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Image Watermarking Using Dither Modulation in Dual-Transform Domain[1]

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Abstract: A new method for inserting invisible watermark into a digital image is described, which uses two layers of orthogonal transforms, pseudorandom data shuffling and a dither modulation technique. Neither the original host image nor the inserted data string is needed in extraction of the watermark. Experiments show that watermark embedded in this way is sufficiently transparent and robust. A desired tradeoff between invisibility, robustness, and embedding capacity can be achieved by appropriately choosing the system parameters and the candidate coefficients for embedding.

1. Introduction

As an effective means for intellectual property right (IPR) protection, watermark is a digital code embedded imperceptibly and robustly into digital media such as still image and audio signals[1,2]. Various orthogonal transforms such as DCT, DFT and KLT have been used[3,4]. In order to achieve different performances and meet various application requirements, watermarks may be embedded into different parts of the host signal and using different embedding strategies such as coefficient replacement, adjustment, and addition.

One method of data adjustment is dither modulation, or quantization index modulation (QIM)[5,6], initially introduced in image watermarking to achieve a balanced performance for acceptable embedding capacity, imperceptibility, and robustness. The technique has later been developed to include some post-processing referred to as distortion compensation[7], leading to better robustness against Gaussian noise and JPEG coding.

Dither modulation has also been applied to audio watermarking in which modification of the host signal is done in the frequency domain[8]. This ensures robustness of the embedded data against various signal manipulations and common attacks including MP3 compression coding.

In this paper, a new approach for embedding watermark into still images is developed using the dither modulation technique in a dual-transform domain. For a desired statistic property, data shuffling is introduced to remove correlation between adjacent data points. The original image and the embedded codes are not required in extraction of the watermark. Experiments are presented to show good anti-attack performances of the proposed technique.

2. Methodology

2.1 Watermarking based on dither modulation

Define a group of functions $s(\mathbf{x}; m)$, each of which , indexed by m, is a perturbed or dithered version of $\mathbf{x}$. Let $\mathbf{x}$ and m represent the host signal and the embedded data respectively. To meet the requirement that distortion introduced by the dithering is imperceptible, the following constraint must be satisfied:

$$s(\mathbf{x}; m) \approx \mathbf{x}; \qquad \forall m \tag{1}$$

Using an ensemble of quantizers to implement the dither modulation, the above method is also termed quantization index modulation[6].

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zation index modulation[6].

This is shown schematically in Fig.1, in which one watermark bit is embedded into each vector **x**. If $m \in \{0,1\}$, two different quantizers are needed, referred to as Q0 and Q1 with reconstruction points denoted by solid dots and circles as shown in Fig.1, respectively. The polygons represent quanzation cells. If a zero is to be embedded, **x** is quantized with Q0 to become s(**x**; 0); if 1 is embedded, **x** is quantized to s(**x**; 1). Distortion introduced by the embedding is proportional to the size of cells, and robustness is related to the minimum distance:

$$d_{\min} = \min_{(i,j):i \neq j} \min_{(x_i, x_j)} \| s(\mathbf{x}_i; i) - s(\mathbf{x}_j; j) \| \tag{2}$$

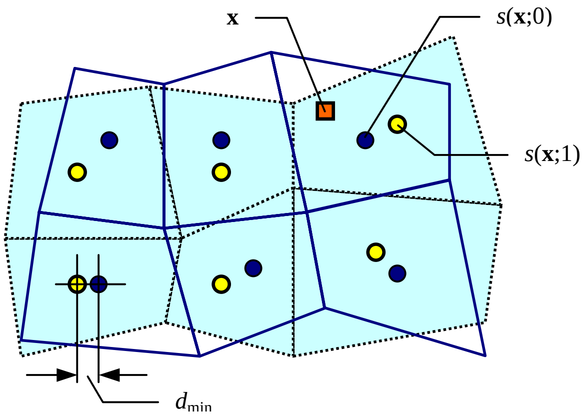

Fig. 1 QIM: solid dots and circles belong to quantizers Q0 and Q1 respectively.

It is clear that a large $d_{\min}$, therefore better robustness, requires large quantization cells hence poor invisibility. By embedding more than one bit into each host data point, embedding capacity may be increased. In this case, however, $d_{\min}$ will be reduced leading to less robustness.

The embedded watermark can be extracted using a minimum distance decoder that finds out the nearest reconstruction point to the received vector **y**. The one associated with this reconstruction point is considered as the embedded bit.

2.1 Dual-transform domain DM embedding

In the present work, two layers of 2D orthogonal transforms, one block DCT and one DFT, are performed before dither modulation. Prior to the DFT, the candidate DCT coefficients are pseudo-randomly shuffled. The following are the proposed embedding steps.

(1) **Block DCT**: The host image **I**, sized $R \times S$, is first segmented into $M \times N = K$ small blocks, where $M = R/P$ and $N = S/Q$. The block size is $P \times Q$. Two-dimensional DCT is performed on each data block.

(2) **Pseudo-random shuffling of DCT coefficients**: Choose one coefficient at the same position in each block of DCT coefficients that correspond to the same spatial frequency, forming a new data group sized $M \times N$. An acceptable tradeoff between invisibility and robustness is the main consideration in the selection. The lower-middle frequency components are recommended since low frequency components are important to visual effects, while high frequency components are susceptible to attacks. Data within the group is then shuffled pseudo-randomly prior to a second-layer transform. The purpose of data shuffling is to remove correlation between adjacent coefficients and, in the mean time, provide a key to prevent unauthorized detection.

(3) **DFT**: Two-dimensional DFT is performed on the shuffled data group. Since correlation between connected data has been removed, the obtained DFT coefficients have a uniform distribution of expected energy. This is essential in design a unified quantization scheme for the entire image to obtain required specifications of robustness and invisibility.

(4) **Dither modulation embedding**: A quantization scheme is described as follows. According to the amount of information to be embedded, some of the DFT coefficients are selected as candidates for modification. Each pair of wa-

termark bits, referred to as a *doublet*, is assigned to each candidate coefficient. A quantization step Δ is defined. The choice of Δ is made based on the performance requirements in particular applications. In General, a smaller Δ results in less visibility and poorer robustness while a larger Δ leads to higher visibility and better robustness. For each candidate coefficient $\mathbf{C}_k$, a complex value $\mathbf{d}_k$ is obtained such that its real and imaginary parts are randomly and independently picked from [–Δ/2, Δ/2]. According to the doublet, 11, 01, 10, or 11, to be embedded, a complex dither vector, $\mathbf{D}_k$, is derived:

$$\mathbf{D}_k = \begin{cases} \mathbf{d}_k & \text{when mark bits are } 11 \\ \mathbf{d}_k - \Delta/2 & \text{when mark bits are } 01 \\ \mathbf{d}_k - j\cdot\Delta/2 & \text{when mark bits are } 10 \\ \mathbf{d}_k - \Delta/2 - j\cdot\Delta/2 & \text{when mark bits are } 00 \end{cases} \quad (3)$$

In Fig.2, two dither-vectors $\mathbf{D}_{k1}$ and $\mathbf{D}_{k2}$ in the complex plane corresponding to doublets 01 and 10 and derived from the initially chosen $\mathbf{d}_{k1}$ and $\mathbf{d}_{k2}$ respectively are shown. All dither vectors are located within a square area bounded by [Δ, –Δ, *j*·Δ, –*j*·Δ]. Two sets of four end points corresponding to all possible dither-vectors derivable from $\mathbf{d}_{k1}$ and $\mathbf{d}_{k2}$ are also shown, amongst which the top-left ones represent $\mathbf{d}_{k1}$ and $\mathbf{d}_{k2}$ themselves respectively that are located within an inner square bounded by [Δ/2, –Δ/2, *j*·Δ/2, –*j*·Δ/2].

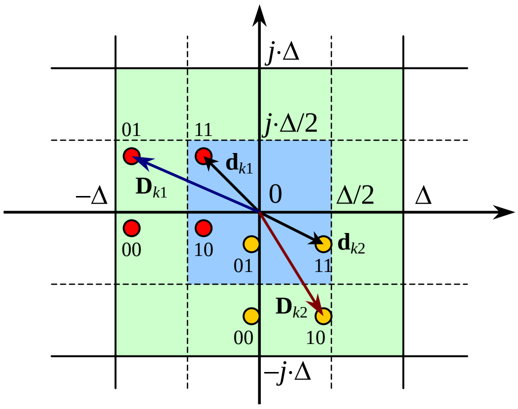

Fig.2 Complex dither vectors $\mathbf{D}_{k1}$ and $\mathbf{D}_{k2}$ derived from randomly chosen complex dither values $\mathbf{d}_{k1}$ and $\mathbf{d}_{k2}$ based on the doublets to be embedded, which are 01 and 10 respectively.

The dual-transform domain coefficient $\mathbf{C}_k$ is then modified to produce $\mathbf{C'}_k$:

$$\mathbf{C'}_k = Q(\mathbf{C}_k + \mathbf{D}_k) - \mathbf{D}_k \quad (4)$$

where the quantizing operation Q is defined as

$$Q(\mathbf{z}) = \text{round}\left[\frac{\text{Re}(\mathbf{z})}{\Delta}\right]\Delta + j\cdot\text{round}\left[\frac{\text{Im}(\mathbf{z})}{\Delta}\right]\Delta \quad (5)$$

The generation of $\mathbf{C'}_k$ from $\mathbf{C}_k$ is illustrated in Fig.3. Meanwhile, the coefficient at the negative frequency symmetric to $\mathbf{C}_k$ is replaced with the complex conjugate of $\mathbf{C'}_k$.

An alternative scheme of QIM watermarking is to use a coarse quantizer in conjunction with a modulation technique such as QAM or PSK, as illustrated in Fig.4. The complex coefficient $\mathbf{C}_k$ is first coarsely quantized, and then combined with a coded watermark symbol $\mathbf{W}_k$ that represents a number of bits depending on the particular modulation technique used. The watermarked coefficient is thus obtained:

$$\mathbf{C'}_k = Q(\mathbf{C}_k) + \mathbf{W}_k \quad (6)$$

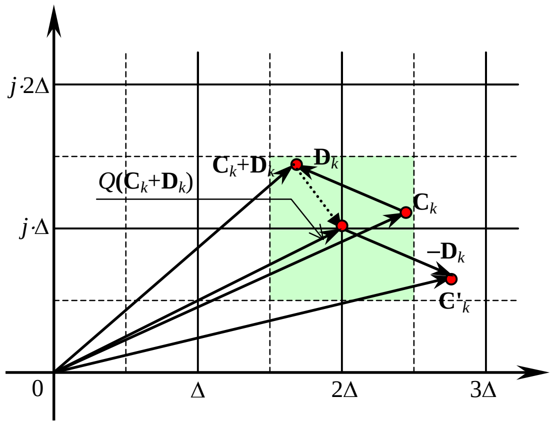

Fig.3 Dither modulation based on Equations (3)~(5). The original complex coefficient $\mathbf{C}_k$ has been modified to $\mathbf{C'}_k$.

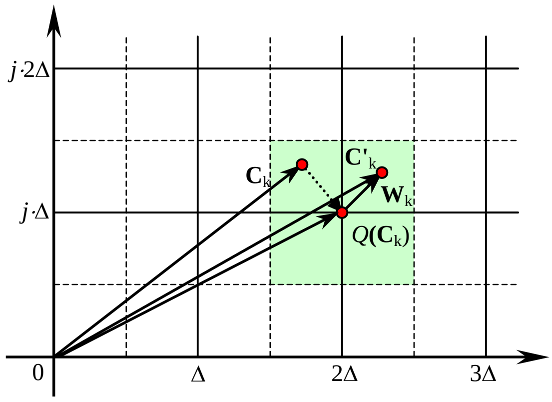

Fig.4 Alternative scheme of QIM in which the host coefficient is quantized and then combined with a coded watermark symbol.

The above-described steps of block DCT, data selection, pseudo-random shuffling, DFT, and dithering are diagrammatically illustrated in Fig.5.

A watermarked image **I'** is obtained after a reversed sequence of operations on the modified coefficients. These steps include IDFT of the dither-modulated dual transform domain coefficients, de-shuffling to restore the original order of selected DCT coefficients, replacing selected DCT coefficients with the modified ones, and finally, block IDCT to produce the watermarked image in the space domain.

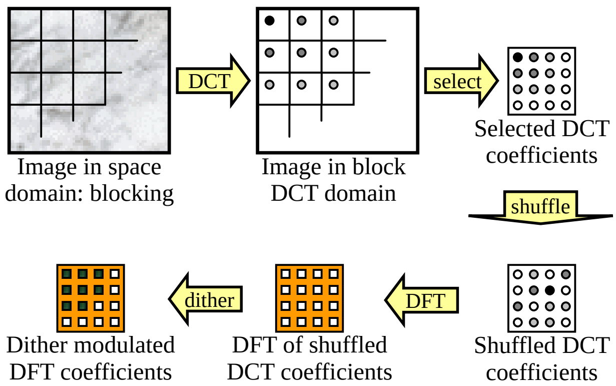

Figure 5 Dither modulation in dual-transform domain

2.3 Watermark extraction

Assume that $\mathbf{C'}_k$ is computed from the received image $\mathbf{I'}$ with the same procedure consisting of block-DCT, pseudo-random shuffling with the known key, and DFT. Then, the watermark bit doublet embedded in $\mathbf{C'}_k$ can be extracted:

$$w_k(l) = \frac{1}{2}\left[(-1)^{h(l)} + 1\right], \quad l = 1, 2 \tag{7}$$

where

$$h(1) = \text{round}\left[\frac{2\,\text{Re}\left(\mathbf{C'}_k + \mathbf{d}_k\right)}{\Delta}\right] \tag{8}$$

and

$$h(2) = \text{round}\left[\frac{2\,\text{Im}\left(\mathbf{C'}_k + \mathbf{d}_k\right)}{\Delta}\right] \tag{9}$$

Here the complex $\mathbf{d}_k$ is the key initially used during the embedding.

Using the second method as expressed in (6), the embedded watermark symbol can be extracted with a reversed operation without the need of a pseudo randomly chosen key:

$$\mathbf{W}_k = \mathbf{C'}_k - Q\left(\mathbf{C'}_k\right) \tag{10}$$

3. Experimental Results

In the experiment, a 256×256 test image Lena was first segmented into 32×32 small pixel blocks, each sized 8×8. Two-dimensional DCT was performed on these blocks, and a 32×32 data group formed using the lower-middle frequency coefficients at position (2, 2) in all the 8×8 blocks. After pseudo-random shuffling and DFT, a 500-bit watermark was embedded into the host image according to Equations (3)~(5).

A watermarked image visually identical to the original host was obtained after reversed operations. As expected, dither modulation produced much less distortion to the host signal than other techniques such as simple replacement of data. It was observed in the experiment that the introduced distortion was small enough to ensure satisfactory imperceptibility. The measured peak signal-to-noise ratio (PSNR) referenced to the original host was 43dB, which is substantially higher than those obtained with many other techniques, and higher than 38dB considered as the lower bound of acceptable distortion caused by watermark embedding [9].

Robustness against additive white Gaussian noise and JPEG compression coding of the proposed approach was tested. Table 1 shows the rate of bit-extraction error under attacks of AWGN. The strength of attack was measured by signal-to-noise ratio. It is seen that reliable extraction was achieved when the SNR was no less than 34dB.

Table 2 gives the rate of bit-extraction error under attacks of JPEG coding at different quality factors. Error-free extraction was obtained when the JPEG quality factor was above 40%.

Table 1 Bit-extraction error rate under AWGN attack

SNR (dB)	30	32	34	36
BER (%)	2.6	0.4	0	0

Table 2 Bit-extraction error rate under JPEG attack

Quality factor (Q)	20	40	60	80
BER (%)	3.4	0.2	0	0

4. Discussion

A double-layered transform approach for embedding invisible watermarks into still images is described. The embedded information is spread over the entire image by modifying coefficients at appropriate frequencies so that the introduced distortion is practically invisible. Dither modulation is performed to embed the watermark. Invisibility is further guaranteed as coefficients in the host are modified based on the embedded information as well as on the randomly chosen value d_k. In this way, the coefficient values are not significantly changed.

Robustness of the watermark is satisfactory. The embedded data can be extracted without error under AWGN and JPEG attacks as long as the image quality is not significantly degraded.

Data shuffling removes correlation between adjacent coefficients so that the second layer transform has a uniform energy distribution. It also helps enhance security of the embedded watermark since it is impossible for any third party without the key to extract the hidden data.

Unlike other approaches using dither modulation where each watermark bit is carried by a number of host data bits[5,6], in the proposed method two watermark bits are carried by only one host coefficient.

The proposed technique is a public scheme since neither the original host image nor the inserted string is needed in watermark extraction.

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