Oblivious image watermarking combined with JPEG compression

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ABSTRACT

For most data hiding applications, the main source of concern is the effect of lossy compression on hidden information. The objective of watermarking is fundamentally in conflict with lossy compression. The latter problem attempts to remove all irrelevant and redundant information from a signal, while the former uses the irrelevant information to mask the presence of the hidden data. Compression on a watermarked image can significantly affect the retrieval of the watermark. Past investigations of this problem have heavily relied on simulation. It is desirable not only to measure the effect of compression on embedded watermark but also to control the embedding process to survive lossy compression. In this paper, we focus on oblivious watermarking by assuming that the watermarked image inevitably undergoes JPEG compression prior to watermark extraction. We propose an image-adaptive watermarking scheme where the watermarking algorithm and the JPEG compression standard are jointly considered. Watermark embedding takes into consideration the JPEG compression quality factor and exploits a HVS model to adaptively attain a proper trade-off among transparency, hiding data rate, and robustness to JPEG compression. The scheme estimates the image-dependent payload under JPEG compression to achieve the watermarking bit allocation in a determinate way, while maintaining consistent watermark retrieval performance.

Keywords: Digital watermarking, data hiding, JPEG, visual masking, DCT

1. INTRODUCTION

With the development of the Information Society, digital images have become an important source of information in the modern world of communication system. In their raw form, digital images require a tremendous amount of memory. So image compression is now essential for applications such as transmission and storage. To date, many still image compression standards have been established. With a high compression ratio and the desired quality, JPEG is the most widely used compression standard. On the other hand, the continual proliferation of open networked multimedia systems has magnified a need for the secure, robust delivery of digital media. One way to address the problem is to embed invisible watermarks to digital media. Digital watermarking and data hiding have a variety of applications including copyright protection and broadcast monitoring. For most data hiding applications, a certain degree of compression is desired and is often constrained by acceptable image quality. Such manipulation is necessary to facilitate efficient information transfer and storage. The effect of lossy compression on the hidden information is a main concern. The retrieval of a watermark embedded in an image is often affected if the watermarked image has undergone compression. The widespread use and growth of JPEG format and its efficiency in compression images make robustness to JPEG compression an important factor for watermarking algorithm design. The objective of watermarking is fundamentally in conflict with lossy compression. JPEG compression algorithm tends to eliminate invisible information that can be related to the watermark, making the watermark detection/retrieval process unreliable. Because it is difficult to analyze the effect of compression on the detection of watermarked image, past investigations of this problem have relied heavily on simulation[16].

In order to make a watermark-based application feasible, one of the fundamental issues is to find the best trade-off among three important properties of image watermarking: imperceptibility, capacity, and robustness to JPEG compression. However, these features are inter-dependent, mutually competitive and cannot be clearly done at the same time. For example, increasing the capacity will decrease the robustness or increasing the visibility. On the other hand, if robustness to strong distribution is an issue, the message that can reliably hidden will be sacrificed. A reasonable compromise is always a necessity. Apart from the above-mentioned requirements, design of a sophisticated blind retrieval technique is also necessary.

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The research of watermarking has resulted in a number of algorithms suited to the divers needs of multimedia industries. A great deal of research has mainly concentrated on the design of robust, unperceivable watermarking strategies[1-3]. Some papers have combined watermarking with compression[4-7]. However, watermarking in the quantized data domain is fragile to re-quantization. Re-encoding of the compressed file generally destroys the embedded watermark. Also, there is a need for more comprehensive work. In many situations, capacity and reliable retrieval performance is more valuable. More recent works[8-11] have analytically studied data hiding capacity and proposed strategies to estimate and access the potential high capacity data hiding in presence of lossy compression by exploiting human visual system models. However, those strategies lack the capability to be used for blind watermarking. An important requirement for many applications is the ability to retrieve the watermark without the original data. This feature results in a very challenging problem especially when capacity and robustness to compression is also desired.

This problem can be nicely solved if the watermarking algorithm and the JPEG compression standard are jointly considered with the underlying assumption that compression is inevitably used during transmission. In this paper, we focus on oblivious watermarking by assuming that the watermarked image inevitably undergoes JPEG compression prior to watermark extraction. We propose an image-adaptive watermarking scheme where the watermarking and compression are jointly considered. Watermark embedding takes into consideration the JPEG compression quality factor and exploits a HVS model to adaptively attain a proper trade-off among transparency, hiding data rate, and robustness to JPEG compression. The scheme estimates the image-dependent payload under JPEG compression to achieve the watermarking bit allocation in a determinate way, while maintaining consistent watermark retrieval performance.

This paper is organized as follows. In the next section, we present our oblivious watermarking algorithm that achieves a good trade-off among transparency, capacity and robustness to JPEG compression. Then in section 3, we provide the experimental results obtained with our new solution. This is followed by a discussion in section 4.

2. THE PROPOSED DIGITAL WATERMARKING ALGORITHM

The main goal of the proposed system is to provide a good trade-off among invisibility, embedding capacity, and robustness to JPEG compression. To achieve this goal, the scheme jointly considers embedding process and JPEG compression. The basic idea is as follow: The embedding capacity of algorithm under desired compression level, which is application-dependent and related to JPEG quality factor, is first estimated based on imperceptible constraint. To grant the invisibility, we use a perceptual model, which provides an upper bound on the amount of modification one can make to the content without incurring perceptual difference, to maximize the watermark strength and improving capacity at the same time. The bit number of the input information should be a little below the bound in order to ensure the recovery of the hidden information later. The major source of error is due to quantization process in JPEG compression. Compression is one of the most destructive for an embedded mark. Even very small quantization distortions can prevent the retrieval of a watermark. This problem is most severe in the case of blind watermarking. So we need to improve the robustness of the watermark using some kind of redundancy. Repetition, a simple and effective error correcting coding method for fading-like attacks[14], is used to survive JPEG compression to a desired quality level.

2.1 Visual masking

Over the past decades, there have been many efforts to develop models or metrics for image quality that incorporate properties of the HVS. These models have been used to help develop image compression systems that optimize the perceived quality of the compressed images, and recently to help design watermarking systems that ensure the imperceptibility of the embedded watermarks[3,9]. The visual models give us a direct way to determine the maximum amount of watermark signal that each portion of an image can tolerate without affecting the visual quality of the image. This allows us to provide the maximum strength watermark and access capacity that in turn, is extremely robust to common image processing and editing such as JPEG compression.

The human visual system (HVS) is very complex and able to deal with huge amount of information. Many models describing its characteristics have been developed. Generally, these models were explored to describe human vision mechanisms based on three main concepts: frequency sensitivity, luminance sensitivity and contrast masking. One of the most popular is based on the just noticeable difference (JND) paradigm[12]. The JND thresholds provide an upper bound on the extent that each of the coefficients can be perturbed without causing perceptual changes to the image quality. It is possible to exploit the limited dynamic range of the human eye to embed information.

Watson's visual model applies the three concepts to 8×8 coefficients blocks in DCT domain. His model can be summarized as follows. An original just noticeable difference—the frequency sensitivity portion of the model, we refers it as *t(i,j),* is assumed to be the same in all blocks. Then these values are all refined by adding a luminance sensitivity $t_k(i,j)$ and contrast masking component $m_k(i,j)$ as in the following equations.

$$t_k(i,j) = t(i,j)\left(\frac{c_k(0,0)}{\bar{c}(0,0)}\right)^{a_T} \tag{1}$$

Where $c_k(0,0)$ is the DC value of the block k, $\bar{c}(0,0)$ is the DC coefficient corresponding to the mean luminance of the display, and a_T is a parameter that controls the degree of luminance sensitivity. The author suggests setting a_T to 0.649.

$$m_k(i,j) = \max(t_k(i,j), \left|c_k(i,j)\right|^{w_{ij}} t_k(i,j)^{1-w_{ij}}) \tag{2}$$

Where w_{ij} is an exponent between 0 and 1. A typical empirical value for w_{ij} is 0.7. The $c_k(i,j)$ is the *(i,j)-th* DCT coefficient of the block *k*.

A watermarking system with such a visual optimization thus provides the maximal watermark power and robustness to attacks, given a desired perceived quality. Our image-adaptive watermarking uses the JND paradigm to insert imperceptible watermarks and approach capacity.

2.2 Capacity estimate

2.2.1 Theoretical capacity

Watermarking procedures are regarded as a communication over a noisy channel. Most of the previous works on the watermark capacity evaluation consist in modeling the watermark-channel as an additive white Gaussian noise (AWGN) channel, so that Shannon's theorem on channel coding can be used. The watermarking capacity is given by

$$Cap = \frac{1}{2}\log_2\left(1+\frac{P}{N}\right) \qquad \textit{(bits/sample)} \tag{3}$$

Where P and N are the uniform power constraints of watermark and noise, respectively. The main limit of (3) is: it is applied to the case that the whole image has uniform watermark power constraint and noise power constraint in all coefficient locations.

HVS model tells us that the power constraints of watermarks are actually not uniform, either in the spatial pixel domain, frequency domain, or frequency-orientation domain. Also, general distortions, such as lossy compression, do not generate uniform noises in these domains.

Lin *et al.*[13] model an image as a channel with spatial-variant states, in which the power constraint of each state can be different in different positions. In a general noise environment, they derived the private watermarking capacity by considering every coefficient as an independent random variable with its own noise distribution. That is,

$$Cap_{total} = \sum_{i=1}^{n} Cap_i = \sum_{i=1}^{n}\frac{1}{2}\log_2\left(1+\frac{P_i}{N_i}\right) \tag{4}$$

where P_i and N_i are the power constraints of watermark and noise in the *i-th* coefficient, respectively. The n is the number of the coefficients due to watermarking.

Using this model, we can estimate the theoretical capacity of private watermarking in which the power constraints are not uniform. So HVS models can be exploited to estimate watermarking capacity. In other words, the capacity is determined by the image characteristics.

2.2.2 Payload of the proposed scheme

The widely used JPEG algorithm provides a high compression ratio and the desired quality. However, compression algorithms tend to remove the embedded watermark. In this section we present the payload estimate of our oblivious watermarking under JPEG compression. The robustness is supposed to survive JPEG compression down to a desired quality level. This will reduce the number of reliably retrievable embedding information. Obviously, if attacks are considered, the capacity of the scheme will come down. Then in that case how many watermark bits can we insert and retrieve using this scheme? We use Watson's HVS model and assumed that coefficients below the JND threshold do not contribute anything perceptually.

In the JPEG standard, a set of $M \times N$ pixel image data is subdivided in 8×8 pixel blocks, which is transformed into 8×8 blocks of discrete cosine series coefficients using the well-known discrete cosine transform (DCT). The coefficients are then quantized using a set of uniform quantizer step sizes. The major error source of watermark retrieval is due to quantization of the 8×8 block DCT coefficients in JPEG compression. Let the DCT coefficients in an 8×8 block be zigzag scanned as C_i with order ranging i from 1 to 64. Given that the quality factor of JPEG compression is pre-set to Q (this is directly related to the level of quantization imposed during lossy compression). The JND thresholds determine the location and maximum strength of modifying signal that can be tolerated in every portion of the coefficients without affecting the perceived image quality. When both data embedding and perceptual coding are applied to an image, the combined effects of the processes should not result in a change to any host signal coefficients that exceed JND. The gap between JND and the expected quantization error, which is determined by JPEG quality factor, is available room for watermarking. So, the maximal watermark strength of the *i-th* coefficient is given by

$$W_i = JND_i - E_i. \tag{5}$$

The E_i is quantization error. It is determined by

$$E_i = C_i - Round(C_i / (Q \times Q\_MATRIX_i)) \times (Q \times Q\_MATRIX_i) \tag{6}$$

Where Q_MATRIX_i is *i-th* value of JPEG quantizer matrix. So the power constraints P_i of watermark in (4) is determined by:

$$P_i = W_i^2 = (JND_i - E_i)^2 \tag{7}$$

An important requirement to consider for many applications is the ability to retrieve the watermark without the original image. In the case of blind watermarking, the host image is not available for extraction and the associated watermark channel has two sources of noise: 1) the noise due to the original image; 2) the attack noise due to compression process. The two independent noise sources can be replaced by a signal Gaussian noise source[8].

$$N_i = C_i^2 + E_i^2 \tag{8}$$

Channel coding is widely used to improve the performance of communications systems. This idea extends to watermarking systems. To achieve high reliability, repetition coding is used. The price we pay for improving the robustness performance of the system is a reduction of the information rate. For a given capacity, the use of channel coding in watermarking decreases the number of bit that convey information. For our blind watermarking system, we use every coefficient pairs to embed one bit watermark. So repetition factor and 2 should divide Cap_{total}, the private watermarking capacity, to obtain the robust and blind watermarking system payload.

2.3 Watermarking embedding

Watermark embedding is achieved by modifying a selected set of DCT coefficients of the image. The selected set is determined by the estimated embedding capacity of a specific image. The payload is obtained by combining JPEG compression and JND perceptual constraint. Input information—in particular, we refer to a binary information assuming values in {0,1}, which is able to convey arbitrarily information—is repeated to enhance robustness. The proposed algorithm inserts watermark in DCT domain of image by modifying selected DCT coefficients, similarly to methods used for image watermarking as introduced by Zhao and Koch[15]. However, their method cannot ensure transparency and reliable retrieval in presence of strong compression. Also, their capacity is very limited and cannot adjust compromisingly among three requirements—transparency, capacity and robustness to JPEG compression. Our new solution allows obtaining the following characteristics, not all of which are available in previous literatures:

- Retrieving the watermark does not require knowledge of the original image.
- The embedded watermark is imperceptible by exploiting visual model.
- It allows embedding information in all suitable coefficients in each block, so higher hiding data rate may be achieved.
- Watermark embedding is combined with the effect of JPEG compression and JND perceptual constraint. So good tradeoff among imperceptibility, capacity and robustness to JPEG compression can be adjusted and achieved.

- The estimate of embedding capacity enable watermarking bit allocation in a determinate way while maintaining consistent watermark retrieval performance.

In order to impose imperceptible changes on the host signal and in the meantime maximize allowable energy to approach the capacity, Watson's frequency HVS model is used to control the change of the DCT coefficient amplitude. As most high frequency coefficients tend to be zero after quantization, especially when the bit rate is low. Watermarks inserted into the high frequencies are vulnerable to JPEG compression, so only the low frequency DCT coefficients to middle frequency components are considered as candidates for data hiding. The coefficients may be used to embed information within a chosen block depend on the payload and the energy profile of the candidates. Any candidate DCT coefficient whose absolute magnitude is less than a threshold T is eliminated. Where T is an empirical threshold for perceptually significant frequency components.

Watermark embedding is implemented as follows:

1. Use the Watson's frequency HVS model and JPEG quality factor Q to estimate the maximal hiding data rate R. (See 2.1 and 2.2) The bit number of the input information should be less than or equal to R.
2. According to Q, decide repetition factor *rept* (odd number). Then every input information bit a_j will be repeated *rept* times to obtain the watermark w_i. Where $a_j \in \{0,1\}, j=1,...,N$

   If $a_j = 0$, then $w_i = -1$

   If $a_j = 1$, then $w_i = +1$

   $i=j+N\times r,\ r=0,1,...,rept-1$

   Allocate all the watermark bits equally to every 8×8 DCT block.
3. Identifying the threshold value for each DCT coefficients, i.e., compute the JND of each 8×8 DCT block by exploiting Watson's model. The variable JND_i denotes the associated JND of coefficient C_i
4. In each 8×8 DCT block, combine every two adjacent coefficients by zigzag scanning order into pairs. Each DCT coefficient pairs, say (C_1, C_2), is embedded 1-*bit* information.
5. The watermark bit w_i is embedded by modifying C_1, C_2 as follows:

   If $w_i = 0$ then $C_1' = C_1 - JND_1$ and $C_2' = C_2 + JND_2$ to make $C_1' < C_2'$

   If $w_i = 1$ then $C_1' = C_1 + JND_1$ and $C_2' = C_2 - JND_2$ to make $C_1' > C_2'$

When $w_i = 0$ (or $w_i = 1$), maybe the relationship $C_1' < C_2'$ ($C_1' > C_2'$) is not achieved after modification. So, we use repetition in the watermark coding to compensate the errors caused by the above factor and by subsequent JPEG compression. Increasing the repetition times can improve watermark retrieval performance. In other words, the repetition factor is increased when there will be greater distortion in subsequent JPEG compression, and decreased when the compression distortion will be less.

2.4 Watermarking retrieval

Watermark retrieval is performed on the DCT domain of image and requires the knowledge of the parameters used in the embedding phase (namely, the length of watermark and repetition times). Those parameters are used to determine the number of the coefficient pairs that are used to hidden watermark bits in every DCT block.

The algorithm executes the following steps:

1. Compute the number of the coefficient pairs in every block *n_block*.
2. In each 8×8 DCT block, combine two adjacent coefficients by zigzag scan order into one pairs (C_1', C_2') to extract 1-*bit* watermark. Extract totally *n_block* watermark bits from every 8×8 block.
3. The watermark bit w_i is extracted by comparing the relationship of C_1', C_2' as follows:

   If $C_1' < C_2'$ then $w_i = 0$

   If $C_1' > C_2'$ then $w_i = 1$
4. Recover the input information a_j:

$$a_j = 1, \text{ if } \sum_i w_i > 0$$

$$a_j = 0, \text{ if } \sum_i w_i < 0$$

$$i = j + N\times r,\ r = 0,...,rept\text{-}1$$

5. RESULT

As we discussed in the previous sections, we can estimate and approach to the highest data rate by combining the watermarking embedding process and JPEG compression coding. The scheme was tested on the standard 256×256 "Flower" and "Elaine" image, showed in Figure 1.

(a)

(b)

Figure1: Original “Flower” image (a) and original image “Elaine” image (b)

Figure 2 shows the watermarked images for "Flower" with the estimated highest data rates which are automatically adjusted for different JPEG quality factors Q=100, 75, 50, 25. The corresponding data rate estimates are 478, 102, 59, 40, respectively. The experimental results show the watermarks are below perceptual detection when the embedding information achieves the highest estimate data rates. The error bit rates are 0.21%(1 bit), 0.98%(1 bit), 0, and 0, respectively in these four cases. The experimental results show we can allocate determinate number of watermark bits according to the estimate capacities to survive desired levels of JPEG compression with excellent image qualities, i.e., we know how much information embedded in a specific image will survive what degree JEPG compression. This feature can be used for watermark bit allocation in multimedia incorporated watermarking. We suggest the hiding data rate should be a little less than the estimated highest data rate to have better data extraction performance (correct retrieval).

(a) (b)

(c) (d)

Figure 2: Four watermarked “Flower” images that achieve highest hiding data rate corresponding different JPEG compression quality factors. (a): Q=100, (b): Q=75, (c): Q=50, (d): Q=25.

Another aspect we address is to attain good image quality and low error bit rates for fixed watermark date rate. For the protection of intellectual property rights, it seems reasonable to assume that one wants to embed an amount of information similar to that used for ISBN, international Standard Book Numbering (roughly 10 digits) or better ISRC, International Standard Recording Code (roughly 12 alphanumeric letters). On top of this, one should also add the year of copyright, the permissions granted on the work, and the rating for it. This means that about 60~70 bits of information should be embedded in the host data. A typical value of 64 bits, which has been proposed in the JPEG2000 standard, corresponds to the length of standard copyright-identifiers used in many fields of electronic market. We choose 64 bits to watermark 256×256 standard test image "Elaine" (Figure1. (b)). The results are illustrated in Table 1. The Q is JPEG compression quality factor and R is the estimate highest hiding data rate. When the practical embedding date rates of watermark are lower than the bounds, the watermarks can be retrieved correctly. Otherwise the error bit rates may increase accordingly with the decrease of estimate capacity.

Q	R	Error		PSNR
		bits	%	
100	431	0	0	42.31
95	266	0	0	41.24
90	182	0	0	40.19
85	141	0	0	39.78
80	116	0	0	38.80
75	99	0	0	37.68
70	86	0	0	36.99
65	77	0	0	36.18
60	69	0	0	35.41
55	63	1	1.56	34.83
50	58	0	0	34.31
45	54	13	20.31	33.37
40	50	3	4.69	33.03
35	46	5	7.81	32.64
30	44	11	17.19	31.93
25	41	10	15.62	31.48
20	39	10	15.62	31.09
15	37	18	28.12	30.65
10	35	16	25	30.46

Table 1: The measures of "Elaine" image watermarked with 64 bits corresponding different JPEG quality factor Q

6. DISCUSSION

We have presented an oblivious image-adaptive watermarking scheme that exploits visual model and jointly considers watermarking and JPEG compression to adaptively achieve proper trade-off among imperceptibility, capacity and robustness to JEPG compression. Since a JND paradigm is used in embedding process to maximize the watermark strength, algorithm should be robust to any fade-like attacks. Our algorithm design is based on assuming that the watermarked image inevitably undergoes JPEG compression prior to watermark extraction, so unlike compressed data domain watermarking, is not sensitive to re-encoding. Experiments appear that efficient and robust data hiding methods can result from the joint study of hiding and perceptual coding. This idea can be extended to video/audio watermarking. The scheme gives image-dependent payload estimates that are useful for watermarking bit allocation among different media when multimedia incorporated watermarking is desirable, which will be discussed in another paper.

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