On the Choice of the Mother Wavelet for Perceptual Data Hiding

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***Abstract*—We investigate the choice of the best mother wavelet for perceptual data hiding in the wavelet domain. The watermarked images are submitted to a series of attacks based on normal image processing techniques. Simulations show that regardless of the content of the images (contours, textures, homogeneous zones), the best mother wavelets are the ones used in the JPEG2000 standard.**

I. Introduction

The idea of digital watermarking has been proposed as a means to protect the copyright of digital images. The majority of watermarking algorithms operate on the spread spectrum (SS) communication principle. A pseudorandom sequence is added to the host image in some critically sampled domain and the watermarked image is obtained by inverse transforming the modified image coefficients. Typical transform domains are the Discrete Wavelet Transform (DWT), the Discrete Cosine Transform (DCT) and the Discrete Fourier Transform (DFT).

This paper is focused on perceptual watermarking in the DWT domain. Specifically, we study a blind watermarking system, where the watermark is masked according to the characteristics of the human visual system (HVS), based on the local standard deviation of the original image [1]. This technique has the advantage of "accommodating" information in lower frequency levels, whenever necessary, making the watermark more attack resilient, as opposed to its predecessor [2]. Initially, the technique was fine-tuned on the DWT with the mother wavelet Daubechies-6. The question is however if this mother wavelet gives the best results in terms of detection, in the case of attacks based on normal processing techniques. Thus, this paper investigates the choice on the best mother wavelet on the watermarking system proposed in [1].

The article is organized as follows. Section 2 introduces perceptual watermarks and more specifically it describes the two similar techniques; simulation results are discussed in Section 3; finally conclusions are drawn in Section 4.

II. Perceptual Watermarking

The insertion of the watermark can be made imperceptible by embedding the watermark in wavelet coefficients of known robustness (which are usually large) or in perceptually significant regions [3], i.e. contours and textures of an image. This can be done empirically, selecting larger coefficients [4] or using a thresholding scheme in the transform domain [5].

Another approach is to insert the watermark in all coefficients of a transform, using a variable strength for each coefficient [2]. Hybrid techniques embed the watermark using a thresholding scheme and a variable strength [5]. These works are based on compression schemes. We focus in this paper on the method developed by the authors in [1]. The results will be compared with Barni's technique [2]. It should be noted that the algorithm developed in [1] is based on the one in [2]. The two algorithms use the mother wavelet Daubechies-6 [1] ('db3' in the Wavelet toolbox in Matlab), respectively, the Daubechies-6 kernel [2]. We want to identify in this paper the mother wavelets that lead to the best detection response of the watermark, regardless of the content of the host image. These are experimentally identified, testing the performance for the Daubechies mother wavelets family, respectively the mother wavelets recommended in the JPEG2000 standard [8].

At the *embedding* side, the image I, of size 2M×2N, is decomposed into 4 DWT levels, where I_l^θ is the subband from level $l \in \{0,1,2,3\}$, and orientation $\theta \in \{0,1,2,3\}$ (horizontal, diagonal and vertical detail subbands, and approximation subband). A binary watermark $x^\theta(i,j)$ is embedded in all coefficients from the subbands from level 0 by addition:

$$\tilde{I}_0^\theta(i,j) = I_0^\theta(i,j) + \alpha w^\theta(i,j) x^\theta(i,j), \qquad (1)$$

where α is the embedding strength and $w^\theta(i,j)$ is a weighing function, which is a half of the quantization step $q^\theta(i,j)$, which is computed as the weighted product of three factors:

$$q^\theta(i,j) = \Theta(l,\theta)\Lambda(l,i,j)\Xi(l,i,j)^{0.2}, \qquad (2)$$

The embedding takes place only in the first resolution level, for $l = 0$. The first factor is the sensitivity to noise depending on the orientation and on the level of detail:

$$\Theta(l,\theta) = \begin{Bmatrix} \sqrt{2}, & \theta = 1 \\ 1, & \text{otherwise} \end{Bmatrix} \cdot \begin{Bmatrix} 1.00 & l \in \{0,1\} \\ 0.66 & l = 2 \end{Bmatrix}. \qquad (3)$$

The 2nd factor takes into account the local brightness based on the gray level values of the approximation image from level l, where the watermark is embedded:

$$\Lambda(l,i,j) = 1 + L'(l,i,j), \qquad (4)$$

where

$$L'(l,i,j)=\begin{cases}1-L(l,i,j), & L(l,i,j)<0.5\\ L(l,i,j), & \text{otherwise}\end{cases}, \tag{5}$$

and

$$L(l,i,j)=\frac{1}{256}I_l^3(i,j). \tag{6}$$

where I_l^3 is the approximation subimage from level *l*. The third factor represents the texture activity around a pixel:

$$\Xi(l,i,j)=\sum_{k=0}^{3-l}\frac{1}{16^k}\sum_{\theta=0}^{2}\sum_{x=0}^{1}\sum_{y=0}^{1}\left[I_{k+l}^{\theta}\left(y+\frac{i}{2^k},x+\frac{j}{2^k}\right)\right]^2\cdot\frac{S_l^3(i,j)}{U_l^3(i,j)} \tag{7}$$

This term is the product of the local mean square value of the DWT coefficients in all detail subbands and the local standard deviation of the image, compressed in the wavelet domain and normalized to its mean [1]. The first contribution is the distance from the edges, whereas the second one the texture. In [2], the second term of eq.(7) was initially the local variance of the low-pass subband, computed in a small 2×2 window centered on the pixel (*i*, *j*). This local variance estimation was not so precise, because it is computed with a low resolution. The reader is referred to [2] for details on the implementation of the original algorithm.

Detection is made using the correlation between the marked DWT coefficients and the watermarking sequence to be tested for presence [2]:

$$\rho=\frac{1}{3MN}\sum_{\theta=0}^{2}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\tilde{I}_0^{\theta}(i,j)x^{\theta}(i,j) \tag{8}$$

The correlation is compared to a threshold T_ρ, computed to grant a given probability of false positive detection, using the Neyman-Pearson criterion. For example, if $P_f \le 10^{-8}$, the threshold is $T_\rho = 3.97\sqrt{\sigma_\rho^2}$, with σ_ρ^2 the variance of the wavelet coefficients, if the image was watermarked with a code Y other than X:

$$\sigma_\rho^2 \approx \frac{1}{(3MN)^2}\sum_{\theta=0}^{2}\sum_{i=0}^{M-1}\sum_{j=0}^{N-1}\left(\tilde{I}_0^{\theta}(i,j)\right)^2. \tag{9}$$

We consider the ratio between the correlation ρ in Eq. (8) and the image dependent threshold T_ρ, a nonlinear detection function with a fixed threshold.

Both methods were fine-tuned using either the Daubechies-6 kernel [2] or Daubechies-6 mother wavelet [1]. We investigate the choice on the best mother wavelet for optimization before and after attacks based on normal processing techniques on various watermarked images in the next section.

III. Simulation Results

Various images [6, 7] have been watermarked at level *l*=0 with embedding strengths α=1.5 [1] and α=0.2 [2] resulting in a similar image quality. From those images we present results for Lena, Texmos1.p512, Baboon [6] and Picasso [7], a less known image, but nevertheless also interesting for its content.

Generally, images contain three types of regions: homogeneous zones, textures and contours. We have identified these regions for the test images using the normalized local standard deviation, *nlv*, of the original image. Pixels with *nlv*>0.35 are from contours, pixels with 0.045<*nlv*<0.35 are from textures and pixels with 0.045>*nlv* are from homogeneous zones. We chose three categories of test images, containing mostly contours (class 3, Texmos1.p512), textures (class 2, Lena and Baboon) respectively homogeneous zones (class 1, Picasso); see Table 2, second column.

For the watermarking method [1], we choose a different mother wavelet for each experiment, having *n* vanishing moments, with *n* ranging from 2 to 7: db2, db3, and so on, as well as the biorthogonal mother wavelets used in the JPEG2000 standard: Daubechies 9/7 (bior4.4) and the 5/3 LeGall wavelet (bior2.2). We chose them because they are extremely short, symmetric, hence avoiding boundary artifacts, with a maximum number of vanishing moments and minimum support [8].

A binary watermark is embedded in all the detail wavelet coefficients of the first resolution level, *l*=0, as previously described. The peak signal-to-noise ratio values are given in Table 1. The highest PSNR values are obtained for the mother wavelet db7, followed by the ones with db6, while the smallest PSNR values are obtained for bior2.2.

The watermarked images were tested against attacks based on normal signal processing techniques: JPEG and JPEG2000 compression, median filtering, cropping, resizing and gamma correction, for different parameters. For each attacked image, the ratio correlation per threshold ρ/T_ρ is computed for $P_f=10^{-8}$. Results obtained for Lena are presented in Table 3. The highest results are marked with bold characters, while the second highest results are marked with bold italic characters. Counting the number of "best" detectors (highest and second highest) for each mother wavelet, the best mother wavelets for the image Lena are: bior2.2, db7, db6, bior4.4, as seen in the third column of Table 2. Repeating the above procedure, we obtain similar results for the other test images; see Table 3, 4 and 5. Practically, we can see that regardless the content of the image, the best mother wavelet that optimizes the detection for the method in [1] is also the one proposed in the standard JPEG2000 (bior2.2 followed closely by bior4.4). Unfortunately, this also leads to smallest PSNR values between the original and watermarked images.

IV. Conclusion

Wavelets have two important properties: the magnitudes of the wavelet coefficients are strongly correlated across scales and the wavelet coefficients of a piecewise smooth image fall into two categories: large amplitude coefficients located near edges, and the smaller ones, located in smooth regions [8]. The JPEG2000 algorithm takes into account these properties. In fact, it uses the filters LeGall 5/3 for lossy compression; these are used to construct the mother wavelet bior2.2 which has a more compact support, and is suitable for edges from an image.

The perceptual masking embeds the watermark with a higher strength in high wavelet coefficients which means the watermarking method in [1] can be optimized on the criterion of the choice of the best mother wavelet, in the same manner as the image compression method recommended in the JPEG2000 standard [8]. Moreover, the two image processing methods are optimized using the same mother wavelet.

The best mother wavelet for the watermarking method proposed in [1], regardless of the content of the host image, is bior2.2, as seen from the detection results. The mother wavelet bior2.2 leads to better detection results than the ones obtained in [2] for all the host images tested here. For highly textured images, there are attacks where Barni's method is better (6 out of 14 cases for Lena and 2 out of 14 cases for Baboon). For images with contours or homogeneous zones, for all attacks, the method in [1] using bior2.2 works better than the method in [2]. This is in accordance with [8]: the approximation properties of the LeGall 5/3 are much better than those of the Daubechies4 filter of the same order.

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TABLE I. COMPARISON OF INVISIBILITY

	PSNR (dB)								
Image vs. Mother wavelet	***db2***	***db3***	***db4***	***db5***	***db6***	***db7***	***bior4.4***	***bior2.2***	***Barni***
Lena	37.92	38.16	38.28	38.33	***38.35***	**38.41**	38.26	35.97	36.39
Picasso	33.97	34.04	34.15	34.25	***34.27***	**34.35**	34.02	32.07	35.95
Texmos1p.512	28.09	28.21	28.28	28.26	***28.29***	**28.33**	28.28	26.08	**29.04**
Baboon	33.30	33.39	33.40	33.43	***33.46***	**33.47**	33.30	31.32	33.33

TABLE II. CLASSIFICATION OF IMAGES USING THE LOCAL STANDARD DEVIATION AND THE BEST MOTHER WAVELET FOR THE WATERMARKING METHOD

Image	**Predominant class /Percentage**	**Best mother wavelet**	**Observations**		
			1/Homogeneous zones	***2/Textures***	***3/Contours***
Lena	2/48.50	bior2.2, db7	46.61%	**48.50%**	4.89%
Picasso	1/56.28	bior2.2, bior4.4	**56.28**%	30.19%	13.54%
Texmos1.p512	3/92.15	bior2.2, bior4.4	0.00%	7.85%	**92.15%**
Baboon	2/76.28	bior2.2, db6	1.21%	**76.28%**	22.51%

TABLE III. ROBUSTNESS IN THE CASE OF DIFFERENT TYPES OF ATTACKS, FOR THE IMAGE LENA.

	Ratio ρ/T for the method in [1] using different mother wavelets and the method in [2]								
Attack vs. Mother wavelet	***db2 (3)***	***db3 (0)***	***db4 (2)***	***db5 (1)***	***db6 (4)***	***db7 (4)***	***bior4.4 (3)***	***bior2.2 (11)***	***Barni (6/14)***
Before	37.61	39.08	39.29	40.88	40.92	***41.01***	40.79	**42.76**	**44.31**
JPEG compression,Q=50	6.08	6.05	4.92	***6.15***	5.53	5.06	6.12	**7.47**	6.46
JPEG compression,Q=20	***2.90***	2.79	1.90	2.89	2.34	1.99	2.66	**3.29**	2.47
Median filtering, 3×3	***3.65***	3.45	3.48	2.91	3.00	2.83	**3.80**	3.50	1.06
Median filtering, 5×5	1.65	1.57	1.63	1.11	1.40	1.15	***1.70***	**1.74**	0.49
Resizing, ¾	14.69	16.24	15.58	17.17	16.81	16.55	***17.38***	**17.83**	14.35
Resizing, ½	***8.19***	1.09	0.56	6.90	0.26	4.42	7.80	**9.04**	2.35
Cropping, 256×256	11.71	11.76	**15.94**	12.25	13.07	15.14	13.35	***15.12***	**17.20**
Cropping, 64×64	1.98	1.91	**3.15**	1.93	2.18	***2.72***	2.22	2.60	**3.34**
Gamma correction, γ=0.5	36.06	37.35	37.62	39.09	39.07	***39.25***	38.95	**40.87**	**44.51**
Gamma correction, γ=2	38.18	39.71	39.81	41.35	***41.49***	41.46	41.25	**43.01**	42.66
Blurring, L=31, θ=31	6.95	8.20	8.92	9.30	***9.56***	**9.82**	9.66	9.28	8.86
JPEG2000, CR=20	20.90	24.69	22.80	24.48	**25.47**	23.09	22.02	***24.81***	**28.91**
JPEG2000, CR=12.5	30.53	33.62	32.43	34.53	***35.01***	33.46	33.05	**35.24**	**38.56**

TABLE IV. ROBUSTNESS IN THE CASE OF DIFFERENT TYPES OF ATTACKS, FOR THE IMAGE PICASSO.

	Ratio ρ/T for the method in [1] using different mother wavelets and the method in [2]								
Attack vs. Mother wavelet	***db2 (2)***	***db3 (2)***	***db4 (1)***	***db5 (1)***	***db6 (0)***	***db7 (1)***	***bior4.4 (7)***	***bior2.2 (12)***	***Barni (0/14)***
Before	22.15	22.90	22.70	24.07	24.05	23.57	***24.41***	**26.60**	18.81
JPEG compression,Q=50	2.89	2.96	2.24	2.78	2.37	1.86	***3.01***	**4.47**	1.51
JPEG compression,Q=20	1.50	***1.66***	0.83	1.54	1.10	0.60	1.58	**2.04**	0.70
Median filtering, 3×3	**2.01**	***1.70***	1.46	1.51	1.19	0.57	1.35	1.36	0.47
Median filtering, 5×5	-0.01	-0.18	-0.28	-0.28	-0.56	-0.76	-0.22	0.05	0.39
Resizing, ¾	8.23	9.15	8.84	9.55	9.28	9.03	***9.72***	**10.16**	5.00
Resizing, ½	***5.11***	0.68	0.42	4.22	-0.14	3.17	4.83	**5.83**	1.20
Cropping, 256×256	8.94	9.68	**10.97**	9.78	10.32	10.95	10.54	**11.79**	8.96
Cropping, 64×64	1.50	2.19	2.56	1.93	1.95	**2.95**	2.59	***2.94***	1.97
Gamma correction, γ=0.5	20.17	20.89	20.62	21.80	21.72	21.29	***22.19***	**24.14**	21.42
Gamma correction, γ=2	25.06	25.83	25.73	27.33	27.46	26.90	***27.44***	**29.84**	17.26
Blurring, L=31, θ=31	3.78	3.48	3.58	**4.16**	4.11	4.01	4.01	**4.26**	2.81
JPEG2000, CR=20	14.09	15.72	14.54	15.50	15.71	14.04	***15.92***	**17.56**	11.81
JPEG2000, CR=12.5	18.26	19.45	18.84	19.94	20.06	19.15	***20.37***	**22.31**	15.90

TABLE V. ROBUSTNESS IN THE CASE OF DIFFERENT TYPES OF ATTACKS, FOR THE IMAGE TEXMOS1.P512.

	Ratio ρ/T for the method in [1] using different mother wavelets and the method in [2]								
Attack vs. Mother wavelet	***db2 (0)***	***db3 (0)***	***db4 (0)***	***db5 (0)***	***db6 (3)***	***db7 (1)***	***bior4.4 (9)***	***bior2.2 (13)***	***Barni (0/14)***
Before	22.34	23.46	24.57	23.67	24.47	24.77	***24.84***	**27.10**	21.87
JPEG compression,Q=50	13.62	14.34	14.86	14.21	14.77	14.75	***14. 92***	**17.24**	12.74
JPEG compression,Q=20	6.91	7.35	7.38	7.16	7.61	7.01	***7.74***	**8.84**	6.09
Median filtering, 3×3	2.62	2.76	2.22	2.46	2.45	2.21	***2.67***	**2.90**	0.25
Median filtering, 5×5	0.36	0.08	-0.08	-0.30	0.03	-0. 44	-0.17	0.08	0.02
Resizing, ¾	8.18	9.70	9.53	9.57	9.92	9.92	***10.32***	**10.94**	6.27
Resizing, ½	4.92	0.91	0.25	4.16	0.11	3.50	***5.41***	**6.57**	1.18
Cropping, 256×256	10.75	11.61	12.16	11.71	12.08	12.10	***12.41***	**13.54**	10.55
Cropping, 64×64	2.74	2.46	2.91	2.88	***2.94***	2.64	2.74	**3.04**	2.48
Gamma correction, γ=0.5	24.46	26.09	27.19	26.24	27.05	***27.61***	27.07	**29.15**	20.05
Gamma correction, γ=2	21.32	21.57	22.55	21.86	22.52	22.47	***23.44***	**25.48**	24.54
Blurring, L=31, θ=31	3.23	3.54	3.85	3.86	3.84	4.14	***4.15***	**4.43**	3.23
JPEG2000, CR=20	8.79	10.61	9.99	9.39	***10.65***	9.71	9.69	**10.74**	9.53
JPEG2000, CR=12.5	14.85	16.89	16.78	15.90	***17.33***	16.73	16.59	**17.93**	15.55

TABLE VI. ROBUSTNESS IN THE CASE OF DIFFERENT TYPES OF ATTACKS, FOR THE IMAGE BABOON.

	Ratio ρ/T for the method in [1] using different mother wavelets and the method in [2]								
Attack vs. Mother wavelet	***db2 (2)***	***db3 (4)***	***db4 (1)***	***db5 (0)***	***db6 (5)***	***db7 (2)***	***bior4.4 (2)***	***bior2.2 (10)***	***Barni (2/14)***
Before	24.23	24.97	24.85	24.91	25.30	25.06	***25.34***	**27.38**	25.16
JPEG compression,Q=50	9.62	***9.78***	9.25	9.59	9.51	9.20	9.76	**11.14**	9.56
JPEG compression,Q=20	5.03	***5.08***	4.17	4.91	4.67	4.20	4.89	**5.81**	4.50
Median filtering, 3×3	**1.52**	1.33	0.95	0.95	0.79	0.72	1.09	***1.44***	0.25
Median filtering, 5×5	-0.16	-0.40	-0.54	-0.51	-0.83	-0.64	-0.47	-0.17	-0.01
Resizing, ¾	9.09	**11.28**	10.49	10.10	***11.24***	10.48	10.34	11.00	8.81
Resizing, ½	***6.05***	0.80	0.20	4.96	0.06	3.79	6.02	**7.33**	1.95
Cropping, 256×256	12.56	12.86	15.00	13.14	13.68	***14.84***	13.88	**15.27**	15.24
Cropping, 64×64	1.79	1.77	**2.74**	1.77	2.00	***2.41***	2.08	2.36	**3.03**
Gamma correction, γ=0.5	23.34	24.56	24.20	24.14	***24.86***	24.34	24.37	**26.40**	24.92
Gamma correction, γ=2	24.53	24.90	24.94	25.04	***25.22***	25.15	25.63	**27.56**	24.85
Blurring, L=31, θ=31	2.92	3.03	3.09	3.10	3.18	3.15	***3.30***	**3.66**	2.69
JPEG2000, CR=20	12.24	**14.28**	13.06	12.99	**14.15**	12.75	12.56	13.78	**14.11**
JPEG2000, CR=12.5	17.69	19.46	18.52	18.62	***19.53***	18.39	18.31	**20.00**	19.57