J. Vis. Commun. Image R. 23 (2012) 798–811

Contents lists available at SciVerse ScienceDirect

J. Vis. Commun. Image R.

journal homepage: www.elsevier.com/locate/jvci

A Markov-based reversible data hiding method based on histogram shifting ☆

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ARTICLE INFO

Article history:
Received 10 November 2010
Accepted 19 April 2012
Available online 25 April 2012

Keywords:
Reversible data hiding
Information theory
Markov
Watermarking
Histogram shifting
Lossless
Embedding data
Man-made picture

ABSTRACT

Applying information theory, this work considers an image as a stream of symbols emitted by a Markov information source. With the Markov model, a reversible data-hiding scheme based on the histogram modification technique is proposed to provide an efficient tradeoff between hiding capacity and quality of a marked image by changing the order of the Markov model. The larger the order is, the higher the capacity is but the lower the quality is, and vice versa. The experimental results show that the proposed scheme yields not only much larger hiding capacity but also smaller image distortion than other reversible data-hiding schemes reported in the literature. This work also proposes two feasible approaches to reduce the overhead yielded during the data embedding.

1. Introduction

Data hiding [22–24] is a technique to embed useful information referred as a watermark into a cover media with acceptable visual distortion and to extract it afterwards. The applications are divided into two different categories – steganography and digital watermarking, by the relationship between the embedded data and the cover media [6–8]. For steganography, the embedded data often have no relationship with the cover media. By contrast, for digital watermarking, the embedded data are relevant to the cover media. Some applications of data hiding, such as copy control and content authentication, allow slightly permanent distortion to the cover media after extraction of the watermark. However, for some applications, especially in medical, military, and legal domains, it is critical to extract the watermark without even the slightest distortion of the cover image. This requirement leads to an interesting hiding technique – *reversible, lossless*, *distortion-free*, or *invertible* data hiding, in which the cover media can be recovered without any loss of information as the watermark has been extracted out.

Recently, reversible data hiding draws a lot of attention and many schemes have been proposed to enhance the embedding capacity or the imperceptibility. In 2001, Fridrich et al. [6] devised a least significant bit (LSB)-based reversible technique that embedded data into quantized DCT coefficients. The study in [9] embedded data bits into the state of each group of pixels. In 2003, Tian [19] proposed a reversible scheme based on the difference expansion (DE) transform of a pair of pixels. Alattar [2] extended Tian's method by using the difference expansion transform of vectors to embed data and by using the generalized integer transform of vector to reduce the difference values. Chang et al. proposed an embedding scheme based on the side match vector quantization (SMVQ) [4], and they also devised a VQ-based scheme in [5]. Thodi et al. [18] improved Tian's method by combining histogram shifting and difference expansion.

In 2006, Ni et al. [16] proposed a novel reversible algorithm that used the zero and the peak points of the histogram of an image to embed data. This histogram-modification scheme could achieve high hiding capacity as well as low distortion. Lee et al. [14] divided an image into blocks and hid watermark data into high-frequency wavelet coefficients of each block. Wang et al. [20] presented two reversible data-hiding schemes for 2-D vector maps based on difference expansion.

Lin et al. [15] proposed a multilevel reversible scheme, which embedded data bits into the pixels associated with peak points in the image-difference histogram. Weng et al. [21] presented an algorithm based on the invariability of the sum of pixel pairs and the pairwise difference adjustment (PDA) to achieve large hiding capacity with small distortion. An improved DE-based reversible scheme [12] used horizontal and vertical difference images to

☆ The work was financially supported by National Science Council, Taiwan under a research grant number NSC 100-2221-E-152-002 and 100-2221-E-152-005.
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http://dx.doi.org/10.1016/j.jvcir.2012.04.009

embed data. The DE-based schemes usually suffer from the overflow problem, and Hu et al. [13] thus proposed a technique to improve the compressibility of the overflow location map. Tai et al. [17] devised an embedding scheme based on the histogram modification and the pixel difference, and used a binary tree structure to save the pairs of peak-zero points.

Most previous schemes suffer from a problem that the imperceptibility of the marked image decreases severely when the embedding capacity increases. To alleviate this problem, this paper proposes a novel approach that can yield high embedding capacity and low distortion of the marked image by applying information theory to data embedding and extracting. The proposed scheme considers the pixels of a grayscale image as symbols emitted by a Markov source. Based on the Markov model, the scheme embeds data into a cover image and afterwards extracts the data from the generated marked image. This work can provide an effective tradeoff between hiding capacity and image quality by adjusting the order of the Markov source and the expected number of embedding bits. This scheme can achieve 1, 2, 3, and 4 bit-per-pixel (bpp) for a 512 × 512 × 8 grayscale image while the PSNR of the marked image is guaranteed to be higher than 48, 38, 31, and 24 dB, respectively. Comprehensive experiments are conducted on some common test images to show the success of this scheme. This work additionally proposes two feasible approaches to reduce the overhead yielded during the data embedding, and evaluates their performance.

The rest of this paper is organized as follows. Section 2 presents the Markov models for an image. The proposed reversible data-hiding approach is introduced in Section 3. The experimental results and comparisons are shown in Section 4. Section 5 discusses the overhead of the proposed scheme, and presents two approaches to alleviate the issue. Brief conclusions are drawn in Section 6.

2. The Markov source models for an image

Applying the information theory [1] to reversible data hiding, this work considers an image as a stream of symbols emitted by an *n*th order Markov source to form a message. The occurrence of a symbol emitted depends upon a finite number *n* of preceding symbols. For a grayscale image, this Markov source emits a sequence of symbols from a fixed finite source alphabet set $S = \{0, 1, 2, \ldots, 255\}$, which represents the possible grayscale values of pixels. The following sub-sections then present two Markov source models for an image.

2.1. The First Order Markov Model for an Image

For the first-order Markov model, the grayscale value of each image pixel depends on the grayscale value of its previous pixel. We create Table 1 to save the dependence. Each table entry, $r(k|m)$, is the conditional recurrence of the next symbol *k* following the given memory *m* (i.e., previous symbol), where $0 \leqslant m, k \leqslant 255$. The first-order Markov model considers each row as a conditional histogram for a given memory *m*, and thus this model generates multiple histograms for a cover image. Furthermore, the scheme proposed by Ni et al. [16] can be considered as a zero order (or memoryless) Markov model, in which the occurrence of a symbol is independent of previous symbols. The scheme thus utilizes only one histogram to embed data.

2.2. The nth Order Markov Model for an Image

Extending the first-order Markov model, this work proposes a general *n*th order Markov source model, which can find more peak and zero points and achieve higher embedding capacity. For the *n*th order Markov source model, the grayscale value of each image pixel depends on the grayscale values of its previous *n* pixels or memory, denoted by $(m_n, m_{n\text{-}1}, \ldots, m_j, \ldots, m_2, m_1)$, where m_j represents the previous *j*th pixel value. We create Table 2 to save the dependence. Each table entry, $r(k|(m_n, m_{n\text{-}1}, \ldots, m_2, m_1))$, is the conditional recurrence of the next symbol *k* following the given memory $(m_n, m_{n\text{-}1}, \ldots, m_2, m_1)$ (i.e., previous *n* symbols), where $0 \leqslant m_1, m_2, \ldots, m_{n\text{-}1}, m_n, k \leqslant 255$. When the order (i.e., the size of *n*) of the Markov source is higher, the possible memory states increases and the number of conditional histograms also becomes larger. Thus, the space for embedding data grows. When the order is large enough, each conditional histogram may contain only one peak point and other values are zero. In this case, a 512 × 512 grayscale image can embed 262144-bit data. That is each pixel can hide one bit.

3. The proposed scheme

This section presents a reversible data-hiding algorithm, called $MRev(n, x)$, which combines the Markov source models with the histogram shifting technique. Here, the two parameters, *n* and *x*, represent the order of the Markov source and the number of embedding bits, respectively. In the proposed scheme, each histogram for a given memory may contain several *waves*, which are utilized to hide data. Fig. 1 shows a histogram generated by $MRev(1,1)$ from the famous image Lena, where the given memory *m* equals 32. The figure contains five waves, [26,51], [52,53], [57,58], [61,63], and [65,66], and [65,66], each of which has a pair of peak-zero points. The difference between the peak and zero points can be used to embed data.

We first define some terms before introducing the proposed scheme. The function $f(x)$ is a function of the expected number of embedding bits *x*

$$f(x) = 2^x - 1 \tag{1}$$

Let *w* be a *wave* of a histogram of a memory *m* according to the expected embedding bits *x*. Suppose that the wave *w* locates at a pixel interval $[i,j]$, where $0 \leqslant i, j \leqslant 255$. Each conditional recurrence $r(k|m)$, $0 \leqslant k \leqslant 255$, in the wave *w* must satisfy (2).

Table 1
The first-order Markov source model for a grayscale image.

Memory (Previous symbol)	Next symbol						
	0	1	2	…	*k*	…	255
0	$r(0\|0)$	$r(1\|0)$	$r(2\|0)$	…	$r(k\|0)$	…	$r(255\|0)$
1	$r(0\|1)$	$r(1\|1)$	$r(2\|1)$	…	$r(k\|1)$	…	$r(255\|1)$
2	$r(0\|2)$	$r(1\|2)$	$r(2\|2)$	…	$r(k\|2)$	…	$r(255\|2)$
…	…	…	…	…	…	…	…
m	$r(0\|m)$	$r(1\|m)$	$r(2\|m)$	…	$r(k\|m)$	…	$r(255\|m)$
…	…	…	…	…	…	…	…
255	$r(0\|255)$	$r(1\|255)$	$r(2\|255)$	…	$r(k\|255)$	…	$r(255\|255)$