Adaptive Reversible Data Hiding in Frequency Domain via Integer-to-Integer Transform

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***Abstract*—This paper proposes an adaptive reversible data hiding algorithm for images, which embeds significant information in frequency domain based on integer-to-integer transform. The embedding method is realized by modifying state-of-the-art one according to integer-to-integer transformed coefficients. It overcomes a problem where the conventional method often generates particular artifacts. The simulation results show that our proposed algorithm outperforms the conventional one about the visual quality of embedded images, objectively and perceptually, while keeping embedding capacity.**

I. Introduction

Image Data hiding is a technique to embed useful information into images for various purposes, such as content authentication, protect privacy, forensic tracking and so on [1]. Especially, it is one of the most significant technique to protect the copyright information of contents.

Recently, several reversible data hiding algorithms have been proposed [1]–[5]. Different from irreversible one, it is able to restore original images after data extraction. The reversibility is essential when the original image should be losslessly restored, such as medical, military, and art images. The method in [3] has large embedding capacity. It multiplies original signals by 2^m $(m \in \mathbb{N})$ and embeds significant information in the lower bits. To avoid the overflow, it subtracts an uniform value depending on an average of original signals from embedded signals. Moreover, to improve a visual quality of embedded images, an adaptive method [5] has been proposed. It divides an image into some blocks, and switches a budget of embedding information according to a variance of each block, adaptively. If the variance is low, a large budget is embedded, because a distortion between original and embedded signals is small, and vice versa. Thus, the adaptive method achieves both excellent visual quality and large embedding capacity. However, particular artifacts often appear at the high embedding capacity. It violates a policy of date hiding that hiding information has not to be recognized.

In this paper, we solve the problem by using an adaptive reversible data hiding algorithm in frequency domain based on integer-to-integer transform, while keeping the high embedding performance. In natural images, a variance of each block in frequency subbands is lower than one in spatial domain, generally. Moreover, distortions generated by embedding significant information spread to neighborhood pixels via the inverse transform, and are not perceptually distinct by human visual system in spatial domain. For a rapid calculation, the proposed algorithm is based on non-lapped transforms. Because, in a case of lapped transforms, a verification that embedded signals do not overflow/underflow is a complicate process. We utilize the integer discrete cosine transform (IntDCT) [6]–[8] as one of the simplest and the most popular integer-to-integer transform techniques. In simulation results, our proposed method outperforms the conventional ones, objectively and perceptually.

II. Review

A. Reversible Data Hiding

In [3], a high capacity reversible data hiding algorithm has been proposed. Let $\mathbf{x} \in \mathbb{Z}^{n+1}$, $\mathbf{y} \in \mathbb{Z}^{n+1}$ and $\mathbf{w} \in \mathbb{Z}^{n}$ be original signals, embedded signals and embedded information, respectively. The algorithm embeds $\mathbf{w}$ in $\mathbf{x}$ to derive $\mathbf{y}$ with an arbitrary capacity parameter k, where $k = 2^m$ $(m \in \mathbb{N})$. Elements of $\mathbf{w}$ are restricted to be represented by $\log_2 k$ bits. Hence, the algorithm can embed $n \log_2 k$ bits into $n+1$ signals, and the capacity parameter controls the embedding rate. It is formulated as

$$y_t = \begin{cases} kx_t - a_{n,k}(\mathbf{x}) & \text{for } t = 0, \\ kx_t - a_{n,k}(\mathbf{x}) + w_{t-1} & \text{for } t \neq 0, \end{cases} \quad (1)$$

where x_t, y_t and w_t are elements of $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{w}$, respectively, $t \in \mathbb{Z}$, $0 \leq t \leq n$,

$$a_{n,k}(\mathbf{x}) = \left\lfloor \frac{2(k-1)\sum_{t=0}^{n} x_t + n(k-1)}{2(n+1)} \right\rfloor,$$

and $\lfloor \cdot \rfloor$ is a floor function. Since (1) is an integer transform, $\mathbf{x}$ and $\mathbf{w}$ are losslessly restored from $\mathbf{y}$. The inverse transform is defined as

$$x_t = y_0 + \left\lfloor \frac{k-1}{n+1} \sum_{t=1}^{n} \left\lfloor \frac{y_t - y_0}{k} \right\rfloor + \frac{n(k-1)}{2(n+1)} \right\rfloor + \left\lfloor \frac{y_t - y_0}{k} \right\rfloor, \quad (2)$$

where w_t $(1 \leq t \leq n)$ is extracted as

$$w_t = y_t - kx_t + a_{n,k}(\mathbf{x}).$$

B. Adaptive Reversible Data Hiding

The adaptive reversible data hiding in spatial domain has been proposed [5]. For images, it divides an image into some blocks which contain $n+1$ signals. At each block, it switches the capacity parameter k according to a variance of signals, adaptively. k of one block is determined depending on the given threshold parameter T and the variance of the block $V(\mathbf{x})$. From experiences, k is restricted as $\{1,2,4,8\}$, and the determination is defined as follows:

1) If $V(\mathbf{x}) \le T/49$ and $\mathbf{x} \in A_8$, $k = 8$.
2) If $V(\mathbf{x}) \le T/9$ and $\mathbf{x} \in A_4$, $k = 4$.
3) If $V(\mathbf{x}) \le T$ and $\mathbf{x} \in A_2$, $k = 2$.
4) Otherwise $k = 1$.

In general, grayscale images are represented by 8-bit, i.e., $0 \le x_t \le 255$. If $\mathbf{x} \in A_k$, the corresponding $\mathbf{y}$ derived by (1) with k is verified in $[0, 255]$, i.e., $\mathbf{y}$ does not have overflow/underflow signals. The set A_k is defined as follows:

$$\begin{aligned} A &= \{\, \mathbf{x} = [x_0, x_1, \cdots, x_n] \mid 0 \le x_t \le 255\} \\ A_k &= \{\, \mathbf{x} \in A \mid 0 \le kx_0 - a_{n,k}(\mathbf{x}) \le 255, \\ &\qquad 0 \le kx_t - a_{n,k}(\mathbf{x}) \le 256 - k \; (1 \le t \le n)\} \end{aligned} \quad (3)$$

C. IntDCT

Discrete cosine transform (DCT) is one of the most useful frequency transform techniques, applied for many signal processing applications. The (i,j) element of type-II DCT matrix $\mathbf{C}$ with M channel $(i,j = 0,1,\cdots,M-1)$ is represented as

$$c_{i,j} = \sqrt{\frac{2}{M}} \alpha_i \cos\left(\frac{i(j+1/2)\pi}{M}\right), \quad (4)$$

where α_i is $1/\sqrt{2}$ $(i = 0)$ or 1 $(i \neq 0)$.

The IntDCT is realized by lifting factorization of DCT. Let $\mathbf{D}$ be a 2×2 matrix whose determinant is 1. $\mathbf{D}$ is factorized into the lifting structures as

$$\mathbf{D} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{d-1}{b} & 1 \end{bmatrix} \begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{a-1}{b} & 1 \end{bmatrix}, \quad (5)$$

where $b \neq 0$ [9] as shown in Fig. 1. The lifting structure with rounding operators transforms integer signals into integer ones. Hence, original signals are losslessly restored from transformed ones via its inverse operation. Based on the lifting factorization, many IntDCTs have been proposed [6]–[8]. In this paper, we utilize an IntDCT which has the least rounding operators and shows efficient image coding performance [6]. The 8-channel IntDCT is shown in Fig. 2, where $C_q^p = \cos(p\pi/q)$, $S_q^p = \sin(p\pi/q)$, and

$$\begin{aligned} \mathbf{T} \;=\; & \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 0 & 0 & 1 \end{bmatrix} \\ & \times \begin{bmatrix} 1 & 0 & 1/2 & 1/2 \\ 0 & 1 & 1/2 & -1/2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix}. \end{aligned} \quad (6)$$

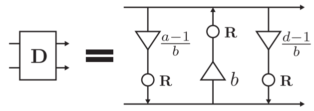

Fig. 1: A lifting structures of a 2×2 matrix $\mathbf{D}$ whose determinant is 1 (R means a rounding operator).

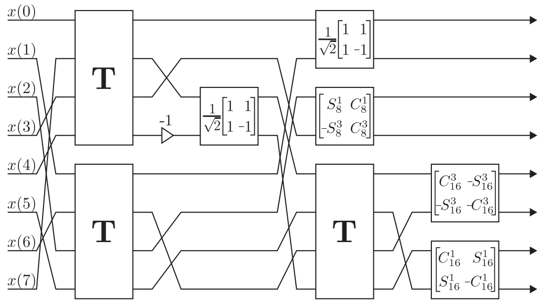

Fig. 2: The 8-channel IntDCT in [6].

III. Adaptive Reversible Data Hiding in Frequency Domain via IntDCT

A. Algorithm

We propose a new adaptive reversible data hiding algorithm. It is realized by applying the adaptive reversible data hiding method in Sec. II-B to the frequency domain.

Initially, we divide an image into some blocks with size $M \times (n+1)$. M corresponds to the channel of IntDCT and an arbitrary number M can be easily obtained by [8]. This paper, however, utilizes an 8-channel IntDCT in [6], i.e., $M = 8$. Next, a block is transformed by the IntDCT as $\mathbf{y}_j = \Phi(\mathbf{x}_j)$ $(j \in \mathbb{Z},\ 0 \le j \le n)$, where $\mathbf{x}_j$ and $\mathbf{y}_j$ are j-th column vector of the input block $\mathbf{X} \in \mathbb{Z}^{M \times (n+1)}$ and the transformed block $\mathbf{Y} \in \mathbb{Z}^{M \times (n+1)}$, respectively, and Φ means a function of the IntDCT operation in Fig. 2. Similarly to (1), the embedded block $\mathbf{Z} \in \mathbb{Z}^{M \times (n+1)}$ is derived from $\mathbf{Y}$ with an embedded information $\mathbf{W} \in \mathbb{Z}^{M \times n}$ and capacity parameters $\mathbf{k} \in \mathbb{Z}^M$. We apply the embed algorithm to each subband of $\mathbf{Y}$, i.e., applying (1) to each row vector of $\mathbf{Y}$. The proposed embed algorithm is defined as

$$z_{i,j} = \begin{cases} k_i y_{i,j} - a_{n,k_i}(\tilde{\mathbf{y}}_i) & \text{for } j = 0, \\ k_i y_{i,j} - a_{n,k_i}(\tilde{\mathbf{y}}_i) + w_{i,j-1} & \text{for } j \neq 0, \end{cases} \quad (7)$$

where $i \in \mathbb{Z}$, $0 \le i \le M-1$, $y_{i,j}$, $z_{i,j}$ and $w_{i,j}$ are (i,j) elements of $\mathbf{Y}$, $\mathbf{Z}$ and $\mathbf{W}$, $\tilde{\mathbf{y}}_i$ is i-th row vector of $\mathbf{Y}$, and k_i is i-th element of $\mathbf{k}$, respectively. Needless to say, a range of $w_{i,j}$ is restricted by k_i.

Finally, the embedded block in the spatial domain is derived from the inverse IntDCT of $\mathbf{Z}$, described as $\Phi^{-1}(\mathbf{Z})$. This algorithm embeds $n \sum_{i=1}^{M} \log_2 k_i$ bits into $M(n+1)$ pixels. It is the same capacity rate as in Sec. II-B. Through an inverse process of the proposed algorithm, both of the original image and the embedded information are losslessly restored.

B. Determination of Capacity Parameters

In this section, we show the determination of capacity parameters. As mentioned above, embedded signals should be in $[0, 255]$, and then the new verification is proposed.

Similar to Sec. II-B, we define a new set $B_{\mathbf{k}}$ as

$$\begin{aligned} B &= \left\{ \mathbf{X} \in \mathbb{Z}^{M\times(n+1)} \mid 0 \leq x_{i,j} \leq 255 \right\}, \\ B_k &= \{ \mathbf{X} \in B \mid 0 - \textstyle\sum_{p=0}^{M-1} c^{-}_{p,i}(k_p - 1) + \alpha \leq e_{i,j} \\ &\quad \leq 255 - \textstyle\sum_{p=0}^{M-1} c^{+}_{p,i}(k_p - 1) - \alpha \}. \end{aligned} \tag{8}$$

where notations are same as the previous section, $c_{i,j}$ is (i, j) element of the DCT matrix $\mathbf{C}$ in (4), α is a arbitrary number as a margin, and $c^{\pm}_{i,j}$ is (i, j) element of $\mathbf{C}^{\pm}$ defined as

$$c^{+}_{i,j} = \begin{cases} c_{i,j} & \text{if } c_{i,j} \geq 0 \\ 0 & \text{if } c_{i,j} < 0 \end{cases}, \quad c^{-}_{i,j} = \begin{cases} 0 & \text{if } c_{i,j} \geq 0 \\ c_{i,j} & \text{if } c_{i,j} < 0 \end{cases}. \tag{9}$$

$e_{i,j}$ is defined with $y_{i,j}$ and $\tilde{\mathbf{y}}_i$ as

$$e_{i,j} = \sum_{p=0}^{M-1} c_{p,i} \left\{ k_p y_{p,j} - a_{n,k_p}(\tilde{\mathbf{y}}_p) \right\}. \tag{10}$$

$e_{i,j}$ is (i, j) element of $\mathbf{Z}$ with $\mathbf{W} = \mathbf{0}$. $\sum_{p=0}^{n} c^{\pm}_{p,i}(k_p - 1)$ are the maximum predicted negative and positive value of $\Phi^{-1}(\mathbf{W})$, which means distortions due to embedding with $\mathbf{k}$. Similar to Sec. II-B, if $\mathbf{X} \in B_{\mathbf{k}}$, corresponding $\Phi^{-1}(\mathbf{Z})$ with $\mathbf{k}$ and $\mathbf{W}$ is guaranteed to avoid the overflow/underflow.

Hence, the determination algorithm of $\mathbf{k}$ is defined with the given threshold parameter T as follows:

1) The initial $\mathbf{k}$ is determined as

$$k_i = \begin{cases} 8 & \text{if } V(\tilde{\mathbf{y}}_i) \leq T/49 \\ 4 & \text{if } V(\tilde{\mathbf{y}}_i) \leq T/9 \\ 2 & \text{if } V(\tilde{\mathbf{y}}_i) \leq T \\ 1 & otherwise \end{cases}$$

where $V(\tilde{\mathbf{y}}_i)$ is a variance of $\tilde{\mathbf{y}}_i$.

2) Let $\hat{k}$ be a maximum of $\mathbf{k}$, and $P = \{i \mid k_i = \hat{k}\}$.
3) If $\mathbf{X} \in B_k$ or $\hat{k} = 1$, escape algorithm with $\mathbf{k}$.
4) $k_p = k_p/2$, where $(p \in P)$ is an index whose $V(\tilde{\mathbf{y}}_p)$ is maximum of $V(\tilde{\mathbf{y}}_i)$. Go to Step 2.

However, if $\mathbf{X} \in B_{\mathbf{k}}$, it is not exactly guaranteed that $\Phi^{-1}(\mathbf{Z})$ does not overflow/underflow, because the rounding error in each lifting step cannot be exactly predicted and it depends on input signals. If the optimal $\mathbf{k}$ is required, $\mathbf{Y}$ is embedded with arbitrary $\mathbf{k}$ and $\mathbf{W}$, and the overflow/underflow is checked, iteratively. However, the iteration requires the high computational cost, and takes a long time to process due to the non-parallel process, i.e., a current block has to wait until the previous blocks are finished. Therefore, to reduce the complexity, we define as (8).

IV. Simulation

As a simulation, the proposed method is compared with the conventional ones. Six images (*Lena*, *Airplane*, *Barbara*, *Boat*, *Goldhill*, and *Baboon*) are used as test images (8-bit grayscale), shown in Fig. 3. As conventional methods, the Luo's and Peng's methods [4], [5], which are the state-of-the-art methods of data hiding, are used. According to [5], the block size is 4×4, and then $n = 15$. A set of capacity parameters is called the location map (LM). The implementation algorithm, which embeds the LM and the embedded information and losslessly extracts them, is similar to [5]. Details are shown in [5].

(a) Lena (b) Airplane (c) Barbara

(d) Boat (e) Goldhill (f) Baboon

Fig. 3: Test images

Table I shows the objective visual quality of embedded images, measured by the peak signal-to-noise ratio (PSNR). The rate is represented in bits per pixel (bpp). At 1.2 [bpp] in *Baboon*, all methods are not able to embed. The proposed method shows the better results than the conventional ones, especially for images with rich high frequency components such as $Barbara$. The capacity-distortion curves are shown in Fig. 4. The proposed method outperforms at the high capacity rate, and a lowest rate, in which the proposed method shows the best result, depends on features of the image. If images have rich high frequency components, the lowest rate is lower, and vice versa. However, the maximum capacity rate of the proposed method is less than one of the Peng's method, because of the determination of capacity parameters.

Fig. 5 shows a particular area of the embedded images in $Lena$ at 1.0 bpp. Although the particular distortions in Peng's method are perceived, the distortions in the proposed images is similar to the ordinary random noise. On the other hand, due to the histogram shifting algorithm processing pixel by pixel, an excessive contrast enhancement and a particular asperous artifact occurs in textures of Luo's images. It is the policy of data hiding that the embedding information has not to be understood. In that sense, the proposed method has better perceptual results because the particular distortion has a higher risk of recognizing the hiding than a random noise.

V. Conclusion

In this paper, we proposed an adaptive reversible data hiding in frequency domain via IntDCT. The proposed method shows better performance than the conventional ones, especially, for the high capacity rate and images with rich high frequency components,.

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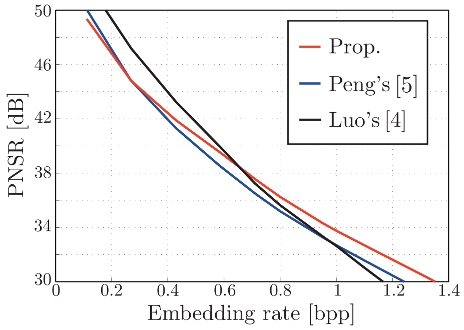
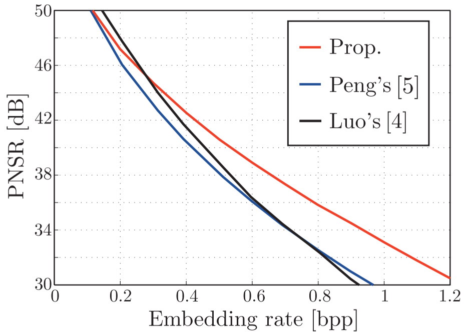
TABLE I: PSNR of embedded images in [dB]

Image	Rate	Luo's [4]	Peng's [5]	Prop.
Lena	0.8	35.63	35.18	**36.24**
	1.0	32.63	32.67	**33.70**
	1.2	29.47	30.44	**31.60**
Airplane	0.8	**39.08**	38.17	38.07
	1.0	**35.81**	35.41	35.58
	1.2	32.81	32.99	**33.31**
Barbara	0.8	32.37	32.48	**35.84**
	1.0	28.67	29.52	**33.08**
	1.2	24.43	26.77	**30.46**
Boat	0.8	30.95	31.53	**33.06**
	1.0	27.51	28.94	**30.47**
	1.2	24.17	26.60	**28.21**
Goldhill	0.8	32.11	31.58	**32.83**
	1.0	28.75	28.96	**30.26**
	1.2	25.32	26.61	**27.88**
Baboon	0.8	23.62	24.68	**35.05**
	1.0	19.56	22.26	**22.46**
	1.2	-	-	-



(a) Lena



(b) Barbara

Fig. 4: The capacity-distortion curve.

Fig. 5: A particular area of embedded images of *Lena* at 1.0 [bpp]: (1st row) Original (2nd row) Luo's [4], (3rd row) Peng's [5], (4th row) Prop.

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