Reversible Data Hiding Using Integer Wavelet Transform and Companding Technique

Guorong Xuan[1], Chengyun Yang[1], Yizhan Zhen[1],
Yun Q. Shi[2], Zhicheng Ni[2]

[1] Tongji University, Shanghai, P.R. of China
grxuan@public1.sta.net.cn
[2] New Jersey Institute of Technology, NJ, USA
shi@njit.edu

Abstract: This paper presents a novel reversible data-embedding method for digital images using integer wavelet transform and companding technique. This scheme takes advantage of the Laplacian-like distribution of integer wavelet coefficients in high frequency subbands, which facilitates the selection of compression and expansion functions and keeps the distortion small between the marked image and the original one. Experimental results show that this scheme outperforms the state-of-the-art reversible data hiding schemes.

1 Introduction

Data hiding has drawn increasingly extensive attention recently. Most multimedia data hiding techniques modify and, hence, distort the cover media in order to insert the additional information. Even though the distortion is often small and imperceptible to human visual systems (HVS), the original cover media usually cannot be restored completely. In other words, they are irreversible data hiding. The irreversibility is not admissible to some sensitive applications, such as legal and medical imaging. For these applications, reversible data hiding is desired to extract the embedded data as well as recover the original host signal. Reversible, also often referred to as lossless, invertible, or distortion-free, data hiding has been a very active research subject in the last a few years. In particular, the scheme by Fridrich et al. [1] losslessly compresses the bit planes in the spatial domain and saves the space to embed the data and bookkeeping data to achieve reversible data hiding. The payload of this technique is quite small owing to the lower compression ratio. Based on this, Celik et al. [2] propose a general LSB embedding technique in spatial domain. The payload, visibility and flexibility of this technique are largely improved because of the more efficient compression technique. Xuan et al. [3] proposed a reversible data hiding algorithm carried out in the integer wavelet transform (IWT) domain. By exploiting the features of superior decorrelation and being consistent with HVS of wavelet transform, this technique embeds the data into high frequency subband coefficients achieving high payload and visual quality. Similarly, Tian [4] embeds the data using the difference expansion technique and results in one of the best reversible data hiding method among all the existing reversible data hiding techqniues. Recently, Yang et al. [5] proposed a reversible data hiding technique using the companding technique. This technique, however, embeds data in discrete cosine transform (DCT) coefficients. Inspired by the techniques reported in [3] and [5], this paper applies the companding technique to the integer wavelet transform domain and selects a more suitable companding function for IWT high frequency coefficients, thus resulting in a reversible data hiding technique that outperforms the state-of-the-art [4]. Both theoretical analysis and experimental results demonstrate the superiority of the proposed technique. The rest of the paper is organized as follows. A brief introduction to companding technique is provided in Section 2. The proposed algorithm is detailed presented in Section 3. Some experimental results and performance analysis are presented in Section 4. The conclusion is drawn in Section 5.

2 Companding Technique

Companding, the processing pair of compression and expansion, is a technique utilized to implement nonuniform quantization in speech communications in order to achieve high signal noise ratio. This has been detailed introduced in many digital communications texts, say, in [6]. Specifically, this procedure first compresses a signal and then expands it. Uniform quantization is carried out after the compression and before the expansion. As a result, with the companding and uniform quantization, nonuniform quantization is equivalently performed. Instead of data compression, compression here means that the dynamic range of the original signal is mapped to a narrower range. After the expansion of the compressed signal, the expanded signal is close to the original signal. In ideal situation, this companding operation can be expressed as

$$E(C(x)) = x$$

where C stands for compression function, E stands for expanding function. If this assumption is satisfied, this technique can be successfully applied to the reversible data hiding. We apply companding in our proposed lossless data hiding.

2.1 Companding Technique Used for Reversible Data Hiding

A simple realization is as follows:

(1) Compression function C is applied to the original signal x to obtain a new signal $y = C(x)$. Assume the binary expression of y is $p_1 p_2 \cdots p_n$, where $p_i \in \{0,1\}$.

(2) A bit $b \in \{0,1\}$ is appended after the least significant bit (LSB) of y. In this way, y becomes $y' = p_1 p_2 \cdots p_n b$, which means $y' = 2 \times y + b$. For generality, we use P to express this appending operation, which means $y' = P(y)$.

(3) If $y' \approx x$, then the modification of the signal will be small and hardly be perceived.

(4) In the hidden data extraction stage, we only need to extract the LSB bit of signal y', which means $b = LSB(y')$ and recover the signal $y = \frac{y'}{2}$.

(5) After obtaining the signal y, we can recover the original signal by expansion, i.e., $x = E(y)$.

From the above steps, we can see that the function C, E and P should satisfy the following two conditions:

(1) $E(C(x)) = x$

(2) $P(C(x)) \approx x$ and $P(C(x))$ is within the range of the original signal x, which means overflow/underflow problem can be avoided.

In dealing with digital signal, however, the above two conditions are difficult to be exactly met owing to the nature of digitization. This is because the quantized companding functions C_Q and E_Q have to be utilized instead, where

$$C_Q = Q(C),\ E_Q = Q(E)$$

and Q denotes the quantization function. Obviously, right now for some signal x, we may have

$$E_Q(C_Q(x)) \neq x$$

namely the difference (error) value is $r = E_Q(C_Q(x)) - x \neq 0$.

Hence in order to recover the original signal x, we must record the difference value r. This is to say that the difference value r and the to-be-embedded data both need to be embedded into the host signal x as overhead and pure payload, respectively.

2.2 Selection of Compression Function in the Companding Technique

Through the analysis of companding function, we find if condition (2) is not considered, any one to one mapping function F can be considered as compression function. For example, the simplest linear function $F(x) = x$ can be considered as a compression function. If multiple x are mapped to y which means we are not able to find the corresponding x from the y, then this function still can be used as compression function. However, some payload must be sacrificed to record this uncertainty. For example, if x_1, x_2 are compressed to obtain y_0, in order to express this mapping relationship, we need to use one bit (bit 0 to express x_1 and bit 1 to express x_2) to record which x is mapped to y_0. These data used for recording are another type of overhead that are also need to be embedded into the original signal. Actually, it is difficult to find a function which satisfies both one-to-one mapping and condition (2). For example, linear function $F(x) = x$ does not satisfy the condition (2) since y' is almost as large as twice of x value and y' may encounter overflow problem.

Hence, actually the compression function is not one-to-one mapping function. For instance, the following compression and expanding functions are used in [5].

$$C(x) = \tfrac{1}{2}\sqrt{x}\,,\ E(x) = (2x)^2$$

in which x is normalized to the range [0,1]. As discussed, of course, quantized compression and expanding functions should be used in digital data hiding system.

3 Integer Wavelet Transform Based Reversible Data Hiding Using Companding Technique

Wavelet transform is widely applied in different tasks image processing. Since wavelet coefficients are highly decorrelated, have compact energy concentration and are consistent with the feature of the HVS, it is also widely applied in image data hiding. The study on human visual system points out that slight modification on wavelet high frequency subband coefficients is hard to be perceived by human eyes. Through out the investigation of wavelet coefficients, we find that if companding technique is applied to wavelet coefficients, the restriction listed in condition (2) will be largely decreased. The followings are detailed discussion.

3.1 Integer Wavelet Transform (IWT)

To recover the original image losslessly, reversible wavelet transform should be used. Hence we employ the integer wavelet transform which maps integer to integer [7] and can reconstruct the original signal without any distortion. Although various wavelet families can be applied to our reversible embedding scheme, through experimental comparison study we have discovered that CDF(2,2) is better than other wavelet families in terms of high embedding capacity and visual quality of marked images. CDF(2,2) format has also been adopted by JPEG2000 standard.

3.2 Distribution of IWT coefficients in High Frequency Subbands and Selection of Companding function

For most of images, the distribution of high frequency coefficients of integer wavelet transform obeys in general a Laplacian-like distribution. The following two features exist in the distribution.

(a) Most high frequency integer wavelet transform coefficients are very small in magnitude. It is then convenient to select the compression function. For example the linear function $F(x)=x$ can be considered as compression function since even though y' is twice the x value, it is still in the range of x.

(b) Although most of high frequency IWT coefficients are small in magnitude, there are still some IWT coefficients having large magnitude. For these large coefficients, compression function selection should consider the restriction of condition (2). In this case, the linear function $F(x)=x$ is no longer suitable to serve as a compression function.

Considering the above two situations, we propose to adopt the following piecewise linear function as the compression function.

$$C(x)=\begin{cases} x, |x|<T \\ sign(x)\cdot(\frac{|x|-T}{2}+T), |x|\geq T \end{cases}$$

where T is a pre-defined threshold. $C(x)$ is depicted below in Figure 1.

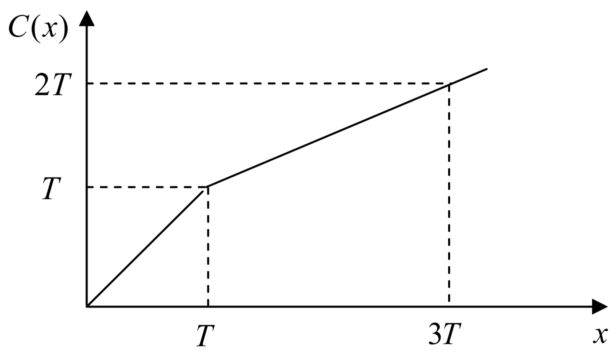

Figure 1. Compression function $C(x)$

As discussed above, in actual realization, however, we have to adopt the compress function in quantized version, namely

$$Q(C) = C_Q(x) = \left\{ \begin{array}{c} x, |x| < T \\ sign(x) \cdot (\left\lfloor \frac{|x| - T}{2} \right\rfloor + T), |x| \geq T \end{array} \right\}$$

It can be derived from the above equation that when $|x| \geq T$, x and $(x+1)$ (or $(x-1)$) are compressed to correspond to a same y value. Hence according to the previous discussion, x and $(x+1)$ (or $(x-1)$) are need to be recoded and the recording data need to be embedded as overhead into the wavelet coefficients. From the above discussion, T is a critical value. When T is small, the coefficients alterations are small and good visual quality of marked image is achieved. When T is large, a larger payload can be achieved. In the actual embedding, we select the T value according to the payload.

3.3 Histogram Modification

For a given image, after data are embedded into some high frequency IWT coefficients, it is possible to cause overflow and/or underflow, which means that after inverse integer wavelet transform the grayscale values of some pixels in the marked image may exceed the upper bound (255 for an eight-bit grayscale image) and/or the lower bound (0 for an eight-bit grayscale image). In order to prevent the overflow and underflow, we adopt histogram modification to narrow the histogram from both sides. The bookkeeping data generated in histogram modification need to be embedded into image as a part of overhead data, which will be used late in the recovery of the original image. For details about histogram modification, readers are referred to [3].

Following Figure 2 is a block diagram for the proposed data embedding and extaction procedures.

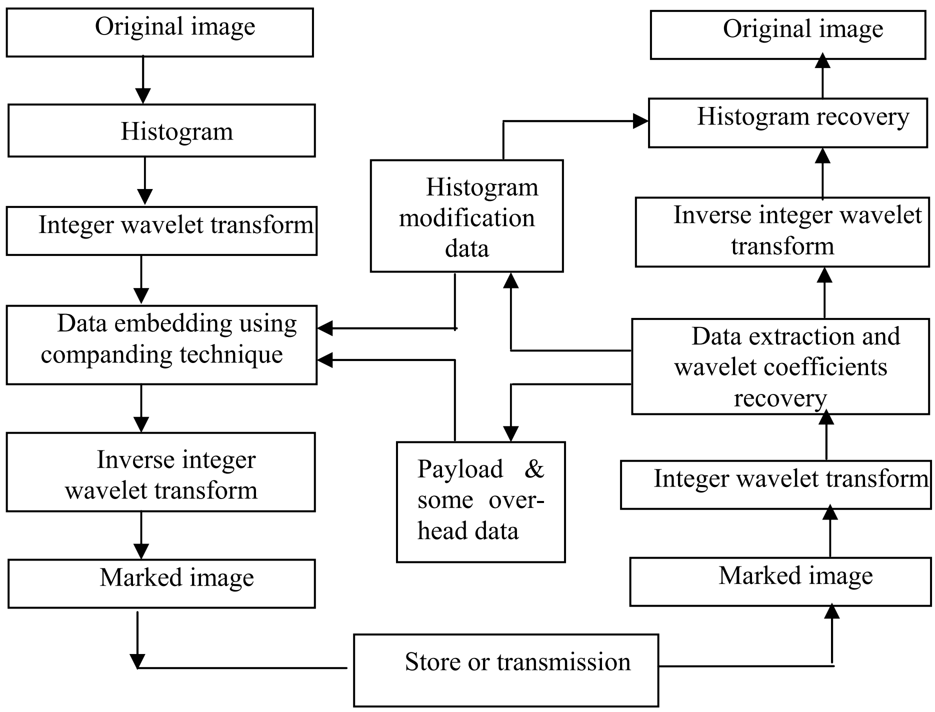

Figure 2. Block diagram of reversible data hiding diagram. Left: data embedding, Right: data extraction.

4 Experimental Results and Analysis

We applied the proposed reversible data hiding algorithm to some frequently used images. Tables 1, 2, 3, and 4 contain the experimental results on four grayscale level images, Lena, Baboon, Barbara and Goldhill of size 512×512 shown in Figure 3. For an image of size of 512×512, a payload 1 bpp (bits per pixel) means that 262,144 (namely 512×512) bits are embedded in the image. The data in these tables indicate that the proposed reversible data hiding algorithm can embed a large payload, while maintaing the high PSNR (peak signal-to-noise-ratio) of the marked image versus the original image. In Figure 4, the comparison results between the difference expansion method [4] and our proposed method are shown. It is observed that our proposed technique can obtain better visual quality in the same payload. More than 2 dB improvement in PSNR has been achieved.

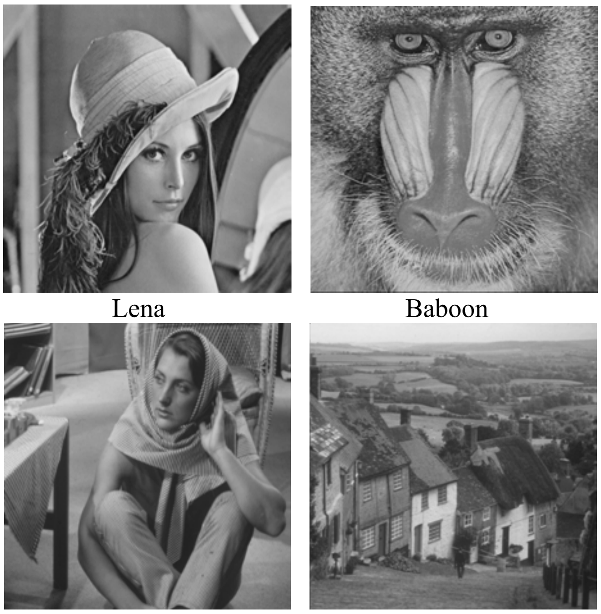

Figure3. Some test images

Table 1. PSNR vs. payload for Lena image

Payload (bpp)	0.1	0.2	0.3	0.4	0.6	0.7
PSNR (dB)	49.53	46.23	44.04	42.28	39.43	37.48

Table 2. PSNR vs. payload for Baboon image

Payload (bpp)	0.1	0.2	0.3	0.4	0.5
PSNR (dB)	43.45	39.66	36.42	33.61	31.51

Table 3. PSNR vs. payload for Barbara image

Payload (bpp)	0.1	0.2	0.3	0.4	0.5	0.6
PSNR (dB)	49.47	46.84	44.70	42.33	40.13	36.77

Table 4. PSNR vs. payload for Goldhill image

Payload (bpp)	0.1	0.2	0.3	0.4	0.5	0.6
PSNR (dB)	47.85	44.74	42.37	40.40	38.36	36.68

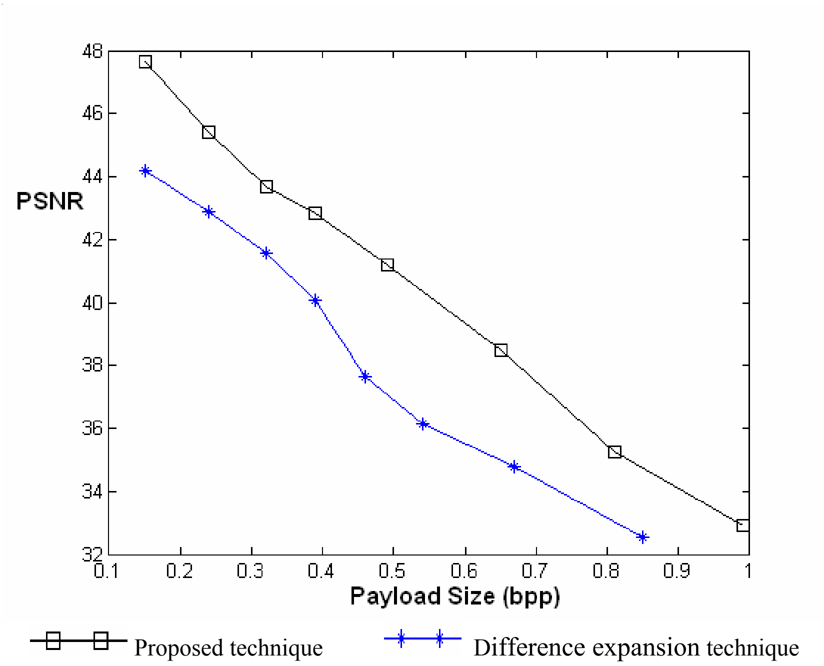

Figure 4. Comparison results on Lena image

We should point out that this proposed can be applied successively for a few times on the same image which means we can continue to embed data on the marked image. Since we embed data in three high frequency subbands of IWT, the theoretical upper bound for data embedding is 0.75 bpp each time. Results reported in Tables 1, 2, 3, and 4 are the results after the first time embedding. For most of images, however, it can embed data at 1.3 bpp after three times data embedding. After that, if we further embed data on the marked image, the payload will increase very slowly while the visual quality drops severely as shown in Figure 4.

0.6 bpp(157286 bits), PSNR: 39.43, one embedding 1.3 bpp(340787 bits), PSNR: 27.93, three embedding

Figure 5. Visual quality on Lena image for different payload

5 Conclusion

This paper proposes a reversible data hiding technique based on the integer wavelet companding technique. Experimental results and the comparison with the difference expansion (Figure 3) method demonstrate that this proposed technique can obtain a better visual quality of the marked image at the same payload. It is expected that this reversible data hiding technique will be deployed for a wide range of applications in the areas such as secure medical image data system, law enforcement, e-government, image authentication and covert communication.

Acknowledgement

This research is supported in part by China NSFC: The Research of Theory and Key Technology of Lossless Data Hiding (90304017), and by New Jersey Commission of Science and Technology via NJWINS.

References

[1] Fridrich, J., Goljan, M., Du, R.: Invertible Authentication. In: Proc. SPIE Photonics West, vol. 3971, Security and Watermarking of Multimedia Contents III, San Jose, California January (2001) 197-208.

[2] Celik, M., Sharma, G., Tekalp, A. M., Saber, E.: Reversible Data Hiding. In: Proceedings of the International Conference on Image Processing 2002, Rochester, NY, September (2002).

[3] Xuan, G., Zhu, J., Chen, J., Shi, Y. Q., Ni, Z., Su, W.: Distortionless Data Hiding Based on Integer Wavelet Transform. In: IEE Electronics Letters, December (2002) 1646-1648.
[4] Tian, J.: Reversible Data Embedding Using a Difference Expansion. In: IEEE Transactions on Circuits and Systems for Video Technology, August (2003) 890-896.
[5] Yang, B., Schmucker, M., Funk, W., Busch, C., Sun, S.: Integer DCT-based Reversible Watermarking for Images Using Companding Technique. In: Proceedings of SPIE Vol. #5306, 5306-41.
[6] Sklar, B.: Digital Communications: Fundamentals and Applications. Englewood Cliffs, New Jersey: PTR Prentice Hall (1988).
[7] Calderbank, A. R., Daubechies, I., Sweldens, W., Yeo, B.-L.: Wavelet Transforms that Map Integers to Integers. In: Applied and Computational Harmonic Analysis, July (1998) 332–369.