PERCEPTUALLY BASED WATERFILLING FOR WATERMARKING

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ABSTRACT

We present a common ground between information theoretic and perceptually based approaches to watermarking. A perceptually based iterative waterfilling algorithm that achieves information theoretic watermarking capacity within perceptual distortion constraints is proposed. Image watermarking is considered for experimental analysis. Experimental results are presented to explain how the proposed algorithm achieves a trade-off between information theoretic capacity, robustness and perceptual distortion. Some general observations about the visual quality of an image and its information theoretic capacity are also made.

1. INTRODUCTION

Information theory has been a valuable tool in studying watermarking problems. Its applications include definition of watermarking capacity [1,2], capacity computation for watermarking channels [1,2,3], definition of watermarking security and many more. Many rich set of mathematical models and tools form the basis of information theoretic studies of watermarks. A parallel approach to watermarking is perceptually based [4,5]. Perceptual models take into consideration the human audio-visual system while information theoretic approaches do not attempt this. Therefore there has been this debate about the pros and cons of information theoretic versus perceptually based approaches to studying watermarking.

Based on statistical models for the watermark signal, host signal and attacks (if any), information theory predicts the maximum amount of watermark information that can be embedded in a host signal. Therefore, a wide class of host signals that have similar statistical characteristics will be treated the same way in this method. While this is helpful in computing the mathematical capacity for this class of signals, it must be noted that the individual signals in this class may themselves possess significantly different perceptual characteristics. Since, for many watermarking applications perceptual distortions must be kept a minimum, the information theoretic capacity may not be accurate from a perceptual sense. Therefore, it is argued by practitioners that information theoretic methods may not be very helpful from a perceptually based real-life application perspective, especially in terms of watermarking capacity. We note with caution that perceptual metrics are themselves controversial and not unique. Moreover, to compute the watermarking capacity from a perceptual point of view, each host signal has to be treated separately thus making this process tedious. It is our opinion that (arguably) perceptual metrics lack the generalization capability of information theory.

This paper is an attempt to investigate a common ground between information theoretic and perceptually based watermarking approaches. Towards this attempt, the information theoretic waterfilling [6] idea is extended to perceptually based image watermarking. We believe that the same idea can be extended to audio and video watermarking also. Traditionally, waterfilling deals with optimally allocating energy for various sub-channels in a communication system that operates under a total energy constraint [6] such that capacity is achieved. Independence of the sub-channels is a typical assumption during this process. In this paper, we propose an iterative waterfilling algorithm for image watermarking that computes the watermark energy allocation based on a perceptual criterion for the various sub-channels derived from an image such that the information theoretic watermarking capacity is achieved.

The paper is organized as follows. Section 2 describes the watermarking capacity computation and the proposed perceptually based waterfilling algorithm that achieves the capacity. Experimental results are given in Section 3 followed by concluding remarks in Section 4.

2. CAPACITY AND PERCEPTUALLY BASED WATERFILLING

In this section we first describe the watermark embedding technique and watermarking capacity for a parallel watermark channel model followed by the proposed waterfilling algorithm.

2.1 Watermark Embedding and Capacity

We employ a variation of the spread-spectrum watermark [8] in the spatial domain and assume blind watermark detection where the detector has access to the watermarking key and other relevant side information. Therefore, the watermark channel

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uncertainty consists of the host image and other attacks. For the current treatment, we ignore uncertainties due to attacks since our primary aim is to introduce a technique that utilizes information theoretic and perceptual analysis in watermark embedding; however, we note that any attack(s) on the watermark can be incorporated into the proposed analysis via appropriate mathematical models without much additional effort.

Before embedding the host image is first partitioned into non-overlapping blocks and without loss of generality let $X_t = \{x_1, x_2, ..., x_L\}$ denote the local mean subtracted pixel values in such a block, $t = 1,2,...N$. Further, let $x_i \sim \mathbf{N}(0,\sigma_k^2)$ be Gaussian distributed. If block k is chosen for embedding, then,

$$y_i = x_i + w_i, \quad i = 1,2,...,L \tag{2.1}$$

where $w_i \sim \mathbf{N}(0,\gamma^2_k)$ is a zero-mean, Gaussian distributed watermark with variance γ^2_k. Note that each watermarked block here can have a different watermark energy or variance. The embedding in Eq. (2.1) is implemented using the following equivalent form,

$$y_i = x_i + \alpha_k \tilde{w}_i \tag{2.2}$$

where $\tilde{w}_i \sim \mathbf{N}(0,1)$ and α_k is a scale parameter that determines the watermark energy for that block, k. If M out of the N blocks are selected for watermark embedding, then treating this as M independent parallel channels, it can be shown that [6] the watermarking capacity is given by

$$C = \frac{1}{2}\sum_{k=1}^{M}\log_2\left(1 + \frac{\gamma^2_k}{\sigma^2_k}\right) \tag{2.3}$$

where $\sum_{k=1}^{M}\gamma^2_k \le E$ is the total watermark energy constraint.

The questions we ask now are the following:

- Which blocks to choose for watermark embedding from a perceptual perspective such that capacity is achieved?
- What must be the watermark energy allocated to the chosen blocks given a total energy constraint?

We answer these two questions in the next subsection using an iterative waterfilling idea based on information theoretic and perceptually based arguments.

2.2 Perceptually Based Waterfilling

Perceptually based watermarking [5] predicts that features of an image that are perceptually significant must be chosen for watermark embedding. The just noticeable difference criterion is usually used for this purpose. This criterion is typically computed in the transform domain. The discrete cosine transform based spread spectrum watermarking [8] technique embeds watermark in the mid-frequency components that are perceptually significant. In [5] transform coefficients that pass a threshold test based a perceptual model are selected for watermark insertion.

In most perceptually based watermarking methods, the notion of capacity achieving embedding has not been considered. Reasons for this include the following:

- Unlike information theoretic capacity, there seems to be no closed form solution to the *perceptual watermarking capacity.*
- A good perceptual metric is itself an active area of research.
- Different perceptual metrics could give rise different notions of perceptual capacity.

Therefore, the natural question to ask this stage is: can we use the information theoretic capacity measure in conjunction with a perceptual metric such that capacity is achieved? We show that this is possible and the solution is consistent with both information theory and perceptual studies.

First we make some key observations. Note that the capacity formula in Eq. (2.3) is based on the total watermark energy constraint, E. What is as good value for E? Since information theory does not provide insights in choosing this value we resort to perceptual criterion. Heuristically, if E is large then the capacity is also large and the watermark is robust against attacks at the expense of increased perceptual distortion. On the other hand, a small value of E results in a smaller perceptual distortion, smaller capacity and not so robust watermark. Note that E is also image dependent. Therefore, we parametrize E and computed its value iteratively for a given image such that capacity is maximized within perceptual distortion constraints. To achieve this goal we again resort to information theory and use the following capacity achieving result [6]:

$$\gamma^2_t = \begin{cases} T - \sigma^2_t, & \text{if } \sigma^2_t < T \\ 0, & \text{if } \sigma^2_t \ge T, \ t = 1,2...N \end{cases} \tag{2.4}$$

Note that N-M of the γ_t's will be equal to zero if only M image blocks are chosen for watermark embedding. Eq. (2.4) is the basis of the waterfilling algorithm which chooses T and optimally fills the sub-channels with appropriate watermark energy such that $\sum_{k=1}^{M}\gamma^2_k$ is maximized. We choose the threshold T based on a perceptual criterion given in [7] such that the overall distortion is acceptable. We can interpret this threshold as the maximum perceptual distortion that can be accommodated by any image block. If the local variance of an image block is less than this threshold then it is chosen for watermark embedding and the energy of the watermark is the difference between this threshold and the local variance of the host image block. If the local variance is greater than or equal to the threshold then that block is not chosen for embedding as it will violate the perceptual distortion constraint. Since there seems to be no straightforward way of computing T, we use an iterative algorithm that iterative perturbs T in small steps and stops when the maximum allowable perceptual distortion metric computed using the method proposed in [7] is reached after energy allocation according to Eq. (2.4) at each step. Obviously, the watermark energy allocation also changes with each iteration and converges to the optimal allocation when the iterative algorithm converges. We note here that the value of E is not fixed *a priori*. This is because there seems to be no clear way of fixing this value. Instead the final value of E is computed as the sum of the watermark energies in the individual sub-channels once the iterative waterfilling algorithm converges. The steps involved in the perceptually based waterfilling algorithm that achieves watermarking capacity from a perceptual perspective is given as follows:

Perceptually Based Iterative Waterfilling Algorithm:

Set an arbitrary initial threshold T_0.
Let i=1.

Step 1:
Embed the Gaussian distributed watermark with zero mean and scale factor α_k based on γ_k computed using Eq. (2.4)

Step 2:
Compute the maximum allowable distortion metric using the transform domain based method given in [7] for the resulting image obtained in the Step 1.

Step 3:
If the maximum allowable perceptual distortion metric is attained then stop, else, i=i+1 and,
if current perceptual distortion > max. allowable
$T_i = T_{i-1} - \varepsilon$
else $T_i = T_{i-1} + \varepsilon$ for some small $\varepsilon > 0$
Go to Step 1 using T_i.

The theoretical convergence of this algorithm will be presented in the final version of the paper. But, our simulation results are observed to always converge for various values of T_0. We observed through experiments that a good choice for T_0 for faster convergence is given by the median value of the variances of the image blocks.

3. EXPERIMENTAL ANALYSIS

For the experimental analysis of the proposed algorithm, 25 images were chosen carefully so that they exhibit a wide variety of image characteristics. Image samples included those with dark backgrounds, light backgrounds, highly textured features, contrasting letters over the background, and paintings. The proposed watermark energy computation technique was tested on these 25 images. We present the results obtained for two images *Fish* and *Lena* here due to space limitations.

The image block size was chosen to be equal to 8x8. Figures 1 and 2 show the individual block variances overlapped with the final threshold T in Eq. (2.4) computed using the iterative algorithm. We observe in these figures that those blocks that have a large variance (e.g., more textured) tend to surpass the threshold and hence the watermark energy in these blocks are set to zero according to Eq. (2.4). This observation is also consistent with the perceptual metric as explained in the next paragraph.

Figures 3 and 4 show the result of the proposed perceptually based waterfilling algorithm. The smooth regions in the images are captured for watermark embedding and energy allocation amongst these blocks are done in an optimal way so that capacity and imperceptibility are achieved simultaneously. For example, in Figure 4, the blocks corresponding to the hair of Lena are not chosen for watermark embedding as these do not correspond to perceptually significant regions for a fixed global threshold. At first this may seem to contradict some of the conventional thinking such as texture based watermarking. But this phenomenon can be justified using both information theoretic and perceptual arguments. From an information theoretic perspective the watermarking channel (image block) corresponding to a smooth or uniform region has a low variance. Therefore in Eq. (2.3) the value of σ_k^2 corresponding to such a block is small thereby increasing the watermarking capacity of that channel. Also, from a perceptual perspective the human visual system is perceptually insensitive to an image block with low variance (e.g., somewhat smooth regions) and blocks that are uniformly bright or dark [9]. Therefore the proposed technique chooses these blocks and adjusts the watermark strength accordingly so that the watermark is rendered imperceptible. This observation is consistent with previous research [9]. Finally we note that robust watermarking algorithms [9] choose low to mid-frequency ranges for embedding which is also consistent with our results.

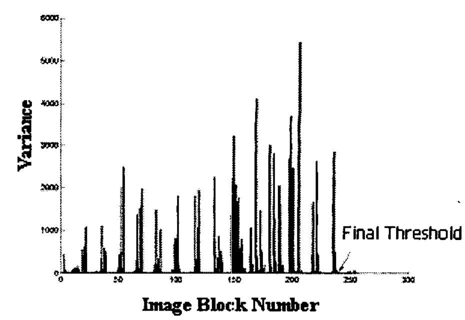

Figure 1: Result of proposed waterfilling algorithm for Fish image.

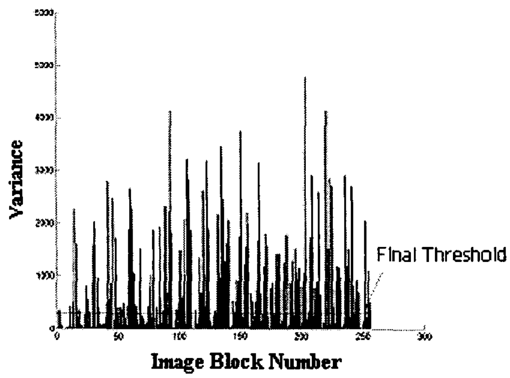

Figure 2: Result of proposed waterfilling algorithm for Lena image.

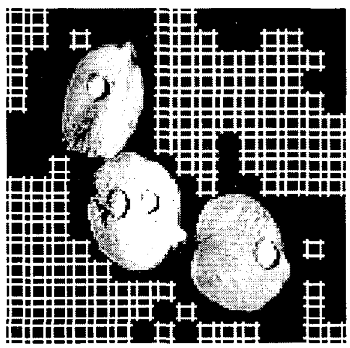

Figure 3: Watermarked blocks for the Fish image are shown as white squares. These blocks and the watermark energy were chosen based on the proposed iterative waterfilling algorithm.

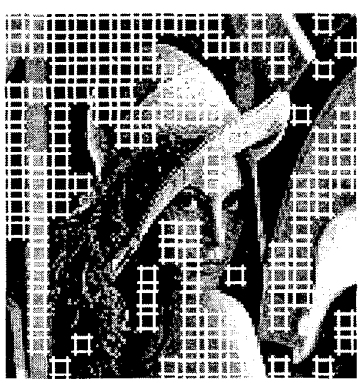

Figure 4: Watermarked blocks for the Lena image are shown as white squares. These blocks and the watermark energy were chosen based on the proposed iterative waterfilling algorithm.

4. CONCLUSION

A common ground between information theoretic and perceptually based watermarking has been identified. A perceptually based iterative waterfilling algorithm is presented that maximizes information theoretic watermarking capacity taking into consideration perceptual distortion constraints. This algorithm provides an automatic way of choosing features of a host signal that qualify for watermark embedding and allocated watermark energy optimally amongst the chosen features to achieve imperceptibility. Experimental results are provided for image watermarking. These results show that the proposed method produces answers to some key watermark embedding questions that are consistent both in an information theoretic and perceptual sense.

5. REFERENCES

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