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A New Watermarking Method Based on the Use of the Hyperanalytic Wavelet Transform

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- The qualities required for a good watermarking system are robustness and capacity.
- Using the discrete wavelet transform (DWT) a high robustness can be obtained, but the capacity is not very high.
- Corina Nafornita proposed, in her PhD Thesis, recently presented, a very robust watermarking method in the DWT domain.
- Loo and Kingsbury proved that the capacity can be increased working with complex wavelets.

Recently was proposed a new complex wavelet transform, the hyperanalytic wavelet transform (HWT).

We have developed last year a new implementation of HWT.

The aim of this paper is to present the adaptation of the watermarking method proposed by Corina Nafornita in her thesis to the HWT and to study the robustness of this new technique.

The Hyperanalytic Wavelet Transform

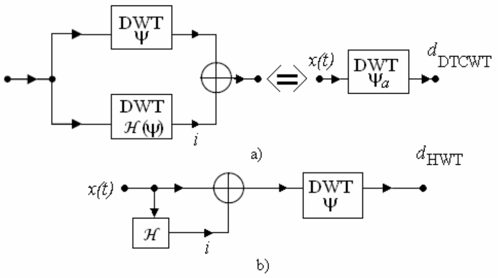
If ψ *is a one-dimensional mother wavelets then* ${}_a\psi = \psi + i\mathcal{H}\{\psi\}$ *is also a mother wavelets*

$$DWT\{x\} = \langle x, \psi_{m,n} \rangle;$$

$$DTCWT\{x\} = \langle x, {}_a\psi_{m,n} \rangle$$ *- analytic wavelet transform*

Its two-dimensional generalization is named Hyperanalytic Wavelet Transform.

The Analytic Wavelet Transform



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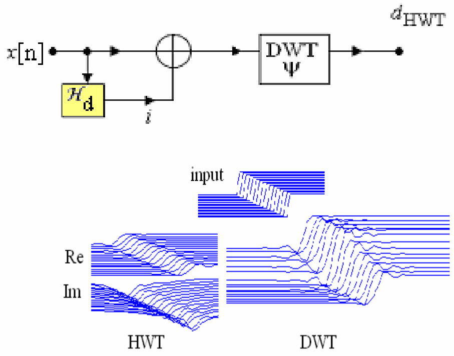
The Proposed Implementation



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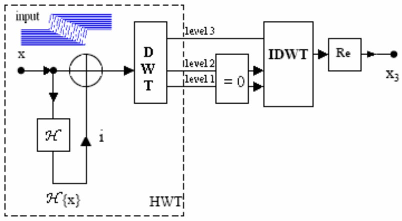
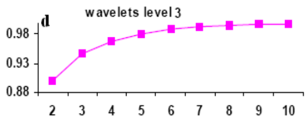
The Translations Invariance

$\text{Deg}=1-d\,/\,m$



Symmlet, 10	HWT	CS , st.=1, 64 del.	CS, st.=1, 512 del.
Redundancy	2	64	512
Scal. fu. Level 3	0.8594	0.7551	0.7551
Wavelets level 3	0.9962	0.9962	0.9995
Wavelets level 2	0.9963	0.9965	0.9996
Wavelets level 1	0.9992	0.9985	0.9998
Daubechies, 10	HWT	CS, st.=1, 64 del.	CS, st.=1, 512 del.
Scal. fu. Level 3	0.8594	0.7551	0.7551
Wavelets level 3	0.9981	0.9965	0.9996
Wavelets level 2	0.9982	0.9968	0.9996
Wavelets level 1	0.9992	0.9985	0.9998



The proposed implementation of the HWT is equivalent to the Cycle Spinning with redundancy 64.

The Hyperanalytic mother wavelet

$$\psi_a(x,y)=\psi(x,y)+i\mathcal{H}_x\{\psi(x,y)\}+$$
$$+j\mathcal{H}_y\{\psi(x,y)\}+k\mathcal{H}_x\{\mathcal{H}_y\{\psi(x,y)\}\}$$

$$i^2=j^2=-k^2=-1,\ and\ ij=ji=k$$

The Hyperanalytic Wavelet Transform

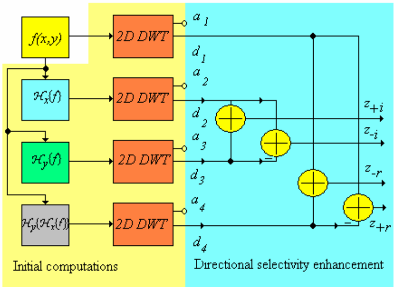
$$HWT\{f(x,y)\} = \langle f(x,y), \psi_a(x,y) \rangle.$$

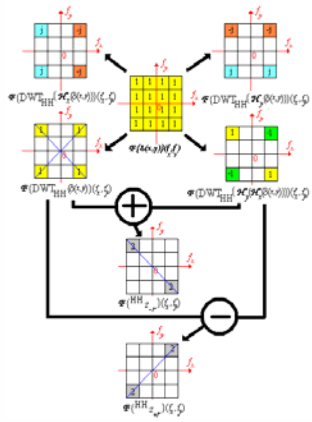
$$HWT\{f(x,y)\} = DWT\{f(x,y)\} +$$
$$iDWT\{\mathcal{H}_x\{f(x,y)\}\} + jDWT\{\mathcal{H}_y\{f(x,y)\}\} +$$
$$+kDWT\{\mathcal{H}_y\{\mathcal{H}_x\{f(x,y)\}\}\} =$$
$$\langle f_a(x,y), \psi(x,y) \rangle = DWT\{f_a(x,y)\}.$$

The Proposed Implementation

The HWT implementation proposed uses four trees, each one implementing a 2D-DWT. The first tree is applied to the input image. The second and the third trees are applied to 1D Hilbert discrete transforms computed across the lines (x) or columns (y) of the input image. The fourth tree is applied to the result obtained after the computation of the two 1D Hilbert transforms of the input image.

The enhancement of the directional selectivity





Digital Watermarking

→ embedding of information (watermark) in media signals *without perceptible changes*

→ copyright protection & ownership id

→ methods

- ✓spatial/time vs. frequency domain
- ✓spread-spectrum (SS) and non-SS: QIM

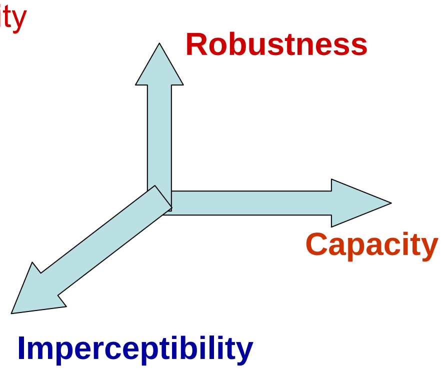
Issues and challenges

Tradeoff among conflicting requirements

✓ Imperceptibility

✓ Robustness & security

✓ Capacity



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So the question is…

- **How to achieve robustness while preserving fidelity?**
- We can embed the watermark in
  - ✓coefficients of known robustness - large coefficients : perceptually significant regions, i.e. contours and textures of an image <u>with the same strength</u>

  OR
  - ✓ use all coefficients & a <u>variable strength</u> for each coefficient
- We can also use multiple embedding to increase robustness…

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Method 1

- [30] M. Barni, F. Bartolini, A. Piva: “Improved wavelet-based watermarking through pixel-wise masking”, IEEE Trans. Image Processing, 10, 5, May 2001, pp. 783 – 791.

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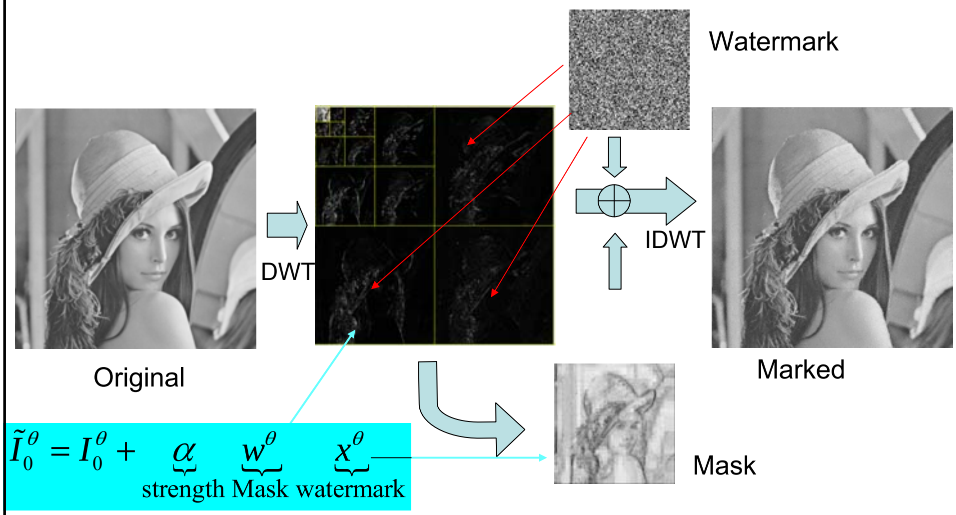
Perceptual watermark using the DWT



$$\tilde{I}_0^\theta = I_0^\theta + \underbrace{\alpha}_{\text{strength}} \underbrace{w^\theta}_{\text{Mask}} \underbrace{x^\theta}_{\text{watermark}}$$

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Perceptual watermarking

The quantization step: $q_l^{\theta}(i,j) = \underbrace{\Theta(l,\theta)}_{\text{sensitivity to noise}} \underbrace{\Lambda(l,i,j)}_{\text{local brightness}} \underbrace{\Xi(l,i,j)^{0.2}}_{\text{texture}}$

$$\Theta(l,\theta) = \begin{Bmatrix} \sqrt{2}, & \theta = 1 \\ 1 & otherwise \end{Bmatrix} \cdot \begin{Bmatrix} 1.00 & l=0 \\ 0.32 & l=1 \\ 0.16 & l=2 \\ 0.10 & l=3 \end{Bmatrix}$$

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

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

$$L(l,i,j) = \frac{1}{256} I_3^3 \left(1 + \left\lfloor \frac{i}{2^{3-l}} \right\rfloor, 1 + \left\lfloor \frac{j}{2^{3-l}} \right\rfloor \right)$$

$\longrightarrow$ the texture content is computed using the approximation image hence it has a low resolution

$$\Xi(l,i,j) = \sum_{k=0}^{3-l} \frac{1}{16^k} \sum_{\theta=0}^{2} \sum_{x=0}^{1} \sum_{y=0}^{1} \left[I_{k+l}^{\theta} \left(y + \frac{i}{2^k}, x + \frac{j}{2^k} \right) \right]^2 \cdot \mathrm{Var} \left\{ I_3^3 \left(1 + y + \frac{i}{2^{3-l}}, 1 + x + \frac{j}{2^{3-l}} \right) \right\}_{\substack{x=0,1 \\ y=0,1}}$$

Disadvantages

- Embedding - only in the highest resolution level, the watermark information can be easily erased by a potential attacker.
- The mask has low resolution.

Detection

- Blind detection, correlation, marked DWT coeff., the watermarking sequence:

$$\rho(l) = \frac{4^l}{3MN} \sum_{\theta=0}^{2} \sum_{i=0}^{M/2^l-1} \sum_{j=0}^{N/2^l-1} \tilde{I}_l^{\theta}(i,j) x_l^{\theta}(i,j)$$

For $P_f \leq 10^{-8}, T = 3.97\sqrt{2\sigma_\rho^2}$

Method 2 - Improved mask

[31] C. Nafornita, "A New Pixel-Wise Mask for Watermarking", Proc. *ACM Multimedia and Security MM&Sec*, Dallas, Sept '07, 221-228.

A modified perceptual mask → models the human visual system behavior in a better way

Embedding → in all detail sub-bands except the coarsest level, for attack resilience;

Ratio correlation / image dependent threshold → detection function nonlinear with a fixed detection threshold

- *Three types of detectors* that take advantage of the wavelet hierarchical decomposition.

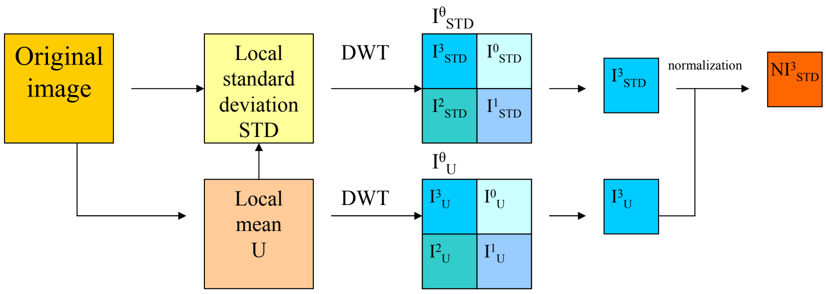
  1) from all resolution levels, **all_levels**
  2) separately, considering the maximum detector response from each level **max_level**
  3) separately, considering the maximum detector response from each subband **max_subband**

→ Compute texture content with the aid of the local standard deviation of the original image, compressed in the wavelet domain:

$$\hat{\sigma}^2(i,j) = \frac{1}{W_S \cdot W_S} \sum_{I(m,n)\in W(i,j)} \left(I(m,n) - \hat{\mu}(i,j)\right)^2$$

$$\Xi(l,i,j) = \sum_{k=0}^{3-l} \frac{1}{16^k} \sum_{\theta=0}^{2} \sum_{x=0}^{1} \sum_{y=0}^{1} \left[I_{k+l}^{\theta}\left(y + \frac{i}{2^k}, x + \frac{j}{2^k} \right) \right]^2 \cdot DWT_l^3 \left\{ \mathrm{Var}(I)_{\substack{x=0,\dots,7 \\ y=0,\dots,7}} \right\}$$

The texture mask – method 2



Other Improvements of Method 2

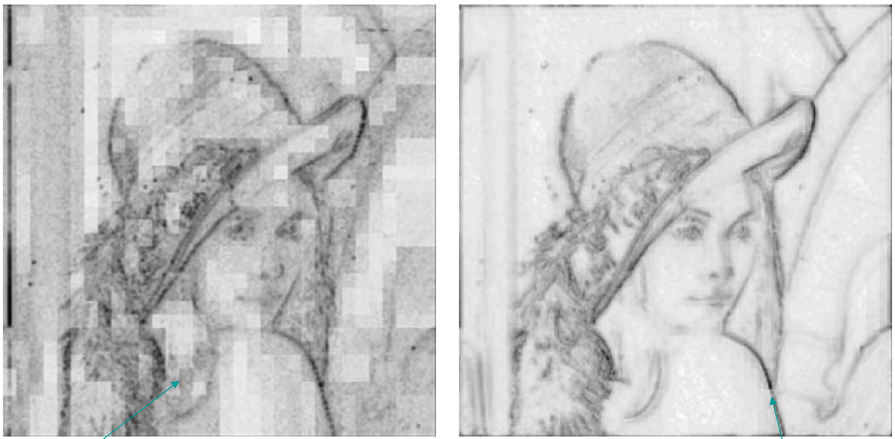
- Method 1 uses only the first decomposition level
- Method 2 uses the first three decomposition levels
- The local brightness is computed with:

$$L(l,i,j) = I_l^3(i,j)/256$$

- The noise sensitivity function is replaced by:

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

Masks for method 1 & method 2



Low resolution
☹ ☹ ☹

$$q_l^{\theta}(i,j) = \underbrace{\Theta(l,\theta)}_{\substack{\text{sensitivity}\\ \text{to noise}}}\ \underbrace{\Lambda(l,i,j)}_{\substack{\text{local}\\ \text{brightness}}}\underbrace{\Xi(l,i,j)^{0.2}}_{\text{texture}}$$

High resolution!!!
☺ ☺ ☺

Watermark Detection

Three types of detectors:

1) **all_level**

$$d_1 = \rho_{d1} / T_{d1}$$

2) **max_level**

$d(l)=\rho(l)/T(l)$, $l \in \{0,1,2\}$,

$$d_2 = \max_l \{d(l)\}$$

3) **max_subband**

$d(l, \theta) = \rho(l, \theta) / T(l, \theta)$; $l, \theta \in \{0,1,2\}$,

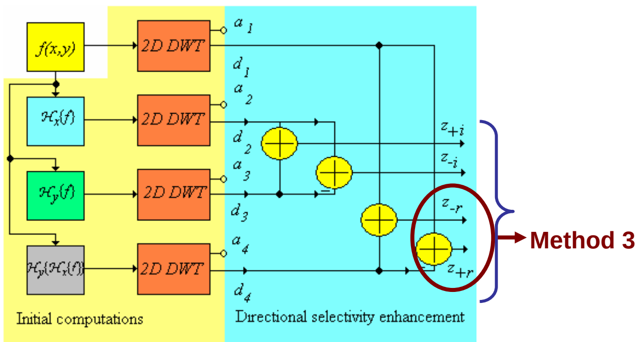
$$d_3 = \max_{\theta,l} \{d(l,\theta)\}$$

Advantages of max_level and max_subband detection

- Evaluating correlations separately per resolution level or subband is sometimes advantageous.
- Cropping: watermark damaged more likely in the lower frequency than in higher frequency
- Low-pass filtering affects higher frequency than lower ones.
- We discard layers or subbands with lower detector responses, similarly to the approach used by *Podilchuk, Zeng, 1998*.

Method 3. The first method in the HWT Domain

The watermark is embedded into the coefficients z_{+r} and z_{-r} using in each case the method 2.



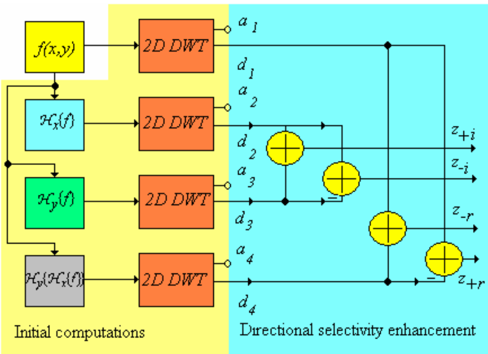
Method 3

- The watermark is embedded using the mask from [31] -- independently for each of these two images.
- The same message was embedded in both images, using the mask from [31].
- the orientations (preferential directions):
  - atan(1/2), $\pi/4$, atan(2) (respectively for θ = 0,1,2), for z_{+r}
  - -atan(1/2), $-\pi/4$, -atan(2), (θ=0,1,2) for z_{-r}
- At the detection side, we consider the pair of images (z_{+r},z_{-r}) with twice as much coefficients than the standard approach,
- θ takes all the possible values, $\pm$atan(1/2), $\pm\pi/4$, $\pm$atan(2).

Method 4. The Second Method in the HWT Domain

The watermark is embedded into the absolute values of the HWT coefficients z_+ and z_- .

$$\left|\tilde{z}_\pm\right|_l^\theta(i,j) = \left|\left|z_\pm\right|_l^\theta(i,j) + \alpha w_l^\theta(i,j) x_l^\theta(i,j)\right|,$$



$$\left|z_\pm\right| = \sqrt{z_{\pm r}^2 + z_{\pm i}^2}$$

Detection, method 4

- Ratio correlations ρ_l and image dependent thresholds $T_{\rho l}$, for the first two decomposition levels.
- If at least one of these ratios is superior to 1 then the watermark is detected with a probability of false alarm inferior to 10^{-8}.

Simulation results, method 3

- Image Lena 512×512, watermarked at levels $l \in \{0,1,2\}$ with the new mask in real images z_{+r}, z_{-r}.
- embedding strength $\alpha = 1.5$.
- Method [31], $\alpha = 1.5$ and $l \in \{0,1,2\} \rightarrow$ PSNR=36.86dB
- Barni *et al.* : ONLY first resolution level, l=0, for α=0.2 $\rightarrow$ similar image quality, PSNR=36.39 dB
- Constant for comparison:
  - the 2D watermarks embedded in the first level,
  - the image quality.

Original and watermarked images with method 3, for α = 1.5, PSNR=35.63 dB; Difference image, amplified 8 times.

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Attacks vs. detector response (ratio between ρ and T)	Method proposed in [31]			Barni's method [30]	First method based on HWT		
	all levels	max level	max subband		all levels	max level	max subband
Before attack	21.57	39.12	33.60	**44.31**	24.78	43.18	26.30
JPEG, Q=50	5.45	6.76	5.02	6.22	6.25	**7.87**	4.85
JPEG, Q=25	3.02	3.67	2.60	3.03	3.23	**4.19**	2.62
JPEG, Q=20	2.55	3.08	2.09	2.38	2.72	**3.58**	2.33
Shift, *li*=128, *co*=128	21.57	39.12	33.59	**44.31**	24.78	43.18	26.30
Median filtering, M=3	4.29	4.58	4.87	1.57	4.59	**5.42**	4.37
Median filtering, M=5	1.66	1.24	**2.27**	0.59	1.61	1.64	1.49
Resizing, 0.75	9.53	15.86	15.64	14.09	10.93	**19.34**	14.67
Resizing, 0.50	4.21	5.72	5.75	2.31	4.56	6.14	**8.71**
Cropping, 256x256	7.40	12.14	17.10	**18.08**	8.68	15.20	13.82
Cropping, 128x128	3.11	4.66	**8.31**	8.01	3.53	6.04	6.86
Cropping, 64x64	1.10	1.72	**4.45**	3.92	1.32	2.47	3.71
Gamma correction, γ=1.5	22.18	39.76	33.74	43.04	25.31	**43.61**	26.45
Gamma correction, γ=2	22.59	39.70	32.98	42.43	25.62	**43.24**	25.88
Blur, L=31, β =11	2.69	7.81	**9.56**	9.05	3.05	9.18	7.55

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- Embedding in the real parts of the HWT transform yields in a **higher capacity** at the same visual impact and robustness.
- In fact the results for method 1 $\rightarrow$ slightly better than the results obtained with the methods described in [30] and [31] for JPEG compression, median filtering with window size M=3, resizing and gamma correction.
- For the other attacks the results are similar with the results of the watermarking methods based on DWT.

The shifting attack

- the watermarked image circularly shifted with *li* lines and *co* columns $\Rightarrow$ the attacked image $(\tilde{I}_t)$
- Supposing that the numbers *li* and *co* are known, the messages at level *l* are circularly shifted with *li*/2^l lines and *co*/2^l columns obtaining the new messages $(x_t)_l^\theta$
- the watermark was detected using the image $(\tilde{I})_t$ and the messages $(x_t)_l^\theta$

The case of the shifting attack

- The robustness of the watermark is given by:
  - the shift invariance degree of the WT used,
  - the masking ability.
- The values of detector responses obtained before and after shifting attack are the same
- So, the ability of masking seems to be more important than the shift invariance degree of the WT used for the conception of counter-measures against the shifting attack, when the numbers of lines and columns used for the attack are **already known**.
- Of course, the detection of these numbers must also be realized, for the implementation of a strategy against the shifting attack

Simulation results, method 4

the value $\underline{\alpha = 1}$ $\rightarrow$ PSNR = 34.43 dB.
Attacks:
- additive white Gaussian noise (AWGN) attack.
- shifting

The robustness of Method 4 against the AWGN attack.

var_no =1	PSNRa =34.24	rat1 =13.6	rat2=3.4
var_no =4	PSNRa =32.17	rat1 =10.9	rat2=3.1
var_no = 9	PSNRa =27.96	rat1 =7	rat2=2.6
var_no =16	PSNRa =23.68	rat1 =4.3	rat2 =2.1
var_no =25	PSNRa =20.03	rat1 =3.4	rat2 =1.8
var_no =100	PSNRa =8.14	rat1 =2.4	rat2 =1.2

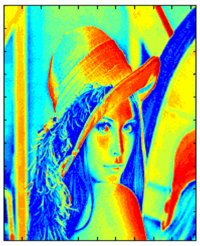

Image watermarked.

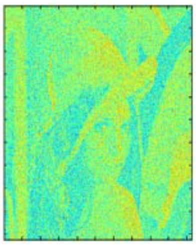

Image watermarked and attacked.

- White noise attack: for variances superior to var_no=16, this attack is useless - degradation of an image with a PSNR inferior to 25 dB.

The robustness of Method 4 against shifting.

li=16	*co*=16	PSNRt =33.82	rat1 =1.25
li =20	*co* =20	PSNRt =33.84	rat1 =1.51
li =24	*co* =24	PSNRt =33.78	rat1 =1.78
li =28	*co* =24	PSNRt =33.82	rat1 =1.65
li =32	*co* =32	PSNRt =33.77	rat1 =1.27

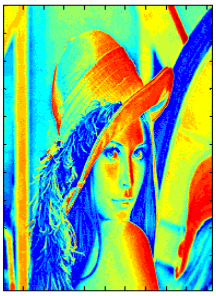

Image watermarked.

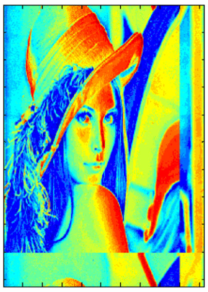

Image watermarked and attacked.

the shift invariance of the absolute values of the HWT coefficients is very good

The detection results for **method 3** are better than the results for **method 4**.
Practically, **method 3** supposes the embedding into the coefficients of two DWTs, z_{+r} and z_{-r}, distributed following the *same statistical model* as in [30] and [31].
In the case of **method 4**, the embedding is made in the coefficients $|z\_|$ and $|z_+|$ which are distributed following a *different statistical model*.

Conclusions

- We proposed a new type of pixel-wise masking for robust watermarking method based on a simple implementation of the HWT, a very modern WT
  - a flexible structure,
  - a high degree of shift-invariance
  - enhanced directional selectivity in the 2D case.
- Modifications made to two existing watermarking techniques in [30] and [31], based on DWT.
- These techniques were selected for their good robustness against the usual attacks.
- The method proposed in [31] was inspired by the method proposed in [30], but it contains some modifications.

- Modifications in [31] were made to all the factors in the mask: texture, luminance and noise sensitivity
- Embedding was possible in all resolution levels, hence the system is more attack resilient [31]
- nonlinear detector with fixed threshold – as ratio between correlation and the image dependent threshold-has been conceived.
- Using it, three watermark detectors were proposed in [31]:
  - 1) from all resolution levels,
  - 2) maximum detector response for each level
  - 3) maximum detector response for each sub-band.
- Two HWT embedding mechanisms are proposed, the first one exploiting the coefficients z_{+r} and z_{-r}, and the second one the absolute values of the complex HWT coefficients z_+ and z_- -> method 3 and method 4.

Conclusions and future research

- **The simulation results presented in this paper illustrate the effectiveness of the proposed algorithms.** We tested **the robustness** of our methods against different attacks, and found out that it **is similar or better than the robustness of the methods described in [30] and [31].**
- Our watermarking methods have **superior capacity** than the method proposed in [30] and even [31].
- Future directions
  - closer analysis on the effects of using realisable Hilbert transformers as the next step of HWT implementation development.
  - Use of an image database, like in [31].
  - consideration of other geometrical attacks (i.e. rotation), taking into account the better directional selectivity of the HWT.
  - complete statistical analysis of the absolute value of HWT coefficients