Histogram-Based Near-Lossless Data Hiding and Its Application to Image Compression

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Abstract. This paper proposes a near-lossless data hiding (DH) method for images where the proposed method can improve the image compression efficiency. The proposed method firstly quantizes an image in accordance with a user-given maximum allowed error. This method, then, embeds data to the quantized image based on histogram shifting (HS). Even this method uses HS-based DH which requires to memorize the shifted bins for data extraction, the method, under some conditions, takes data out from the marked image by just applying re-quantization as least significant bitplane (LSB) substitution-based DH. So the proposed method is based on unification of HS- and LSB substitution-based DH. In the method, lossless compression of the marked image can achieve better compression efficiency than lossy compression of the original image. Experimental results show the effectiveness of the proposed method.

Keywords: Reversible watermarking · Visually lossless · Non-uniform quantizer · Lossless compression · Histogram packing

1 Introduction

A data hiding (DH) method for images once distorts an image to hide data to the image [8,10] where the image and data are referred to as the *original* image and the *payload*, respectively. The method takes the payload out from the distorted image called the *stego* image. Most earlier methods and those for security related issues such as copyright protection [24] leave the stego image as distorted, i.e., *lossy*. A simple lossy DH mechanism is based on least significant bitplane (*LSB*) *substitution* [27] which replaces the LSB of an original image with a payload.

Later, in particular, for military and medical imagery, *lossless* DH methods have been proposed [5,17] where a method perfectly restores the original image from a stego image in addition to taking the payload out from the stego image. One major class of lossless DH is based on *histogram shifting* [4,12,20] (HS) where a payload is hidden to an original image based on the tonal distribution of the image. Another class is based on *generalized LSB substitution* [6] where LSB substitution-based DH is reconsidered as the combination of uniform quantization of the original image and payload addition.

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Similar to image compression, *visually-lossless* and *near-lossless* (NLL) DH methods have been also developed. A method removes the hidden payload from a stego image where a pixel in the payload-removed image slightly differs from that in the original image. For this category, two approaches exist; A lossy-based approach controls the distortion of DH [3,16,25], whereas a lossless-based approach applies lossless DH to a pre-distorted image [7,15,28]. This paper focuses on the latter approach.

This paper develops a NLL DH method based on lossless DH, where a payload is hidden to an image by using HS-based DH but the payload can be taken out based on LSB substitution, viz., LSB substitution- and HS-based techniques are unified. The proposed method also include the conventional NLL DH method [15] as its special form. In addition, the proposed method can improve the image compression efficiency by utilizing the sparsity of stego images, whereas distorted images generally deteriorate the compression efficiency.

2 Preliminary

This section mentions LSB substitution-based DH and its generalization, HS-based lossless DH and its generalization, and the conventional NLL DH method.

2.1 LSB Substitution-Based DH

As shown in Fig. 1(a), the essence of the simplest LSB substitution-based method replaces the LSB of $X \times Y$-sized B-bit grayscale original image $\mathbf{f} = \{f(x,y)\}$ with payload $\mathbf{p}_{\mathrm{LSB}} = \{p_{\mathrm{LSB}}(x,y)\}$ to embed $\mathbf{p}_{\mathrm{LSB}}$ to $\mathbf{f}$;

$$\hat{f}_{\mathrm{LSB}}(x,y) = p_{\mathrm{LSB}}(x,y) + \sum_{b=2}^{B} 2^{(b-1)} f_b(x,y), \tag{1}$$

where $\hat{\mathbf{f}}_{\mathrm{LSB}} = \left\{\hat{f}_{\mathrm{LSB}}(x,y)\right\}$ is a stego image, $\mathbf{f}_b = \{f_b(x,y)\}$ is the b-th LSB of $\mathbf{f}$, $x = 0,1,\ldots,X-1$, $y = 0,1,\ldots,Y-1$, $b = 1,2,\ldots,B$, $p(x,y) \in \{0,1\}$, $f(x,y) \in \left[0 \,..\, 2^B - 1\right]$, $f_b(x,y) \in \{0,1\}$, and $\hat{f}(x,y) \in \left[0 \,..\, 2^B - 1\right]$. So, the payload size is XY [bits] and the *capacity* which is the maximum conveyable payload size is also XY [bits].

LSB substitution-based DH was generalized [6], c.f., Fig. 1(b), as

$$\hat{f}_{\mathrm{GLSB}}(x,y) = qQ_{\mathrm{F}}\left(f(x,y), q\right) + p_{\mathrm{GLSB}}(x,y) \tag{2}$$

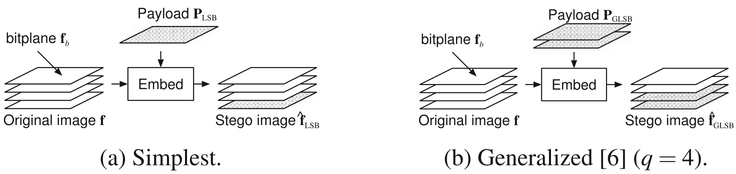


Fig. 1. LSB substitution-based DH ($B = 4$).

0	1	2	0
1	2	2	5
2	1	3	3
4	5	7	7

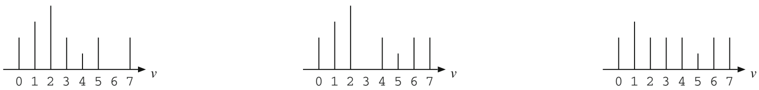
(a) Original **f**.

0	1	2	0
1	2	2	6
2	1	4	4
5	6	7	7

(b) Shifted $\tilde{\mathbf{f}}_{\mathrm{HS}}$.

0	1	2	0
1	3	3	6
2	1	4	4
5	6	7	7

(c) Stego $\hat{\mathbf{f}}_{\mathrm{HS}}$.



(d) Original **h**. (e) Shifted $\tilde{\mathbf{h}}_{\mathrm{HS}}$. (f) Stego $\hat{\mathbf{h}}_{\mathrm{HS}}$.

Fig. 2. HS-based DH [20] ($X = Y = 4$, $B = 3$, $v_{\max} = 2$, $v_{\min} = 6$, $h(v_{\max}) = 4$, $h(v_{\min}) = 0$, and $\mathbf{p}_{\mathrm{HS}} = \{0, 1, 1, 0\}$.

by introducing floor function-based q-level uniform scalar quantizer $Q_{\mathrm{F}}(f(x,y), q) = \lfloor f(x,y)/q \rfloor$ and payload $\mathbf{p}_{\mathrm{GLSB}} = \{p_{\mathrm{GLSB}}(x,y)\}$ consisting of q-ary symbols, i.e., $p_{\mathrm{GLSB}}(x,y) \in \{0, 1, \ldots, q-1\}$, where $\hat{\mathbf{f}}_{\mathrm{GLSB}} = \left\{\hat{f}_{\mathrm{GLSB}}(x,y)\right\}$ is a stego image and $\lfloor \cdot \rfloor$ returns the integer part of the input, i.e., the floor function. The payload size and capacity are both given as $XY \log_2 q$ [bits]. It becomes the original LSB substitution-based DH when $q = 2$. A lossless DH method was developed based on this generalization [6].

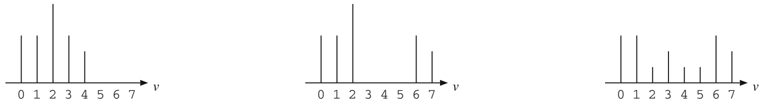
2.2 HS-Based DH

The original HS-based method [20] shown in Fig. 2 firstly derives tonal distribution $\mathbf{h} = \{h(v)\}$ from original image $\mathbf{f}$ where $v = 0, 1, \ldots, 2^B - 1$ and $h(v) = |\{(x,y) \mid f(x,y) = v\}|$. This method then finds two pixel values $v_{\min} = \arg\min h(v)$ and $v_{\max} = \arg\max h(v)$, here it assumes for the simplicity that $h(v_{\min}) = 0$ and $v_{\max} < v_{\min}$. The method shifts a part of the *histogram* of $\mathbf{f}$ toward $h(v_{\min})$;

$$\tilde{f}_{\mathrm{HS}}(x,y) = \begin{cases} f(x,y) + 1, & v_{\max} < f(x,y) < v_{\min} \\ f(x,y), & \text{otherwise} \end{cases}, \tag{3}$$

where $\tilde{\mathbf{f}}_{\mathrm{HS}} = \left\{\tilde{f}_{\mathrm{HS}}(x,y)\right\}$ is the histogram shifted image and $\tilde{f}_{\mathrm{HS}}(x,y) \in \left[0 \mathinner{..} 2^B - 1\right]$. In tonal distribution $\tilde{\mathbf{h}}_{\mathrm{HS}} = \left\{\tilde{h}_{\mathrm{HS}}(v)\right\}$ of $\tilde{\mathbf{f}}_{\mathrm{HS}}$, the *peak histogram bin* is followed by one *zero histogram bin*, i.e., $\tilde{h}_{\mathrm{HS}}(v_{\max}) = \max \tilde{h}_{\mathrm{HS}}(v)$ and $\tilde{h}_{\mathrm{HS}}(v_{\max} + 1) = 0$. Finally, stego image $\hat{\mathbf{f}}_{\mathrm{HS}} = \left\{\hat{f}_{\mathrm{HS}}(x,y)\right\}$ conveying payload $\mathbf{p}_{\mathrm{HS}} = \{p_{\mathrm{HS}}(l)\}$ is given by modifying the pixel value of a pixel with $v_{\max}$ in accordance with payload bit $p_{\mathrm{HS}}(l)$ to be hidden;

$$\hat{f}_{\mathrm{HS}}(x,y) = \begin{cases} \tilde{f}_{\mathrm{HS}}(x,y), & (x,y) = m_l \text{ and } p_{\mathrm{HS}}(l) = 0 \\ \tilde{f}_{\mathrm{HS}}(x,y) + 1, & (x,y) = m_l \text{ and } p_{\mathrm{HS}}(l) = 1 \\ \tilde{f}_{\mathrm{HS}}(x,y), & \text{otherwise} \end{cases}, \tag{4}$$



(a) Original $\mathbf{h}_{\mathrm{GHS}}$. (b) Shifted $\tilde{\mathbf{h}}_{\mathrm{GHS}}$. (c) Stego $\tilde{\mathbf{h}}_{\mathrm{GHS}}$.

Fig. 3. Generalized HS-based DH [2,13,14] ($B = 3, v_{\max} = 2, v_{\min,\min} = 5, v_{\min,\max} = 7$, $h\left(v_{\max}\right) = 5$, and $q = 4$).

where m_l is the l-th element of set $M = \{(x, y) \mid f(x, y) = v_{\max}\}$, $\hat{f}_{\mathrm{HS}}(x, y) \in \left[0 \mathinner{..} 2^B - 1\right]$, $p_{\mathrm{HS}}(l) \in \{0, 1\}$, $l = 0, 1, \ldots, L - 1$, and payload size L should be less than or equal to capacity $|M| = h\left(v_{\max}\right)$. With pixel values $v_{\max}$ and $v_{\min}$, $\mathbf{p}_{\mathrm{HS}}$ is extracted by tracing pixels with $v_{\max}$ and $(v_{\max} + 1)$. Decreasing the pixel value of pixels with $(v_{\max} + 1)$ by one gives $\tilde{\mathbf{f}}$, and then the inverse shifting is applied to $\tilde{\mathbf{f}}$ to restore $\mathbf{f}$. It is noted that this method requires to memorize $v_{\max}$ and $v_{\min}$ to take out $\mathbf{p}_{\mathrm{HS}}$ from $\hat{\mathbf{f}}_{\mathrm{HS}}$ whereas descendent methods overcome this disadvantage [11].

HS-based DH was also generalized [2,13,14]. Let $\mathbf{f}_{\mathrm{GHS}} = \{f_{\mathrm{GHS}}(x, y)\}$ be an original image with $(q - 1)$ successive zero histogram bins, i.e., $h_{\mathrm{GHS}}(\omega) = 0$ for $v_{\min,\min} \leq \omega \leq v_{\min,\max}$ and $|v_{\min,\max} - v_{\min,\min} + 1| = (q - 1)$ where $f_{\mathrm{GHS}}(x, y) \in \left[0 \mathinner{..} 2^B - 1\right]$ and $\mathbf{h}_{\mathrm{GHS}} = \{h_{\mathrm{GHS}}(v)\}$ is the tonal distribution of $\mathbf{f}_{\mathrm{GHS}}$. It is assumed here that $v_{\max} < v_{\min,\min}$. Generalized HS-based DH shifts a part of $\mathbf{h}_{\mathrm{GHS}}$ as shown in Fig. 3 by

$$\tilde{f}_{\mathrm{GHS}}(x, y) = \begin{cases} f_{\mathrm{GHS}}(x, y) + (q - 1), & v_{\max} < f_{\mathrm{GHS}}(x, y) < v_{\min,\min} \\ f_{\mathrm{GHS}}(x, y), & \text{otherwise} \end{cases}, \tag{5}$$

where $\tilde{\mathbf{f}}_{\mathrm{GHS}} = \left\{\tilde{f}_{\mathrm{GHS}}(x, y)\right\}$ is the histogram shifted image and $\tilde{f}_{\mathrm{GHS}}(x, y) \in \left[0 \mathinner{..} 2^B - 1\right]$. Tonal distribution $\tilde{\mathbf{h}}_{\mathrm{GHS}} = \left\{\tilde{h}_{\mathrm{GHS}}(v)\right\}$ of $\tilde{\mathbf{f}}_{\mathrm{GHS}}$ has $(q - 1)$ successive zero histogram bins preceded by $\tilde{h}_{\mathrm{GHS}}\left(v_{\max}\right)$. In accordance with q-ary payload symbol $p_{\mathrm{GHS}}(l) \in \{0, 1, \ldots, q - 1\}$ to be inserted, the pixel value of a pixel with $v_{\max}$ is changed to the value between $v_{\max}$ and $(v_{\max} + (q - 1))$;

$$\hat{f}_{\mathrm{GHS}}(x, y) = \begin{cases} \tilde{f}_{\mathrm{GHS}}(x, y) + p_{\mathrm{GHS}}(l), & (x, y) = m_{\mathrm{GHS},l} \\ \tilde{f}_{\mathrm{GHS}}(x, y), & \text{otherwise} \end{cases}, \tag{6}$$

where $m_{\mathrm{GHS},l}$ is the l-th element of set $M_{\mathrm{GHS}} = \{(x, y) \mid f_{\mathrm{GHS}}(x, y) = v_{\max}\}$, $\hat{\mathbf{f}}_{\mathrm{GHS}} = \left\{\hat{f}_{\mathrm{GHS}}(x, y)\right\}$ is the stego image, and $\hat{f}_{\mathrm{GHS}}(x, y) \in \left[0 \mathinner{..} 2^B - 1\right]$. With $v_{\max}$, $v_{\min,\min}$, and $v_{\min,\max}$, $\mathbf{p}_{\mathrm{GHS}}$ is taken out from $\hat{\mathbf{f}}_{\mathrm{GHS}}$ and $\tilde{\mathbf{f}}_{\mathrm{GHS}}$ are restored. Original image $\mathbf{f}_{\mathrm{GHS}}$ is obtained by applying the inverse shifting to $\tilde{\mathbf{f}}_{\mathrm{GHS}}$. Blind methods which are free from memorizing $v_{\max}$, $v_{\min,\min}$, and $v_{\min,\max}$ were also developed [13,14].

2.3 NLL DH

HS-based DH mentioned in the preceding section needs one zero histogram bin at least, so when $h(v_{\min}) \neq 0$, it has to change the pixel value of pixels with $v_{\min}$ to another value for ensuring a zero histogram bin, and it simultaneously has to memorize $v_{\min}$ and set $R = \{(x, y) \mid f(x, y) = v_{\min}\}$ for restoring original image $\mathbf{f}$.

The conventional NLL DH method [15] accepts slight distortion less than or equal to user-given maximum allowed error δ in payload-removed images, i.e., NLL, instead of memorizing image-dependent $v_{\min}$ and R. This method firstly change the pixel value of pixels with $(v_{\max}+1)$ (or $(v_{\max}-1)$) to $v_{\max}$ by a non-uniform quantizer to get a zero histogram bin and to increase the capacity simultaneously. The method then applies HS-based lossless DH to hide a payload to the pre-distorted image, so the pre-distorted image is obtained from a stego image where a pixel in the pre-distorted image differs from that in the original image by not more than $\delta = 1$.

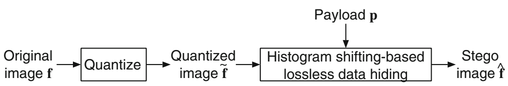
3 Proposed Method

Figure 4 shows the block diagram of the proposed NLL DH method, where original image $\mathbf{f}$ is fed to a quantizer, for making the image histogram sparse, and payload $\mathbf{p}$ is inserted to quantized image $\tilde{\mathbf{f}}$ by HS-based lossless DH. Even HS-based DH is used, hidden payload $\mathbf{p}$ can be taken out from stego image $\hat{\mathbf{f}}$ by using the same quantizer as that is applied to $\mathbf{f}$. That is, memorizing $v_{\max}$ and so on is not required.

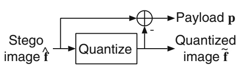
Quantization error is not compensated in this method, so it generally obtains $\tilde{\mathbf{f}}$ from $\hat{\mathbf{f}}$. The method described here accepts any quantizer, whereas scalar quantizers are assumed hereafter for the simplicity. With quantizers guaranteeing that a pixel in $\tilde{\mathbf{f}}$ differs from that in $\mathbf{f}$ by not more than δ, NLL DH can be achieved. Note that the conventional NLL DH method [15] is regarded as the special form of the proposed method.

3.1 Example Algorithms

A simple example of the proposed method is developed here. Quantizer $Q_{\mathrm{F}}(\cdot, q)$ is used here where $q = \delta + 1$. Whereas the prediction error of pixels which give

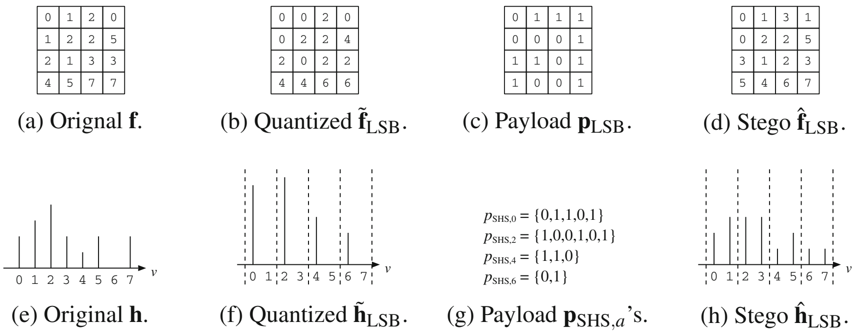


(a) Data hiding.



(b) Payload extraction and image recovery.

Fig. 4. The proposed NLL DH method.



(a) Orignal $\mathbf{f}$. (b) Quantized $\tilde{\mathbf{f}}_{\rm LSB}$. (c) Payload $\mathbf{p}_{\rm LSB}$. (d) Stego $\hat{\mathbf{f}}_{\rm LSB}$.

(e) Original $\mathbf{h}$. (f) Quantized $\tilde{\mathbf{h}}_{\rm LSB}$. (g) Payload $\mathbf{p}_{{\rm SHS},a}$'s. (h) Stego $\hat{\mathbf{h}}_{\rm LSB}$.

Fig. 5. Unifying LSB substitution- and HS-based techniques ($X = Y = 4$, $B = 3$). Adding $\mathbf{p}_{\rm LSB}$ to quantized image $\tilde{\mathbf{f}}$ in LSB substitution-based DH is interpreted as HS-based DH in split sub histograms.

much larger peak histogram bin is often utilized to increase the capacity [26], this paper uses the original HS-based DH [20] to focus the concept of the proposed method.

Embedding

Step 1. Apply $Q_{\rm F}(\cdot, q)$ to $\mathbf{f}$ to obtain $\tilde{\mathbf{f}} = \left\{\tilde{f}(x,y)\right\}$ where

$$\tilde{f}(x,y) = qQ_{\rm F}\left(f(x,y), q\right). \tag{7}$$

Step 2. Add q-ary symbols $\mathbf{p}_q = \{p_q(x,y)\}$ to $\tilde{\mathbf{f}}$ to serve $\hat{\mathbf{f}}$ as

$$\hat{f}(x,y) = \tilde{f}(x,y) + p_q(x,y). \tag{8}$$

This algorithm becomes the generalized LSB substitution [6] and the generalized HS [2,13,14] when $\forall(x,y)p_q(x,y)$ satisfies and $\forall(x,y) \in Mp_q(x,y)$, respectively.

Payload Extraction and Image Restoration.

Step 1. Apply $Q_{\rm F}(\cdot, q)$ to $\hat{\mathbf{f}}$ to reproduce $\tilde{\mathbf{f}}$ where $\tilde{f}(x,y) = qQ_{\rm F}\left(\hat{f}(x,y), q\right)$.

Step 2. Subtract $\tilde{\mathbf{f}}$ from $\hat{\mathbf{f}}$ to take $\mathbf{p}_q$ out from $\hat{\mathbf{f}}$ as $p_q(x,y) = \hat{f}(x,y) - \tilde{f}(x,y)$.

Payload $\mathbf{p}_q$ is retrieved and quantized image $\tilde{\mathbf{f}}$ is restored.

3.2 Features

This section summarizes five features of the proposed method.

Unification of DH Techniques. LSB substitution- and HS-based DH techniques are preparatorily unified in the proposed method.

LSB substitution-based DH given by Eq. (1) is represented with Eq. (2) as

$$\hat{f}_{\mathrm{LSB}}(x, y) = 2Q_{\mathrm{F}}\left(f(x, y), 2\right) + p_{\mathrm{LSB}}(x, y). \tag{9}$$

Here, tonal distribution $\tilde{\mathbf{h}}_{\mathrm{LSB}} = \left\{\tilde{h}_{\mathrm{LSB}}(v)\right\}$ of quantized image $\tilde{\mathbf{f}}_{\mathrm{LSB}} = \left\{\tilde{f}_{\mathrm{LSB}}(x, y)\right\}$ is focused, where $\tilde{f}_{\mathrm{LSB}}(x, y) = 2Q_{\mathrm{F}}(f(x, y), 2)$ and $\tilde{h}_{\mathrm{LSB}}(v) = \left|\left\{(x, y) \mid \tilde{f}_{\mathrm{LSB}}(x, y) = v\right\}\right|$. Similar to the idea which splits the histogram of an image to sub histograms [4], $\tilde{\mathbf{h}}_{\mathrm{LSB}}$ is split to $2^{(B-1)}$ sub histograms where each sub histogram consists of two histogram bins; a peak histogram bin at even pixel value $2a$ and a zero histogram bin at odd pixel value $(2a + 1)$ where $a = 0, 1, \ldots, 2^{(B-1)} - 1$. So, adding a payload bit to the quantized image can be reformulated as HS-based DH as shown in Fig. 5:

$$\hat{f}_{\mathrm{LSB}}(x, y) = \tilde{f}_{\mathrm{LSB}}(x, y) + p_{\mathrm{SHS},a}\left(l_a\right), \quad (x, y) = m_{a,l_a}, \tag{10}$$

where $\mathbf{p}_{\mathrm{SHS},a} = \{p_{\mathrm{SHS},a}\left(l_a\right)\}$ is the sub payload for peak histogram bin $\tilde{h}_{\mathrm{LSB}}(2a)$, m_{a,l_a} is the l_a-th element of set $M_a = \left\{(x, y) \mid \tilde{f}_{\mathrm{LSB}}(x, y) = 2a\right\}$, and $l_a = 0, 1, \ldots, |M_a|$. It is noted that $\sum_{a=0,1,\ldots,2^{(B-1)}-1} |M_a| = XY$.

So, LSB substitution- and HS-based techniques are unified. It is noted that this unification can be extended to any q, viz., generalized LSB substitution- and generalized HS-based techniques are also unified.

NLL DH. By using q-level uniform quantizer $Q_{\mathrm{F}}\left(\cdot, q\right)$ and payload with q-ary symbols $\mathbf{p}_q$ as described in Sect. 3.1, the proposed method serves NLL DH where $\delta = q - 1$. Quantization error $\left|\tilde{f}(x, y) - f(x, y)\right|$ and distortion by DH $\left|\hat{f}(x, y) - \tilde{f}(x, y)\right|$ are up to δ. Consequently, this method achieves NLL DH. It is noteworthy that a histogram-based non-uniform quantizer losslessly quantizes an image in some conditions [18,19], so the method with this quantizer can restore $\mathbf{f}$.

Asymmetric DH. As described in Sect. 3.1, the hidden payload is taken out from a stego image based on LSB substitution, i.e., requantization, even the payload is hidden to the image based on HS. This feature is realized by the unification of two DH techniques and it makes the proposed method blind, viz., no parameter has to be memorized. This feature is important for practical use of DH; When parameters are stored in a parameter database, the stego image is firstly identified among all possible images in the database to retrieve the corresponding parameters. The other possible way is hiding parameters to the stego image by another lossless DH method, but it should introduce multiple lossless DH methods to the system.

Flexible Control of Distortions and Capacity. By controlling δ, the proposed method can flexibly control quantization error and distortion by DH. In addition, the number of sub histograms to be marked can be controlled, the proposed method is able to control the capacity.

Compression Efficiency Improvability. Quantization makes the histogram of an image sparse and images with a sparse histogram can be efficiently compressed by a lossless encoder with histogram packing (HP) [9,21]. This feature is meaningful for distributing stego images to receivers.

4 Experimental Results

Five grayscale images with zero histogram bins [23] shown in Fig. 6 and seven grayscale images without zero histogram bins [15,22] shown in Fig. 7 are used in this section.

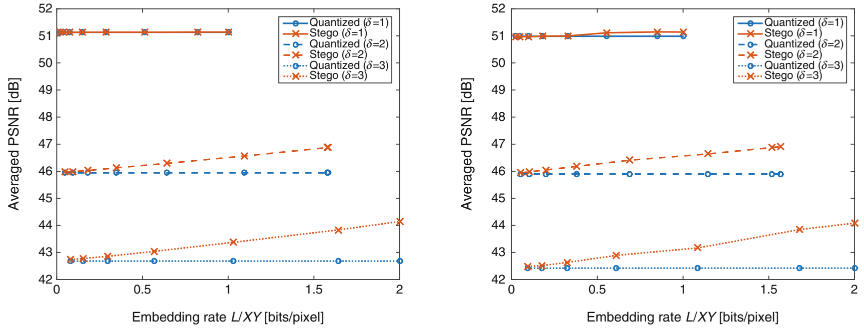
Figure 8 shows the averaged peak signal-to-noise ratio (PSNR) between quantized and original images and that between stego and original images of image 'Lena' and '15' by the proposed method with the algorithms described in Sect. 3.1. The number of marked sub histograms are 1, 2, 4, 8, 16, 32, 64, and 128, and ten different payloads consisting of uniformly distributed q-ary random symbols are used for each condition where $q = \delta + 1$. In contrast to the conventional NLL DH method [15] in which the highest embedding rate is 0.26 bits/pixel for image '20' and the blind generalized HS-based method [13,14] in which the highest embedding rate is 0.29 bits/pixel for image 'airplane,' the proposed method is flexible in controlling the achievable embedding rate. It is found that hiding a payload to the quantized image improves the PSNR of stego images (slightly for $\delta = 1$ of 'Lena') because a pixel value once becoming smaller by quantization (Eq. (7)) gets larger by DH (Eq. (8)). It is noted that almost similar results are derived for other images.

(a) Airplane. (b) Baboon. (c) Lena. (d) Peppers. (e) Sailboat.

Fig. 6. Five images with zero histogram bins [23] ($X = 512$, $Y = 512$, and $B = 8$).

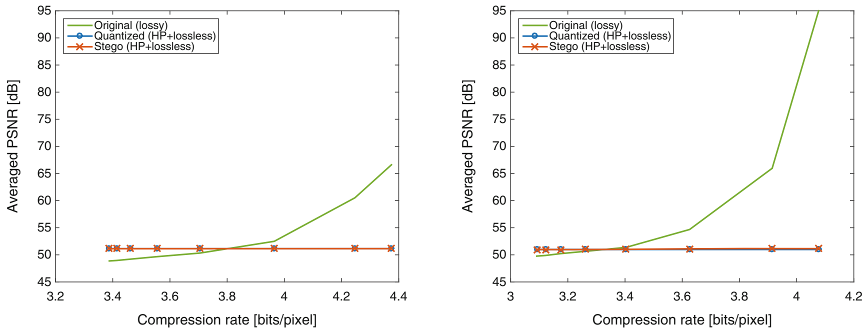
(a) 05. (b) 08. (c) 14. (d) 15. (e) 17. (f) 18. (g) 20.

Fig. 7. Seven images without zero histogram bins [15,22] ($X = 768$, $Y = 512$, and $B = 8$).



(a) Lena. (b) 15.

Fig. 8. PSNR versus embedding rate.



(a) Lena. (b) 15.

Fig. 9. Compression efficiency Improvement ($\delta = 1$).

Figure 9 shows the compression efficiency of stego images. First, stego images for 'Lena' given by the proposed method with $\delta = 1$ are HPed [9,21] and losslessly compressed by a JPEG 2000 [1] standard encoder (JasPer). Then, the averaged compression rate was derived including the bzip2-compressed table for histogram unpacking. The green curve in Fig. 9 indicated by 'Lossy' shows the PSNR between original and lossily JPEG 2000 compressed original images where the compression rate is the same as the above derived rate. It is found that the proposed method can give images with higher PSNR than those lossily compressed by the standard JPEG 2000 encoder, whereas distorted images generally deteriorates the compression efficiency. For stego images with lower embedding rates or stego images with sparser histograms, the efficiency improvement by HP more than compensates for the efficiency deterioration by quantization and DH. It is noted that almost similar results are confirmed for other images.

5 Conclusions

This paper has proposed a histogram-based NLL data hiding method. By the unification of LSB substitution- and HS-based techniques, data are hidden to and extract from an image based on both techniques, and the method is flexible in capacity and distortion. In addition, stego images can be efficiently lossless compressed.

Performance evaluation with zero skip quantization [18,19] is a further work.

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