A Survey of Wavelet-domain Watermarking Algorithms

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ABSTRACT

In this paper, we will provide an overview of the wavelet-based watermarking techniques available today. We will see how previously proposed methods such as spread-spectrum watermarking have been applied to the wavelet transform domain in a variety of ways and how new concepts such as the multi-resolution property of the wavelet image decomposition can be exploited.

One of the main advantages of watermarking in the wavelet domain is its compatibility with the upcoming image coding standard, JPEG2000. Although many wavelet-domain watermarking techniques have been proposed, only few fit the independent block coding approach of JPEG2000. We will illustrate how different watermarking techniques relate to image compression and examine the robustness of selected watermarking algorithms against image compression.

Keywords: watermarking, wavelet, robustness, compression, JPEG2000, survey

1. INTRODUCTION

The development of compression technology – such as the JPEG, MPEG and more recently the JPEG2000[1] image coding standards – allowed the wide-spread use of multimedia applications. Nowadays, digital documents can be distributed via the World Wide Web to a large number of people in a cost-efficient way. The increasing importance of digital media, however, brings also new challenges as it is now straightforward to duplicate and even manipulate multimedia content. There is a strong need for security services in order to keep the distribution of digital multimedia work both profitable for the document owner and reliable for the customer. Watermarking technology plays an important role in securing the business as it allows to place an imperceptible mark in the multimedia data to identify the legitimate owner, track authorized users via fingerprinting[2] or detect malicious tampering of the document.[3]

Previous research[4] indicates that significant portions of the host image, e.g. the low-frequency components, have to be modified in order to embed the information in a reliable and robust way. This led to the development of watermarking schemes embedding in the frequency domain. Nevertheless, robust watermarking in the spatial domain can be achieved[5] at the cost of explicitly modeling the local image characteristics. These characteristics can be more easily obtained in a transform domain, however.

Many image transforms have been considered, most prominent among them is the discrete cosine transform (DCT) which has also been favored in the early image and video coding standards. Hence, there is a large number of watermarking algorithms that use either a block-based[6] or global DCT.[4] Other transforms that have been proposed for watermarking purposes include the discrete Fourier transform (DFT),[7] the Fourier-Mellin transform[8] and the fractal transform.[9] In this work, we focus on the wavelet domain for the reasons given below.

With the standardization process of JPEG2000 and the shift from DCT- to wavelet-based image compression methods, watermarking schemes operating in the wavelet transform domain have become even more interesting. New requirements such as progressive and low bit-rate transmission, resolution and quality scalability, error resilience and region-of-interest (ROI) coding have demanded more efficient and versatile image coding.[10] These requirements have been met by the wavelet-based "Embedded Block Coding with Optimized Truncation" (EBCOT) system,[11] which was accepted with minor modifications as the upcoming JPEG2000 image coding standard.[1] The wavelet transform[12] has a number of advantages[13,14] over other transforms such as the DCT that can be exploited for both, image compression and watermarking applications. Therefore, we think it is imperative to consider the wavelet transform domain for watermarking applications.

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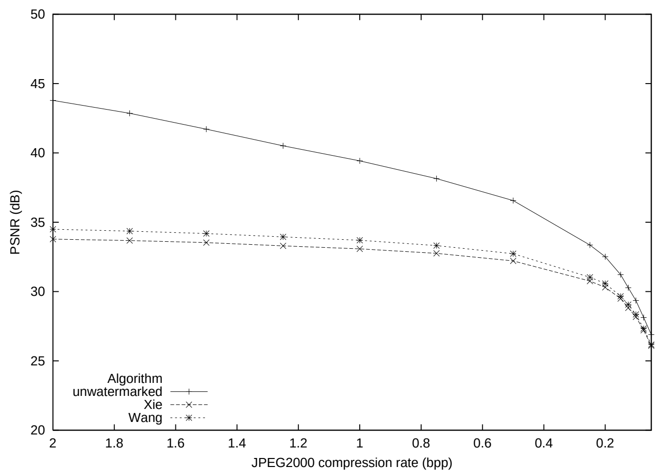
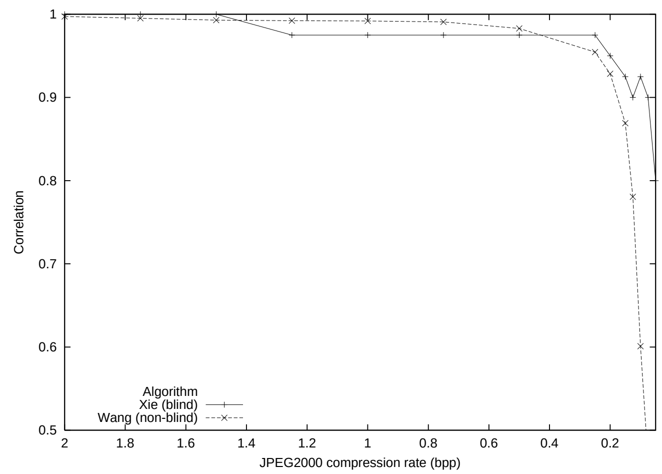


(a) PSNR



(b) watermark correlation

Figure 1. Illustration of the “distortion gap”. The “Lena” image was watermarked with two watermarking schemes, proposed by Xie and Wang, respectively, and subjected to JPEG2000 compression at different compression rates. Even though the watermarked images look identical to the original image, their PSNR is much lower than the compressed version (a). The normalized correlation of the embedded and recovered watermark is shown on the right side (b). The watermarks become undetectable as soon as the “distortion gap” closes at a coding rate of about 0.2 bits per pixel (bpp) with a PSNR of approximately 30 dB.

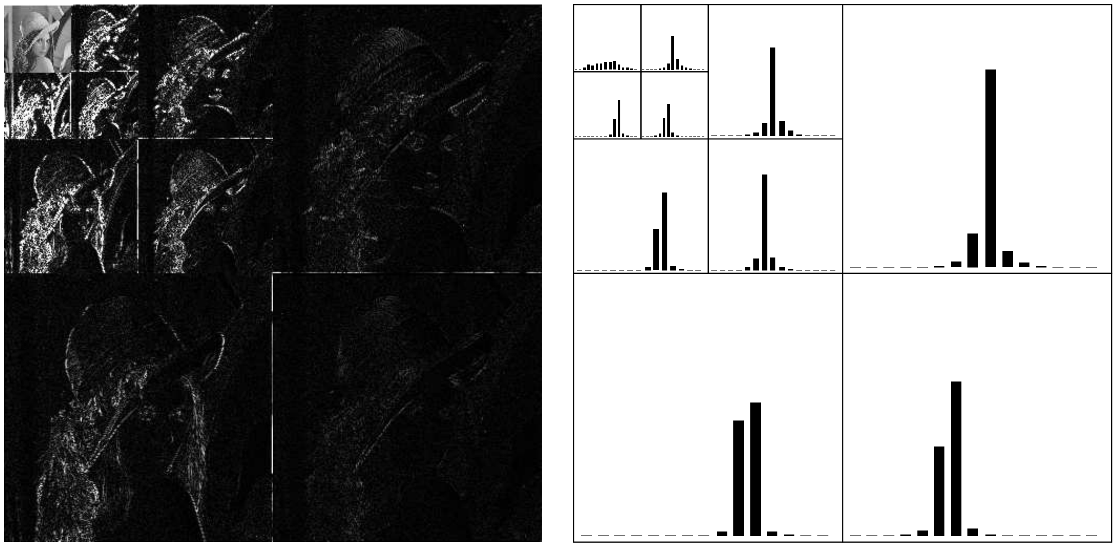
Space-frequency localization. The wavelet domain provides good space-frequency localization for analyzing image features such as edges or textured areas. To a large extent, these features are represented by the large coefficients in the detail sub-bands at various resolutions; see figure 2 (a).
Su's[15] watermarking scheme benefits from the locality of the transform coefficients to implement ROI coding.

Multi-resolution representation. Due to the multi-resolution representation of the image,[16] hierarchical processing is available in a straightforward way. This is important for e.g. progressive and scalable transmission but also for successive decoding of the watermark. As outlined by Zhu,[17] a lot of processing time can be saved – especially for video applications – by trying to detect a nested watermark from the low-resolution sub-bands first. Failing that, the algorithm can resort to the higher resolution sub-bands and try to detect the nested watermark with the aid of the additional coefficient data.

Superior HVS modeling. Watermarking as well as image compression methods can benefit from a good model of the human visual system (HVS). It allows to adapt the distortion introduced by either quantization or watermark embedding to the masking properties of the human eye. The dyadic frequency decomposition of the wavelet transform resembles the signal processing of the HVS and thus permits to excite the different perceptual bands individually.

Linear complexity. The wavelet transform has linear computational complexity, $O(n)$, as opposed to $O(n \cdot \log n)$ for the DCT (where n is the length of the signal to be transformed). The difference is important only when the DCT is applied the entire image, such as in Cox's[4] scheme. Compared to the block-based DCT, the wavelet transform is computationally more expensive.

Adaptivity. The wavelet transform is flexible enough to adapt to a given set of images or a particular type of application. The decomposition filters and the decomposition structure can be chosen to reflect the characteristics of the image. The wavelet packet transform[18] has been applied to watermarking only very recently.[19,20]
Besides the predominant fully-decimated wavelet decomposition, also the complex wavelet transform (CWT) has been employed for watermarking due to the better diagonal selectivity.[21]



(a) three-level decomposition (b) coefficient distribution

Figure 2. The transform coefficients (a) of the "Lena" image obtained by a three-level wavelet decomposition with 7/9-biorthogonal filters. The coefficient distribution of the different sub-bands is depicted in the histogram (b), where we can see that except for the approximation image, most coefficients in the detail sub-bands are close to zero.

While lossy image compression systems aim to discard redundant and perceptual insignificant information in the coding process, watermarking schemes try to add invisible information to the image. An optimal image coder would therefore simply remove any embedded watermark information. This duality has been pointed out by a number of authors. However, even state-of-the-art image coding systems such as JPEG2000[1] do not achieve optimal coding performance and therefore there is a "distortion gap" that can be exploited for watermarking; see figure 1. We watermark the "Lena" image with Xie's[22] and Wang's[23] embedding algorithm and plot the rate/distortion performance for both, the original and watermarked image; see (a). The amount of watermark information, measured as normalized correlation, that "survives" the attack is shown as well and demonstrates that the watermark can be recovered until the "capacity gap" closes; compare with figure 1 (b).

In the next section, we try to classify different wavelet-based watermarking techniques. The most interesting and important concepts of previously proposed watermarking schemes in the wavelet domain are presented in section 3. In section 4, we discuss how some of the properties of the human visual system are modeled and employed in watermarking applications. Experimental robustness results are examined in section 5 where we also give some concluding remarks.

2. CLASSIFICATION

The large number of wavelet-based watermarking schemes that has been proposed in the past five years makes it necessary to point out a few characterizing features of the algorithms. Due to the intense ongoing research and the large number of publications, it is not possible to discuss all contributions.

Decomposition strategy. Most schemes suggest three or four decomposition steps, depending on the size of the host image, using one of the well-known wavelet filters such as Haar, Daubechies-4, Daubechies-6 or 7/9-biorthogonal filters. Some wavelets achieve to represent certain types of images in a more compact way than others. For instance, images with sharp edges would benefit from short wavelet filters due to the spatial location of such features.
Hsu[24] states that the criteria to evaluate wavelet filters for watermarking purposes are different compared to image compression applications. Wavelet filters that pack most energy of the host image in the lowest resolution approximation image might not be a good choice when watermarking occurs in the detail sub-bands.[25] The

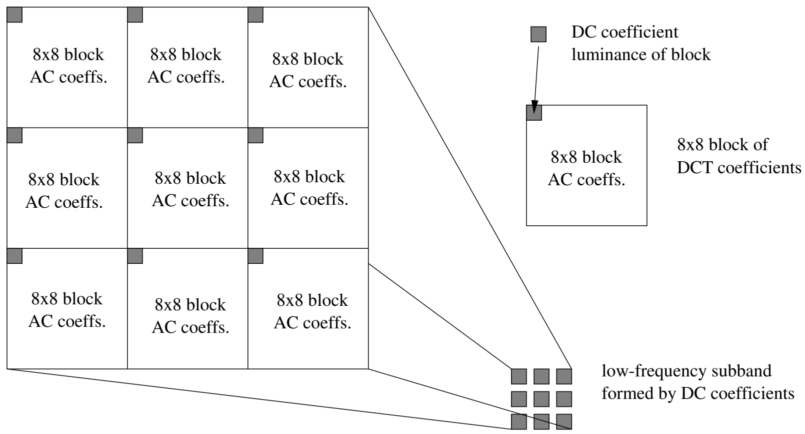


Figure 3. The DC coefficients of all the 8×8 DCT coefficient blocks of an image can be arranged to form a low-resolution approximation image of the image which is equivalent to the approximation image obtained by a three-level wavelet decomposition.

suitability of different transform domains and wavelet filters was evaluated by Kundur[26] and Wolfgang[27] with regard to image compression attacks.

The wavelet packet transform can be used to derive a decomposition structure capturing the image activity in particular sub-bands,[28] as an additional key to improve security[20] or to embed watermark information in the transform structure itself.[19]

Coefficient selection. The selection of the coefficients that are manipulated in the watermarking process is determined by the embedding technique and the application. The main distinction is between the approximation image (LL) which contains the low-frequency signal components and the detail sub-bands (LH_j, HL_j, HH_j, j is the resolution level) that represent the high-frequency information in horizontal, vertical and diagonal orientation; see figure 4 (a).

HVS modeling. The masking properties of the human visual system are taken into account either implicitly or explicitly.[29] In section 4, we discuss the aspects of coefficient selection and HVS modeling in more detail.

Embedding technique. Watermark information can be embedded in selected coefficients by adding a pseudo-random noise-like spread-spectrum sequence or via a quantization-and-replace strategy.

Image fusion is the process where a smaller "logo" image is encoded in the host image. The logo is first transformed to the wavelet domain before it is added to the host image.[30,31]

Extraction method. Regarding the requirements for watermark extraction, we can distinguish blind, semi-blind and non-blind (or private) schemes. While private watermarking methods need access to the original, unwatermarked image to recovery the watermark, semi-blind methods only require some reference data. Blind methods can extract the watermark given only the host image and are therefore most flexible but also most difficult to realize.

Application. Wavelet-based watermarking methods have been proposed for copyright protection, image authentication and tamper detection, data hiding and image labeling applications. The vast majority of research concentrates on still image data, but wavelet-domain watermarking of video[17] and 3D polygonal models[32] has also been examined.

3. WATERMARKING TECHNIQUES

3.1. Approximation image methods

The first authors[33,34] that refer to the wavelet domain for watermarking describe an embedding strategy that operates on the coefficients of a low-resolution approximation representation of the host image. This approximation image can be derived in various way. For example, the approximation image computed by a three-level wavelet decomposition is equivalent to the subband formed by the DC coefficients of a DCT on 8x8 image blocks; see figure 3. Watermarking schemes that operate in this general low-frequency subband – without depending on any particular feature of the wavelet decomposition – have been proposed by Liang,[35] Ohnishi[36] and Tzovaras.[37]

The watermarking schemes of Liang and Ohnishi both apply the DFT on the approximation image. Ohnishi segments the approximation image and applies the DFT on sub-blocks. For each sub-block the DC coefficient is quantized to encode on bit of watermark information. On the other hand, Liang adds a pseudo-random Gaussian sequence to the DFT coefficients similar to Cox's approach.[4]

Corvi[34] builds on Cox's[4] additive spread-spectrum watermark and, instead of marking the 1000 largest coefficients of a global DCT, places the watermark in the coefficients of the approximation image of suitable size. Later on, in an attempt to fix the invertibility problem,[38] Nicchiotti[39] resorts to a quantize-and-replace strategy to embed the mark. Another technique manipulating approximation image coefficients is Xie's[22] algorithm which quantizes the median coefficient of a 3×1 sliding window.

Pereira[40] describes a method based on a one-level decomposition of non-overlapping 16×16 image blocks using Haar wavelet filters. The proposed watermarking algorithm uses linear programming to optimize watermark robustness within a visual distortion constraint given by JND threshold maps. For each bit to be embedded, a 2×2 block of neighboring coefficient is selected from a LL subband of size 8×8. The information is embedded using differential coding. It is important to select neighboring coefficients since it is assumed that their difference is 0 on average.

Watermarking in the approximation image is rather straightforward and the techniques of previously proposed embedding algorithms for the spatial or DCT domain, such as uni- or bi-directional coding[33,41] and additive spread-spectrum watermarking,[4,14] respectively, can be readily applied.

3.2. Detail subband methods

While the magnitude of the approximation image coefficients is rather uniform, the distribution of the detail subband coefficients follows a Laplacian; see the histogram in figure 2 (b). Most coefficients are close to zero, only the few large peaks which correspond to edge and texture information in the image contain significant energy. These features which are localized in space in the wavelet transform domain are represented at different scales with decreasing resolution, thus allowing multi-resolution analysis,[16] highlighting both, small and large image features.

To reliably embed the watermark in detail subband coefficients, either only sufficiently large coefficients are selected or the watermark strength has to be weighted in order to place more energy in the significant coefficients. The embedding intensity can be adapted to the energy of the subband,[42] the decomposition level[43] or the orientation of the subband.[44] In several schemes,[23] the significance of a coefficient is determined by comparing it with the threshold

$$T_l^o = \frac{\max\{|c_l^o|\}}{2}$$

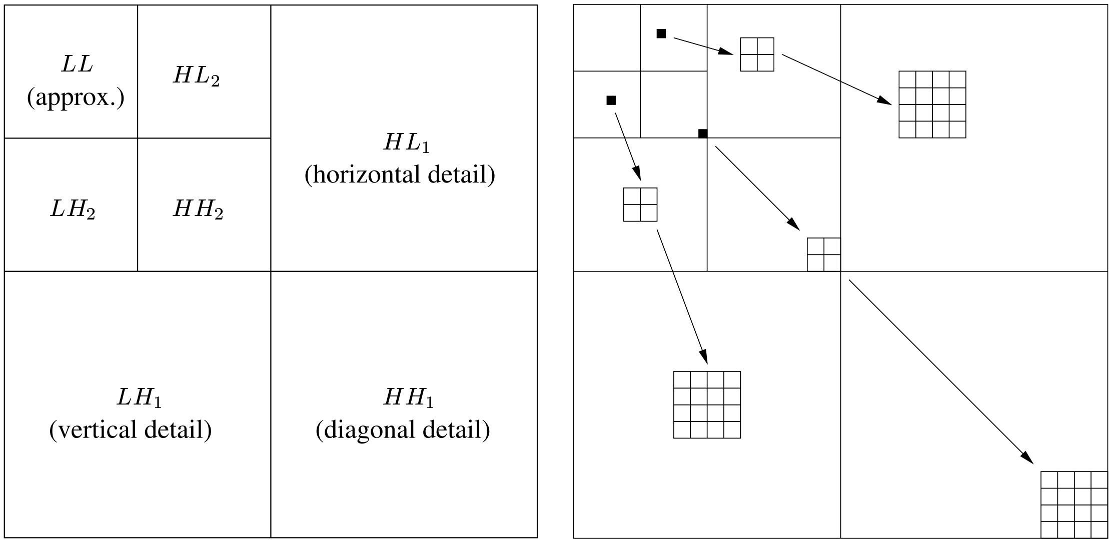
which is derived from the maximum absolute coefficient value of the subband with orientation o at decomposition level l. The same significance measure is used in image coding, e.g. Wang's[45] "Multi-Threshold Wavelet Coder" (MTWC), for successive subband coding.

Based on a multi-resolution technique by Xia,[13] Kim[43] utilizes DWT coefficients of all sub-bands including the approximation image to equally embed a random Gaussian distributed watermark sequence in the whole image. Perceptually significant coefficients are selected by level-adaptive thresholding to achieve high robustness. The energy of the watermark is depending on the level of the decomposition to avoid perceptible distortion.

Tsekeridou[46] exploits the multi-resolution property of the wavelet transform domain and embeds a circular self-similar watermark in the first- and second-level detail sub-bands of a wavelet decomposition. The self-similarity proves useful for watermark detection without the original image since the search-space to locate the embedded watermark can be drastically reduced if the image has undergone geometric distortion.

Kundur[47] embeds a binary watermark by modifying the amplitude relationship of three transform-domain coefficients from distinct detail sub-bands of the same resolution level of the host image. Each selected coefficient tuple is sorted and the middle coefficient is quantized to encode either a zero or a one bit. To strengthen the blind watermark extraction process, Kundur resorts to repetition and a reference mark.

Davoine[48] compares a watermarking scheme similar to the one proposed by Kundur to a new technique which partitions the union of the lowest-resolution detail sub-bands into distinct regions that have approximately the



(a) two-level decomposition structure (b) zero-tree structure

Figure 4. On the left side, we show the decomposition structure (a) after two steps of high/low-pass filtering in horizontal and vertical direction. The image decomposition structure and the parent-child relationship ("zerotree") between subband coefficients of different resolutions is illustrated on the right (b). If a wavelet coefficient at a coarse scale is insignificant (close to zero), then all child coefficients are likely to be insignificant as well.

same number of significant coefficients. The significant coefficients of a region are quantized to represent one bit of watermark information. The later algorithm is more flexible, as it is not limited to quantizing coefficient triples but can adapt the number of significant coefficients per region to robustness requirements. However, the new approach only achieves semi-blind watermark extraction since reference data is required: the locations of the coefficient triples in the first case or the partitioning of the detail sub-bands in the second case.

3.3. Exploiting the relationship to image coding

Jayawardena[49] successively applies binary wavelet filters to obtain a multi-resolution domain. The algorithm selects a significant bit-layer of the detail sub-bands. First, all bits in that layer are set to one and the inverse wavelet transform is computed. The resulting image is denoted by I_1. Next, all bits in the selected layer are set to zero and, again, the inverse transform is applied to compute I_0. Now, we observe for which locations of the selected bit-plane the embedded information is "stable" when the image is subjected to lossy image compression with decreasing bit rates. Moreover, a given visual distortion bound has to be respected for each prospective bit storage location. The set of "stable" locations is used to directly embed the binary watermark.

Zerotree coding[50] is based on the hypothesis that if a wavelet coefficient at a coarse scale is insignificant with respect to a given threshold T, then all wavelet coefficients of the same orientation in the same spatial location at a finer scale are likely to be insignificant with respect to T. A zerotree root is encoded with a special symbol indicating that the whole tree is insignificant. This results in gross code symbols savings because at high frequency sub-bands many insignificant coefficients can be discarded. The notion of zerotree coding has been applied to watermarking by Inoue[51] who replaces the insignificant coefficients of a zerotree with small positive or negative values corresponding to the watermark information to be embedded; compare with figure 4 (b).

Xie's[22] embedding algorithm mentioned earlier can be integrated into the SPIHT coder,[52] exploiting the zerotree coding approach. The direct descendants of a significant coefficient, a 4×4 window, is likely not to be discarded by the coder. Therefore, the capacity of of the watermark can be increased by encoding information in these coefficients.

An early attempt to integrate wavelet-based image coding and watermarking has been made by Wang[53] and Su.[54] While the first approach was based on the "Multi-Threshold Wavelet Codec" (MTWC),[45] the later pro-

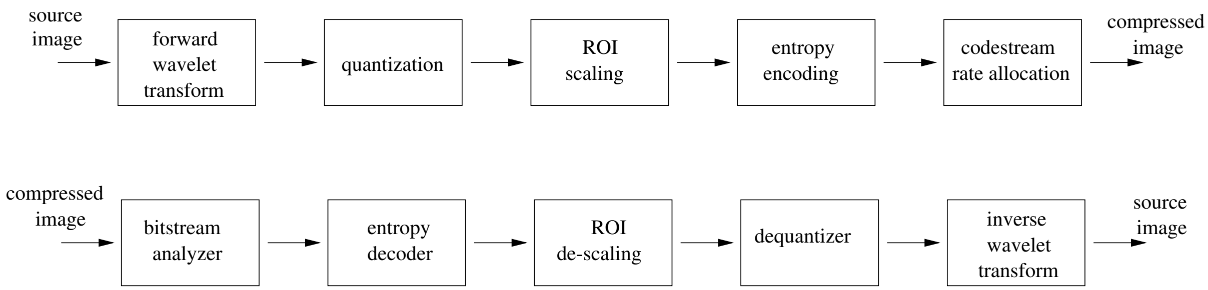


Figure 5. The JPEG2000 coding pipeline.

posal builds on "Embedded Block Coding with Optimized Truncation" (EBCOT)[11] which is also the basis for the upcoming JPEG2000 image compression standard. Both watermarking algorithms add a pseudo-random Gaussian noise sequence to the significant coefficients of selected detail sub-bands. The watermark embedding and recovery process is performed on-the-fly during image compression and decompression. The computational cost to derive the transform domain a second time for watermarking purposes can therefore be saved.

The major difference between previously proposed wavelet-based image compression algorithms such as SPIHT[52] is that EBCOT as well as JPEG2000 operate on independent, non-overlapping blocks which are coded in several bit layers to create an embedded, scalable bit-stream. Instead of zero-trees, the JPEG2000 scheme depends on a per-block quad-tree structure since the strictly independent block coding strategy precludes structures across sub-bands or even code-blocks. These independent code-blocks are passed down the "coding pipeline" shown in figure 5 and generate separate bit-streams. Transmitting each bit layer corresponds to a certain distortion level. The partitioning of the available bit budget between the code blocks and layers ("truncation points") is determined using a sophisticated optimization strategy for optimal rate/distortion performance.

The main design goals behind EBCOT and JPEG2000 are versatility and flexibility which are achieved to a large extent by the independent processing and coding of image blocks.[10] The default for JPEG2000 is to perform a five-level wavelet decomposition with 7/9-biorthogonal filters and then segment the transformed image into non-overlapping code-blocks of no more than 4096 coefficients.

In order to fit the JPEG2000 coding process, a watermarking system has to obey the independent processing of the code-blocks. Algorithms which depend on the inter-subband[47] or the hierarchical multi-resolution[51] relationship can not be used directly in JPEG2000 coding. Due to the limited number of coefficients in a JPEG2000 code-block, correlation-based methods[44,53] fail to reliably detect watermark information in a single independent block. Obviously, watermarking methods that require access to the original image or reference data for watermark extraction are not suited as well – this precludes all the non-blind watermarking schemes.[34,13,43]

4. HVS MODELING

Robust image watermarking techniques should exploit the characteristics of the human visual system (HVS) in order to maximize the strength of the watermark, while, at the same time, guarantee imperceptibility.[44,55]

The response of the HVS depends on the luminance and the frequency of a visual stimulus but also on the contrast masking effects which occur when two signal components, characterized by spatial location, frequency and orientation, excite the same channel of the cortex.[56] Several authors claim that the wavelet transform is closer to the human visual system than the DCT because it splits the signal into multi-resolution bands of particular scale and orientation that can be processed independently.

The visibility of wavelet quantization noise[57] and the possibilities of visual masking[58] in the wavelet domain have been extensively studied for image compression. However, image compression schemes can not take full advantage of visual masking because the quantization parameters for the local model would have to be sent as side information to the decoder.[55] This is not the case for watermarking applications, where the received image can be used to estimate the original image; this might explain the "distortion gap" mentioned in section 1.

A concept shared between image compression and watermarking systems is the "just noticeable difference" (JND) threshold. The JND threshold is an upper bound on the quantization step size and the watermark intensity, respectively, and determines the amount of distortion that can be added to each coefficient without being visible.

We can distinguish image-adaptive[55] and non-adaptive perceptual coding methods. For non-adaptive techniques such as frequency weighting, depending only on the viewing conditions, i.e. viewing distance and display resolution, it is possible to derive a static threshold for each frequency band. On the other hand, luminance sensitivity and visual masking depend on the local characteristics of the signal. It is therefore convenient to compute a JND map, containing a weighting factor for each transform domain coefficients to be modified.

The watermarking algorithms proposed by Podilchuk,[55] Barni[44] and Pereira[40] incorporate a weighting factor $j_l^o(m,n)$ in the embedding function,

$$\tilde{c}_l^o(m,n) = c_l^o(m,n) + \alpha \cdot j_l^o(m,n) \cdot w_i.$$

The weighting factor depends on the resolution level, l, and the orientation, o, of the subband, the local luminance, which can be derived from the corresponding coefficient in the approximation image, and the texture activity in the neighborhood of the coefficient. Watson[57] provides experimental quantization factors for different resolution levels and orientations, Lewis[50] suggests means to compute the local brightness and texture activity. Daly[58] presents a point-wise non-linear function that is used to implement visual masking in JPEG2000.

In contrast to the more complicated explicit HVS modeling described above, most watermarking methods resort to simple implicit modeling[29] which can be performed in the coefficient selection step or just takes into account the energy of a particular coefficient or subband. The watermark signal is simply scaled according to the energy of the wavelet-domain coefficient[17,29,43] $(\beta = 1)$. Xia[13] suggests to amplify large coefficients by setting $\beta = 2$.

$$\tilde{c}_l^o(m,n) = c_l^o(m,n) + \alpha \cdot |c_l^o(m,n)|^\beta \cdot w_i$$

Since large coefficients in the detail sub-bands represent edge and texture information, more watermark energy is placed in the image regions the human eye is less sensitive to.

Watson's quantization matrix[57] indicates that the HVS is least sensitive to distortion in the HH sub-bands (diagonal orientation). Watermarking methods address this fact in that either the HH subband is not used at all to embed watermark information because image compression will employ coarse quantization here, e.g. Inoue's[51] algorithm, or that the embedding intensity is increased.[44] Furthermore, following Watson's observations, the noise visibility threshold decreases when going from high-resolution to lower-resolution sub-bands – an effect which is exploited in Kim's[43] watermarking method.

5. DISCUSSION

In figure 6, we show copies of the "Lena" image where a watermark has been embedded with the algorithms described by Xia,[13] Kim,[43] Xie[22] and Kundur[47] (from left to right). The difference images depicted in the second row reveal the regions of the host image that were manipulated to embed the watermark. Modifying large detail subband coefficients results in a watermark placed in the edge region (first column). The effect of approximation image watermarking is a low-frequency pattern being added to the image (third column).

We tried to compare the robustness of selected watermarking algorithms against image compression. The algorithms have been re-implemented, closely following the description in the papers. The 512×512 gray-scale image "Lena" was watermarked with a group of blind and non-blind watermarking algorithms. It is well known that blind watermark extraction is more difficult than watermark recovery with the aid of a reference image, hence, results should only be compared within one group. To make the detection results of the different types of watermarks comparable, we calculated the normalized correlation between the embedded and the extracted mark. The distortion introduced by JPEG, SPIHT[52] and JPEG2000 compression* was measured in terms of PSNR and used to plot the correlation results; see figure 7. The PSNR range from 43 to 30 dB corresponds to the quality factors of 95 down to 10 for JPEG compression and bit rates of 1.75 to 0.1 per pixel for SPIHT and JPEG2000 compression.

To analyze the effect of matching the compression and watermarking domain,[27] we also include the results of the well-known blind and non-blind DCT-based schemes by Koch[6] and Cox.[4] Besides Inoue's[51] embedding algorithm based on the zero-tree structure which has a synchronization problem that explains the sharp fall-off

*For our experiments, we used the JasPer version 0.026 implementation of JPEG2000, available at `http://spmg.ece.ubc.ca/people/mdadams/jasper/index.html`.

Algorithm	Xia	Kim	Xie	Kundur
PSNR	38.71	38.57	34.24	43.91

Figure 6. The 512×512 "Lena" gray-scale image, watermarked with the algorithms by Xia, Kim, Xie and Kundur; top row. The difference images in the second row reveal the regions that have been modified to embed the watermark. The PSNR of the watermarked images is given in the table.

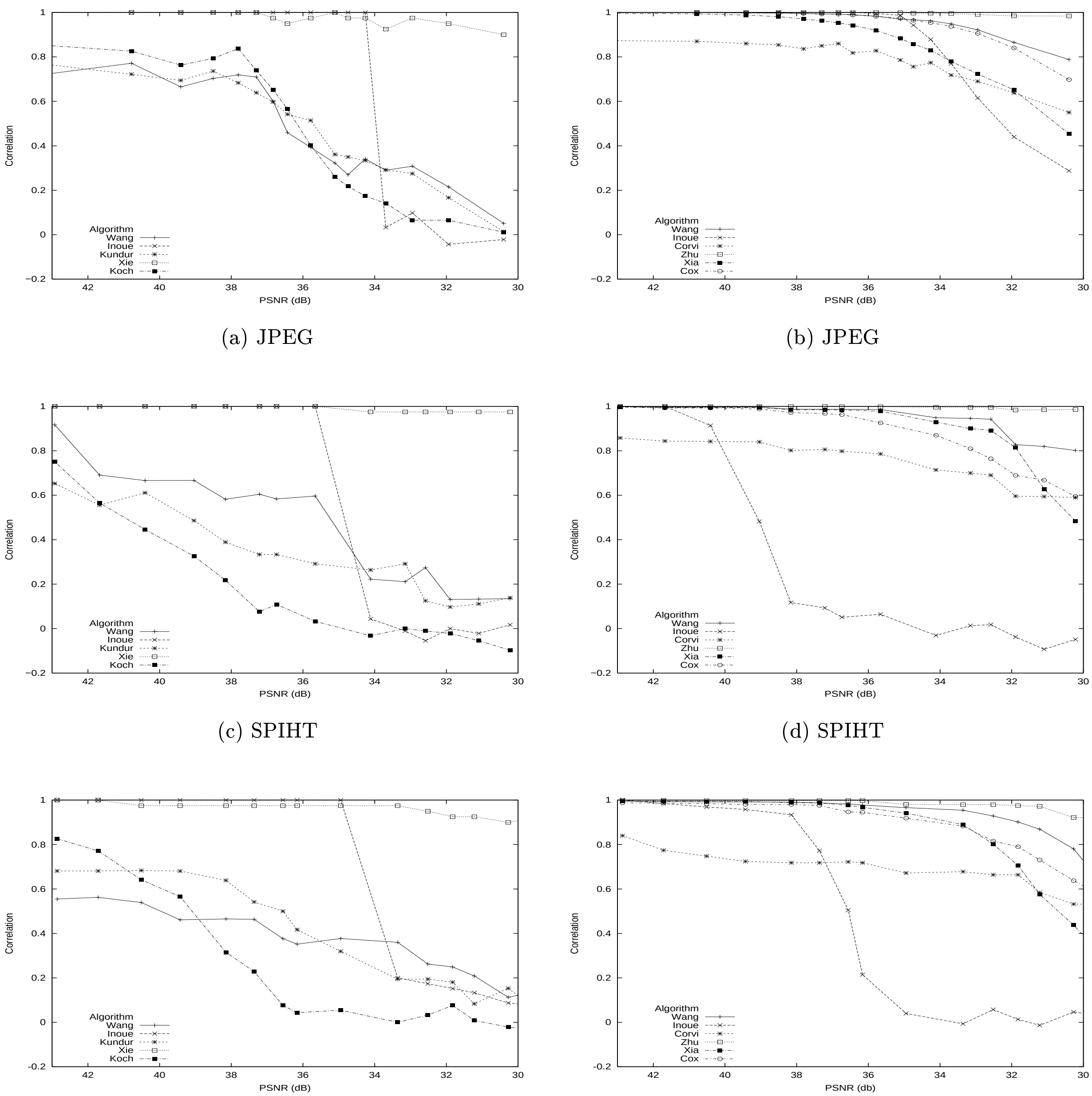
at higher distortion levels, all proposed watermarking schemes are robust to image compression attacks when the original image can be used for watermark recovery. All selected non-blind algorithms are extensions to Cox's[4] spread-spectrum embedding method which allows to compare the results directly. Therefore, we can attribute the superior performance of Wang's[23] and Zhu's[17] approach to the advantages of the wavelet domain.

Among the blind watermarking methods, Xie's[22] low-frequency embedding algorithm shows exceptional performance. However, a fair comparison of the algorithms is not possible given the different security and capacity requirements.

We believe that wavelet-domain watermarking is becoming even more interesting in the light of JPEG2000. Some considerations and constraints of previously proposed watermarking schemes have been presented in this paper.

REFERENCES

1. "JPEG2000 part 1 final committee draft version 1.0," tech. rep., ISO/IEC FCD15444-1, March 2000.
2. J. Dittmann, A. Behr, M. Stabenau, P. Schmitt, J. Schwenk, and J. Ueberberg, "Combining digital watermarks and collusion secure fingerprints for digital images," in *Proceedings of the 11th SPIE Annual Symposium, Electronic Imaging '99, Security and Watermarking of Multimedia Contents*, P. W. Wong, ed., vol. 3657, (San Jose, CA, USA), January 1999.
3. D. Kundur and D. Hatzinakos, "Digital watermarking for telltale tamper-proofing and authentication," in *Proceedings of the IEEE: Special Issue on Identification and Protection of Multimedia Information*, vol. 87, pp. 1167 – 1180, July 1999.
4. I. J. Cox, J. Kilian, T. Leighton, and T. G. Shamoon, "Secure spread spectrum watermarking for multimedia," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '97*, vol. 6, pp. 1673 – 1687, (Santa Barbara, California, USA), October 1997.
5. O. Bruyndonckx, J.-J. Quisquater, and B. M. Macq, "Spatial method for copyright labeling of digital images," in *Proceedings of the IEEE International Workshop on Nonlinear Signal and Image Processing*, pp. 456 – 459, (Marmaras, Greece), 1995.
6. E. Koch and J. Zhao, "Towards robust and hidden image copyright labeling," in *Proceedings of the IEEE International Workshop on Nonlinear Signal and Image Processing*, pp. 452 – 455, (Marmaras, Greece), June 1995.
7. M. Ramkumar, A. N. Akansu, and A. A. Alatan, "A robust data hiding scheme for images using DFT," in *Proceedings of the 6th IEEE International Conference on Image Processing ICIP '99*, pp. 211 – 215, (Kobe, Japan), October 1999.
8. J. J. K. O'Ruanaidh and T. Pun, "Rotation, scale and translation invariant spread spectrum digital image watermarking," *Signal Processing* **66**, pp. 303 – 317, May 1998.



(a) JPEG (b) JPEG

(c) SPIHT (d) SPIHT

(e) JPEG2000 (f) JPEG2000

Figure 7. Normalized correlation results of the recovered watermark after image compression. The left column shows the results for blind watermarking, while on the right side, the algorithms that refer to the original image for watermark detection are shown. Selected watermarking algorithms were used to encode a suitable watermark in the 512×512 "Lena" gray-scale image. We used JPEG, SPIHT and JPEG2000 for image compression.

9. J.-L. Dugelay and S. Roche, "Fractal transform based large digital watermark embedding and robust full blind extraction," in *Proceedings of the IEEE International Conference on Multimedia & Computing Systems ICMCS '99*, vol. 2, pp. 1003 – 1004, (Florence, Italy), June 1999.
10. M. Charrier, D. S. Cruz, and M. Larsson, "JPEG2000, the next millennium compression standard for still images," in *Proceedings of the IEEE International Conference on Multimedia & Computing Systems ICMCS '99*, vol. 1, pp. 131 – 132, (Florence, Italy), June 1999.
11. D. Taubman, "High performance scalable image compression with EBCOT," *IEEE Transactions on Image Processing* **9**, pp. 1158 – 1170, July 2000.
12. I. Daubechies, *Ten lectures on wavelets*, SIAM Press, Philadelphia, PA, USA, 1992.
13. X.-G. Xia, C. G. Boncelet, and G. R. Arce, "Wavelet transform based watermark for digital images," *Optics Express* **3**, p. 497, December 1998.
14. A. Lumini and D. Maio, "A wavelet-based image watermarking scheme," in *Proceedings of the IEEE International Conference on Information Technology: Coding and Computing*, pp. 122 – 127, (Las Vegas, NV, USA), March 2000.
15. P.-C. Su, H.-J. Wang, and C.-C. J. Kuo, "Digital image watermarking in regions of interest," in *The IS&T Image Processing, Image Quality, Image Capture, Systems Conference PICS '99*, pp. 295 – 300, (Savannah, GA, USA), April 1999.
16. S. Mallat, "A theory for multiresolution signal decomposition: The wavelet representation," *IEEE Transactions on Pattern Analysis and Machine Intelligence* **11**, pp. 674 – 693, July 1989.
17. W. Zhu, Z. Xiong, and Y.-Q. Zhang, "Multiresolution watermarking for images and video: a unified approach," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '98*, pp. 465 – 468, (Chicago, IL, USA), October 1998.
18. R. R. Coifman, Y. Meyer, S. Quake, and M. V. Wickerhauser, "Signal processing and compression with wavelet packets," in *Proceedings of the International Conference Wavelets and Applications*, Y. Meyer, ed., pp. 77 – 93, (Toulouse, France), 1992.
19. J. L. Vehel and A. Manoury, "Wavelet packet based digital watermarking," in *Proceedings of the 15th International Conference on Pattern Recognition*, (Barcelona, Spain), September 2000.
20. M.-J. Tsai, K.-Y. Yu, and Y.-Z. Chen, "Wavelet packet and adaptive spatial transformation of watemark for digital image authentication," in *Proceedings of the IEEE International Conference on Image Processing*, (Vancouver, Canada), September 2000.
21. P. Loo and N. G. Kingsbury, "Watermarking using complex wavelets with resistance to geometric distortion," in *Proceedings of the 10th European Signal Processing Conference EUSIPCO '00*, (Tampere, Finland), September 2000.
22. L. Xie and G. R. Arce, "Joint wavelet compression and authentication watermarking," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '98*, (Chicago, IL, USA), 1998.
23. H.-J. Wang and C.-C. J. Kuo, "Image protection via watermarking on perceptually significant wavelet coefficients," in *Proceedings of the 1998 IEEE Workshop on Multimedia Signal Processing*, (Los Angeles, CA, USA), December 1998.
24. C.-T. Hsu and J.-L. Wu, "Multiresolution watermarking for digital images," *IEEE Transactions on Circuits and Systems II* **45**, pp. 1097 – 1101, August 1998.
25. M. Ramkumar, A. N. Akansu, and A. A. Alatan, "On the choice of transforms for data hiding in compressed video," in *Proceedings of ICASSP '99*, vol. 6, pp. 3049 – 3052, (Phoenix, AZ, USA), March 1999.
26. D. Kundur and D. Hatzinakos, "Mismatching perceptual models for effective watermarking in the presence of compression," in *Proceedings of the SPIE Conference on Multimedia Systems and Applications II*, vol. 3845, (Boston, MA, USA), September 1999.
27. R. B. Wolfgang, C. I. Podilchuk, and E. J. Delp, "The effect of matching watermark and compression transforms in compressed color images," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '98*, (Chicago, IL, USA), October 1998.
28. M. Ejima and A. Miyazaki, "A wavelet-based watermarking for digital images and video," in *Proceedings of the IEEE International Conference on Image Processing*, (Vancouver, Canada), September 2000.
29. R. Dugad, K. Ratakonda, and N. Ahuja, "A new wavelet-based scheme for watermarking images," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '98*, (Chicago, IL, USA), October 1998.
30. D. Kundur and D. Hatzinakos, "A robust digital image watermarking method using wavelet-based fusion," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '97*, vol. 1, pp. 544 – 547, (Santa Barbara, California, USA), October 1997.
31. J. J. Chae, D. Mukherjee, and B. S. Manjunath, "A robust embedded data from wavelet coefficients," in *Proceeding of SPIE EI '98 Stroage and Retrieval for Image and Video Database VI*, vol. 3312, pp. 308 – 317, (San Jose, CA, USA), 1998.
32. S. Kanai, H. Date, and T. Kishinami, "Digital watermarking for 3d polygons using multiresolution wavelet decomposition," in *Proceedings of the Sixth IFIP WG 5.2 International Workshop on Geometric Modeling: Fundamentals and Applications*, pp. 296 – 307, (Tokyo, Japan), December 1998.
33. F. M. Boland, J. J. K. O'Ruanaidh, and C. Dautzenberg, "Watermarking digital images for copyright protection," in *IEE Conference Proceedings on Image Processing and its Applications*, No. 410, pp. 326 – 330, IEEE, July 1995.

34. M. Corvi and G. Nicchiotti, "Wavelet-based image watermarking for copyright protection," in *Scandinavian Conference on Image Analysis SCIA '97*, (Lappeenranta, Finland), June 1997.
35. J. Liang, P. Xu, and T. D. Tran, "A universal robust low frequency watermarking scheme," *submitted to IEEE Transactions on Image Processing* , May 2000.
36. J. Ohnishi and K. Matsui, "A method of watermarking with multiresolution analysis and pseudo noise sequences," *Systems and Computers in Japan* **29**, pp. 11 – 19, May 1998.
37. D. Tzovaras, N. Karagiannis, and M. G. Strintzis, "Robust image watermarking in the subband or discrete cosine transform," in *Proceedings of the 9th European Signal Processing Conference EUSIPCO '98*, pp. 2285 – 2288, (Island of Rhodes, Greece), September 1998.
38. S. Craver, N. Memon, B.-L. Yeo, and M. M. Yeung, "On the invertibility of invisible watermarking techniques," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '97*, vol. 1, p. 540, (Santa Barbara, California, USA), October 1997.
39. G. Nicchiotti and E. Ottaviano, "Non-invertible statistical wavelet watermarking," in *Proceedings of the 9th European Signal Processing Conference EUSIPCO '98*, pp. 2289 – 2292, (Island of Rhodes, Greece), September 1998.
40. S. Pereira, S. Voloshynovskiy, and T. Pun, "Optimized wavelet domain watermark embedding strategy using linear programming," in *SPIE AeroSense 2000: Wavelet Applications VII*, H. H. Szu, ed., (Orlando, FL, USA), April 2000.
41. I. Pitas, "A method for signature casting on digital images," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '96*, vol. 3, pp. 215 – 218, (Lausanne, Switzerland), September 1996.
42. Y.-S. Kim, O.-H. Kwon, and R.-H. Park, "Wavelet based watermarking method for digital images using the human visual system," *Electronic Letters* **35**, pp. 466 – 467, June 1999.
43. J. R. Kim and Y. S. Moon, "A robust wavelet-based digital watermark using level-adaptive thresholding," in *Proceedings of the 6th IEEE International Conference on Image Processing ICIP '99*, p. 202, (Kobe, Japan), October 1999.
44. M. Barni, F. Bartolini, V. Cappellini, A. Lippi, and A. Piva, "A DWT-based technique for spatio-frequency masking of digital signatures," in *Proceedings of the 11th SPIE Annual Symposium, Electronic Imaging '99, Security and Watermarking of Multimedia Contents*, P. W. Wong, ed., vol. 3657, (San Jose, CA, USA), January 1999.
45. H.-J. Wang and C.-C. J. Kuo, "High fidelity image compression with multithreshold wavelet coding (MTWC)," in *SPIE's Annual meeting - Application of Digital Image Processing XX*, (San Diego, CA, USA), August 1997.
46. S. Tsekeridou and I. Pitas, "Embedding self-similar watermarks in the wavelet domain," in *Proceedings of the IEEE ICASSP 2000*, (Istanbul, Turkey), June 2000.
47. D. Kundur, "Improved digital watermarking through diversity and attack characterization," in *Proceedings of the ACM Workshop on Multimedia Security '99*, pp. 53 – 58, (Orlando, FL, USA), October 1999.
48. F. Davoine, "Comparison of two wavelet based image watermarking schemes," in *Proceedings of the IEEE International Conference on Image Processing*, (Vancouver, Canada), September 2000.
49. A. Jayawardena, B. Murison, and P. Lenders, "Embedding multiresolution binary images into multiresolution watermark channels in wavelet domain," in *Proceedings of the IEEE ICASSP 2000*, (Istanbul, Turkey), June 2000.
50. A. S. Lewis and G. Knowles, "Image compression using the 2-d wavelet transform," *IEEE Transactions on Image Processing* **1**, pp. 244 – 250, April 1992.
51. H. Inoue, A. Miyazaki, A. Yamamoto, and T. Katsura, "A digital watermark based on the wavelet transform and its robustness on image compression," in *Proceedings of the IEEE International Conference on Image Processing, ICIP '98*, (Chicago, IL, USA), 1998.
52. A. Said and W. A. Pearlman, "A new, fast, and efficient image codec based on set partitioning in hierarchical trees," in *IEEE Transactions on Circuits and Systems for Video Technology*, vol. 6, pp. 243 – 250, June 1996.
53. H.-J. Wang and C.-C. J. Kuo, "An integrated approach to embedded image coding and watermarking," in *Proceedings of IEEE ICASSP '98*, (Seattle, WA, USA), May 1998.
54. P.-C. Su, H.-J. Wang, and C.-C. J. Kuo, "Digital watermarking on EBCOT compressed images," in *Proceedings of SPIE's 44th Annual Meeting: Applications of Digital Image Processing XXII*, vol. 3808, (Denver, CO, USA), July 1999.
55. C. I. Podilchuk and W. Zeng, "Image-adaptive watermarking using visual models," *IEEE Journal on Selected Areas in Communications, special issue on Copyright and Privacy Protection* **16**, pp. 525 – 539, May 1998.
56. A. B. Watson, "The cortex transform: rapid computation of simulated neural images," *Computer Vision, Graphics, and Image Processing* **39**(3), pp. 311 – 327, 1987.
57. A. B. Watson, G. Y. Yang, J. A. Solomon, and J. Villasenor, "Visibility of wavelet quantization noise," *IEEE Transaction in Image Processing* **6**, pp. 1164 – 1175, 1997.
58. S. Daly, W. Zeng, J. Li, and S. Lei, "Visual masking in wavelet compression for JPEG2000," in *Proceedings of IS&T/SPIE's 12th Annual Symposium, Electronic Imaging 2000: Security and Watermarking of Multimedia Content II*, P. W. Wong, ed., vol. 3971, (San Jose, CA, USA), January 2000.