(x+\Delta x) - f_{Cmp}(x)}{\Delta x} \cong \frac{\partial f_{Cmp}}{\partial x}\,. \qquad (13)$$

The blue line in the figure indicates that a noise $\Delta x$ =1 in middle brightness ($0.4<x<0.6$) is 1.1 to 2.2 times magnified by 'Cmp' in Fig.3. On the contrary, 'Cmp$^{-1}$' magnifies 3.5 to 4.1 times in dark pixels ($x \cong 0$) and bright pixels ($x \cong 0.98$).

## V. CONCLUSIONS

In this report, we proposed bit depth scalable coding methods for HDR images in floating point data format. We divided a given tone mapping into a reversible logarithmic mapping and its compensation. It was confirmed that both of the proposed methods reduce bit depth of the residual image in the enhance layer by 3.6 to 4.0 [bit] comparing to an existing method, under the condition that coding performance in the base layer is maintained.

It is necessary to evaluate its performance for color images in the future.

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