AN ADAPTIVE QIM- AND SVD-BASED DIGITAL IMAGE WATERMARKING SCHEME IN THE WAVELET DOMAIN

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ABSTRACT

This paper presents a blind, adaptive quantization index modulation (QIM)- and singular value decomposition (SVD)-based watermarking scheme to embed watermark bits in the approximation subband of the wavelet domain. The QIM technique adaptively determines the quantization step for each embedding block using a statistical model. The SVD technique uses the quantization step to modify the SVs of each embedding block. This modification ensures the SVs of highly textured blocks are largely modified and the SVs of smooth textured blocks are slightly modified. The successive packing interleaving (SPI) scheme and the one-way hashing functions are respectively applied to improve the robustness of the proposed system. A statistical-clustering method is also applied offline to decide two optimal weighting parameters for the QIM technique so the adaptive quantization steps are optimal for all embedding blocks. Experimental results demonstrate our scheme is robust against JPEG compressions down to a level of 20% quality factor. It also performs better than a peer SVD-based wavelet domain watermarking approach.

Index Terms— Watermarking, quantization index modulation, singular value decomposition, wavelet

1. INTRODUCTION

The authentication and copyright protection from unauthorized manipulation of rapidly growing digital images become an essential concern in the digital multimedia era. Digital watermarking, one of the possible viable solutions, has recently attracted considerable attention. Among the several categories of watermarking schemes, we will briefly review two kinds of schemes related to our proposed approach, namely, wavelet-based and singular value decomposition (SVD)-based schemes.

Most wavelet-based watermarking schemes directly embed the watermark bits by modifying the wavelet coefficients at certain locations. For example, Xia *et al.* [1] embed pseudorandom codes to the large coefficients at both high and middle frequency subbands in the wavelet domain. Tsai *et al.* [2] apply the chaotic transformation to select the embedding locations in the wavelet domain. Wei *et al.* [3] introduce a perception-based watermarking technique to embed the watermark in certain wavelet coefficients which lead to small just-noticeable visual distortions. Barni *et al.* [4] incorporate the characteristics of the human visual system (HVS) in a texture and luminance-based mask to decide the embedding positions in the wavelet domain. However, these schemes may be vulnerable to a relatively high compression since the embedded watermark coefficients may be destroyed in the compression process.

Most SVD-based watermarking schemes indirectly embed the watermark bits by modifying the singular values (SVs). For example, Gorodetski *et al.* [5] embed the watermark to the SVs of all small segments of an image in the spatial domain. Liu and Tan [6] embed a watermark (in the form of a matrix) in the SV matrix of an image in the spatial domain. Ganic and Eskicioglu [7] embed the watermark by modifying the SVs of each wavelet subband at horizontal, vertical, and diagonal directions. Bao and Ma [8] embed the watermark to the SVs of all block-based wavelet coefficients in certain subbands. However, most of these SVD-based schemes are non-adaptive and therefore unable to offer a consistent perceptual transparency for different images. Bao's approach [8] tried to solve the non-adaptive issue using the structure (i.e., local mean and standard deviation) of each wavelet block. However, several parameters are empirically determined and may not be suitable for certain categories of images.

In this paper, we design a novel image-adaptive watermarking scheme by applying a quantization index modulation (QIM) process [9] on the SVs of an image in the wavelet domain. The watermark bits are embedded in the SVs in the SVD layers of each block in the approximation subband. The quantization steps are determined to be adaptive to the statistical model of the block. Specifically, a statistical-clustering method is applied offline to learn two optimal weights measuring the contributions of mean and standard deviation of each block. These two weights ensure the adaptive quantization steps are optimal for all embedding blocks. That is, the overall luminance change is perceptually unnoticeable and the watermarked image is robust against the compression attacks. The successive packing interleaving (SPI) scheme and the one-way hashing

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functions are also applied to improve the robustness of the watermarking system. The remainder of the paper is organized as follows: Sections 2 and 3 present the proposed embedding and extraction scheme, respectively. Section 4 demonstrates the experimental results. Section 5 draws conclusions.

2. THE PROPOSED EMBEDDING SCHEME

The proposed watermarking system applies the QIM and SVD techniques to embed watermark bits in the approximation subband of the wavelet domain. Specifically, the QIM technique adaptively determines the quantization step for each block in the approximation subband using a statistical model. A statistical-clustering method is applied offline to decide two optimal weighting parameters to be used by the QIM technique. The SVD technique uses the quantization step to modify the SVs for each block. This modification ensures a high perceptual quality of watermarked image and a low bit error rate (BER) of the extracted watermark. The SPI scheme and the one-way hashing functions are respectively applied to improve the robustness of the watermarking system. This SPI scheme obtains the shuffled and secure watermark bit sequence using a secret key. The one-way hashing functions generate the highly secure embedding positions using two secret keys. The following subsections explain all the components in detail.

2.1. Adaptive QIM- and SVD-Based Embedding

The algorithmic view of the embedding process is described as below:

1. Obtain a wavelet coefficient matrix H by performing a 1-level "db2" wavelet transform on host image h.
2. Partition the approximation subband Ha into non-overlapping blocks B of size 4×4.
3. For each block B_i ($i = 1, 2, \ldots, k$ where k is the total number of blocks in Ha)
    - 3.1 Compute its average value m_{Bi} and standard deviation σ_{Bi}.
    - 3.2 Compute the value w_i, which measures the homogeneity of the block, by:

$$w_i = w_{mean} \cdot m_{Bi} + w_{std} \cdot \sigma_{Bi} \tag{1}$$

   where w_{mean} and w_{std} are the weighting parameters for m_{Bi} and σ_{Bi}, respectively.

4. Find the maximum value $w_{\max}$ and the minimum value $w_{\min}$ for all the w_i's (i = 1, 2, …, k)
5. Apply the SPI scheme [10] on the original watermark bits to obtain the shuffled and secure watermark sequence SWm.
6. Apply a one-way hashing function [11] to generate the highly secure watermark embedding positions (i.e., the indices for the blocks in Ha).
7. For each block $NewB_i$ ($i = 1, 2, \ldots, k$) corresponding to the block sequence generated in step 6.
    - 7.1 Apply SVD to compute its U_i, S_i, and V_i.
    - 7.2 Compute $n_{v_i} = \| v_i \| + 1$, where v_i is a vector formed by the SVs of $NewB_i$. That is, $v_i = \left(\lambda_1^i, \lambda_2^i, \lambda_3^i, \lambda_4^i\right)$ where λ_j^i is the value on the diagonal direction of S_i.
    - 7.3 Compute its quantization step d_i:

$$d_i = d_m + (d_M - d_m) \times \frac{w_i - w_{\min}}{w_{\max} - w_{\min}} \tag{2}$$

   where d_m and d_M are the minimum and maximum quantization step values, respectively. They are empirically decided to be 9 and 45, respectively.

    - 7.4 Compute $C = \lfloor n_{vi} / d_i \rfloor$.
    - 7.5 Embed the i^{th} watermark bit b in SWm by:

```
if b = 1
    if C is an odd number, C = C + 1 ;
    else C remains unchanged.
if b = 0
    if C is an even number, C = C + 1 ;
    else C remains unchanged
```

    - 7.6 Compute the value $n'_{vi} = d_i \times C + d_i / 2$ and the modified SV as:

$$\left(\gamma_1^i, \gamma_2^i, \gamma_3^i\, \gamma_4^i\right) = \left(\lambda_1^i, \lambda_2^i, \lambda_3^i, \lambda_4^i\right) \times n'_{vi} / n_{vi} \tag{3}$$

    - 7.7 Compute the matrix of the block using the modified SV:

$$\widetilde{B}_i = \sum_{j=1}^{w} \gamma_j^i U_j(i) V_j^T(i) \tag{4}$$

8. Reconstruct the watermarked image h' using all the modified blocks $\widetilde{B}_i$.

2.2. Determination of Two Weighting Parameters

An offline learning approach is applied to predetermine two parameters, w_{mean} and w_{std} in (1), so the adaptive quantization steps are optimal for all embedding blocks. We apply a grid search algorithm to find the effective pairs (w_{mean}, w_{std})'s for a set of training images covering a variety of textures ranging from high, medium, low, to extremely low textures. The algorithmic view of this grid search is summarized in Fig. 1. That is, it tests the sequences of w_{mean} ranging from -3 to 3 and the sequences of w_{std} ranging from -6 to 6 with a step size of 0.2. Our proposed watermarking scheme, which uses all possible pairs of (w_{mean}, w_{std})'s to compute (1), is then applied on each image in the chosen training image set to create the watermarked image. Nine compression attacks with quality factors ranging from 20 to 100 are then applied to generate 9 distortions on the watermarked image. The PSNR value of each watermarked image and the average BER value of the watermarks extracted from its 9 attacked watermarked images are used to evaluate the effectiveness of the chosen (w_{mean}, w_{std}) pair.

In general, the larger PSNR value and the smaller average BER value indicate that the smaller visual distortion and the smaller extraction errors are produced when applying compression attacks to watermarked images. Consequently, the corresponding (w_{mean}, w_{std}) pair is more effective.

```
For $w_{mean}$ = -3 : 0.2 : 3  //Grid $x$
  For $w_{std}$ = -6 : 0.2 : 6  //Grid $y$
    1. Embed watermark to host image $h$ using ($w_{mean}$, $w_{std}$) pair to compute (1)
    2. Save the watermarked image
    3. Compute its PSNR value
    4. For i = 1 : 9
         Apply attack i to the watermarked image
         Extract watermark from the attacked image
         Compute $BER_i$
       End
    5. AverageBER = mean($BER_i$)  //Compute average
    6. GridPSNR($w_{mean}$, $w_{std}$) = PSNR;
    7. GridBER($w_{mean}$, $w_{std}$) = AverageBER;
  End
End
```

Fig. 1: The grid-search algorithm.

The effective candidate pairs, (w_{mean}, w_{std})'s, for each training image are chosen as follows. 1) Set all the positions in GridPSNR(w_{mean}, w_{std}) whose values are greater than its average PSNR as 1's and the remaining positions as 0's. 2) Set all the positions in GridBER(w_{mean}, w_{std}) whose values are less than its average BER as 1's and the remaining positions as 0's. 3) Apply the logic "and" operation to keep the positions where both values in two modified matrices are 1's. These kept positions correspond to the values of all effective candidate pairs (w_{mean}, w_{std})'s.

A statistical-clustering method, an unsupervised k-means algorithm [12], is then used to cluster all effective (w_{mean}, w_{std})'s from all training images into several groups. This is an automatic and iterative clustering process. That is, we start with the clustering with k=2 and adaptively and gradually increase k until a small average distance between the points in the cluster and the cluster center is reached. The cluster center with the smallest average distance to all the points in the cluster is chosen as the optimal (w_{mean}, w_{std}) pair in our proposed system. Fig. 2 shows the plot of all the effective pairs (w_{mean}, w_{std})'s together with the final clustering results. The cluster center pointed by the arrow is the optimal (w_{mean}, w_{std}) pair determined by the learning process. In our system, this pair is (-2.4639, 2.7608).

3. THE PROPOSED EXTRACTION SCHEME

The extraction of the watermark is summarized as follows:

1. Obtain a wavelet coefficient matrix H' by performing a 1-level "db2" wavelet transform on the image h'.
2. Partition the approximation subband Ha' into non-overlapping blocks B' of size 4×4.

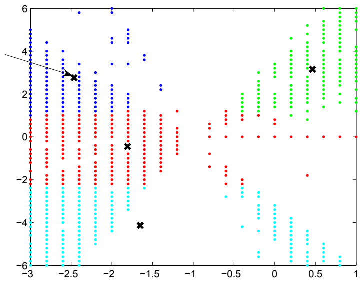

Fig. 2: The plot of the offline learning results with k = 4 (each cluster is indicated by a unique color)

3. Apply a one-way hashing function [11] to generate the highly secure watermark embedding positions (i.e., the indices for the blocks in Ha').
4. For each $NewB'_i$ (i = 1, 2, …, k), which corresponds to the block sequence generated in step 3
   - 4.1 Apply SVD to compute its U'_i, S'_i, and V'_i.
   - 4.2 Compute $n'_{vi} = \| v'_i \| + 1$, where v'_i is a vector formed by the SVs of $NewB'_i$. That is, $v'_i = (\lambda'^{i}_1, \lambda'^{i}_2, \lambda'^{i}_3, \lambda'^{i}_4)$ where λ'^{i}_j is the value on the diagonal direction of S'_i.
   - 4.3 Compute its quantization step d'_i in the same manner as in the embedding process.
   - 4.4 Compute $C' = \lfloor n'_{vi} / d'_i \rfloor$.
   - 4.5 If C' is an even number, then the embedded bit is 1. Otherwise, it is 0.
5. Apply the successive-packing de-interleaving (SPD) scheme [10] to reshuffle the extracted bits to obtain the final extracted watermark bits.

4. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed watermarking scheme, experiments have been conducted on various images with different textures and various JPEG compression attacks.

Watermark invisibility is evaluated on images of Lena (Le), Peppers (Pe), Plane (Pl), Baboon (B), Texture (T), and Lake (La), as shown in Fig. 3. The PSNRs of these six watermarked images are 43.67, 44.26, 46.03, 44.54, 42.71, 44.40 db, respectively. These PSNR values are all greater than 35.00 db, which is the empirical value for the image without perceivable degradation. These six values are also higher than the PSNR values (41.08, 42.83, 44.13, 42.51, 40.47, 42.86) obtained by applying Bao's SVD-based wavelet approach [8]. The average improvement of the PSNR values on these six images is 1.955 db.

Fig. 3: The original images with different textures

Simulation results of the robustness of our proposed watermarking scheme against JPEG compression attacks at different quality factors (QF) ranging from 10% to 90% are presented in Table 1. The BER of each extracted watermark is summarized in this table. It clearly shows that the proposed algorithm is successful against JPEG compression down to a level of 50% QF since the extracted watermarks are perfectly matched with the original embedded watermarks. It also achieves small BERs, i.e., average BERs of 0.2% and 1.25% for JPEG QF levels of 40% and 30%, for all the testing images. The average BER values of the six testing images at JPEG QF levels of 20% and 10% are 8.98% and 45.13%, respectively.

Table 1: BERs of watermarks extracted from JPEG compressed watermarked images (our approach)

BER QF	Le	Pe	Pl	B	T	La
0.5-1.0	0	0	0	0	0	0
0.4	0.002	0.001	0.002	0.003	0	0.004
0.3	0.006	0.008	0.009	0.010	0.019	0.023
0.2	0.076	0.091	0.098	0.087	0.099	0.088
0.1	0.424	0.439	0.434	0.468	0.401	0.542

We implemented Bao's approach [8] to compare with our approach. Table 2 summarizes the BERs of extracted watermarks by applying Bao's method on the same six images under various JPEG compression attacks. It shows that small BERs are occurred for some images for a JPEG compression down to 50% QF. The BERs at lower QF (from 10% to 50%) are much higher than the BERs of our proposed scheme at the same compression level. Specifically, the average BER values of the six testing images at JPEG QF levels of 40%, 30%, 20% and 10% are 1.22%, 4.33%, 19.03%, and 53.82%, respectively. It is clear that our method achieves higher robustness against JPEG compressions than Bao's method in all cases.

Table 2: BERs of watermarks extracted from JPEG compressed watermarked images (Bao's approach [8])

BER QF	Le	Pe	Pl	B	T	La
0.9	0	0	0	0	0.002	0
0.8	0	0	0	0	0.004	0
0.7	0	0	0	0	0.006	0
0.6	0	0	0	0	0.011	0
0.5	0.001	0	0	0	0.018	0
0.4	0.023	0.004	0.003	0.006	0.029	0.008
0.3	0.060	0.038	0.027	0.027	0.065	0.043
0.2	0.265	0.188	0.167	0.126	0.189	0.207
0.1	0.550	0.561	0.514	0.512	0.502	0.59

5. CONCLUSIONS

This paper presents a blind, adaptive QIM- and SVD-based watermarking scheme to embed watermark bits in the approximation subband of the wavelet domain. The proposed system is adaptive and robust since the watermark embedding is based on the quantization of the SV of blocks and the quantization parameters are modeled by the block statistics in the wavelet domain. The contributions are as follows: 1) Apply the QIM technique to adaptively determine the quantization step for each embedding block. 2) Apply a statistical-clustering method offline to decide two optimal weighting parameters for the QIM technique. 3) Apply the SVD technique to modify the SVs of each embedding block using the adaptive quantization step so that the SVs of highly textured structures are largely modified and the SVs of smooth textured structures are slightly modified. 4) Apply the SPI scheme and the one-way hashing functions to improve the robustness of the system.

We will incorporate the human visual system to improve the adaptive capability of the system. A statistical model will be further studied to derive the maximum and minimum quantization step values in (2).

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