Exhibition QIM-based Watermarking for Digital Cinema

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ABSTRACT

The copyright protection of Digital Cinema requires the insertion of forensic watermarks during exhibition playback. This paper presents a low-complexity exhibition watermarking method based on quantization index modulation (QIM) and embedded in the DCI compliant decoder. Watermark embedding is proposed to fit in the JPEG2000 decoding process, prior to the inverse wavelet transform and such as it has a minimal impact on the image quality, guarantying a strong link between decompression and watermarking. The watermark is embedded by using an adaptive-Spread Transform Dither Modulation (STDM) method, based on a new multi-resolution perceptual masking to adapt watermark strength. Watermark detection is thereafter performed over the wavelet transformation of the recovered images. The proposed approach offers a wide range of channel capacities according to robustness to several kinds of distortions while maintaining a low computational complexity. Watermarking detection performance on Digital Cinema pictures captured with a video camera from a viewing room has been preliminary assessed, showing very promising results. The proposed approach provides high levels of imperceptibility, yet good robustness to degradations resulting from camcorder exhibition capture, to common signal processing operations such as filtering or re-sampling, and to very high compression.

Keywords: exhibition watermark, quantization index modulation, perceptual masking, JPEG2000, Digital Cinema

1. INTRODUCTION

Digital watermarking is a widely proposed solution in securing media as it allows proving the ownership of digital data by tracing of unauthorized users, detecting malicious tampering of the document or tracking illegal copies of the copyrighted material.

Research on digital watermarking started on still images, presenting the basic trade-off between the imperceptibility and robustness of the mark [1]. More sophisticated methods have been proposed since then to improve watermark robustness while maintaining its imperceptibility. One of the most active research fields in watermarking actually is the study of human visual system (HVS) adaptive methods. These methods essentially differ from the first approaches in the way they fix the watermark strength. The maximum amount of change that can be tolerated before the human eye detects a difference is determined in those methods by the exploitation of HVS perceptual characteristics.

While prior research activities mainly focused on watermarking of still images, many new watermarking schemes are being proposed for other types of digital multimedia data as audio, text, video or 3D meshes. Recently, much research effort has shifted towards the watermarking of video due to the variety of applications specific to moving pictures, such as copy and copyright protection of digital versatile disks (DVD), broadcast monitoring, fingerprinting, video authentication or Digital Cinema [2]. Although several digital watermarking solutions for Digital Cinema have been proposed and implemented [3][4], there is still room for improvements on invisibility and robustness, including retrieval from compressed camcorder captures of exhibited data; as well as for increasing the implementation security by integrating the watermarking in the Digital Cinema decoding process.

Indeed, watermarking for Digital Cinema, and video content in general, states some additional difficulties in the two fundamental requirements of digital watermarking, namely robustness and imperceptibility. In a Digital Cinema system, piracy can occur at various points in content distribution, in particular at the end of a given distribution pathway, where the content is decrypted, decoded, and displayed. The final stage of the distribution chain, the exhibition, has been identified by members of the Motion Picture Association (MPA) as the most susceptible and damaging source of theft and unauthorized distribution of motion picture data [5]. Piracy can be done by capturing the decrypted data files, the
decompressed data from video buffers, or using camcorders to capture exhibited data from the screen, what is usually called *exhibition capture*. The issue is whether the watermark can survive the numerous degradations that occur when a movie is copied from the screen using a DV-camera. These degradations include magnification changes, warping of perspective, loss of sharpness, changes in contrast and color, temporal sampling rate changes, and more.

Another major problem in video watermarking for Digital Cinema is the difficulty of satisfying the strict imperceptibility criterions imposed by content owners. Introduction of perceptual measures have significantly improved the performance of algorithms for still images, however, this approach has not been fully extended to video yet. Perceptual measures for video exist but the major challenge consists in being able to exploit them in real-time. Based on this, the proposed method exploits frequency and spatial information of wavelet coefficients to adapt the embedding strength to perceptual characteristics of the human eye. An adaptive low-complexity exhibition watermarking method based on Quantization Index Modulation (QIM) is proposed to fit in the JPEG2000 decoding process, prior to the inverse wavelet transform, and such that it has minimal impact on image quality.

This paper is structured as follows. In section 2, we give a brief review of some actual video watermarking tendencies. After a brief introduction to quantization index modulation (QIM), section 3.1 describes Spread-Transform Dither Modulation. A detailed description of the proposed method is given in section 4. Section 5 resumes the evaluation results of the proposed scheme, focusing on robustness and fidelity.

## 2. VIDEO WATERMARKING METHODS

When considering the problem of watermarking video data we can differentiate between two approaches depending, broadly, on the domain within the information is hidden.

Most of the actual approaches work on raw motion pictures, either in the spatial or in some transformed domain. This is the most simple and straightforward approach as it considers video as a succession of still images and tend to reuse existing watermarking schemes for still images. The first proposed algorithm for video coding was, indeed, Motion-JPEG, which compresses each frame of the video with the image compression standard JPEG. Thus, the idea of extending previous results for still images has been, and continues to be, widely used. Barni et al. presented in [6] the simplest way of extending a watermarking scheme for still images by embedding the same watermark in all the frames of the video at a regular rate. As for still images, the proposed methods focus the problem of invisibility in two different ways. A first kind of approaches allows arbitrary small modifications within frames in different transform domains. In a DWT approach [7] Y-frames are decomposed into sub-levels and the low-frequency components are watermarked by using a controlled quantization process. Other methods take HVS into account in order to improve invisibility. The majority of such methods are Spread-Spectrum (SS) methods. SS methods were introduced firstly by Cox et al. [1] in DCT-domain for still images, where watermark energy weighting was done using frequency coefficients to approximate the contrast masking principle of the HVS. Another adaptive SS approach adapted to video watermarking was proposed in [8] using 3D-wavelet transform.

Some industrial solutions for Digital Cinema were also proposed to work on raw video data. Honsinger et al. [9] use a blind spread-spectrum watermarking approach on uncoded video with a tiling pattern used for automatic registration, that has been demonstrated to survive camcorder capture but at inadequate fidelity. Lubin et al. [3] use very low spatio-temporal frequency watermark carriers taking into account JND metric to deal with watermark imperceptibility, achieving quite good fidelity and camcorder capture robustness.

A completely different approach in video watermarking considers and exploits the additional temporal dimension in order to design robust video watermarking algorithms. While still-image watermarking schemes can be easily exported to video with a straightforward frame-per-frame adaptation, the obtained watermark is not optimal in terms of visibility since it does not consider the temporal sensitivity of the human eye. Several approaches have investigated the integration of the temporal dimension, some of them designing new video-driven perceptual measures [10]. Temporal wavelet decomposition is used in [11], embedding the watermark in each wavelet frame using watermark energy weighting according to spatial and contrast masking characteristics of the HVS. Haitsma et al. propose a SS watermarking scheme for Digital Cinema [12] embedding the same watermark bit in the mean value of the Y-component into a number of successive frames to avoid flickering. In [13], they propose to use DCT together with a DFT transform in the temporal
direction in order to utilize the temporal contrast thresholds of the HVS to determine the maximum strength of the watermark.

The last approach basically considers a video stream as some data compressed according to a specific video compression standard and the characteristics of such a standard can be used to obtain an efficient watermarking scheme. First proposed methods on compressed video watermarking, work on MPEG video streams. A method robust against camcorder capture is proposed in [14] in which watermarking is embedded by modifying the DCT-quantization matrices present in the MPEG-2 bit-stream. While some of those approaches consider motion compensation in the MPEG standard as a constraint and propose generally to embed the watermark into I-frames, some others have exploited the motion vectors of the MPEG stream to embed a watermark by slightly altering their length and direction [15] using in some cases adaptive schemes to improve perceptual fidelity [16]. Similar methods are also proposed for H.264 compressed video sequences [17]. Embedding the watermark directly in the compressed video stream often allows real-time processing of the video. However, the watermark is inherently tied to a video compression standard and may not survive video format conversion.

3. QUANTIZATION INDEX MODULATION

One of the most popular families of watermarking methods is spread-spectrum (SS). These methods modify linearly the host signal to embed some information. SS methods are very successful mainly because of the ease of adapting them to many domains and signal characteristics, and due to its proved robustness to many kinds of distortions. In this class of embedding methods, the host signal $x$ acts as an additive interference to estimate correctly the watermark message $Z_m$. Consequently, these methods can usually embed only a small amount of information and are useful primarily either for non-blind schemes or when the host signal interference is much smaller than the channel interference.

Blind watermarking schemes are convenient for exhibition video watermarking since in detection the receiver will not necessarily have access to the original video data. In addition, information embedding systems can achieve host-interference rejection when knowledge of the host signal at the encoder is adequately exploited in the system design. Thus, the interference from the host signal can be eliminated when embedding the watermark in a non-linear way as quantization. Quantization schemes perform non-linear modifications and detect the embedded message by quantizing the received samples to map them to the nearest reconstruction point. The basic idea of Quantization Index Modulation (QIM), as introduced in [18], is the quantization of a signal sample using a quantizer chosen from a set of quantizers based on the embedding information. For instance, to embed a message $\omega_m \in \{S_1, S_2\}$ in host signal $x$, we would need two different quantizers. To embed $\omega_m = S_1$, we’ll use one of the quantizers $Q_1$, and to embed $\omega_m = S_2$ we will quantize the host signal $x$ with $Q_2$. Detection in QIM is performed without access to the original data or the original watermark.

3.1 STDM

Spread-transform dither modulation (STDM) is a special case of QIM exhibiting more robustness but maintaining low-complexity, in which the host signal $x \in \mathbb{R}^L$ is projected onto a randomly generated spreading vector $p \in \mathbb{R}^L$ before the quantization (see Fig.1). The embedding of each information bit occurs in the projection of the host signal $x$ onto the spreading vector by quantizing it with a uniform, scalar, dithered quantizer. Thus, the projection of the watermarked signal onto $p$ is

$$s^T p = Q_m(x^T p) = Q(x^T p + d_m) - d_m, \quad m = 0, 1$$

where $d_m$ represents the dither value modulated by the information bit embedded. The distortion due to the embedding in the transform space, is then projected onto $p$ to shift the transformation components back and generate the overall watermarked signal:

$$s = x + (Q_m(x^T p) - x^T p)p, \quad m = 0, 1$$

(1)

The STDM decoder makes a decision based on the projection of the channel output $y$ onto the spreading vector $p$. The detection can be then performed with a minimum distance decoder.
Distortion compensation (DC) is a post-quantization processing that improves the distortion-robustness trade-off of QIM methods [18]. DC consists on scaling all the quantizers by a parameter $\alpha \leq 1$. The additional distortion that this scaling of the quantization step produces, is compensated by adding a fraction $1-\alpha$ of the quantization error. Methods used in this paper consider, in all cases, distortion-compensation spread-transform dither modulation (DC-STDM). For simplicity, it is not always detailed and we refer to it as STDM.

4. PROPOSED APPROACH

As discussed previously, much research effort has been invested on the watermarking of video bit-streams for some well-known video codecs, as well as on the watermarking of uncoded video data. However, for applications like Digital Cinema, which contemplates the insertion of forensic watermarks during exhibition playback, the integration of watermarking techniques in the video decoding process becomes a practical and interesting solution.

Motion-JPEG2000 has been adopted by the Digital Cinema Initiatives (DCI) [19] to be the coding format for Digital Cinema, which encapsulates JPEG2000 compressed frames and enables synchronization with audio data [20]. In this paper, as an alternative to the conventional methods, a new method of digital watermarking based on the discrete wavelet transform is proposed to fit in the JPEG2000 decoding pipeline. Embedding takes place after entropy decoding and de-quantization but prior to the inverse wavelet transform stage. Each bit in the watermark is embedded in a vector of wavelet coefficients using spread-transform dither modulation.

4.1 Digital Cinema System overview

DCI is the entity created to establish uniform specifications for Digital Cinema. They define technical specifications and requirements for the mastering of, distribution of, and theatrical playback of Digital Cinema content [19].

The output of the Digital Cinema post-production process is referred to as the Digital Cinema Distribution Master (DCDM). At the mastering stage, the image data in the DCDM is compressed using JPEG2000, then encrypted and packaged for delivery to the theatres. The data is then transported to the exhibition site and unpackaged, unencrypted and uncompressed for its exhibition. The DCI specifications contemplate the insertion of forensic watermarks into both audio and images in order to uniquely identify the theater at which the motion picture was shown, as well as a time and date stamp indicating the particular exhibition. The watermarking data payload is required to be at least 35 bits, out of which, 16 bits are reserved for a time stamp to be embedded every 15 minutes. The remaining 19 bits are used to identify the
location of the exhibition. All 35 bits are required to be included in each five minute segment, embedding performed in real-time. The specifications allow the use of up to 30 minutes of content for recovery of the watermark.

4.2 JPEG2000 integrated watermarking

The DCI specification requires frames to be compressed individually via JPEG2000. For Digital Cinema, tiling is disallowed, thus, the entire image should be encoded and decoded as a single tile. There are two image structures defined for Digital Cinema: 2K resolution (up to 2048x1080 pixels) and 4K resolution (up to 4096x2160 pixels). The wavelet transform required is the 9/7 irreversible wavelet transform, with the maximum number of transform levels being 5 for 2K content and 6 for 4K content.

DCI also requires the use of the irreversible colour transform (ICT) in which the input colour space is $X'Y'Z'$ and therefore, the transformed components do not correspond exactly to Y, Cb, and Cr but to $Y'Cb'Cr'$. Watermark embedding is proposed to fit in the JPEG2000 decoding process, the last step before exhibition.

Watermarking embedding stage is invoked after region-of-interest (ROI) de-scaling and de-quantization and prior to inverse wavelet transform to obtain the decoded frames (see Fig. 2).

![JPEG2000 coding and decoding pipeline](image_url)

Fig. 2. JPEG2000 coding and decoding pipeline

At that point, sub-bands have been reconstructed based on the code-blocks coming from the entropy decoding channels writing the decoded code-blocks at the right location inside the sub-band they belong to. The inverse quantization steps had been applied as specified in the stream header. A different inverse quantization step is available for each sub-band resulting in differently weighted frequency sub-bands. That context makes us able to work directly on wavelet coefficients in their right location.

4.3 Adaptive STDM

Barni et al. [21] proposed a masking model in wavelet domain for still images as an adaptation of Lewis and Knowles’s [22] method to evaluate the optimum quantization step for each DWT coefficient according to psycho visual considerations. Barni et al. use this adapted model to compute the maximum visibly tolerable watermark energy that can be used for each DWT coefficient.

Wavelet transform properties linked to HVS are generally exploited in three fields:

- Human eye is less sensitive to noise in high resolution bands, and in diagonal bands.
- Changes in high or low brightness areas of the image are less perceptible.
- The eye is less sensitive to noise in highly textured areas but, among these, more sensitive near the edges.

In spread transform dither modulation the alteration introduced to each DWT coefficient is initially controlled by the quantization error. From (1) we can see that change occurs entirely in the direction of the spreading vector $p$. We propose the inclusion of a visual model in this framework by implementing $p$ in the direction of least perceptual distortion.

Given an image $I$ and its $K$-level discrete wavelet transformation coefficients $h(i, j)$, we can compute the local brightness of each coefficient $(i, j)$ in each resolution level $l =0..K-1$ based on the grey-level values of the low pass version of the image, $I^{L\times L}_{k}$, as:

$$L(l, i, j) = \frac{1}{L^{\times L}_{k\_max}} I^{L\times L}_{k} \left( 1 + \left\lfloor \frac{i}{2^{K-l}} \right\rfloor + 1 + \left\lfloor \frac{j}{2^{K-l}} \right\rfloor \right)$$

(2)
As human eye is less sensitive to lower brightness as well, we can consider the following expression
\[
L'(l,i,j) = \begin{cases} 
1 - L(l,i,j) & \text{if } L(l,i,j) < 0.5 \\
L(l,i,j) & \text{otherwise}
\end{cases}
\] (3)

to indicate the capacity of the corresponding DWT coefficient to support changes based on brightness perceptual properties. The larger the value of \( L'(l,i,j) \), the more we may change the corresponding DWT coefficient before the change becomes noticeable.

The proposed adaptive STDM assigns to the corresponding projection vector \( p \) the values computed by (2) and (3) for each wavelet coefficient in the host vector. Note that the projection vector \( p \) is now a function of the host vector; thus, it is variable for each bit embedded.

### 4.4 Watermark embedding

In a Digital Cinema environment, the playback system should be able to insert the watermark identifying the time and location of the projection at the same rate the motion pictures are decoded. In order to meet the real-time requirement, the complexity of the watermarking algorithm should be as low as possible. By integrating the watermarking process into the JPEG2000 decoder, the image is already decomposed into DWT coefficients and inverse DWT will be performed by the following step of JPEG2000 decoding. Hence, the embedding process consists uniquely in using the technique described as follows and some pre-processing on the de-quantized wavelet coefficients to improve the system performance.

In the algorithm described here only the luminance component is marked. The choice of watermarking the luminance component is mainly motivated by robustness reasons. Note that DCT-based compression, for example, preserves better the luminance than chrominance components. Anyway, marking the chrominance components has several other disadvantages. For instance, the human eye is much more sensitive to slight color changes compared to slight luminance changes.

While some approaches exploit explicitly the spatial thresholds of the HVS to determine the location of the watermark, our approach uses all the available coefficients of some selected sub-bands and exploits HVS properties in the wavelet transform to determine the spreading strength of the information bits within those coefficients. As DWT has poor directional selectivity for diagonal features (there is only one filter for diagonal features), no embedding is done in diagonal sub-bands. Initially, we would say that we only embed information bits in the third-level horizontal and vertical sub-bands of a 5-level wavelet decomposition.

The discrete wavelet transform performs good de-correlation of the data and distributes the energy of the image on a few significant coefficients, so it also provides a good tool for edges and textures detection. High activity regions are essential for both compression and watermarking: compression needs to preserve their integrity and the HVS is less sensible to modifications in these regions, which is a useful property for watermarking. In the masking model proposed in [21], edges and textures activity need the analysis of several sub-bands, what may increase computational complexity of the watermarking method. Instead of that, to exploit edges and textures sensitivity, a non-linear scaling function is used before the embedding, applying the corresponding inverse scaling after embedding, to put more watermark energy in edges and textured areas. Thus, host vectors are composed of scaled coefficients as:
\[
x(i,j) = \text{sign}(h(i,j))|h(i,j)|^\beta, \quad \beta \leq 1
\] (4)

To embed the watermark, a non-overlapping window of size \( L \times 1 \) is slid over the scaled coefficients. The size of the window is determined by the coding rate and the size of watermark to embed. At each window position one bit of the watermark is embedded by using the adaptive Spread-Transform Dither Modulation scheme introduced in section 4.3.

### 4.5 Watermark extraction

Neither the original image nor the original watermark are required during the extraction stage. The embedder and the decoder, however, share some key information which includes the wavelet transform, quantization parameter \( \Delta \), scaling and distortion compensation parameters and watermark payload.
The extraction procedure is as follows:

**Transform step:** N-level wavelet transform of the received image $I_w'$ is performed.

For each vector $y$ in the selected sub-bands:

**Spreading vector estimation:** We compute the local luminance for each coefficient from Eq. (2) and estimate the projection vector $p$ using Eq. (3).

**Scaling step:** We scale the wavelet coefficients on $y$ using Eq. (4) and key information $\beta$.

**Reading step:** Project the received vector $y$ and use a minimum distance decoder to find the closest reconstruction point, belonging to either a 0 or a 1-bit:

$$\hat{m} = \arg \min \| y^T p - Q_{\Delta,m}(y^T p) \|$$

5. **EXPERIMENTAL RESULTS**

As Motion JPEG2000 (M-JPEG2000) simply compresses each frame of the video with the image compression standard JPEG2000, tests have been done on still images. A set of eight 2K-raw video frames of digital cinema content were obtained and subjected to the watermark insertion process. Test material was obtained from StEM DCI material, RED cameras sample shots and Big Buck Bunny open movie project. All images have 1920x1080 pixel spatial resolution and 8-bit depth in each color channel.

A 5-level, 9/7 wavelet decomposition is performed firstly, as it is specified for JPEG2000 compression of 2K resolution content [19]. The total information payload is 35bits, embedded in the level-3 LH and HL entire sub-bands. The watermark embedding strength is controlled in the proposed approach by the quantization step size used in STDM. The distortion-compensation parameter $\alpha$ is set to 0.77, the scaling factor fixed at 0.85. Experiments were performed to determine both fidelity and robustness of the watermarking algorithm.

5.1 **Perceptual Quality**

Subjective and quantitative evaluation of the distortion introduced through the watermarking process has been performed. As mentioned previously, the watermark robustness depends directly on the embedding strength, which in turn influences the visual degradation on the image.

In the proposed scheme, we fix the embedding intensity $\Delta$, however this quantization step is applied differently at each coefficient due to the luminance masking. Figure 3 shows the relation between the quantization step per coefficient and the peak signal-to-noise ratio (PSNR) for three of the test frames, computed in the luminance channel with reference to the original frame. The number of the embedded data is 70 bits/frame and PSNR stands for the average value for several repetitions on each image.

![Fig. 3. Quantization step per coefficient vs. PSNR](image-url)
Butterfly tests on large-screen projections were performed with five critical observers to evaluate image fidelity. Each of the eight test frames were watermarked with 3 different embedding intensities, keeping always the PSNR above 50dB. Watermarked frames were presented in couple with its respective original, and observers were required to choice the watermarked frame from each couple.

Results show that no perceptible distortion is produced on watermarked images for PSNRs above 50dB. In any case, none of the viewers was able to reliably identify the watermarked frame. A sample watermarked frame is shown in Fig. 4, together with the difference with the original frame.

![Fig. 4. Frame from “The Magic Hour” (StEM): original (top), watermarked (middle), and difference (bottom).](image-url)
5.2 Robustness

We considered two possible attack scenarios: Perfect Capture and Camcorder Capture.

**Perfect Capture.** We assume the decoded bit-stream can be captured from some digital output port after embedding without any distortions. Experimental results show that the proposed method is robust against image processing attacks, including low-pass filtering and anti-aliasing, noise reduction filtering, noise addition, compression/decompression, application of FFT, DCT transformations, re-sampling, re-quantization and common signal enhancements to image contrast and color.

Digital video is usually compressed with low bit rate MPEG. A 5% quality image compression rate degrades severely the image so to consider the algorithm robust to compression. Fig. 5 gives that 5% of compression rate has an ignorable BER and it is feasible to make it zero by the use of several frames of the video content.

![Fig. 5. Mean bit-error rate on watermark detection of JPEG compressed watermarked images where PSNR=52.9dB.](image1)

**Camcorder Capture.** Forensic image watermark for Digital Cinema is required to survive camcorder capture and low bit rate compression. The set of test frames, each watermarked in seven different quantization conditions, is displayed on a projection room and captured using a DV-camera. Mean recovering results from all test frames are plotted in Fig. 7.

![Fig. 6. Camcorder frame capture from ‘Crossing the Line’ (RED)](image2)
As can be seen in the sample frame in Fig. 6, the capture introduced arbitrary scaling, rotation, some perspective projection, blurring and compression. Using widely available tools, each captured frame have been processed such that any black-bars or boundary pixels are removed, resulting on approximately 500x375 resolution images. Detection is performed after individual image registration using the morphon method [23]. Registered images present a peak signal-to-noise ratio of about 27-28dB. Morphon is a non-rigid registration method which registers two- or three-dimensional images using an iterative, multi-resolution deformation scheme. The method is initiated on a coarse resolution scale and proceeds to finer scales, performing a number of iterations per scale using quadrature filter phase difference to estimate the local displacement. The deformation process is done in three steps: displacement estimation, deformation field accumulation and deformation.

Recovering results are shown in Fig. 7. Bit-error rate in this figure is the watermark recovering rate from a single frame in very good quality image conditions, PSWR above 50dB. Watermark detection is required to be done within up to 30 minutes of Digital Cinema video content [19]. Error rates below 20% in a single frame are soon diminished to zero when using several watermarked frames to recover the information.

6. CONCLUSIONS

We have proposed a robust exhibition watermarking algorithm, embedded in the decompression preceding Digital Cinema movies projection in theaters, to deter capture and unauthorized redistribution of electronically distributed movies. The algorithm has a very low complexity and is suitable for implementation inside the JPEG2000 decoding pipeline. Based on our tests and structuring of our method, we can say that our watermarking method highly preserves the image quality and is robust enough to signal processing. The watermark survives low bit-rate compression and capture with a video camera, allowing us to reach the watermark recovering constraint of the DCI (detection over up to 30min of content) without compromising image quality. Currently, we are investigating the constraints that temporal dimension presents in order to avoid temporal distortions in the watermarked video as flicker effect. Nonetheless, the registration of captured sequences requires the knowledge of a non-deformed copy of the original content. We will further expand our experiments to study the addition of specific video registration technique for watermark detection, as well as study its robustness to collusion attacks.
REFERENCES