An Extended Reversible Data Hiding Method for HDR Images Using Edge Estimation

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***Abstract*—We extend a reversible data hiding method for high dynamic range (HDR) images with RGBE format in this paper. In RGBE format, the edge distribution in each channel is similar to those in the other channels. The proposed method focuses on this feature and improves the edge estimation algorithm of the conventional method to detect more accurate prediction values. Optimal prediction values are first obtained for target pixels based on the edge estimation, and then the payload is embedded using a histogram of the prediction errors. Our experimental results show that the prediction values, which are close to the target pixel values, can be obtained, and thus the hiding capacity of the proposed method is higher than that of the conventional method.**

I. Introduction

Copyright protection of digital content is important according to the spread of Internet services and increasing opportunities for uploading and sharing images through social networking services (SNS) and cloud services. Data hiding techniques, which embed a payload into an image, have been studied as one of the techniques to prevent unauthorized copying and secondary use [1]–[6]. These techniques derive a marked image without increasing the file size. Data hiding can be divided into two types: irreversible data hiding (IDH) [1], [2] and reversible data hiding (RDH) [3]–[6]. The former is basically resilient against some attacks and has high hiding capacity. However, it cannot exactly restore the original image since the retrieved image has slightly deteriorated even after data extraction. In contrast, the latter is usually more vulnerable to such attacks and has less hiding capacity than IDH, but it can completely retrieve the original image.

The range of luminance, which we experience in the real world, is much larger than that of images in display devices. Those image often includes overexposure or underexposure. Therefore, HDR images [7], [8] have been designed to represent the whole luminance range and color gamut, which human can perceive. HDR images are expected to apply in various fields, e.g., computer graphics, vision sensor, and security camera. Data hiding techniques for HDR images have been actively studied [9]–[14] to enhance the security of HDR images. Lin et al. proposed a data hiding method for HDR images with OpenEXR [9]. The marked image quality can be kept high without severe distortion by hiding a payload into the mantissa channel. Bai et al. proposed an RDH method for HDR images with OpenEXR [10]. The payload is embedded using prediction error based on multi-model predictor. Yu et al.'s method and Chang et al.'s method embed a payload into an HDR image with RGBE format by using the homogeneous representation [11], [12]. The hiding capacity of these methods are, however, significantly low, i.e., around 0.1 bpp. He et al. proposed another RDH method for HDR images with RGBE format by using the edge estimation [13]. The edge of the target pixel is estimated by the neighboring pixels to obtain the optimal prediction value. A payload is embedded using the prediction error. However, their method does not ensure full reversibility because they cannot correctly distinguish the pixels containing the payload bits from the pixels without them in data extraction process. Based on He et al.'s method [13], the payload is embedded into HDR images with RGBE format by using the two-dimensional prediction error histogram in Gao et al.'s method [14].

In this paper, we propose an RDH method to ensure complete reversibility and increase the hiding capacity by extending He et al.'s method [13]. Even a small change in the E channel may cause the considerable distortion in the marked image since the E channel determines the range of the luminance intensity. Therefore, a payload is embedded into the color channels. The edge information of the target pixel is estimated by referring to the E and two color channels because the edge distribution in each channel is similar to those in the other channels in RGBE format. In the edge estimation process, we confirm whether the target pixel is located in the edge or flat area and determine the appropriate direction to calculate the prediction value. The payload is embedded by expanding the prediction error. In the proposed method, we improve the edge estimation algorithm of the conventional method [13] to detect more accurate prediction values. Consequently, the hiding capacity of the proposed method is higher than that of the conventional method without visible artifacts in the marked image. The performance of the proposed method is confirmed by the experimental results.

II. Preliminary

A. HDR images

The range of luminance, which human can perceive at the same time, is larger than that of images in consumer digital cameras and display devices. HDR images [7], [8] are thereby designed to express the whole luminance range and color gamut, which are perceived by human eyes. There exist multiple formats for HDR images, e.g., RGBE and OpenEXR.

An HDR image with RGBE format is composed of three color channels R, G, B and a common exponent channel E. The 32-bit value of (R, G, B, E) can be converted into the floating point value of (r, g, b) by

$$\begin{aligned} r &= \frac{R+0.5}{256} \cdot 2^{E-128}, \\ g &= \frac{G+0.5}{256} \cdot 2^{E-128}, \\ b &= \frac{B+0.5}{256} \cdot 2^{E-128}. \end{aligned} \tag{1}$$

Since E determines the range of the luminance intensity, a small change of the luminance may affect the E channel.

B. *Prediction-Error Expansion with Histogram Shifting [6]*

Sachnev et al. proposed an RDH method called Prediction-Error Expansion with Histogram Shifting (PEE-HS) [6]. In this method, we first calculate the prediction value of each pixel by using the neighboring pixels and obtain the difference between the target pixel value and prediction value, namely, the prediction error. Then, the payload is embedded by shifting the histogram of the prediction errors. The hiding capacity of PEE-HS method is higher than those of the histogram shifting based method [4] and the difference expansion method [5]. We extend Sachnev et al.'s PEE-HS method to reduce the additional information and increase the hiding capacity. The hiding procedure for an image with $M \times N$ pixels includes the following steps:

Step1: Define the threshold T ($T > 0$), which is a parameter to control the hiding capacity.

Step2: Modify the pixel values, which may cause overflow or underflow by embedding:

$$\dot{x} = \begin{cases} x+T, & \text{if } \ x \in [0, T), \\ x-T, & \text{if } x \in (255-T, 255], \\ x, & \text{otherwise}. \end{cases} \tag{2}$$

The location map is prepared to conserve the coordinates of the modified pixels.

Step3: Classify all pixels into two fields, i.e., dot and cross fields, as shown in Fig. 1.

Step4: Calculate the prediction value $\hat{x}$ for the target pixel value $\dot{x}$ by using the neighboring pixels in the cross field.

Step5: Obtain the prediction error p by

$$p = \dot{x} - \hat{x}. \tag{3}$$

Step6: Embed the payload w using p by

$$p' = \begin{cases} 2p+w, & \text{if } \ p \in [-T, T), \\ p+T, & \text{if } \ p \geqq T, \\ p-T, & \text{if } \ p < -T, \end{cases} \tag{4}$$

where p' is the updated prediction error after data hiding.

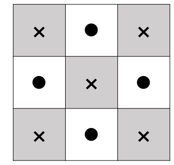


Fig. 1. Region segmentation [6]

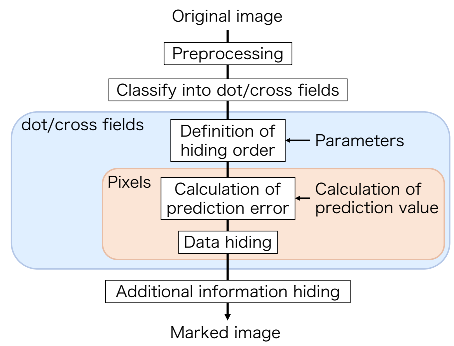


Fig. 2. Outline of proposed method

Step7: Compose the marked pixel x' by adding $\hat{x}$ to p':

$$x' = \hat{x} + p'. \tag{5}$$

Since the prediction values, which are close to the target pixel values, can be attained, the hiding capacity becomes relatively high. Additionally, the marked image quality is also high in PEE-HS method.

III. Proposed method

We extend the RDH method for HDR images [13] to ensure complete reversibility and also increase the hiding capacity. Fig. 2 shows the data hiding procedure of the proposed method. We embed the payload into three color channels, that is, R, G, and B channels except E channel, because a small change in the E channel may cause the considerable deterioration in the marked image. The edge distribution in each channel is similar to each other in RGBE format. Thus, the edge information of a color channel is estimated from the E channel and the other color channels. We calculate the prediction values based on the edge estimation, and embed the payload using the prediction errors. In the following subsections, we describe edge estimation, calculation of the prediction values, data hiding, and data extraction, respectively. Subsequently, the features of the proposed method are discussed by comparing with the conventional method.

A. *Edge estimation and calculation of prediction values*

In the proposed method, we calculate the optimal prediction value based on edge estimation. The target pixel is first confirmed whether it is located in the edge or flat area in the E channel. In case that the pixel is located in the flat area of the E channel, we explore the direction to obtain the

I_E^1	I_E^2	I_E^3
I_E^4	I_E	I_E^5
I_E^6	I_E^7	I_E^8

(a) E channel

$I_{C_i}^1$	$I_{C_i}^2$	$I_{C_i}^3$
$I_{C_i}^4$	I_{C_i}	$I_{C_i}^5$
$I_{C_i}^6$	$I_{C_i}^7$	$I_{C_i}^8$

(b) Color channel

Fig. 3. Current and neighboring pixels

optimal prediction value by referring to two color channels. The detailed procedure includes the following steps. Here, we define C_1 and C_2 as two reference color channels, respectively. The other color channel is C_3, where the data hiding process is conducted.

Step1: Confirm whether the target pixel is located in the edge or flat area in the E channel I_E by using four neighboring pixels I_E^2, I_E^4, I_E^5, and I_E^7 as shown in Fig. 3(a).

- If $I_E = I_E^2 = I_E^4 = I_E^5 = I_E^7$, it is defined that the target pixel is located in the flat area for the luminance. Go to Step 3.
- Otherwise, it is defined that the target pixel is located in the edge area for the luminance. Proceed only Step 2.

Step2: In the E channel, calculate four absolute values of the prediction errors D_h, D_v, D_d, and D_{ad} in the horizontal, vertical, diagonal, and anti-diagonal directions, respectively.

$$\begin{aligned} D_h &= \left| \frac{I_E^4 + I_E^5}{2} - I_E \right|, \\ D_v &= \left| \frac{I_E^2 + I_E^7}{2} - I_E \right|, \\ D_d &= \left| \frac{I_E^1 + I_E^8}{2} - I_E \right|, \\ D_{ad} &= \left| \frac{I_E^3 + I_E^6}{2} - I_E \right|. \end{aligned} \tag{6}$$

The smallest error is denoted as $D_{E,min}$. Then, the prediction value $\hat{I}_{C_3}$ is given by

$$\hat{I}_{C_3} = \min\left\{ \left\lfloor \sum_{k=1}^{8} \lambda^k \delta^k \right\rfloor, 255 - T \right\}, \tag{7}$$

where $\lfloor \cdot \rfloor$ is the floor function, and δ^k is defined by

$$\delta^k = I_{C_3}^k \times 2^{I_E^k - I_E}, \quad k = \{1, 2, \cdots, 8\}. \tag{8}$$

Here, T is the threshold for data hiding. λ^k is a weight coefficient. If δ^k is used for calculation of the prediction value, λ^k with the equal k to δ^k is 0.5; otherwise, λ^k is 0.

Step3: Calculate the absolute values of the prediction errors in the four directions. The two reference color channels C_1, C_2 are used for this step, and thus the four values are obtained for each color channel, respectively. Those values are derived using the neighboring pixels, which are shown in Fig. 3(b):

$$\begin{aligned} D_h &= \left| \frac{I_{C_i}^4 + I_{C_i}^5}{2} - I_{C_i} \right|, \\ D_v &= \left| \frac{I_{C_i}^2 + I_{C_i}^7}{2} - I_{C_i} \right|, \\ D_d &= \left| \frac{I_{C_i}^1 + I_{C_i}^8}{2} - I_{C_i} \right|, \\ D_{ad} &= \left| \frac{I_{C_i}^3 + I_{C_i}^6}{2} - I_{C_i} \right|. \end{aligned} \tag{9}$$

The smallest and biggest errors in each color channel are denoted as $D_{i,min}$ and $D_{i,max}$ $(i = 1, 2)$, respectively.

Step4: Detect the direction to obtain the optimal prediction value in C_1 and C_2 using the threshold τ ($\tau = 5, 10, 15$, or 20).

- If $D_{i,max} - D_{i,min} < \tau$, the target pixel is located in the flat area in C_i.
- If $D_{i,max} - D_{i,min} \geqq \tau$, the target pixel is located in edge area in C_i. The direction of C_i is defined as the direction of $D_{i,min}$.

Step5: Explore the direction to obtain the optimal prediction value.

- If the target pixel is located in the flat area in both C_1 and C_2, we estimate that the pixel is also located in the flat area in C_3. In this case, obtain the prediction value $\hat{I}_{C_3}$ by the mean of the four neighboring pixels:

$$\hat{I}_{C_3} = \left\lfloor \frac{I_{C_3}^2 + I_{C_3}^4 + I_{C_3}^5 + I_{C_3}^7}{4} \right\rfloor. \tag{10}$$

- In case that the pixel is located in the edge area in one reference color channel and located in the flat area in another channel, use the direction of $D_{i,min}$ in the former channel to derive the prediction value in C_3. The prediction value $\hat{I}_{C_3}$ is given by

$$\hat{I}_{C_3} = \left\lfloor \sum_{k=1}^{8} \lambda^k I_{C_3}^k \right\rfloor. \tag{11}$$

- In case that the pixel is located in the edge area in both C_1 and C_2 and the direction of $D_{1,min}$ is equal to that of $D_{2,min}$, use their direction to calculate the prediction value in

C_3. The prediction value is attained by Eq. (11).

- If the directions of $D_{i,min}$ in C_1 and C_2 are different from each other, the horizontal and vertical directions take priority of the diagonal and anti-diagonal directions. The prediction value is obtained by Eq. (11). In the meanwhile, if they are orthogonal to each other, namely, the horizontal and vertical directions or the diagonal and anti-diagonal directions, assume that the pixel is located in the flat area in C_3 and calculate the prediction value $\hat{I}_{C_3}$ according to Eq. (10).

The small change in the E channel may cause considerable deterioration of the HDR image quality. Thus, it should be better to calculate the prediction value avoiding the edge rather than simply taking the mean of the four neighboring pixels. In other words, we can obtain the optimal prediction value by the edge estimation referring to the E and two color channels.

B. Data hiding

We embed the payload by PEE-HS method using the prediction values, which have been obtained the former section. The data hiding procedure of PEE-HS method is as follows. Note that the target color channel for data hiding is C_3, and thus the following procedure is conducted to C_3.

Step1: Assign R, G, and B channels to C_1, C_2 and C_3, respectively.

Step2: Define the threshold T ($T > 0$), which is a parameter to control the hiding capacity.

Step3: Modify the pixel value, which may cause overflow or underflow, by Eq. (2), and the target pixel value I_{C_3} turns out $\dot{I}_{C_3}$. The location map is prepared to conserve the coordinates of the modified pixels.

Step4: Substitute the least significant bits (LSBs) of 25 pixels from the top-left corner in the original image with 0. The additional information will be embedded into those LSBs. The original LSBs will be stored in Step 9.

Step5: Classify all pixels into two fields, i.e., dot and cross fields, as shown in Fig. 1. We first embed the payload bits into the pixels in the cross field.

Step6: Determine the order of to-be-marked pixels within the field to suppress the distortion of the marked image quality. We introduce three parameters in this step, which are the same as the conventional method [13].

Step7: Estimate the edge and calculate the prediction value for each pixel as described in Section III-A.

Step8: Derive the prediction error p:

$$p = \dot{I}_{C_3} - \hat{I}_{C_3}. \tag{12}$$

Step9: Embed the payload bit w using Eq. (4). The payload is composed of the length of the data, the original LSBs, which are extracted in Step 4, and the location map outside of the pure payload.

Step10: Compose the marked pixel I'_{C_3} by adding the modified prediction error p' to $\hat{I}_{C_3}$:

$$I'_{C_3} = \hat{I}_{C_3} + p'. \tag{13}$$

Step11: If the payload amount is larger than the hiding capacity in the cross field, repeat Steps 6 - 10 for the dot field.

Step12: Embed the additional information, i.e., the threshold T (5 bits) and the coordinate of the pixel, where the final payload bit is embedded (20 bits), into the top-left pixels by LSB substitution.

Step13: If there still exists a portion of the payload, which has not been embedded yet, repeat the above steps by switching C_3 to another color channel.

When we adopt Step 13, one or two marked color channels are employed as the reference color channels in the iteration process. Therefore, the prediction accuracy would degrade compared to the first process.

C. Data extraction

The data extraction procedure from the marked HDR image is explained as follows. It is noted that the proposed method has perfect reversibility, and the original HDR image can be restored through data extraction.

Step1: Assign R, G, and B channels to C_1, C_2, and C_3, respectively.

Step2: Extract the LSBs of 25 pixels from the top-left corner in the marked image, and retrieve the threshold T and the coordinate of the pixel, where the final payload bit is embedded. The LSBs are substituted by 0.

Step3: Classify all pixels into two fields, i.e., dot and cross fields.

Step4: If the pixel, where the final payload bit is embedded, is located in the dot field, extract the payload from the pixels in that field. Otherwise, extract the payload from the pixels in the cross field.

Step5: Determine the order of to-be-marked pixels by calculating three parameters, and extract the payload in the inverse order of embedding.

Step6: Estimate the edge and calculate the prediction value for each pixel as described in Section III-A.

Step7: Derive the prediction error p':

$$p' = I'_{C_3} - \hat{I}_{C_3}. \tag{14}$$

Step8: Extract the payload bit w by

$$w = p' \bmod 2, \quad \text{if} \quad p' \in [-2T, 2T). \tag{15}$$

The prediction error p is also retrieved by

$$p = \begin{cases} \left\lfloor \dfrac{p'}{2} \right\rfloor, & \text{if } p' \in [-2T, 2T), \\ p' - T, & \text{if } p' \geqq 2T, \\ p' + T, & \text{if } p' < -2T. \end{cases} \quad (16)$$

Step9: Compose the pixel $\dot{I}_{C_3}$, where overflow and underflow are considered, by using the retrieved prediction error p:

$$\dot{I}_{C_3} = \hat{I}_{C_3} + p. \quad (17)$$

Step10: If the above steps have been conducted in the dot field, repeat Steps 5 - 9 for the cross field.

Step11: Replace the LSBs of 25 pixels from the top-left corner with the original LSB values, which have been extracted in Step 8.

Step12: Restore the original pixel value I_{C_3}, which were modified to avoid overflow and underflow, by using the location map extracted from Step 8:

$$I_{C_3} = \begin{cases} \dot{I}_{C_3} - T, & \text{if } \dot{I}_{C_3} \in [0, 2T), \\ \dot{I}_{C_3} + T, & \text{if } \dot{I}_{C_3} \in (255 - 2T, 255], \\ \dot{I}_{C_3}, & \text{otherwise.} \end{cases} \quad (18)$$

Step13: If there still exists a portion of the payload, which has not been extracted yet, repeat the above steps by switching the current color channel to another one.

If the data hiding process was repeated for multiple color channels, the order of selecting C_3 in Step 1 is opposite to that in data hiding. Owing to pixel classification into two fields, the order of to-be marked pixels in data hiding is equal to that in data extraction. The payload can be extracted in the inverse order of data hiding.

D. Features of proposed method

He et al. proposed the RDH method for HDR images [13]. In their method, the location map is generated to identify the pixels, which may cause overflow or underflow. Those pixels are exclude from the data hiding procedure, and the location map is embedded in conjunction with the pure payload. Therefore, it is difficult to distinguish the pixels containing the payload bits from the pixels without them. Consequently, the payload is not correctly extracted, and the original image is not completely retrieved. In other words, the conventional method does not ensure reversibility.

On the other hand, the proposed method first modifies the pixel values, which may cause overflow or underflow, before data hiding. The coordinates of the modified pixels are stored in the location map. We embed the payload, which contains the location map, into the preprocessed image by PEE-HS method. Owing to the preprocessing, the proposed method exactly guarantee reversibility.

Moreover, in edge estimation of the target pixel, the proposed method refers the E and two color channels, while the conventional method refers the E and single color channel. The correlation between the two reference color channels is counted in edge estimation in the proposed method. Therefore, we can get more accurate estimation results than the conventional method. In consequence, the proposed method can increase the hiding capacity and suppress the distortion of the marked image quality.

IV. Experimental results

We validate the performance of the proposed method using ten test images from an image database [15]. Fig. 4(a) shows an original image, which is converted to the low dynamic range (LDR) image by Reinhard et al.'s tone mapping [16]. We use three metrics, i.e., root mean square error (RMSE) for r, g, and b values of HDR images derived from Eq. (1), peak signal-to-noise ratio (PSNR), and structural similarity (SSIM) for LDR images. The payload is composed of 1s except the additional information; it is the most severe condition to deteriorate the marked image quality. Consequently, the marked image has the worst image quality in all marked images. Another important point is that we embedded the payload in the order of B, R, and G. It has been confirmed that this order is appropriate to suppress the distortion of the marked images by our experiment.

Figs. 4(b) and (c) depict the marked images by the proposed and conventional methods, respectively, where $\tau = 20$ and $T = 1$. Table I shows the hiding capacity and marked image quality. Each value indicates the mean value of the ten test images. The PSNR and MSSIM values are calculated using the luminance channel in the LDR images. It is confirmed that the hiding capacity of the proposed method is higher than that of the conventional method in all cases. τ is the threshold to determine whether the target pixel is located in the edge of flat area in the reference color channel. The number of the pixels in the flat area increases as τ has a large value. In this case, it would be difficult to detect the edges in the reference channels, and thus the hiding capacity is decreased. In contrast, T determines the range of the prediction error to embed the payload. The number of the embeddable pixels, that is, the hiding capacity, is improved when T has a large value. Fig. 5 shows the PSNR and MSSIM values by using different Ts. Those values deteriorate according to increasing the value of T. Basically, there exists a trade-off between the hiding capacity and marked image quality. We should choose the appropriate values of τ and T depending on the texture of the original image and the payload amount. The maximum value of T depends on original images. Even when having the same value of T, the hiding capacity and marked image quality would be different among the images.

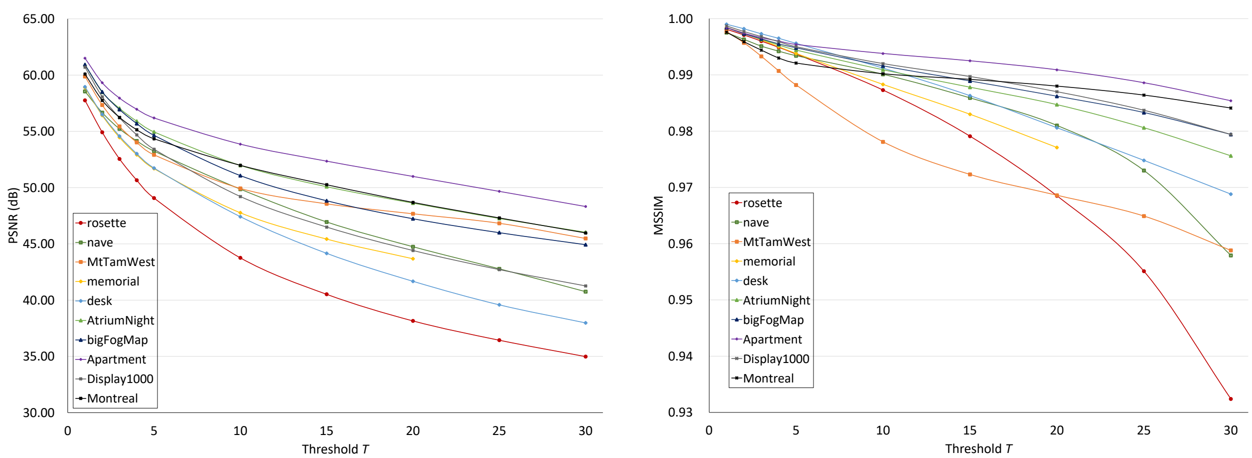
As shown in Table I, the marked image quality can be kept high without severe distortion in both the proposed method and conventional methods. Our method has more high capacity than the conventional method under the condition that the values of T and τ are same in both methods. Nevertheless,

(a) Original image (b) Marked image by proposed method (c) Marked image by conventional method

Fig. 4. Original and marked images (memorial: 512 × 768 pixels)

TABLE I
HIDING CAPACITY AND MARKED IMAGE QUALITY (MEAN VALUES OF TEN TEST IMAGES)

		Proposed method				Conventional method [13]			
T	τ	Payload (bpp)	RMSE	PSNR (dB)	MSSIM	Payload (bpp)	RMSE	PSNR (dB)	MSSIM
1	5	0.6120	0.1759	59.87	0.9982	0.5943	0.1759	59.85	0.9982
	10	0.5975	0.1759	59.84	0.9982	0.5808	0.1760	59.83	0.9982
	15	0.5852	0.1760	59.83	0.9982	0.5714	0.1760	59.82	0.9982
	20	0.5764	0.1759	59.82	0.9982	0.5652	0.1760	59.81	0.9982
2	20	1.0351	0.3030	57.39	0.9970	1.0164	0.3031	57.35	0.9970
3	20	1.3677	0.4310	55.66	0.9958	1.3451	0.4312	55.59	0.9958



(a) PSNR (b) MSSIM

Fig. 5. Graph of marked image quality vs threshold T

the PSNR values of the proposed method are higher than those of the conventional method, and the MSSIM values are same in both the proposed and conventional methods. Our experimental results suggest that the proposed method outperforms the conventional method.

V. Conclusion

We proposed an extension of the previous RDH method for HDR images with RGBE format. In the proposed method, the direction to calculate the optimal prediction value is explored by referring to the E and two color channels. Then, the prediction value of the target pixel is obtained based on the edge estimation, and the payload is embedded by PEE-HS method. We can get more accurate estimation results than the conventional method. Our experimental results showed that the prediction values, which are closer to those of the target pixels, can be obtained, and the hiding capacity of the proposed is higher than that of the conventional method. Our future work involves application of the proposed framework for compressed domain such as JPEG-XT.

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