IMPROVED CONTROL FOR LOW BIT-RATE REVERSIBLE WATERMARKING

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ABSTRACT

The distortion introduced by reversible watermarking depends on the embedding bit-rate. This paper proposes a fine control of the embedding bit-rate for low capacity histogram shifting reversible watermarking. The basic idea of our approach is to split the prediction error histogram into several histograms and to ensure the fine tuning of the bit-rate by selecting the appropriate bins for each histogram. The splitting is performed as a function of the prediction context. The bins (two for each histogram, one for the right side, another for the left side of the histogram) are selected by linear programming in order to minimize the distortion introduced by the watermarking. The proposed scheme outperforms in terms of embedding distortion the prior state of the art.

Index Terms— reversible watermarking, histogram shifting, low bit-rate, bit-rate control

1. INTRODUCTION

Reversible watermarking completely removes the watermark and exactly recovers the original signal/image. Its usefulness is in media annotation, covert communication, authentication, etc. Since the distortion introduced by the watermarking depends on the embedding bit-rate, a problem of interest in reversible watermarking is the fine control of the bit-rate to strictly match the requirements.

We have recently investigated the problem of bit-rate control for difference expansion reversible watermarking [1]. The classical control of difference expansion reversible watermarking is the threshold control scheme, i.e. only differences lower than a predefined threshold are used for data embedding. The threshold control does not provide fine tuning of the embedding capacity. In [1], the pair of two consecutive thresholds that bounds the desired capacity are found. Then a threshold is used for marking a part of the image and the other one for marking the remaining part of the image so that the desired capacity is obtained at the cost of a minimum distortion.

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At low capacity, i.e., for embedding capacities between the ones provided by the two lowest thresholds of the difference expansion scheme, it appears that histogram shifting schemes provide better results. This made us investigate the problem of capacity control for histogram shifting (HS) reversible watermarking.

We remind that HS reversible watermarking originates in the work of Ni et al., [2]. In the original approach, a gap is created near the most populated histogram bin by shifting certain image graylevels with one position. The pixels of the most populated histogram bin are further used to encode a bit of data. More precisely, they are kept unchanged when a bit of ”0” should be encoded, or flipped into the free graylevel to encode a ”1”. The capacity provided in a single embedding level is of the order of the most populated bin of the histogram. Since image histograms are rather evenly distributed, the embedding capacity provided in a single embedding level is low. In order to gain in embedding capacity, the straight embedding into image histogram was replaced with the embedding into sharper histograms with prominent peaks. This is the case of Laplacian distributed histograms as the one of the difference between adjacent pixels [3], prediction error histograms [4, 5, 6, 7], etc., or interpolation error histograms [8]. The better the prediction, the sharper the histogram and the higher the embedding bit-rate. In fact, both the first and the second peaks are usually simultaneously embedded [4].

The HS algorithms are very interesting for low bit-rates since they provide very low embedding distortion. More precisely, pixels are shifted with at most one graylevel. This is true for capacities of the order of the ones provided in the first level of embedding. At such embedding bit-rates, as said above, the HS schemes outperform their corresponding DE schemes.

The case when the required embedded bit-rate is less than the one provided in a single embedding level was investigated in [9]. The scheme does not embed into the two maximum bins, but into the ones that ensure the needed capacity. The two bins are selected in order to minimize the distortion introduced by the watermarking. The paper of [9] does not provide implementation details. This paper refines the tuning of the embedding capacity and offers practical solutions for the implementation. The basic idea of our approach is to

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split the prediction error histogram in several histograms and to ensure the fine tuning of the embedding capacity by selecting the appropriate bins for each histogram. The splitting is performed as function of the prediction context. The bins (two for each histogram, one for the left side of the prediction error histogram, another for the right side of the prediction error histogram) are selected by linear programming in order to minimize the global watermarking distortion. The proposed scheme outperforms in terms of embedding distortion the scheme of [9].

The outline of the paper is as follows. The principle of the histogram shifting reversible watermarking is briefly reviewed in Section 2.1 and the proposed control scheme is presented in Section 2.2. Experimental results on standard graylevel images are presented in Section 3. The conclusions are drawn in Section 4.

2. IMPROVED BIT-RATE CONTROL OF HS

First we briefly review the basic principles of the HS reversible watermarking. Then we present the proposed scheme for bit-rate control.

2.1. Histogram shifting reversible watermarking

The HS reversible watermarking considers the histogram of a pixel based feature as, for instance, the prediction error. Let e be the prediction error. The embedding of one data bit into each pixel where the prediction error is equal to a predefined value t is done by creating a gap in the histogram either at $e = t+1$ or at $e = t-1$. If the gap is created at $t+1$, the pixels having the prediction error greater than t are increased with one graylevel. Consequently, the prediction error of these pixels increases with one graylevel. Alternatively, for $t-1$, the pixels having the prediction error less than t are decreased with one graylevel. The embedding is done by adding (subtracting) the bits to be embedded from the pixels with $e = t$. Thus, the modified prediction error when the bit to be embedded is $b = 1$ takes exactly the value corresponding to the gap. More precisely, the image is scanned pixel by pixel and each pixel is modified as follows:

$$x' = \begin{cases} x + b & \text{if } e = t \text{ and } t \geq 0 \\ x + 1 & \text{if } e > t \text{ and } t \geq 0 \\ x - b & \text{if } e = t \text{ and } t < 0 \\ x - 1 & \text{if } e < t \text{ and } t < 0 \end{cases} \tag{1}$$

Let H be the prediction error histogram. By embedding into the pixels having the prediction error t, an embedding capacity of $H(t)$ bits is obtained. The cost is the distortion introduced by the embedding of the data bits and by the shifting of pixels (in order to create place for embedding). The embedding distortion appears only when the bit to be embedded is equal to one, i.e. in about half of the cases. The total embedding error is $H(t)/2$. Depending on the position of the gap (on $t-1$ or on $t+1$), the shifting error is either $\sum_{i<t} H(i)$ or $\sum_{i>t} H(i)$. The shifting error is minimized by selecting the location of the gap according to the prediction error histogram. Since the prediction error has a Laplacian distribution, it is reasonable to assume that if $t > 0$, the minimum is obtained for shifting the histogram to the right and similarly, if $t < 0$, the minimum appears for shifting to the left.

When high embedding capacity is needed, either one considers for t the maximum bin of the histogram, or one almost doubles the capacity by considering for embedding, in the same stage, both the maximum and the second largest bins [4]. For Laplacian distribution, the largest bin is $H(0)$ and the second largest bin is either $H(-1)$ or $H(1)$. In fact, due to symmetry, $H(1) \approx H(-1)$.

At low embedding capacity, the embedding into the maximum and the second largest bins can provide extra capacity at the price of a supplementary distortion. Obviously, the idea is to select for embedding two bins that provide exactly the needed capacity and meantime, while minimizing the total embedding distortion. Since the prediction error histogram has one sharp maximum, a good choice is to select one bin from the left side of the prediction error histogram, l, with the corresponding gap at $l-1$ and another from the right side of the prediction error histogram, r, with the corresponding gap at $r+1$. The selection for embedding of one bit from the left and and one from the right side of the prediction error histogram is motivated by the fact that only the tails of the prediction error histogram should be shifted. The pixels with prediction errors in $e \in (l, r)$ do not introduce any error. Let $C_{l,r}$ be the embedding capacity obtained by using l and r and let $E_{l,r}$ be the corresponding square error. One has:

$$C_{l,r} = H(l) + H(r) \tag{2}$$

and

$$E_{l,r} = \frac{H(l) + H(r)}{2} + \sum_{i<l} H(i) + \sum_{i>r} H(i) \tag{3}$$

Let c be the required capacity. The problem of parameter selection is to find l and r in order to ensure:

$$C_{l,r} \geq c \tag{4}$$

and

$$\min_{l,r} \left(\frac{H(l) + H(r)}{2} + \sum_{i<l} H(i) + \sum_{i>r} H(i) \right) \tag{5}$$

The upper bound of $C_{l,r}$ is provided for $l = -1$ and $r = 0$, i.e., the capacity provided by the classical scheme [4] in the first embedding level.

The embedding into two bins from the left and right sides of the prediction error histogram was proposed in [9], but no practical solution has been given for the selection of the two bins. Obviously, once the prediction error histogram is computed, one can test all the combinations (l, r) in order to select the one that fulfils equations (4), (5).

A suboptimal solution could be the following. The scheme starts with the lowest bin from one side of the histogram, let it be the left side. If the lowest bin from the left does not satisfy the capacity, it considers also the lowest bin from the right side of the histogram. If the capacity of the two bins is still not enough, it alternatively advances one step from the left, one step from the right and so on until there is enough capacity. Thus the required capacity is provided at a low cost, namely the shift with one position of the right and left tails of the histogram.

2.2. Proposed capacity control

In [9], experimental results are provided for MED and GAP predictors. Instead of embedding by using directly the prediction error histogram produced by MED or GAP, we first split the histogram and we embed the data by using the resulted histograms. It should be noticed that, at detection, l and r should be known. Similarly, if the histogram is split, one should know for each pixel the histogram used for embedding, i.e., the corresponding values for l, r.

A natural solution for splitting is the use of the prediction context. Both for marking and detection, the same prediction context exists for each pixel. Hence, the parameters used for marking can be simply recovered at detection. Since MED or GAP are context adaptive predictors, we investigate the use of the same adaptive scheme both for prediction and for histogram splitting.

MED is a very efficient predictor used in JPEG-LS standard [10]. With MED, $\hat{x}$, the estimate of pixel x is:

$$\hat{x} = \begin{cases} \min(a,b), & \text{if } c \geq \max(a,b) \\ \max(a,b), & \text{if } c \leq \min(a,b) \\ a+b-c, & \text{otherwise.} \end{cases} \tag{6}$$

where a, b, c are the right, lower and lower-diagonal neighbors of x. The predictor tends to select b in cases where a vertical edge exists right to the current location, a in cases of a horizontal edge below x, or $a+b-c$ if no edge is detected. MED is used in [9] as in many other schemes [11, 12], etc.

The gradient-adjusted predictor, GAP, is used in CALIC (context-based, adaptive, lossless image coding) algorithm [13]. The GAP predictor is considerably more complex than MED. First of all, the prediction context is extended from 3 to 7 pixels. While MED uses three predictors, GAP uses seven. The detection is based on local gradients and experimentally determined thresholds. The reversible watermarking schemes based on GAP outperform the ones based on MED (see [12]).

With MED, instead of a simple histogram one can consider three histograms, one for each predictor of MED. For the case of GAP, one can use up to 7 histograms.

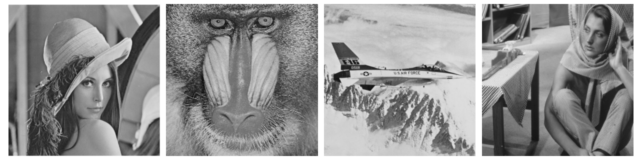

Fig. 1. Standard test images: *Lena, Mandrill, Jetplane* and *Barbara*.

In the general case, let us consider the splitting of the histogram in k histograms H_j, $j = 1, \ldots, k$. One has:

$$H = H_1 + H_2 + \ldots + H_k \tag{7}$$

Furthermore, for each histogram H_j, $j = 1, \ldots, k$, one can determine, as discussed above, two prediction error values, one for the left side (l_j) and the other for the right side (r_j). Equation (2) becomes:

$$C_{l_1, r_1 \ldots, l_k, r_k} = \sum_{j=1}^{k} (H_j(l_j) + H_j(r_j)) \tag{8}$$

Similarly, instead of equation (3), one gets:

$$E_{l_1, r_1, \ldots, l_k, r_k} = \frac{1}{2} \sum_{j=1}^{k} (H_j(l_j) + H_j(r_j)) + \sum_{j=1}^{k} \left(\sum_{i<l_j} H_j(i) + \sum_{i>r_j} H_j(i) \right) \tag{9}$$

The problem of capacity control becomes the finding of the values $l_1, r_1, \ldots, l_k, r_k$ in order to have the desired capacity c. The use of k histograms brings more flexibility. More intermediate values are found than for the case of a single histogram. On the other hand, the selection of the l_i and r_i values becomes more complex. One must select the solution from an exponential solutions space. The problem can be solved by using linear programming. The objective function F is the following:

$$F = \arg \min_{l_1, r_1, \ldots, l_k, r_k} E_{l_1, r_1, \ldots, l_k, r_k} \tag{10}$$

where $l_i < r_i, \forall i = \overline{1, k}$. We impose as constraint the restriction for capacity:

$$C_{l_1, r_1 \ldots, l_k, r_k} \geq c \tag{11}$$

The proposed linear integer model proposed above can be implemented and solved by using a general purpose linear programming solver.

3. EXPERIMENTAL RESULTS

In this section we present the results obtained by using the proposed capacity control scheme. Four standard graylevel

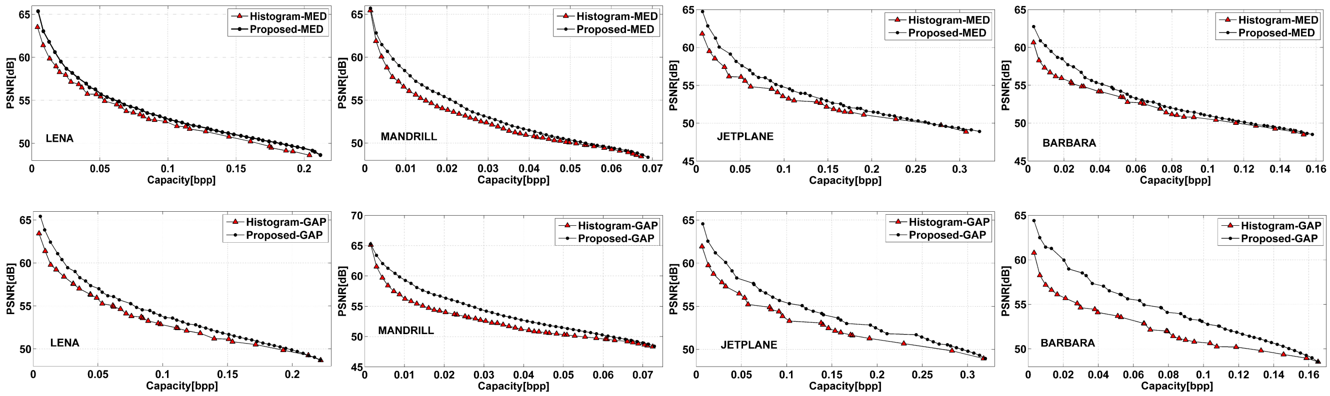

Fig. 2. Experimental results for MED (first row) and GAP (second row).

test images of size 512×512 are considered, namely *Lena, Mandrill, Jetplane* and *Barbara*. The test images are presented in Fig. 1.

The proposed scheme was implemented by using Matlab and Mosel. The Mosel programming language from FICO Xpress MP, [14], was used for the implementation of the linear programming model.

Let us consider first the scheme based on the MED predictor. As said in Section 2.2, the optimization of the parameters is performed on three prediction error histograms. Up to 6 bins can be used for data embedding. The results on three histograms are compared with the ones obtained for optimization on a single histogram as discussed in [9].

Let us consider a simple example. In order to obtain a bit-rate of 0.01 bpp (i.e. an embedding capacity of 2,620 bits) for the test image *Barbara*, one can use the standard histogram shifting with embedding into the maximum bin of the histogram. Instead of the 2,620 bits, one gets almost eight times more embedding space (20,673 bits). The corresponding embedding distortion is 51.49 dB. If instead of embedding into the maximum bin, one consider the embedding into the pair left/right bins of the prediction error histogram that minimizes the embedding distortion one gets for $l = -94$ and $r = 10$ an embedding capacity of 2,620 bits at a PSNR of 57.18 dB. By splitting the prediction error histogram according to the three predictors of MED and by optimizing the selection of the bins, one gets the same capacity, 2,620 bits, but at 60.06 dB. The optimal bins are $r_1 = 4$, $l_2 = -44$ and $r_3 = 70$, where r_1 refers to the prediction error histogram corresponding to the first line of equation (6) and so on. For the same image, the proposed method provides the embedding bit-rate of 0.02 bpp (5,245 bits) bpp by using six thresholds ($l_1 = -61$, $r_1 = 2$, $l_2 = -33$, $r_2 = 62$, $l_3 = -86$ and $r_3 = 70$) at 57.96 dB. The optimization on the global histogram provides 0.024 bpp at 55.42 dB, with about 2.5 dB less than the proposed method.

Comparisons between the proposed method for MED and the straight optimization on the global prediction error histogram are presented in Fig. 2 (first row). As it can be seen, the proposed method outperforms the optimization on a single histogram. The maximum gain in PSNR is 2.00 dB for *Lena*, 2.13 dB for *Mandrill*, 2.93 dB for *Barbara* and 3.62 dB for *Jetplane*.

The plots of Fig. 2 present the results obtained in a single embedding level. It should be noticed that the proposed method provides a slightly larger capacity than the optimization on a single histogram. The gain in capacity is 435 bits for *Mandrill*, 1,264 bits for *Barbara*, 2,105 bits for *Lena* and 4,007 bits for *Jetplane*.

The results obtained for GAP on the same test images are presented in Fig. 3. With GAP, the number of prediction error histograms is extended to 7. This offers more possibilities to select the thresholds and consequently, the gain is greater than the one obtained for MED. For instance, at 0.01 bpp, for the test image *Barbara*, the proposed method selects 10 bins out of the 14 available and provides the required capacity at 61.35 dB. Compared with the result obtained for MED, the gain in PSNR is of 1.29 dB. At 0.02 bpp, one gets 59.98 dB for GAP compared to 57.96 dB for MED. Compared with the direct optimization on a single histogram, the proposed scheme for GAP offers a maximum gain of 2.50 dB for *Lena*, 3.20 dB for *Mandrill*, 3.05 dB for *Jetplane* and 4.68 dB for *Barbara*.

4. CONCLUSIONS

The fine control of histogram shifting reversible watermarking based on context adaptive predictors has been approached by splitting the prediction error histogram in function of the prediction context and by selecting the appropriate bins in order to obtain the desired capacity at a minimum embedding distortion. Examples for the case of MED and GAP based schemes are provided. In a single level of embedding, the proposed scheme provides fine tuning of the embedding capacity and clearly outperforms the straight optimization on the global histogram.

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