Generalized Histogram Shifting-Based Reversible Data Hiding with an Adaptive Binary-to-q-ary Converter

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***Abstract*—This paper increases the flexibility of generalized histogram shifting-based reversible data hiding (HS-RDH). An RDH method modifies an original image to hide data to the image, and the method not only extracts the hidden data but also restores the original image from the distorted image which conveys the hidden data. A generalized HS-RDH method increases (or decreases) particular pixel values in an original image by $(q-1)$, based on its tonal distribution, to hide q-ary data symbols, whereas an ordinary HS-RDH method shifts a part of the histogram by one to embed binary symbols. This paper introduces an adaptive binary-to-q-ary watermark converter and a tonal distribution analysis to increase conveyable hidden data size, whereas a conventional generalized HS-RDH method with an arithmetic decoder-based converter cannot always convert the extracted q-ary strings to original binary strings correctly and the other method embeds $\hat{q}$-symbols instead of q-ary symbols where $\hat{q}$ is a power of two equal to or less than q. In addition, histogram packing technique is introduced in this paper to further increase q. Experimental results show the effectiveness of the proposed method.**

I. INTRODUCTION

Data hiding technology has been diligently studied, for not only security-related problems [1], [2], in particular, intellectual property rights protection of digital contents [3], but also non security-oriented issues [1], [4] such as broadcast monitoring [5]. A data hiding technique embeds data into a target signal referred to as the *original* signal. It, then, generates a slightly distorted signal that is referred to as a *stego* signal. Many of data hiding techniques extract hidden data but leave a stego signal as it is [6].

In military and medical applications, restoration of the original signal as well as extraction hidden data are desired [7], so *reversible* data hiding (RDH) techniques that recover the original image have been proposed [7]–[12]. Among many RDH methods, this paper focuses *histogram shifting*-based RDH (HS-RDH) methods [9]–[12]. HS-RDH methods modify the histogram of an original image [9] or a processed image [10]–[12] to hide data into the image.

HS-RDH has been *generalized* to increase the hidden data *capacity* which is the maximum amount of conveyable hidden data, by hiding q-ary data symbols to images instead of binary symbols [13], [14]. By exploiting $(q-1)$ successive zero histogram bins, generalized HS-RDH hides q-ary symbols similar to the manner of q-ary pulse position modulation [14]. Generalized HS-RDH serves the flexibility by adding operating points on the capacity-distortion curve [13].

As most of data to be hidden consist of binary symbols [13], generalized HS-RDH methods use binary-to-q-ary watermark converters, but each of them has a problem; a converter which uses $\hat{q}$-ary symbols instead q-ary symbols where $\hat{q}$ is a power of two equal to or less than q [14] does not fully exploit $(q-1)$ successive zero histogram bins, and an arithmetic decoder-based converter [13] cannot always convert extracted q-ary strings to original binary strings correctly, i.e., extracted data are corrupt.

This paper proposes a practical generalized HS-RDH method with a decodable converter. Based on an image-dependent analysis, the proposed method adaptively converts several data bits to a d-digit q-ary number which maximize the data hiding capacity. Moreover, this paper applies histogram packing (HP) technique [15], [16] to an image before data hiding to make the length of successive zero histogram bins longer, i.e., to further increase q. These features of the proposed method increases the flexibility of generalized HS-RDH.

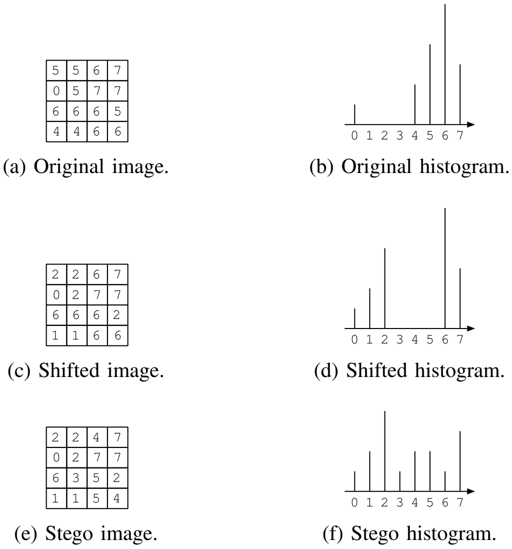
II. PRELIMINARIES

This section briefly describes generalized HS-RDH and figures out the problems of binary-to-q-ary watermark converters used in conventional generalized HS-RDH methods [13], [14]. It also mentions HP [15], [16].

A. Reversible Data Hiding Based on Generalized Histogram Shifting

Though several improved HS-RDH methods have been proposed to increase the hidden data capacity in which the methods shift the histogram of processed image, e.g., each image tiles [10] or differences between pixels or prediction error [11], [12], and so on, this paper focuses generalized HS-RDH [13], [14].

A generalized HS-RDH method firstly derives tonal distribution $\mathbf{h} = \{h(p)\}$ of an original image in which $h(p)$ represents the number of pixels with pixel value p where $p \in \{0, 1, \ldots, 2^K - 1\}$ for K-bits quantized pixels, and the method finds pixel value $p_{\max}$ which pixels with $p_{\max}$ are the most significant in the original image. This method also finds the longest successive zero histogram bins which are from



(a) Original image. (b) Original histogram.

(c) Shifted image. (d) Shifted histogram.

(e) Stego image. (f) Stego histogram.

Fig. 1. An example of the histogram modification in generalized histogram shifting-based reversible data hiding ($K = 3$, $p0_{\min} = 1$, $p0_{\max} = 3$, $p_{\max} = 6$, $h(p_{\max}) = h_{\max} = 6$, and $q = 4$). 6 quaternary data symbols are hidden and the hidden data capacity is $h_{\max} \log_2 q = 12$ [bits].

$p0_{\min}$ to $p0_{\max}$, i.e.,

$$p_{\max} = \arg\max_p h(p), \tag{1}$$

$$h_{\max} = h(p_{\max}) = \max h(p), \tag{2}$$

$$h(\pi) = 0,\ \forall \pi : p0_{\min} \leq \pi \leq p0_{\max} < p_{\max}, \tag{3}$$

where it is assumed here that

$$p0_{\min} \leq p0_{\max} < p_{\max} \tag{4}$$

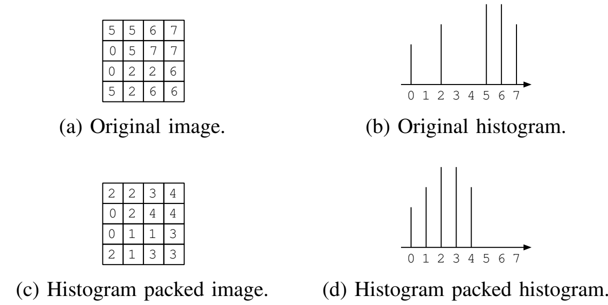
for the simplicity.

The method, then, subtracts $(q-1)$ in pixel values from pixels with values between $(p0_{\max}+1)$ and $(p_{\max}-1)$, where

$$q = |p0_{\max} - p0_{\min}| + 2, \tag{5}$$

so $q \geq 2$. The histogram of the image now has $(q-1)$ successive zero histogram bins followed by $h_{\max}$. According to a q-ary data symbol to be hidden, the pixel value of a pixel with $p_{\max}$ is changed to the value between $(p_{\max}-q+1)$ and $p_{\max}$. Through this process, the method embeds $h_{\max} \log_2 q$-bits data to the image. Figure 1 show an example of the data hiding of the method.

To extract hidden data and to recover the original image, the method memorizes $p_{\max}$, $p0_{\max}$, and $p0_{\min}$. This method easily knows q by Eq. (5), and it, then, extracts a hidden q-ary symbol from a pixel with pixel values between $(p_{\max}-q+1)$ and $p_{\max}$. After extracting all symbols from pixels with pixel values between $(p_{\max}-q+1)$ and $p_{\max}$, the pixel value in all pixels which carried hidden symbols in themselves is returned to $p_{\max}$. Finally, add $(q+1)$ to the pixel value of pixels with pixel values between $p0_{\min}$ and $(p_{\max}-q)$ to recover the original image.



(a) Original image. (b) Original histogram.

(c) Histogram packed image. (d) Histogram packed histogram.

Fig. 2. An example of histogram packing. Non-zero histogram bins are gathered to make a contiguous histogram.

B. Problems on Conventional Binary-to-q-ary Watermark Converters

The above mentioned generalized HS-RDH takes q-ary data symbols, even most of data to be hidden are compound of binary symbols [13]. So, binary-to-q-ary converters are used in generalized HS-RHD methods.

A converter [14] uses $\hat{q}$-ary symbols instead of q-ary symbols in which

$$\hat{q} = 2^{\lfloor \log_2 q \rfloor}, \tag{6}$$

where $\lfloor r \rfloor$ rounds real number r to the nearest integer towards minus infinity. That is, $\hat{q}$ is powers of two which is equal to or less than q. It is obvious that $\hat{q} \leq q$, so this converter uses only $(\hat{q}-1)$ successive zero histogram bins, i.e., it does not always fully utilize $(q-1)$ successive zero histogram bins. It consequently results in an inefficient symbol conversion.

The other [13] converts a binary string to a q-ary string by an arithmetic decoder. As an arithmetic encoder can choose any arbitrary binary string among all possible binary strings representing a q-ary string, the inverse conversion from a q-ary string to the original binary string has ambiguity. That is, this converter cannot always back an extracted q-ary strings to original binary strings correctly, viz., it is impractical.

C. Histogram Packing

HP [15], [16] is a technique originally developed to improve the coding efficiency of lossless compression of images. Some kind of images do not use the complete set of available pixel values, so the histogram of such image has many zero bins. HP maps the pixel values of an image into a contiguous set, maintaining the original order. Figure 2 shows an example of HP.

HP generates an image-dependent look-up table when it maps pixel values to a contiguous set. With this table, HP perfectly recovers the original image by inversely mapping from a contiguous set to the original pixel values.

In the next section, a new generalized HS-RDH method with an adaptive converter is proposed. The proposed practical converter does inversely map q-ary strings to the original binary strings without any ambiguity and it is designed to maximize the data hiding capacity.

III. Proposed Method

This section proposes a generalized HS-RDH method with a new binary-to-q-ary converter. The proposed method converts a binary watermark string to d-digit q-ary string which d maximizes the data hiding capacity being subject to q and largest bin $h_{\max}$ of the histogram.

A. Algorithm

The algorithm described here is applied to a $X \times Y$-sized original grayscale image $\mathbf{f} = \{f(x,y)\}$ with K-bits quantized pixels to hide binary data $\mathbf{w} = \{w(a)\}$ where $f(x,y) \in \left\{0,1,\ldots,2^K-1\right\}$, $x = 0,1,\ldots,X-1$, $y = 0,1,\ldots,Y-1$, and $w(a) \in \{0,1\}$. It is assumed again for the simplicity that Eq. (4) is satisfied.

1) As the conventional generalized HS-RDH methods [13], [14], find histogram peak $h_{\max}$ and its corresponding pixel value $p_{\max}$ by Eqs. (2) and (1), respectively, from histogram $\mathbf{h} = \{h(p)\}$ of the image where $p \in \left\{0,1,\ldots,2^K-1\right\}$. The longest successive zero bins from $p0_{\min}$ to $p0_{\max}$ is also found from histogram $\mathbf{h}$, and q is derived by Eq. (5).
2) Based on $h_{\max}$ and q, number of digits d which maximizes the data hiding capacity is determined as
$$d = \arg\max_{\delta} \left(\lfloor h_{\max}/\delta \rfloor \lfloor \delta \log_2 q \rfloor \right), \tag{7}$$
where
$$\delta = 1,2,\ldots,h_{\max}. \tag{8}$$
3) To hide q-ary symbols to the image, data $\mathbf{w}$ is converted from binary strings to q-ary strings $\tilde{q}$-bits-by-$\tilde{q}$-bits, where
$$\tilde{q} = \lfloor d \log_2 q \rfloor. \tag{9}$$
Each $\tilde{q}$-bits string is converted to a d-digits q-ary symbols, and the converted q-ary symbols are represented as $\mathbf{v} = \{v(b)\}$ where $b = 0,1,\ldots,Bd-1$ and $v(b) \in \{0,1,\ldots,q-1\}$, and
$$B = \lfloor h_{\max}/d \rfloor. \tag{10}$$
4) Subtracts $(q-1)$ in pixel values from pixels with pixel values between $(p0_{\max}+1)$ and $(p_{\max}-1)$ to make the room to hide data to the image:
$$\hat{f}(x,y) = \begin{cases} f(x,y)-(q-1), & p0_{\max} < f(x,y) < p_{\max} \\ f(x,y), & \text{otherwise} \end{cases}, \tag{11}$$
where $\hat{\mathbf{f}} = \left\{\hat{f}(x,y)\right\}$ is the histogram shifted image and $\hat{f}(x,y) \in \{0,1,\ldots,2^K-1\}$.
5) $\beta := 1$.
6) The β-th q-ary symbol $v(\beta)$ is hidden to the β-th pixel with pixel value $p_{\max}$ as
$$\tilde{f}(x,y) = \begin{cases} \hat{f}(x,y)-v(\beta), & \hat{f}(x,y) = p_{\max} \\ \hat{f}(x,y), & \text{others} \end{cases}, \tag{12}$$
where $\tilde{\mathbf{f}} = \left\{\tilde{f}(x,y)\right\}$ is the stego image and $\tilde{f}(x,y) \in \left\{0,1,\ldots,2^K-1\right\}$.
7) $\beta := \beta+1$. Continue to Step 6 unless $\beta = B$.

The proposed method hides up to B of d-digits q-ary symbols, or Bd of q-ary symbols as mentioned in Step 3, to the image. That is, the data hiding capacity in this method is
$$B\tilde{q} = \lfloor h_{\max}/d \rfloor \lfloor d \log_2 q \rfloor \quad \text{[bits]}. \tag{13}$$
To extract the hidden watermark, a user is required to memorize $p_{\max}$, d, and q in the proposed method. It is noted that the conventional method [14] is considered as a special form of the proposed method when $d = 1$.

B. Features

This section summarizes the features of the proposed HS-RDH method with an adaptive converter.

The proposed method uses d of q-ary symbols as a d-digit q-ary string in which binary-to-q-ary conversion and the inverse conversion work properly, whereas the conventional method [13] sometimes fails the inverse conversion. With this consideration, Step 2 chooses number of digits d which maximizes the data hiding capacity. So, the data hiding capacity of the proposed method is higher than that of the conventional method [14] which is the special form of the proposed method when $d = 1$.

Even binary data $\mathbf{w}$ may consist of equiprobable zeros and ones, q-ary symbols are not equiprobable; $\tilde{q}$-bits binary string is input to the converter, $2^{\tilde{q}}$ among q^d numbers are used in the proposed method. The remaining $\left(q^d - 2^{\tilde{q}}\right)$ numbers never appear. For example, it is assumed here that $q = 3$ and $d = 2$. Eq. (9) derives $\tilde{q} = 3$, so three-bits binary strings $\{000,001,010,011,100,101,110,111\}$ are converted to two-digit ternary strings $\{00,01,02,10,11,12,20,21\}$, respectively, and the converter never outputs 22. The occurrence probability of ternary symbols, i.e., 0, 1, and 2, are $\rho_0 = 3/8$, $\rho_1 = 3/8$, and $\rho_2 = 2/8$, respectively, where ρ_m represents the occurrence probability of q-ary symbol m and $m = 0,1,\ldots,q-1$.

Thus, the expected value of the peak signal-to-noise ratio (PSNR) of a stego image is
$$10\log_{10} \frac{XY\left(2^K-1\right)^2}{\text{SSE}_{\text{shift}} + \text{SSE}_{\text{embed}}} \text{[dB]}, \tag{14}$$
where $\text{SSE}_{\text{shift}}$ and $\text{SSE}_{\text{embed}}$ are errors introduced by Eqs. (11) and (12), respectively, and are given by
$$\text{SSE}_{\text{shift}} = (q-1)^2 \sum_{l=p0_{\max}}^{p_{\max}-1} h(l), \tag{15}$$
$$\text{SSE}_{\text{embed}} = h_{\max} \sum_{m=0}^{q-1} m^2 \rho_m, \tag{16}$$
respectively.

IV. Experimental Results

With seven 512×512-sized 8-bits grayscale images including four images used in the literature [13], the proposed method was evaluated, i.e., $X = Y = 512$ and $K = 8$. Figure 3 and Table I show the achievable embedding rate (data hiding capacity normalized by the number of pixels in an image)

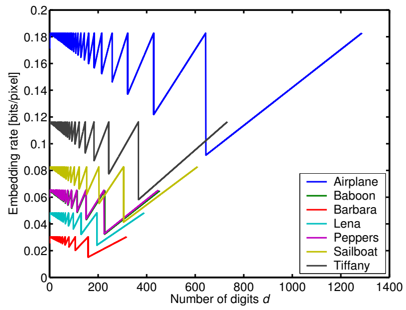


Fig. 3. Embedding rate versus d.

TABLE I
EMBEDDING RATE AND STEGO IMAGE QUALITY. THE CONVENTIONAL METHOD [14] IS THE SPECIAL CASE OF THE PROPOSED FOR $d = 1$.

Image	$h_{\max}$	q	Embedding rate [bits/pixel]		d	Averaged PSNR [dB]	
			Conventional [14]	Proposed		Conventional [14]	Proposed
Airplane	9002	40	0.172	0.183	9002	23.61	21.51
Baboon	3169	41	0.060	0.065	3169	20.70	18.48
Barbara	2217	12	0.025	0.030	739, 2217	32.52	28.59
Lena	2723	25	0.042	0.048	2723	26.08	21.98
Peppers	3136	44	0.060	0.065	98, 196, 392, 784, 1568, 3136	20.38	17.47
Sailboat	4263	34	0.081	0.083	1421, 4263	23.85	23.30
Tiffany	5120	62	0.098	0.116	1024, 5120	20.55	14.63

for the images. Table I also lists the averaged PSNR of stego images by using equiprobable q-ary and $\hat{q}$-ary symbols for the proposed and conventional [14] methods, respectively. It was confirmed that determination of d by Eq. (7) maximizes the capacity and that the capacity is increased by the proposed binary-to-q-ary converter.

In addition, HP [15], [16] is introduced, prior to data hiding, to make the method more flexible. Table II shows the achievable embedding rate for HPed images. A look-up table for unpacking was compressed by bzip2 and was embedded to the image as well as data. It is confirmed that applying HP further increases the whole data hiding capacity. It was, however, found that compressed look-up table is overweight for images with smaller q, c.f., the pure capacity.

Figure 4 shows tangible examples by the proposed method.

V. CONCLUSIONS

This paper has proposed a generalized HS-RDH method with a new binary-to-q-ary converter to increase the flexibility of RDH. The proposed method uses d of q-ary symbols as a d-digit q-ary value to increase the capacity, whereas the conventional method [14] does not fully possible q. The proposed converter inversely converts d-digit q-ary value to a binary string, whereas the conventional method [13] sometimes fails.

Future works include the analysis of occurrence probability ρ_m's and the investigation of capacity-quality surface for various q's and d's.

TABLE II
EMBEDDING RATE IMPROVEMENT BY HISTOGRAM PACKING [15], [16]. THE LOOK-UP TABLE IS COMPRESSED AND EMBEDDED TO AN IMAGE.

Image	q	Whole embedding rate [bits/pixel]	Pure embedding rate [bits/pixel]	Averaged PSNR [dB]
Airplane	70	0.211	0.197	17.86
Baboon	62	0.072	0.058	17.09
Barbara	22	0.038	0.021	27.08
Lena	41	0.056	0.041	21.29
Peppers	60	0.071	0.056	17.14
Sailboat	52	0.093	0.078	20.87
Tiffany	99	0.130	0.117	12.33

(a) Original. (b) Stego (23.61 dB). (c) HP+stego (17.84 dB).

Fig. 4. Image examples by the proposed method.

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