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ABSTRACT

We describe effective channel coding strategies which can be used in conjunction with linear programming optimization techniques for the embedding of robust perceptually adaptive DCT domain watermarks. The main contributions lie in the proposal of a coding strategy based on the magnitude of a DCT coefficient, the use of turbo codes for effective error correction, and finally the incorporation of JPEG quantization tables at embedding.

1. INTRODUCTION

The idea of using a robust digital watermark to detect and trace copyright violations has stimulated significant interest among artists and publishers in recent years. In order for a watermark to be useful it must be robust to a variety of possible attacks by pirates. These include robustness against compression such as JPEG, scaling and aspect ratio changes, rotation, cropping, row and column removal, addition of noise, filtering, cryptographic and statistical attacks, as well as insertion of other watermarks. In this publication however, we consider only attacks that do not change the geometry of the image.

Much work has been been done in the now relatively mature field of DCT domain watermarking. The most recent work involves sophisticated masking models incorporating brightness, frequency and contrast which have been used in combination with an embedding into 8x8 DCT blocks [1, 2]. With few exceptions, the work in watermarking has involved a one bit watermark. That is, at detection a binary decision is made as to the presence of the watermark most often using hypothesis testing [3]. Barni [4] encodes roughly 10 bits by embedding 1 watermark from a set of 1000 into the DCT domain. The recovered watermark is the one which yields the best detector response. In practice however, many more applications are possible when the watermark length is of the order 80 bits since this allows for a unique identifier specifying the owner and buyer of an image as well as possibly indicating the type of content in the image. Such schemes are much more flexible, but the problem is more challenging.

In [5] we propose a flexible framework in which we demonstrate how to optimally embed a transform domain watermark given the constraints imposed by a given mask in the spatial domain. This framework overcomes the problems with many proposed algorithms which adopt a suboptimal spatial domain truncation or modulation as determined by masking constraints which leads inevitably to the degradation of the watermark in the transform domain. In this paper, we present recent results which demonstrate that by an appropriate coding strategy, we can significantly improve results. Furthermore, we also demonstrate how to include JPEG Quantization tables as *a priori* information in the embedding. In section 2 we review the embedding algorithm proposed in [5] and then in section 3 we present a new coding strategy. In section 4 we present our results followed by the conclusion in section 5.

2. PROBLEM FORMULATION

We assume that we are given an image to be watermarked denoted $\boldsymbol{I}$. If it is an RGB image we work with the luminance component. We are also given a masking function $\boldsymbol{V}(\boldsymbol{I})$ which returns 2 matrices of the same size of $\boldsymbol{I}$ containing the values $\Delta_{pi,j}$ and $\Delta_{ni,j}$ corresponding to the amount by which pixel $I_{i,j}$ can be respectively increased and decreased without being noticed. We note that these are not necessarily the same since we also take into account truncation effects. That is pixels are integers in the range $0-255$; consequently it is possible to have a pixel whose value is 1 which can be increased by a large amount, but can be decreased by at most 1. The function $\boldsymbol{V}$ can be a complex function of texture,luminance, contrast, frequency and patterns. We wish to embed $\boldsymbol{m} = (m_1, m_2 ... m_M)$ where $m_i \in \{0, 1\}$ and M is the number of bits in the message. Without loss of generality we assume the image $\boldsymbol{I}$ is of size 128×128 corresponding to a very small image. For larger images the same procedure is adopted for each 128×128 large block. To embed the message, we first divide the image into 8×8 blocks and perform the DCT. In order to embed a 1 or 0 we respectively increase or decrease the DCT coefficient so that at decoding, we take the sign of the DCT coefficient and apply the mappings $(+ \rightarrow 1)$,$(- \rightarrow 0)$. In order embed the largest possible values while satisfying masking constraints, the problem is formulated for each 8x8 block as a constrained optimization problem. For each block we select 2 mid-frequency coefficients in which we will embed the information bits. We then have:

$$\min_{\boldsymbol{x}} \boldsymbol{f}'\boldsymbol{x} \qquad ; \qquad \boldsymbol{Ax} \leq \boldsymbol{b} \tag{1}$$

where $\boldsymbol{x} = [x_{11} \ldots x_{81} x_{12} \ldots x_{82} \ldots x_{18} \ldots x_{88}]^t$ is the vector of DCT coefficients arranged column by column. $\boldsymbol{f}$ is a vector of zeros except in the positions of the 2 selected coefficients where we insert a (-1) or (1) depending on whether we wish to respectively increase or decrease the value of a coefficient. $\boldsymbol{Ax} \leq \boldsymbol{b}$ contain the constraints which are partitioned as follows.

$$\boldsymbol{A} = \begin{bmatrix} IDCT \\ ----- \\ -IDCT \end{bmatrix} ; \quad \boldsymbol{b} = \begin{bmatrix} \Delta_p \\ ----- \\ \Delta_n \end{bmatrix} \tag{2}$$

where IDCT is the matrix which yields the 2D inverse DCT transform of $\boldsymbol{x}$ (with elements of the resulting image arranged column by column in the vector). We also note that we take Δ_p and Δ_n to be column vectors where the elements are taken column wise from the matrices of allowable distortions. Stated in this form the problem is easily solved by the well known Simplex method. Stated as such the problem only allows for spatial domain masking, however many authors [6] suggest also using frequency domain masking. This is possible by adding the following constraints:

$$\boldsymbol{L} \leq \boldsymbol{x} \leq \boldsymbol{U} \tag{3}$$

Here $\boldsymbol{L}$ and $\boldsymbol{U}$ are the allowable lower and upper bounds on the amount by which we can change a given frequency component. The Simplex method can also be used to solve the problem with added frequency domain constraints.

We note that by adopting this framework, we in fact allow *all* DCT coefficients to be modified (in a given 8x8 block) even though we are only interested in 2 coefficients at decoding. In words, we are "making space" for the watermark in an optimal fashion by modifying elements from the orthogonal complement of the coefficients we are interested in, while satisfying spatial domain constraints.

3. CHANNEL CODING

Rather than coding based on the sign of a coefficient as in [5], we propose using the magnitude of the coefficient. To encode a 1 we will increase the *magnitude* of a coefficient and to encode a 0 we will decrease the *magnitude*. At decoding a threshold T will be chosen against which the magnitudes of coefficients will be compared. The coding strategy is summarized in table 1 where c_i is the selected DCT coefficient. The actual embedding is performed by setting $\boldsymbol{f}$ in equation 1 based on whether we want to increase or decrease a coefficient.

Table 1. Magnitude Coding

sign(c_i)	bit	Coding
$+$	0	decrease c_i (set $\boldsymbol{L}$ to stop at 0)
$-$	0	increase c_i (set $\boldsymbol{U}$ to stop at 0)
$+$	1	increase c_i
$-$	1	decrease c_i

The major advantage of this scheme over encoding based on the sign is that the image is no longer treated as noise. As noted by Cox [7] this is an important characteristic of the potentially most robust schemes since all *a priori* information is used . Clearly the best schemes should not treat the image as noise since it is known at embedding. However most algorithms in the literature do not take advantage of this knowledge except in the extraction of perceptual information. In our case, based on the observed image DCT coefficient we encode as indicated in table 1. At decoding the image is once again not noise since it contributes to the watermark.

It is also possible to incorporate JPEG quantization tables into the model in order to increase the robustness of the algorithm. Assume for example that we would like to aim for resistance to JPEG compression at quality factor 10. Table 2 contains the threshold value below which a given DCT coefficient will be set to 0. In order to improve the performance of the algorithm we can add bounds based on the values in table 2 to the amount by which we increase a coefficient. In particular, if we wish to embed a 1 we need only increase the magnitude of a coefficient to the threshold given in table 2 in order for it to survive a JPEG compres-

Table 2. JPEG thresholds at quality factor 10

30	30	30	40	60	100	130	130
35	35	35	50	65	130	130	130
40	35	45	45	65	130	130	130
40	45	60	75	130	130	130	130
50	55	95	130	130	130	130	130
60	90	130	130	130	130	130	130
125	130	130	130	130	130	130	130
130	130	130	130	130	130	130	130

sion at quality factor 10. This is accomplished by setting the bounds $\boldsymbol{L}$ and $\boldsymbol{U}$. Since 2 bits are embedded per block, the remaining energy may be used to embed the other bit. It is important to note that it may not be possible to achieve the threshold since our visibility constraints as determined by $\boldsymbol{V}$ in the spatial domain must not be violated, however the algorithm will embed as much as much energy as possibly via the minimization in equation 1. We note that we choose only to embed the watermark in randomly chosen coefficients where the value in table 2 is less than 70 since for larger values we will require more energy to be sure that the coefficient survives at low JPEG compression. We avoid the 4 lowest frequency components in the upper left hand part of the DCT block since these tend to be visible even with small modifications.

4. RESULTS

The algorithm was tested on several small images of size 128x128. Prior to embedding the 80 bit message, we first append a 20 bit checksum and then encode the message using turbo codes [8] to yield a binary message of length 512. Turbo codes provide near optimum performance and are consequently superior to other codes used currently in watermarking (mostly BCH and convolution). The 20 bit checksum is essential in determining the presence of the watermark. At detection if the checksum is verified we can safely say (with probability $\frac{1}{2^{20}}$ of error) that a watermark was embedded and successfully decoded. The simple masking function of luminance and texture in [5] was adopted. Our results indicate that the algorithm is robust down to a level of 10% quality factor and is resistant as well to low and high pass filtering. This is a significant improvement over [5] which was resistant to a quality factor of 30%. Work is currently under way to apply the ideas of [9] so as to make the algorithm resistant to geometric changes as well.

5. CONCLUSION

In this article we have described channel coding techniques for optimizing the algorithm proposed in [5]. The central contributions lie in the proposal of a coding scheme based on magnitude coding, the incorporation of JPEG quantization tables, and the introduction of turbo codes for added robustness. A key feature of the algorithm is that the image is no longer treated as noise at embedding. While the method has been optimized for JPEG compression the ideas are currently being extended to the wavelet domain for resistance to wavelet compression schemes proposed in the JPEG2000 standard.

6. REFERENCES

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