PROTECTING INTELLECTUAL RIGHTS: DIGITAL WATERMARKING IN THE WAVELET DOMAIN

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Abstract: The objective of the paper is to analyse the advantages and disadvantages of spatial, DFT, DCT and DWT domains and highlight the advantages offered by watermarking wavelet coefficients rather than the DCT or FFT coefficients. The reasons for the DWT advantage are analysed and the choice of a particular wavelet basis is explained. As an illustration of these advantages, the paper presents a high capacity blind video watermarking system, which embeds the data payload in the wavelet domain. In this paper the video sequence is regarded as a noisy communications channel, and the multi-bit watermark as the hidden message. In order to maximize the information capacity in the presence of attacks, the payload is embedded according to a HVS model, and is protected by state-of-the-art error correction (Turbo codes). It is shown that the DWT is significantly more robust to scaling and cropping, and gives a useful capacity improvement under a compression attack.

Keywords: copyright protection, video watermarking, spread spectrum, wavelet transform

I. INTRODUCTION

Nowadays virtually all multimedia production and distribution is digital. The advantages of digital media, for creation, processing and distribution are all well known: superior quality, more quicker and easier to edit and modify, possibility of software processing rather than the more expensive hardware alternative (if the real time processing is not a requirement), and maybe the most important advantage is the unlimited copying of digital data without any loss of quality whatsoever. This latter advantage is not desired at all by the media producers and content providers, in fact is perceived like a major threat, because it may cause them considerable financial loss.

Once the digital technology is widely available to the public, the piracy suddenly becomes a major issue. This generates the need for protecting the copyrighted material against piracy. Some typical examples are the recent court battles between the music industry and Napster, Kazaa and Morpheus. The movie and music industry are particularly keen to develop any system which will stop users copying the digital media especially now, after the introduction of Internet sharing technologies which allow users from the entire planet to share any kind of digital media between them (like Napster, Gnutella, Morpheus and many others).

In an attempt to stop this trend, the recording industry recently introduced a copyright protection system for the audio CD's which actually tries to prevent the users from copying their own legitimate CD's, and even playing these CD's on a computer. This protection system deliberately introduces during the fabrication process a substantial number of errors on the disk, in fact so many, that even the powerful error correction capability of the computer drives is defeated. This is a rather "sad" method which destroys the very core of the digital technology, lowering not only the quality, but also the reliability of the disk.

Unlike this "crude" method, digital watermarking is an unobtrusive way of protecting such material and for audio, images and video it operates by hiding a perceptually invisible signal into the host signal.

II. WATERMARKING METHODS FOR UNCOMPRESSED VIDEO

To main methods are currently used for embedding a watermark into digital media. The first method, less used is the quantisation watermarking. The second method – by far the most popular one, due to its major advantages – is the spread spectrum watermarking.

Spread spectrum radio techniques have been developed for military applications, since mid 1940's for their anti-jamming and low-probability-of-intercept properties. They allow the reception of radio signals that are over 100 times weaker than the atmospheric noise.

Moreover, the spread spectrum techniques are offering a good flexibility and are very suitable for watermarking due to the similarities between the watermarking and spread spectrum communications. The digital watermarking can be seen as a hidden communication system, in which the original image plays the role of the channel noise and attackers may try to disrupt the transfer of information. In both cases the channel is a very difficult one characterised by high levels of noise. The large bandwidth required by a spread spectrum technique is not a problem, since usually the video sequences are quite big, offering a large number of coefficients and therefore the chip rate is sufficiently high for obtaining a robust watermarking system. The noise like spread spectrum signal is very difficult to detect/intercept and jam and is obviously spread in the entire video sequence, therefore suggesting a good robustness to certain attacks and a very secure system. Furthermore, the system can be relatively easy implemented, the watermark embedding and retrieving are based on secret keys and the system doesn't require the presence of the original video for watermark retrieving. The secret key is used for generating the same PN sequence for both embedding and retrieving. The spreading is achieved by multiplying this PN sequence with the data payload. As a result each watermark data bit is randomly spread in the entire video sequence, with a chip rate c_r. Typical for a video watermarking system, the recovery of the mark is blind, e.g. without resorting to the original video. The watermark is recovered by using cross-correlation methods, in the form of a correlation receiver of a matched filter, following the principle of optimum reception.

The uncompressed video, as found in TV studios is described by the ITU-R 601 standard. The video sequences are in raw Y-C_B-C_R format. Only the luminance component Y is marked. The chrominance components are not robust at all, because they can be easily discarded, without affecting the video quality in any other way except the resulting black and white picture. Anyway marking the chrominance components has several other disadvantages. The human eye is much more sensitive to slight colour changes compared to slight luminance changes. As a result, these components have to be more lightly marked (with reduced amplitude) and from this reason are less robust compared with the luminance. Moreover, the complexity of the algorithm which uses the chrominance components is more than double, while the gain is quite small and it could be even zero if an attacker decides to discard the chrominance components. This is a strong enough reason to avoid the marking of chrominance components. Maybe in the applications where the real time requirement is not important and the cost can be tolerated one could use them in order to get a bit more robustness.

III. SPATIAL DOMAIN WATERMARKING TECHNIQUES

The first attempts to watermark an image/video sequence were done in the spatial domain. The main advantage of watermarking in the spatial domain is simplicity. Therefore the implementation time is shorter, hardware requirements are much reduced and in terms of execution time, usually the algorithms are quicker than those designed in frequency domain. Obviously this has DSP implementation advantages, being much easier to design a real-time system. Because of the lack of good visual models for spatial domain, one has to use rather empirical models as a replacement.

In terms of watermark capacity, the spatial domain is the worst place to insert a high capacity watermark. Usually, the frequency domain offers higher capacity and better robustness to attacks.

IV. WATERMARKING IN THE DFT DOMAIN

From all important frequency domain methods, the Fourier transform is the less used one. Probably the most important advantage of the DFT is its shift (translation) invariance. In other words, cyclic shifts of the video frame in spatial domain do not affect the magnitude of the DFT coefficients and therefore a watermark embedded in the magnitude of the DFT coefficients will be shift invariant. This is a highly desirable property since eliminates the need of a computationally expensive 2-D sliding window correlator.

On the other hand, due to its complex nature, the DFT offers the possibility of watermarking either the magnitude or the phase of the DFT coefficients. The phase is far more important than the magnitude of the DFT values for the intelligibility of an image, so embedding a watermark in the most important component of an image is very good since any attempts of removing the watermark will lead to heavy artefacts. Moreover, as known from the communication theory, the phase modulation often possesses superior noise immunity in comparison with amplitude modulation.

Unfortunately, in practice watermarking the phase of the DFT coefficients gives only modest results, and is very susceptible to attacks. Experiments show that the phase is quite sensitive to JPEG and MPEG attacks.

One major disadvantage of both phase and magnitude marking is the fact that in order to obtain a real image after the IDFT, one has to preserve complex conjugate symmetry of the DFT coefficients.

Changes in magnitude must preserve the positive symmetry of the Fourier coefficients:

$$F(k1,k2) = F^{*}(N1-k1, N2-k2) \tag{1}$$

and changes in phase must preserve the negative symmetry of the Fourier coefficients:

$$\begin{aligned} &\measuredangle F(k1,k2) \leftarrow \measuredangle F(k1,k2)+\delta \\ &\measuredangle F(N1-k1,N2-k2) \leftarrow \measuredangle F(N1-k1,N2-k2)-\delta \end{aligned} \tag{2}$$

These symmetry requirements are basically halving the watermarking space and therefore the capacity, being a serious drawback.

Another disadvantage of the Fourier domain is the lack of HVS (Human Visual System) models.

Although watermarking in Fourier domain is relatively seldom, the FFT transform is present in many watermarking systems in one way or another. For example due to its shift invariance, the FFT transform is often used to implement fast cross-correlators. According to the convolution theorem, correlation in spatial domain is equivalent with convolution in the FFT domain, and vice versa. Since a sliding correlator (e.g. a cross-correlator which is able to search for the right position of the watermark in an attacked image) is very

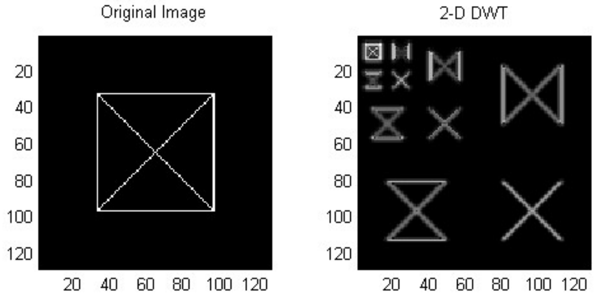


***Figure 1** The 2-dimensional DWT: the original and λ = 3 levels of decomposition*

computationally expensive, the efficiency of the FFT correlators is particularly welcomed. An example of such a correlator is the SPOMF (Symmetrical Phase Only Matched Filter) which is often used in image processing and pattern recognition.

Another particular area which involves the use of Fourier transform is the case of RST (Rotation, Scaling and Translation) invariant watermarking schemes.

V. WATERMARKING IN THE DCT DOMAIN

The DCT domain is far the most popular one, from several reasons. One reason is that all the major compression techniques were developed in the DCT domain (JPEG, MJPEG, MPEG1, MPEG2, H26x) and therefore the image processing community was familiar with it. Much research was carried out in developing various perceptual models for the DCT domain, and these models could be easily applied to watermarking, since watermarking and compression are very closely related. Since the compression algorithms are well known, one could compensate for it during the watermark embedding process, making the algorithm robust against compression. Furthermore marking in the frequency domain rather than spatial domain has few advantages: better robustness against certain attacks, higher capacity, more close to the HVS and relatively good frequency localisation of the coefficients. Those who are marking in the bit-stream domain (MPEG2) have the additional advantage of the direct bit-stream marking, without decoding and re-encoding the signal.

VI. WATERMARKING IN THE WAVELET DOMAIN

At the moment, the most advanced choice from all the frequency domain methods is the DWT. The advantages of the wavelet transform are presented in the following sections.

A. Multiresolution Property

The DWT is a hierarchical transform (unlike the FFT and the DCT) and offers the possibility of analysing a signal at λ different resolutions or levels (λ integer). Such multiresolution analysis gives a frequency domain representation as a function of time (or space in the 2-D case) i.e. both time/space and frequency localisation. In order to achieve this, the analysing functions must be localised in time. Formally we refer to scale and resolution, where, for the dyadic case, scale is defined as $a = 2^{\lambda}$ and resolution as $r = \frac{1}{a} = 2^{-\lambda}$. The greater the resolution, the smaller and finer are the details that can be analysed. For the 1-D case, a certain wavelet is defined by the mother wavelet function $\Psi(x)$ and a scaling function (or father wavelet) $\Phi(x)$, where the analysing wavelets are scaled and translated versions of the mother wavelet:

$$\frac{1}{\sqrt{a}}\Psi\left(\frac{x-b}{a}\right) \tag{3}$$

Defining translation $b = ka$, (k, λ integer) the dyadic case becomes:

$$\begin{aligned}\Psi_{\lambda,k}(x) &= 2^{-\frac{\lambda}{2}}\Psi(2^{-\lambda}x-k)\\ \Phi_{\lambda,k}(x) &= 2^{-\frac{\lambda}{2}}\Phi(2^{-\lambda}x-k)\end{aligned} \tag{4}$$

For a signal $f(x)$ a wavelet coefficient is then defined as:

$$C(\lambda,k) = \int_{-\infty}^{\infty} f(x)\Psi_{\lambda,k}(x) \quad dx \tag{5}$$

For the 2-D case, we have one scaling function $\Phi(x,y)$ and three wavelet functions $\Psi_{\theta}(x,y)$, where θ denotes orientation.

Different orientations extract different features of the frame, such as vertical, horizontal, and diagonal information, Fig.1. Generally speaking, edges and textures will be represented by large coefficients in the high frequency sub-bands, and are well localised within the sub-band. The use of the DWT for spread-spectrum based image/video watermarking is indicated in Fig.3 for $\lambda = 3$, and is discussed later.

B. Wavelet selection

In practice wavelet analysis is performed using multilevel filter banks. Essentially this comprises a succession of filtering and sub-sampling operations and has been widely described in the literature [2, 3, 4, 6].

For watermarking we need to select an appropriate wavelet or basis. Most of the basis development has taken place in the context of image compression [4], and fortunately watermarking and compression have many things in common. On the other hand, we certainly need to choose a basis that offers compact support. The smaller the support of the wavelet, the less nonzero wavelet coefficients will correspond to an edge for example, so basically the transform compacts more energy in the high frequency sub-bands [5]. Also we are restricted to a class of either orthogonal or bi-orthogonal wavelets. To narrow the choice even more, filter regularity, symmetry and a smooth wavelet function are important for the reconstructed image quality. In addition, we need a reasonably good HVS model for the selected basis. Finally, for watermarking we ideally would like shift invariance in order to handle geometric attacks.

For this work we selected the Antonini 7.9 wavelet (Fig. 2), this being one of the best wavelets available for image compression [2, 3, 4]. Its important properties are highlighted below:

- Bi-orthogonal wavelet, with compact support, symmetric
- Good regularity (each filter has 2 factors [1+Z]) and the lpf and hpf are quite similar
- Simple filters (only 7 and 9 taps) with linear (zero) phase
- Shift invariant at level 1 (from the energy point of view)
- HVS model available [5]
- Smooth wavelet function

This wavelet is widely used in image compression algorithms (EZW, SPIHT), and is used in the FBI fingerprint compression standard.

C. Advantages for Watermarking

The basis function for the DFT ($f(x)=\exp(i\omega x)$) or DCT (infinite cosine) has perfect localisation in frequency but is not time/space localised. In contrast, wavelets offer a trade-off between time/space and frequency/scale, and so a watermarking scheme based on the DWT will produce a watermark with both spatially local and spatially global support (see Fig.1). This localisation makes a wavelet based scheme more robust than the DCT scheme, given geometric attacks such as cropping and scaling.

For instance, in the case of cropping, the lower frequency levels will be affected more than the high frequency ones, because of the fact that the watermark from the higher levels corresponds to a smaller spatial support. Looked at in the frequency domain, cropping corresponds to convolving the frequency components with a *sinc* function, where the width of the main lobe is inversely proportional to the width of the cropped window size [7]. This will affect all the frequency components of any scheme based on a global transform, but since the wavelet scheme has a watermark with local spatial support, the watermark will be unaffected by the cropping.

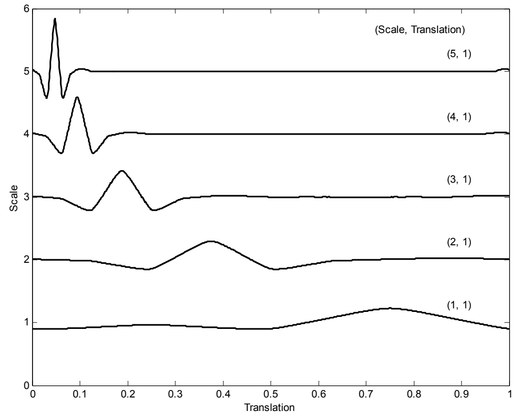


Figure 2 *The Antonini 7.9 wavelets at various scales (same translation).*

For scaling, because the DWT coefficients are localised both in space and frequency, whilst the DCT coefficients are only localised in frequency, it is likely that this kind of attack will be less serious for a DWT scheme. Simulation confirms this to be the case. Finally, the global spatial support of a DWT scheme will tend to be robust to operations such as low pass filtering/compression (which attenuate high frequency levels).

Another fundamental advantage of the DWT lies in the fact that it performs an analysis similar to that of the HVS. The HVS splits an image into several frequency bands and processes them independently. In a similar way, the DWT permits the independent processing of different sub-bands without significant perceptible interaction between them. Again, this is because the analysing functions Ψ are localised in space, being zero outside a space domain U i.e. the signal values located outside of domain U are not influencing the values of the coefficients within U. Similarly, if Ψ is translated to position b, the wavelet coefficient will analyse the signal around b. This local analysis is specific to the compact support wavelets. Basically for a small scale, a local analysis is performed whilst for a large scale we have a global analysis. Fig.2 shows how the wavelet functions change for different scales.

Finally, more general advantages of the DWT are:

- It is not a block based transform, and so the annoying blocking artefacts associated with the DCT are absent.
- Its multiresolution property offers more degrees of freedom compared with the DCT.
- Lower computational cost than the FFT or DCT: $O(n)$ instead of $O(n\log(n))$, where n is the order of the transform input vector.
- Better energy compaction than both the FFT and DCT in the sense that it is closer to the optimal Karhunen-Love transform.

VII. THE WAVELET-BASED WATERMARKING SCHEME

Watermark embedding and the corresponding retrieval are shown in Fig.3. We have chosen to use 3 levels of decomposition. As for DCT systems, embedding uses the spread-spectrum approach and retrieval is via cross-correlation (matched filtering). The interleaver uses a separate key to that of the PN sequence in order to enhance system security and provide a random distribution of the data bits within each sub-band. Here we are exploiting the hierarchical nature of the DWT by choosing to insert a self-contained watermark in each sub-band. This means that all of the data bits are inserted in each sub-band, the chip rate reducing as λ increases. Although reducing chip rate may appear to be a disadvantage, the advantage of this type of marking comes at the retrieval.

The watermark is embedded using amplitude modulation as follows:

$$C_i^M = \begin{cases} C_i + \underbrace{\alpha \dfrac{Q(\lambda,\theta)}{Q_{\min}} \cdot \dfrac{|C_i|}{mean(C_i)}}_{S} \cdot W_i, & \text{(details)} \\ if \quad S > 24, \quad then \quad S = 24. & \\ C_i + \alpha \dfrac{Q(\lambda,\theta)}{2} \cdot \dfrac{|C_i|}{mean(C_i)} \cdot W_i, & \text{(approximation)} \end{cases} \tag{6}$$

where Q_{min} is the minimum value from matrix Q, W_i is the watermark, C_i is the original wavelet coefficient and C_i^M is the marked one. The HVS is incorporated in the quantization matrix $Q(\lambda,\theta)$, where θ is the orientation. Although this is a much simpler model than the ones used in the DCT schemes, overall performance is better. $Q(\lambda,\theta)$ offers only one quantization factor for an entire sub-band, and incorporates only limited information about the HVS (essentially only the frequency sensitivity of the eye). In other words, the model is HVS dependent since it incorporates some aspects of the human vision (MTF – Modulation Transfer Function of the eye), but unfortunately it is not media dependent, a significant drawback. For computing $Q(\lambda,\theta)$ we use a visual model developed by Watson for the Antonini 7.9 DWT [5]:

$$Q(\lambda,\theta) = \frac{2\ a}{A_{\lambda,\theta}} \cdot 10^{k\left(\log \frac{2^{\lambda} f_o\, g_\theta}{r}\right)^2} \tag{7}$$

with $a = 0.495$, $k = 0.466$, $f_o = 0.401$, $r \approx v \cdot d \cdot \pi / 180$ $g_\theta = \{1.501,\ 1,\ 0.534,\ 1\}$ and $\theta = 1 \ldots 4$, where d is the display resolution in pixels/cm, v is the viewing distance in cm, and $A_{\lambda,\theta}$ are the basis function amplitudes for the Antonini 7.9 wavelet [5]. $Q(\lambda,\theta)$ is only a rough measure of the visibility for each sub-band, and, as stated, it is not media dependent. This dependence is required for a robust watermark and is provided by the embedding algorithm in Eq.(6). This marks more heavily the high frequency sub-bands and the largest coefficients, since modification of these coefficients is less likely to incur visible artefacts.

For retrieval, it is advantageous to have a self-contained watermark (all data bits) in each sub-band, since a SNR can be determined for each sub-band as an indicator of sub-channel quality. Different types of attack affect different levels and orientations in different ways, and so it is always possible to select an optimal sub-band via SNR. Correlation is therefore performed separately for each sub-band, obtaining a set of cross-correlation peaks (one peak for each embedded data bit) for each sub-band. A SNR is then computed for each set of cross-correlation peaks, and retrieval is carried out for the sub-band with the highest SNR.

VIII. PERFORMANCE OF THE WAVELET-BASED SCHEME

Fig.4 illustrates the performance of the system under several attacks: cropping, scaling/rescaling, JPEG compression and MPEG2 compression. The magnitude of these attacks is quite extreme, leading to unacceptable visual artefacts. The scaling was performed with a very bad quality interpolation filter, just to see how well the system performs. For JPEG compression, important artefacts become visible for a quality factor lower than about 25% (10:1 compression). MPEG2 compression at 2Mbps is again a drastic attack, which leads to visual

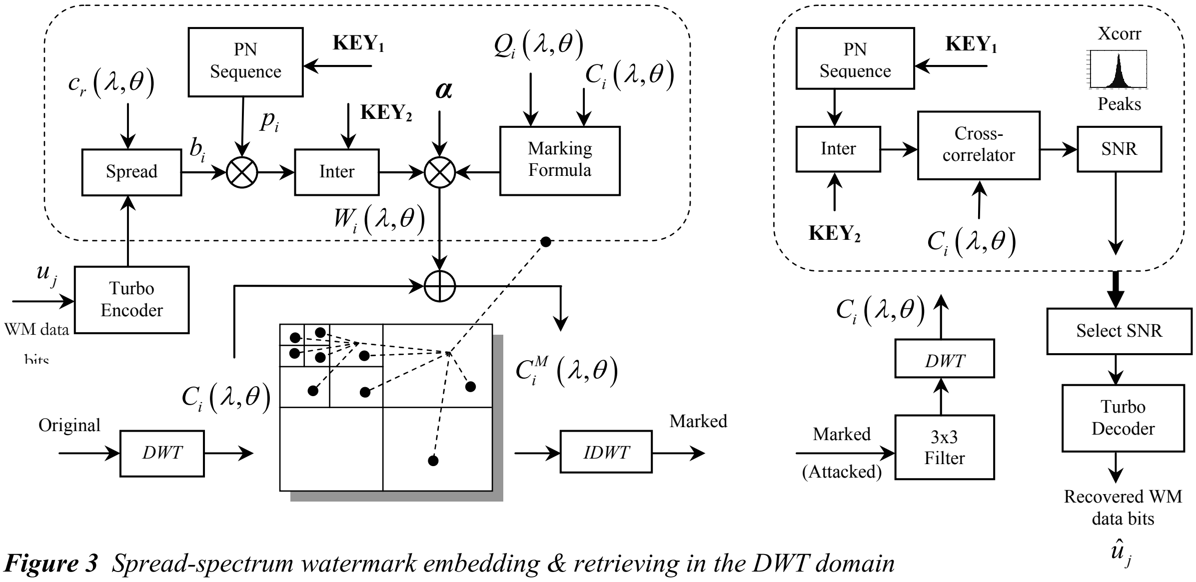
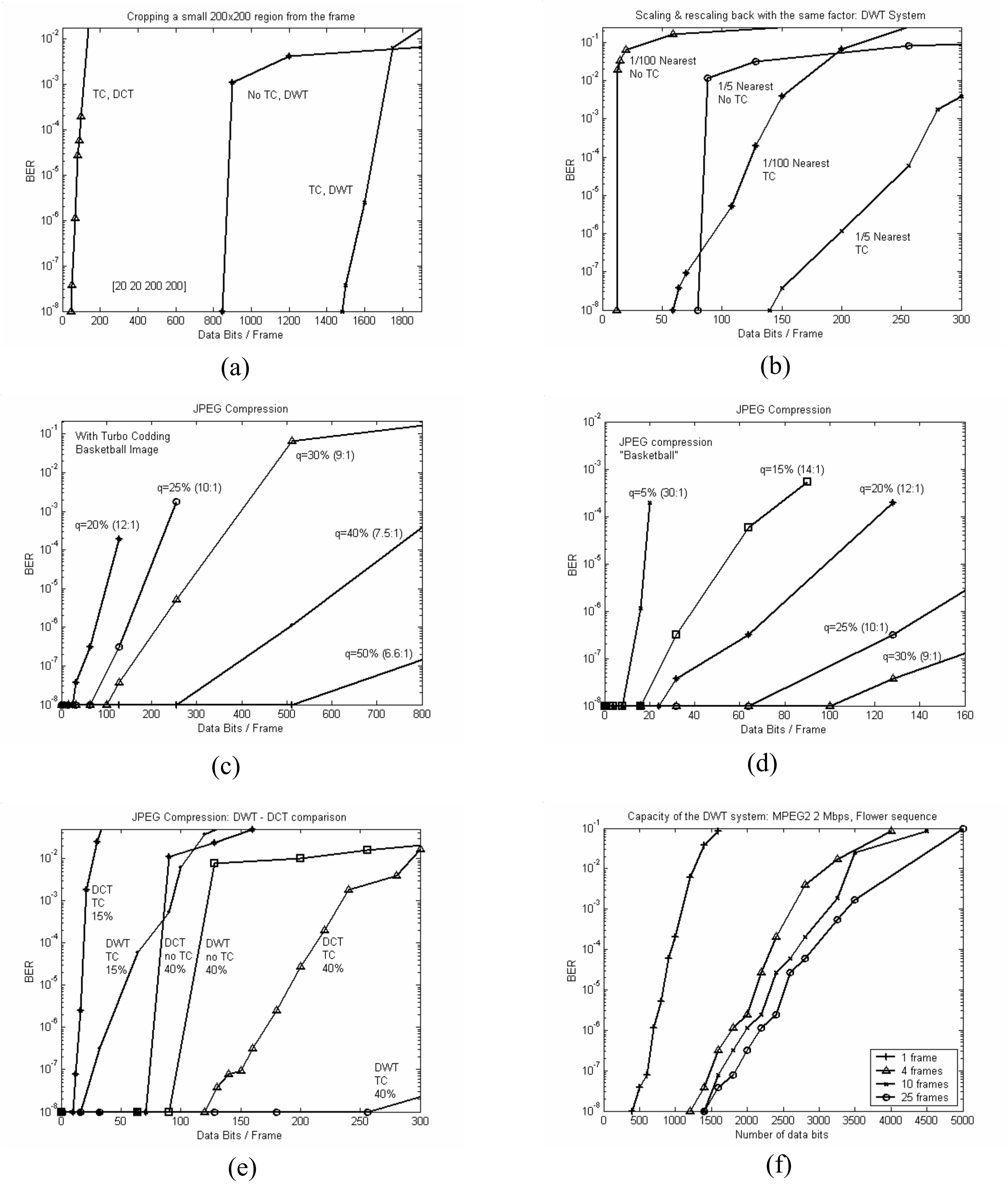


Figure 3 *Spread-spectrum watermark embedding & retrieving in the DWT domain*

artefacts.

The DCT scheme used for comparison is the one described in [10, 11].

As might be expected from the compact support, the most significant advantage of wavelets occurs under cropping and scaling. For cropping, a rectangle of 200x200 pixels was selected from the upper left corner of the frame, as shown in Fig. 5(d). This location was selected since it has average detail. Clearly, cropping to this degree is an extreme case and is unlikely to occur in practice. It is apparent from Fig. 4(a) that the DCT scheme has poor performance even with FEC, whereas the DWT scheme performs very well without FEC (over 20 kbps at $BER = 10^{-8}$). With FEC the capacity increases



(a)

(b)

(c)

(d)

(e)

(f)

***Figure 4** Performance of the DWT system for cropping (a), scaling-rescaling (b), medium quality JPEG (c), low quality JPEG (d), DWT/DCT comparison for medium quality JPEG (e) and MPEG2 (f) attacks.*

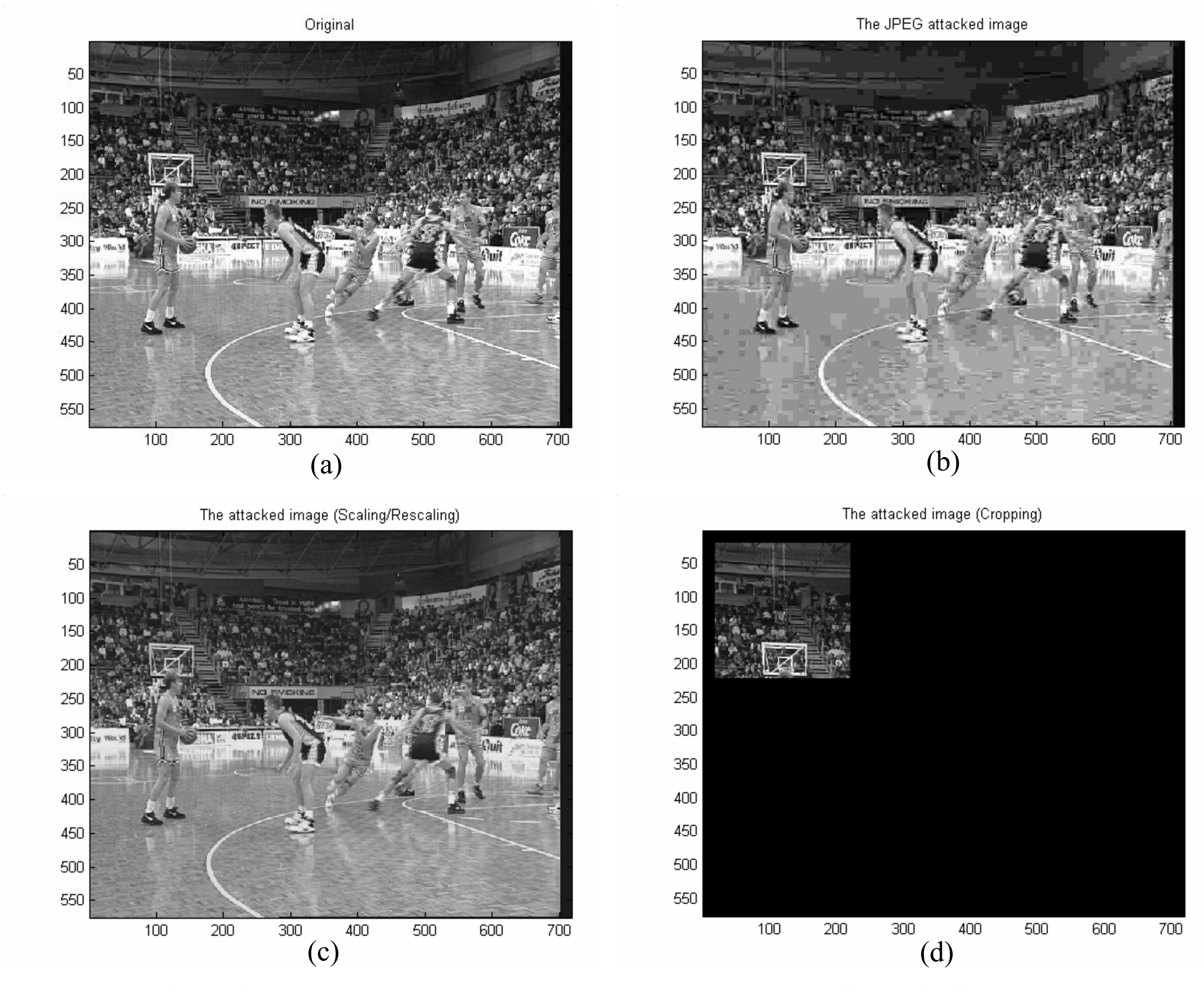
to 37 kbps, but will reduce markedly under a combined attack.

Fig. 4(b) shows the results for scaling. The frame is scaled up or down and then brought back to the original size (720x576). Even so, with the worst kind of scaling, the DWT system performs quite well. The effect of this kind of attack results in luminosity changes and geometric distortion, Fig. 5(c). A DCT system can't cope with this attack. In contrast, the DWT gives very acceptable performance, especially when using FEC. For example, for 1/5 "nearest" scaling, the capacity is about 80 bpf (2 kbps), increasing to about 140 bpf (3.5 kbps) with FEC.

The results for JPEG compression with several different quality factors are presented in Fig. 4(c) and Fig. 4(d). As Fig. 4(d) indicates, For a relatively high compression factor of 10:1 (25% quality, slight visual artefacts) and with Turbo coding, the wavelet scheme can achieve a capacity of 64bpf (bits per frame). Even under extreme JPEG compression (30:1 compression, 5% quality, with heavy blocking artefacts) the wavelet scheme has a capacity of 8bpf. This attack is illustrated in Fig. 5(b).

A comparison of the DCT and DWT schemes under JPEG compression attack is shown in Fig. 4(e). For a quality factor of 40%, the DWT more than doubles the capacity when Turbo coding is used, the capacity being over 6 kbps at $BER = 10^{-8}$. This result clearly shows the advantage of FEC. The wavelet scheme is net superior to the DCT scheme, especially for higher quality factors and when using FEC. Again, with FEC, for a quality factor of 40% (7.5:1 compression) the capacity of the DWT scheme is double compared with the DCT scheme.

Since the capacity per frame is quite high, we can afford to increase the robustness (and the capacity as well) by inserting the same watermark in a number of n ($n \leq 25$) successive frames. In this way the recovery is much simplified since takes place only once, and is easier to combat frame dropping. This case is illustrated in Fig. 3(f) for MPEG2 compression attack, which gives an impressive capacity of about 1Kbps, when at least 4


Original

The JPEG attacked image

The attacked image (Scaling/Rescaling)

The attacked image (Cropping)

(a)

(b)

(c)

(d)

Figure 5 *A frame from the original "Basketball" sequence (a) and the effects of different attacks: (b) JPEG compression (5% quality factor, 30:1 compression ratio), (c) scaling/rescaling (1/5 and back using the 'nearest' method) and (d) cropping a small area from the original (200x200 rectangle with the upper left corner at the location [20,20])* frames are averaged together. The improvement between the 4, 10 and respectively 25 frames averaging seems to be quite small, however this is due to the high compression applied in this case (2Mbps); for a medium level of compression the difference between these cases are much more obvious.

IX. CONCLUSIONS

The results suggest that the DWT has significant advantages under attacks which are likely to be encountered in studios e.g. compression, scaling, and cropping. Under a compression attack, the DWT can more than double the capacity of a DCT system. Under a typical scaling/re-scaling attack, a Turbo coded DWT scheme can yield capacities in excess of 1 kbps, whilst under the same conditions a DCT scheme fails. The DWT scheme has been found to be particularly robust to cropping: for example, the Turbo coded DWT scheme had a capacity of some 37 kbps, compared to 1 kbps for the DCT scheme.

The improved robustness of the DWT scheme is mainly attributed to the spatially local and spatially global support of wavelets. For example, wavelets with local support are less likely to be affected by cropping, compared to the theoretically infinitely long basis functions used in Fourier analysis. The multiresolution feature can also be exploited to optimize retrieval, by embedding all data bits in each sub-band and measuring sub-band SNR, and it gives a fundamental advantage by performing an analysis similar to that of the HVS. The DWT also has a computational advantage compared with the DCT, it does not suffer from the blocking artefacts of the DCT, and a relatively simple HVS model may suffice.

As it is shown in [8, 9], by using a second watermark embedded in the spatial domain (who acts as a reference) and by employing image registration techniques, the system can be extended in order to cope with many geometrical attacks like arbitrary scaling, rotation, shifting, and even combinations of some of them. Such a system can successfully withstand very powerful geometric attacks [8, 9].

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