Digital Watermarking Enhancement Using Wavelet Filter Parametrization

Piotr Lipiński and Jan Stolarek

Institute of Information Technology
Technical University of Lodz
Poland
piotr.kazimierz.lipinski@gmail.com, stolarek@ics.p.lodz.pl

Abstract. In this paper a genetic-based enhancement of digital image watermarking in the Discrete Wavelet Transform domain is presented. The proposed method is based on adaptive synthesis of a mother wavelet used for image decomposition. Wavelet synthesis is performed using parametrization based on an orthogonal lattice structure. A genetic algorithm is applied as an optimization method to synthesize a wavelet that provides the best watermarking quality in respect to the given optimality criteria. Effectiveness of the proposed method is demonstrated by comparing watermarking results using synthesized wavelets and the most commonly used Daubechies wavelets. Experiments demonstrate that mother wavelet selection is an important part of a watermark embedding process and can influence watermarking robustness, separability and fidelity.

1 Introduction

The concept of digital watermarking is to embed additional data ("a watermark") into the media. This can be used either to ensure that medium was not modified (such watermarks should be fragile i.e. they should be destroyed when the medium is altered in any way) or to allow copyright verification (such watermarks should be persistent i.e. removal of watermark should be impossible without damaging the watermarked medium beyond usability). In this paper persistent blind watermarking [5] of images is considered.

In the recent years digital watermarking in the wavelet domain has gained much popularity. This is caused by the good time-frequency localization properties of the Discrete Wavelet Transform (DWT), which allows to embed watermark only in the selected regions and frequencies of an image. So far authors of the watermarking algorithms have been arbitrarily choosing the basis wavelet function used for image decomposition and synthesis (Haar or Daubechies wavelets in most cases). The influence of the wavelet on the watermarking process has been noticed be some authors [7, 13], while others have proposed wavelet parametrization to improve watermark security [3, 6, 9]. Nevertheless, the problem of

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adjusting the wavelet in order to improve watermarking robustness and fidelity has not been addressed so far. Authors of this paper have already done some research in that field. In [17] it was demonstrated that wavelets synthesized in order to maximize energy compaction can also improve performance of watermarking algorithms proposed in the literature. However, the proposed approach did not take into account neither the characteristics of the cover image nor the watermark and the watermarking algorithm itself.

In this paper that problem is addressed. Genetic algorithm will be used to adapt wavelets to the cover image, the embedded watermark and the watermarking algorithm. It will be shown that such approach can significantly improve watermark embedding robustness, separability and fidelity. Robustness will be defined as an ability to confirm presence of a watermark in the watermarked image. Separability will be defined as an ability to faultlessly distinguish the extracted watermark from random watermarks. Fidelity will be measured in terms of minimizing the distortions introduced to the image by the watermarking process. It will be demonstrated that proposed approach synthesizes wavelets that, in comparison to Daubechies wavelets, perform better in terms of all the above criteria.

This paper is divided into the following sections. Section 2 introduces the basic concepts of a DWT-based digital watermarking algorithm. Section 3 presents embedding algorithm, the concept of a lattice structure used for wavelet parametrization and describes the genetic algorithm used for wavelet synthesis. Section 4 presents testing methodology and results of performed experiments. Section 5 summarizes the paper and discusses the directions of the future research.

2 Digital watermarking in the DWT domain

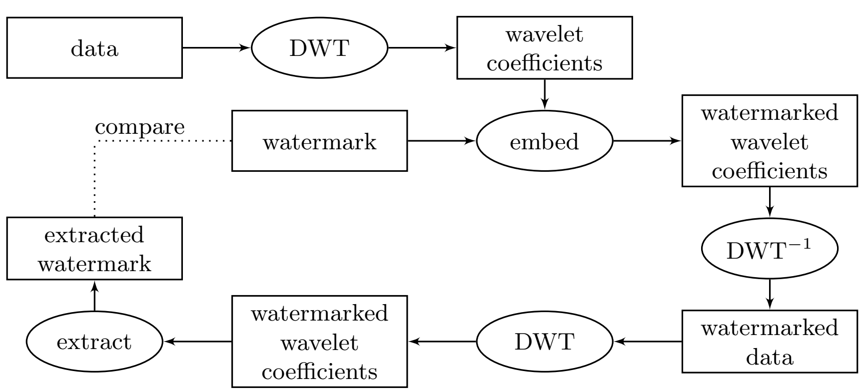


Fig. 1: Generic scheme of watermark embedding and extraction in the wavelet transform domain.

Many digital watermarking algorithms operating in the the DWT domain have been proposed in the recent years [1, 2, 8, 10, 11, 19, 20]. All these algorithms share the watermark embedding scheme shown in Figure 1. In this scheme original data is first decomposed using DWT. The watermark is then embedded by applying a selected embedding algorithm. Inverse DWT (DWT^{-1} in Figure 1) is applied to reconstruct the data. To extract the embedded watermark, DWT must be applied to the watermarked data. Watermark is extracted from the wavelet coefficients and compared with the original one.

3 Genetic-based digital image watermarking enhancement

In the proposed adaptive digital image watermarking enhancement approach, the DWT and DWT^{-1} steps in Figure 1 are modified. Instead of using an arbitrarily chosen mother wavelet, a genetic algorithm is applied to adapt the mother wavelet to the cover image, a watermark and an embedding algorithm.

3.1 Embedding algorithm

Due to the proliferation of wavelet-based watermarking algorithms, in this paper a generic watermarking algorithm based on E_BLIND/D_LC algorithm (Embedding: Blind / Detection: Linear Correlation) [5] is used to demonstrate the proposed watermarking enhancement method, without the loss of generality. In this algorithm watermark w_r is a random sequence of N integer numbers of the set $\{-1, 1\}$. Multilevel wavelet decomposition of the image is performed using the Mallat's algorithm. N largest wavelet coefficients from all three detail subbands on third level of image decomposition are selected. The watermark is embedded in selected coefficients using formula

$$c_w = c_0 + \alpha w_r \quad , \tag{1}$$

where c_0 are the selected wavelet coefficients, α is the embedding strength, w_r is the watermark and c_w are the watermarked wavelet coefficients. To extract the watermark, watermarked image has to be decomposed using the Mallat's algorithm. Watermark is detected by computing normalized correlation between the watermarked wavelet coefficients and the original watermark according to formula

$$C = \frac{1}{N-1} \sum_i \frac{(c_w(i) - \overline{c_w})(w_r(i) - \overline{w_r})}{\sigma_c \sigma_w} \quad , \tag{2}$$

where N is the length of the watermark, c_w denotes the watermarked coefficients, $\overline{c_w}$ is the mean value of the watermarked coefficients, w_r denotes the embedded watermark, $\overline{w_r}$ is the mean value of the embedded watermark, σ_c and σ_w are standard deviations of watermarked coefficients and the watermark respectively. Presence or absence of the watermark is usually determined with a threshold τ.

If the correlation C is greater than τ then the watermark is present, otherwise it is absent. Therefore, it is important to maximize the correlation.

3.2 Wavelet parametrization

In this paper wavelet parametrization based on an orthogonal lattice structure is used [21]. Such structure can be used to perform wavelet decomposition of a signal. Properties of this structure are presented and discussed in detail in [18]. Below is a short summary.

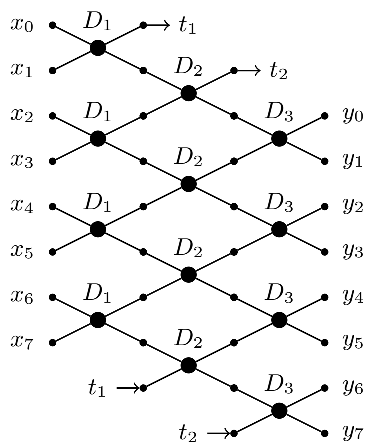


Fig. 2: Lattice structure performing 6–tap transform.

Lattice structure is based on the two-point base operations

$$D_k = \begin{bmatrix} w_{11}^k & w_{12}^k \\ w_{21}^k & w_{22}^k \end{bmatrix} \quad , \tag{3}$$

where k stands for the index of the operation (see Fig. 2). Such two-point base operation can be written in form of a matrix equation:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = D_k \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad . \tag{4}$$

Lattice structure is composed of $K/2$ stages, each containing D_k operations repeated $N/2$ times, where K and N are the lengths of the filter's impulse response and of a processed signal respectively. On each stage of the lattice structure, elements of the signal are processed in pairs by D_k base operations. After each stage, base operations are shifted down by one and a lower input of the last base operation in the current stage is connected to the upper output of the first base operation in the preceding stage (t_1 and t_2 on Fig. 2). Upper outputs of base operations in the last layer (y_0, y_2, y_4 and y_6 on Fig. 2) correspond to the low-pass filter signal and lower outputs (y_1, y_3, y_5 and y_7 on Fig. 2) correspond to the high-pass filter signal. Wavelet filter bank coefficients are calculated based on the D_k base operations.

Let us assume such D_k base operation, that condition

$$D_k \cdot D_k^T = I \tag{5}$$

holds true, i.e. D_k matrix is orthogonal. This implies that

$$w_{11}^k w_{21}^k + w_{12}^k w_{22}^k = 0 \ , \tag{6}$$

$$(w_{11}^k)^2 + (w_{12}^k)^2 = 1 \ . \tag{7}$$

As was proposed in [15], the following substitution into equation (3) is a sufficient condition to satisfy equation (6):

$$\begin{aligned} w_{21}^k &= w_{12}^k \ , \\ w_{22}^k &= -w_{11}^k \ . \end{aligned} \tag{8}$$

Substituting equation (8) to equation (3), we can rewrite D_k base operation in a new form of S_k base operation containing only two parameters w_{11}^k and w_{12}^k, instead of four:

$$S_k = \begin{bmatrix} w_{11}^k & w_{12}^k \\ w_{12}^k & -w_{11}^k \end{bmatrix} \ . \tag{9}$$

Equation (7) implies that S_k transform preserves energy. Such S_k base operation is called orthogonal base operation and the lattice structure based on S_k operations is called orthogonal lattice structure. An orthogonal lattice structure must be used in order to synthesize orthogonal wavelets that fulfil conditions of wavelet the decomposition [4, 14].

Let us assume

$$\begin{aligned} w_{11}^k &= cos(\alpha_k) \ , \\ w_{12}^k &= sin(\alpha_k) \ . \end{aligned} \tag{10}$$

For such assumption equation (7) holds true, and we can rewrite equation (9) as

$$S_k = \begin{bmatrix} cos(\alpha_k) & sin(\alpha_k) \\ sin(\alpha_k) & -cos(\alpha_k) \end{bmatrix} \ , \tag{11}$$

which allows to replace two weights of S_k base operation with only one parameter α_k. Therefore lattice structure consisting of N layers can be represented using only N numbers $(\alpha_1, \alpha_2, \ldots, \alpha_N)$, where each $\alpha_i \in [0, 2\pi)$.

3.3 Wavelet synthesis algorithm

An orthogonal lattice structure allows to adapt a wavelet filter bank by adjusting the base operations. When the base operations are modified, the output signal from the lattice structure changes. This signal can be then rated in terms of its fitness in respect to some quality criteria. In the digital image watermarking, discussed in this paper, there are two contradicting fitness criteria:

1. the difference between:
   (a) correlation of the extracted watermark with the embedded watermark and
   (b) correlation of the extracted watermark with random watermarks

   should be maximized,
2. visual difference between the original image and the watermarked image should be minimized.

This turns the problem of mother wavelet synthesis using lattice structure into a multiobjective optimization problem, which is usually solved using evolutionary approach. In [16] a genetic algorithm for synthesizing a wavelet that compacts energy into low-pass wavelet coefficients was introduced. Simple Genetic Algorithm with Evolutionary Strategies was applied to synthesize the optimal mother wavelet by optimizing a defined objective function. Algorithm 1 shows an outline of that algorithm. This method can be easily adapted to synthesize wavelets conforming to both above-mentioned criteria by modifying the fitness functions.

Algorithm 1 Genetic algorithm outline

```
initialize random population P of μ individuals
for k = 1 to ITERATIONS_COUNT do
   evaluate fitness of individuals in population P
   create temporary population T containing λ individuals using tournament selec-
   tion from population P
   perform crossover and mutation on individuals in population T
   evaluate fitness of individuals in population T
   select μ individuals to form new population P
end for
display best individual in population P
```

To evaluate the fitness in terms of criterion 1, a set of random watermarks must be generated. Normalized correlation between the extracted watermark and the embedded watermark is calculated and then the normalized correlation between the extracted watermark and the random watermarks is calculated. Since the normalized correlation falls into range $[-1, 1]$, the fitness of i-th individual in terms of condition 1 is calculated using formula

$$F_{i1} = \max\left(\frac{\min_j(C_e - C_{rj})}{2}, 0\right) \quad , \tag{12}$$

where C_e is the normalized correlation between the extracted watermark and the embedded watermark and C_{rj} is the normalized correlation between the extracted watermark and j-th random watermark. This means that we select the smallest ("the worst") difference. Since both C_e and C_{rj} fall in range $[-1, 1]$, the result of $C_e - C_{rj}$ falls in range $[-2, 2]$. The fitness must be from range $[0, 1]$, hence the division by 2 and the $\max(\cdot)$ function have to be applied.

Fitness of i-th individual in terms of criterion 2 is calculated using the formula

$$F_{i2} = 1 - \frac{MSE}{PMSE} \quad , \tag{13}$$

where MSE stands for Mean Square Error and PMSE stands form Peak Mean Square Error between the original and the watermarked image. After F_{i2} values have been calculated for all the individuals in a population, they are normalized to fit into range $[0, 1]$. Thus the worst individual has fitness 0 and the best individual has fitness 1.

Algorithm 2 Fitness evaluation

```
  for all (individual_i ∈ population) do
    convert (α_i1, α_i2, ..., α_iN) to wavelet filter coefficients
    embed watermark in an image
    calculate fitness F_i2 of the watermarked image
    extract watermark
    calculate fitness F_i1
  end for
Require: ∀_i  F_i1 ∈ [0,1] ∧ F_i2 ∈ [0,1]
  for all (individual_i ∈ population) do
    F_i = min(F_i1, F_i2)
  end for
```

As a method for multiobjective optimization Global Optimality Level [12] is used. The concept of this approach is to calculate individuals' fitness for all optimization criteria, ensure that they fall into the same range ($[0, 1]$ in presented approach) and for each individual select the worst of its partial fitnesses as a total fitness of that individual. Evaluation of individuals fitness is outlined in Algorithm 2. Presented enhancement method is a generic one and can be used to improve any digital watermarking algorithm. This requires modifying "embed watermark in an image" and "extract watermark" steps in the Algorithm 2. In this paper these steps represent embedding the watermark using equation (1) and extracting it using equation (2), but they can be substituted with any embedding/extraction algorithm.

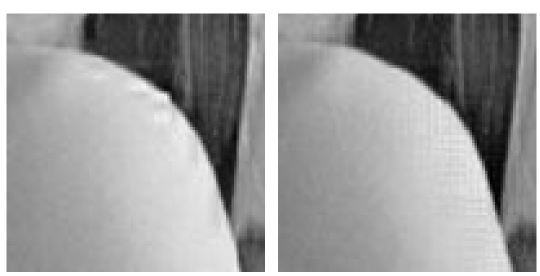
It will be demonstrated that the fitness evaluation method outlined above leads to synthesis of wavelets that perform better than Daubechies wavelets in terms of robustness, separability and fidelity.

4 Experimental results

Experiments were carried out to verify the effectiveness of the proposed approach. 64 grey scale images from USC-SIPI Image Database have been chosen (e.g. Lena, Mandrill, Boat, House, etc.). Watermark was a sequence of 256 random numbers from set $\{-1, 1\}$. For every image adaptive 4-tap wavelet has been synthesized using the genetic algorithm approach. Performance of this wavelet was compared with the Daubechies 4 wavelet in terms of robustness, separability and fidelity. Table 1 shows comparison of the results. Image fidelity is expressed using Peak Signal-to-Noise Ratio between the original image and the watermarked one. First row is the average value for all 64 images. Second row contains standard deviation, to provide deeper insight into distribution of the results. Remaining two rows contain minimal and maximal values of measured quantities. It can be clearly noticed, that Daubechies wavelet has been outperformed significantly in terms of correlation and separability. In case of image fidelity adaptive wavelet performs slightly better.

Table 1: Results comparison

	correlation		separability		PSNR [dB]	
	Daubechies	Adaptive	Daubechies	Adaptive	Daubechies	Adaptive
Average	0.38	0.87	0.18	0.87	46.97	47.09
Std. deviation	0.17	0.13	0.17	0.13	1.08	1.19
Min. value	0.00	0.33	-0.20	0.33	43.36	43.37
Max. value	0.88	1.00	0.68	1.00	50.60	50.59



(a) Daubechies wavelet (b) Adaptive wavelet

Fig. 3: Comparison of image watermarking artifacts.

Figure 3 shows two fragments of the Lena image. Figure 3a demonstrates artifacts caused by watermark embedding using the Daubechies 4 wavelet for image decomposition. On Figure 3b the same watermark has been embedded using adaptively synthesized 4-tap wavelet. It can be noticed, that amplitude of watermarking distortions is smaller with adaptive wavelets, and therefore they are less visible. It must be noted however, that in case of some images visual difference is practically imperceptible.

5 Conclusions

Robustness, separability and fidelity are the three major requirements in the digital image watermarking. The aim of this paper was to prove that it is possible to improve all these three parameters simultaneously by adjusting mother wavelet to the properties of an image, a watermark and an embedding algorithm. To achieve this goal, a genetic-based enhancement method has been developed and tested using well-known test images. As was shown in section 4, the proposed method can effectively synthesize wavelets that outperform the Daubechies wavelets in terms of the watermarking robustness, the watermark separability and the image fidelity. Tests were carried out using a generic watermarking algorithm, however the proposed method can be used to enhance any existing watermarking algorithm operating in the DWT domain.

Within further research the presented algorithm can be extended to adaptively select the length of a wavelet filter, the number of image decomposition levels and the subbands to be watermarked. The algorithm can also take into account various attacks against the embedded watermark. Image quality evaluation based on Human Visual System can be introduced instead of the MSE-based one.

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