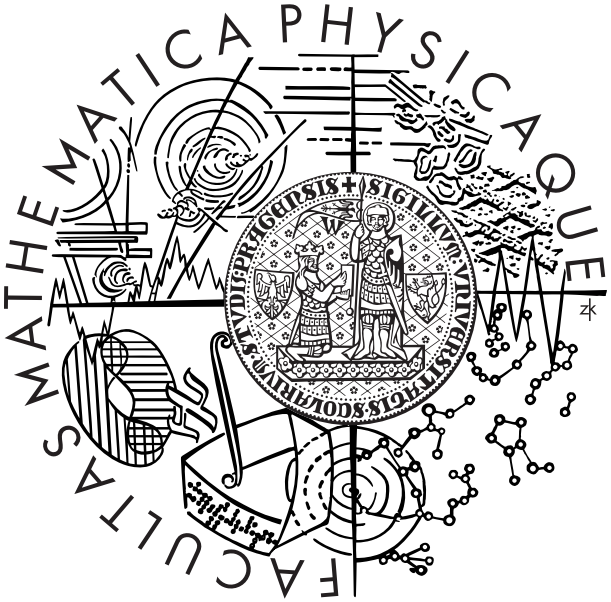
Charles University in Prague
Faculty of Mathematics and Physics

MASTER THESIS



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Video Watermarking

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I would like to thank my supervisor, RNDr. Josef Pelikán, for his professional leadership and valuable advice.

I hereby declare that I have written this master thesis on my own, using exclusively cited sources. I approve of lending the thesis.

Prague, April 20, 2007 Martin Zlomek

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Název práce: Watermarking videa
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Abstrakt: Navrženy a implementovány byly tři různé metody pro watermarking video sekvencí, které jsou komprimovány podle standardu H.264. Dvě z těchto metod reprezentují metody, které watermark vkládají ve frekvenční oblasti, zatímco třetí patří mezi metody, které watermark vkládají do obrazové oblasti. Vkládání watermarku ve frekvenční oblasti probíhá změnou transformačních koeficientů, které jsou získány přímo z komprimovaného proudu dat. Watermark, který má být vložen v obrazové oblasti, je před vložením do těchto koeficientů nejprve transformován do frekvenční oblasti.

Dále byl navržen a implementován obecný watermarkovací systém, který poskytuje jednoduché rozhraní usnadňující implementaci konkrétních metod. Odolnost navržených metod vůči různým útokům byla prověřena a vzájemně porovnána sadou několika testů. Testy simulují následující útoky: rekompresi, změnu měřítka, ořezání, zbavení šumu, zašumění, rozmazání, zaostření, mnohonásobné vkládání watermarku a tzv. konspirační útok.

S ohledem na robustnost a viditelnost watermarku v obraze je metoda, která watermark vkládá do obrazové oblasti, preferována před ostatními metodami.
Klíčová slova: watermarking, komprimované video, H.264, frekvenční oblast, obrazová oblast

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Abstract: Three different watermarking methods for video sequences compressed according to the H.264 video coding standard have been designed and implemented. Two of them represent frequency domain methods while the third belongs to spatial domain methods. Embedding in frequency domain is applied to transform coefficients obtained directly from the compressed video stream. The spatial domain watermark is transformed to frequency domain before embedding.

Further, a generic watermarking framework has been designed and implemented in order to provide a simple interface for easy implementation of particular watermarking methods.

The proposed methods have undergone several simulation tests in order to check up and compare their robustness against various attacks. The test set comprises recompression, scaling, cropping, denoising, noising, blurring, sharpening, multiple watermark embedding and collusion attack.

The spatial domain watermarking method is preferred to frequency domain methods with respect to robustness and perceptibility.
Keywords: watermarking, compressed video, H.264, frequency domain, spatial domain

Chapter 1

Introduction

Nowadays, digital multimedia content (audio or video) can be copied and stored easily and without loss in fidelity. Therefore, it is important to use some kind of property rights protection system.

The majority of content providers follow wishes of production companies and use copy protection system called Digital Rights Management (DRM). A DRM protected content is encrypted during the transmission and the storage at recipient's side and thus protected from copying. But during playing it is fully decrypted. Besides recipients must have a player capable to play DRM encrypted content, the main disadvantage of DRM is that once the content is decrypted, it can be easily copied using widely available utilities.

Disadvantages of DRM can be eliminated by using another protection system, watermarking. Watermarking can be considered to be a part of information hiding science called steganography. Steganographic systems permanently embed hidden information into a cover content so that it is not noticeable. Thus, when anybody copies such content, hidden information is copied as well.

Three aspects of information hiding systems contend with each other: capacity, security and robustness. Capacity refers to amount of information that can be hidden, security to ability of anybody to detect hidden information, and robustness to the resistance to modifications of the cover content before hidden information is destroyed. Watermarking prefers robustness, i.e. it should be impossible to remove the watermark without severe quality degradation of the cover content, while steganography demands high security and capacity, i.e. hidden information is usually fragile and can be destroyed by even trivial modifications.

Watermarks used in fingerprinting applications typically contain

information about copyright owner and authorized recipient of the distributed multimedia content. Hereby, it allows tracking back illegally produced copies of the content, as shown in Figure 1.

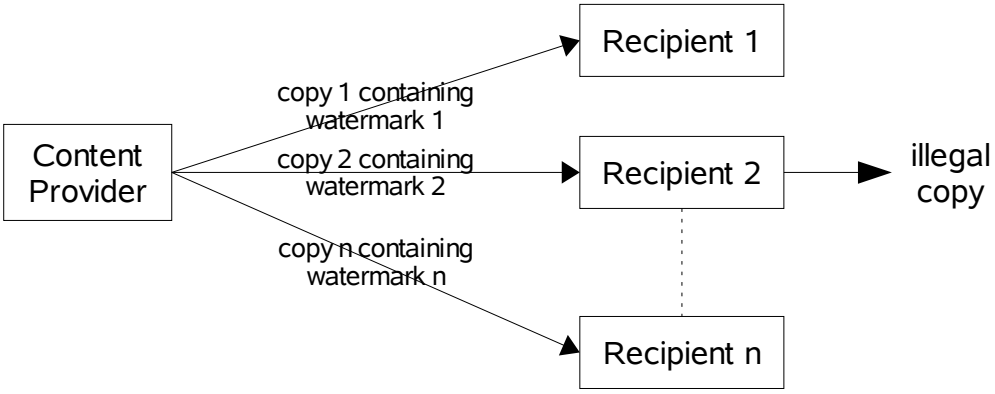


Figure 1: Principle of fingerprinting watermarks

This thesis focuses on fingerprinting watermarks being embedded into video sequences. Several watermarking methods are designed, implemented and compared with each other in terms of their perceptibility and robustness.

Some of the methods are inspired by existing ones, some are completely new. Making the method implementations perfect or improving existing methods are not the tasks, the thesis aims to comparing the methods as they are. One of the methods is chosen as the best and left for future improvements.

Chapter 2

Watermark Theory

A watermark is a digital code permanently embedded into a cover content, in case of this thesis, into a video sequence.

A watermark can carry any information you can imagine but the amount of the information is not unlimited. The more information a watermark carries the more vulnerable that information is. Anyway, the amount is absolutely limited by the size of particular video sequence. Watermarking prefers robustness to capacity, thus a watermark typically carries tens to thousands of hidden information bits per one video frame.

In order to be effective, the watermark should, according to [1], be:

Unobtrusive
The watermark should be perceptually invisible.

Robust
The watermark should be impossible to remove even if the algorithmic principle of the watermarking method is public. Of course, any watermark can be removed with sufficient knowledge of particular embedding process. Therefore, it is enough if any attempts to remove or damage the watermark result in severe quality degradation of the video sequence before the watermark is lost.

In particular, the watermark should be robust to:

Common signal processing – the watermark should be retrievable even if common signal processing operations (such as digital-to-analog and analog-to-digital conversion, resampling, recompression and common signal enhancements to image contrast and color) are applied to the video sequence.

Common geometric distortions – the watermark should be immune from geometric image operations (such as rotation, cropping and scaling).

Subterfuge attacks: Collusion and Forgery – the watermark should be robust to collusion by multiple individuals who each possesses a differently watermarked copy of the same content combining their copies to destroy the watermark. Moreover, it should be impossible to combine the copies to create a new valid watermark.

Unambiguous
The retrieved watermark should uniquely identify the copyright owner of the content, or in case of fingerprinting applications, the authorized recipient of the content.

In order for a watermark to be robust, it must be embedded into perceptually significant regions of video frames despite the risk of eventual fidelity distortion. The reason is quite simple: if the watermark were embedded in perceptually insignificant regions, it would be possible to remove it without severe quality degradation of the cover content.

Further, perceptually significant regions should be chosen with respect to sensitivity of human visual system which is tuned to certain spatial frequencies and to particular spatial characteristics such as edge features.

2.1 Watermark Classification

There are several criteria how watermarks for images or video sequences can be classified.

Watermarking techniques can be classified into spatial or frequency domain by place of application. Spatial domain watermarking is performed by modifying values of pixel color samples of a video frame (such as in [2]) whereas watermarks of frequency domain techniques are applied to coefficients obtained as the result of a frequency transform of either a whole frame or single block-shaped regions of a frame. Discrete Fourier Transform (watermarking using this transform is presented in [3]) and Discrete Wavelet Transform (in [4] or [5]) belong among whole-frame frequency transforms. The representative of the block frequency transform is Discrete Cosine Transform (in [6]). Classification into these groups is according to the way how the transforms are usually used in practice.

Video sequences compressed by modern techniques offer another type of domain, motion vectors. Watermarking in this domain slightly alters length and direction of motion vectors (as in [7]). More information about motion vectors is provided in Chapter 3.

Further, watermarks for video sequences can be classified by the range of application – e.g. hidden information carried by a watermark can be spread over all frames of the video sequence, then the whole sequence is necessary to retrieve

that information, or each frame contains watermark with the same information, then only a single frame should be enough.

In one frame, one single element of the watermark can be embedded into one pixel, into a block of pixels or even into the whole frame.

2.2 Embedding and Detection

At first, general embedding and detection processes in raw uncompressed images are described, then they are extended to compressed images. Watermarking of a video sequence can be considered watermarking of a set of single images but (especially in compressed video sequences) there are some obstacles, as will be mentioned in Chapter 4.

Raw uncompressed images provide spatial domain by nature because values of pixel color samples are directly accessible for modifications. For simplicity, grey-scaled images are considered only.

Let us denote a picture to be watermarked by P and values of its pixel color samples by P_i, a watermarked version of picture P by P^* and values of its pixel color samples by P^*_i. Let us have as many elements of watermark W with values W_i as number of pixels in picture P. Watermark W hereby covers the whole picture P. Further, it is possible to increase the watermark strength by multiplying watermark element values by weight factor α. Then the natural formula for embedding watermark W into picture P is:

$$P^*_i = P_i + \alpha W_i \tag{1}$$

That means that values of the watermark elements are simply added to values of pixel color samples. But in practice, minimum and maximum values of the samples have to be considered so the watermark can be impaired already during the embedding process by clipping the results to the allowed range.

The detection process of the watermark is possible by computing inverse function to (1) to derive possibly impaired watermark W^*, therefore the original picture P is needed.

In fingerprinting applications, watermark W^* is then compared with the original watermark W for statistical significance because it is more important to check the presence of the watermark rather than fully retrieve hidden information.

The requirement of the original picture for successful detection of the watermark can be eliminated by using correlation (mentioned in Chapter 4), by coding watermark element values into mutual relations among more pixels, or by using different watermarking method.

For example, the following method could be used. Let us have a binary

watermark, i.e. values of the watermark elements are either 0 or 1. When 0 is to be embedded into a pixel, the value of the pixel color sample is altered to the nearest even value. Similarly, when 1 is to be embedded into a pixel, the value of the pixel color sample is altered to the nearest odd value.

The detection process then consists in reading even pixel color sample values as 0 and odd values as 1.

This method is not robust very much because the watermark can be completely destroyed by altering all the sample values to become either odd or even. These modifications definitely do not severely degrade quality of the picture; the method is mentioned only to give more comprehension what watermarking is about.

Watermarking of uncompressed images in frequency domain requires doing the particular frequency transform of the image before the embedding and the inverse transform after the embedding.

The result of the transform is frequency spectrum of the image. Value of each coefficient C_i represents amplitude of the corresponding frequency. In this case, the following embedding formula is better than formula (1) because especially small amplitudes would be altered too much using formula (1), which would lead to perceptible distortion in the picture:

$$C_i^* = C_i(1 + aW_i) \tag{2}$$

It must be mentioned that this formula is invertible only if C_i is not zero, therefore implementations must count on this.

The classical approach to watermarking of a compressed image is to decompress the image, embed the watermark using spatial or frequency domain technique and recompress the image again. Full decompression and recompression of the image can be computationally expensive, especially concerning a video sequence.

The majority of compression algorithms used in image and video formats are based on a frequency transform, thus watermarking in frequency domain can be applied directly to coefficients of that transform. In practice, it means that the compressed image is partially decoded to obtain those transform coefficients, watermarked and encoded back again.

With certain knowledge of the particular transform, spatial domain watermarking is possible in a such way as described in the previous paragraph.

For example, 2D-DCT of a block of size 8×8 can be implemented as multiplication of the block by a transform matrix from left and the same but transposed matrix from right. Forward (matrix T_f) and inverse (matrix T_i) transforms are then expressed by the following formulas (P is a 8×8 matrix of

pixel color samples, C is a 8×8 matrix of transform coefficients of those samples):

$$\begin{aligned} C &= T_f \cdot P \cdot T_f^T \\ P &= T_i^T \cdot C \cdot T_i \end{aligned} \tag{3}$$

and the embedding formula is the following (W is a 8×8 block of watermark elements):

$$\begin{aligned} C^* &= T_f \cdot P^* \cdot T_f^T \\ &= T_f \cdot (P + W) \cdot T_f^T \\ &= T_f \cdot (T_i^T \cdot C \cdot T_i + W) \cdot T_f^T \\ &= T_f \cdot T_i^T \cdot C \cdot T_i \cdot T_f^T + T_f \cdot W \cdot T_f^T \\ &= C + T_f \cdot W \cdot T_f^T \end{aligned} \tag{4}$$

The interpretation of this result is to transform a block of the watermark via the forward transform and add the result to corresponding transform coefficients of the original compressed image.

2.3 Watermark Attacks

This section gives a survey of possible attacks on watermarks. Only attacks that do not severely degrade quality of the cover content are considered.

Watermark attacks can be, according to [8], classified into four main groups:

Simple attacks are conceptually simple attacks that attempt to damage the embedded watermark by modifications of the whole image without any effort to identify and isolate the watermark. Examples include frequency based compression, addition of noise, cropping and correction.

Detection-disabling attacks attempt to break correlation and to make detection of the watermark impossible. Mostly, they make some geometric distortion like zooming, shift in spatial or (in case of video) temporal direction, rotation, cropping or pixel permutation, removal or insertion. The watermark in fact remains in the cover content and can be recovered with increased intelligence of the watermark detector.

Ambiguity attacks attempt to confuse the detector by producing fake watermarked data to discredit the authority of the watermark by embedding several additional watermarks so that it is not obvious which was the first, authoritative watermark.

Removal attacks attempt to analyse or estimate (from more differently watermarked copies) the watermark, separate it out and discard only the watermark. Examples are collusion attack, denoising or exploiting conceptual cryptographic weakness of the watermark scheme (e.g. knowledge of positions of single watermark elements).

It should be noted that some attacks do not clearly belong to one group.

Chapter 3

The H.264 Standard

The H.264 standard represents an evolution of the existing video coding standards. It has been jointly developed by the ITU-T Video Coding Experts Group and the ISO/IEC Moving Picture Experts Group in response to the growing need for higher compression of moving pictures.

The standard has been published by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) as ISO/IEC 14496-10, also known as MPEG-4 Part 10 or AVC (Advanced Video Coding), and by the Telecommunication Standardization Sector of the International Telecommunication Union (ITU) as ITU-T Recommendation H.264 [9].

This standard has been chosen because it is the latest video compression standard and offers significant efficiency improvement over the previous standards (i.e. better bit-rate to distortion ratio).

3.1 The H.264 Structure

3.1.1 NAL Units and Pictures

A H.264 video stream consists of so called Network Abstraction Layer (NAL) units. A NAL unit stands for a top most placed peace in the hierarchy of syntactical structures.

A NAL unit contains either a set of parameters, describing properties of the stream, or video data in slices (see Section 3.1.2).

There are two parameter sets: the Sequence Parameter Set (SPS) which typically contains information about resolution and color coding, and the Picture Parameter Set (PPS) containing information about picture coding, picture

partitioning into slices (see Section 3.1.2) and entropy coding (see Section 3.2). Usually, there is only one SPS and one PPS in the stream at the beginning.

A set of NAL units compounding exactly one picture of the video sequence is called access unit, as depicted in Figure 2. A picture is either the whole frame of the video sequence or one of two frame fields. One field contains odd rows of the frame while the other contains even ones.

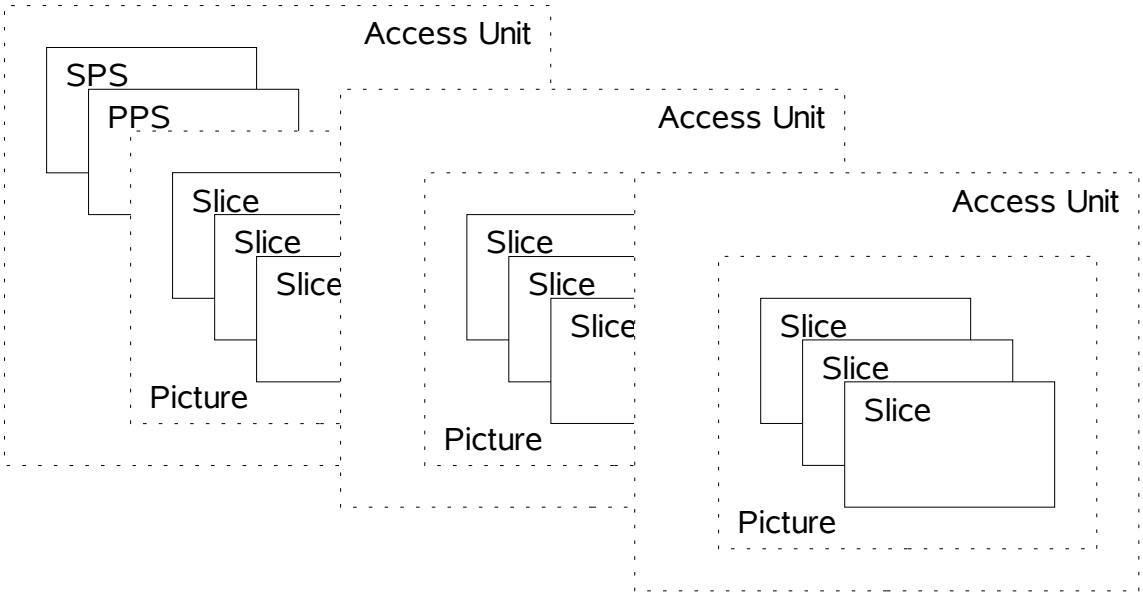


Figure 2: NAL units sequence

3.1.2 Slices

One picture can be partitioned into several slices, each coded in separate NAL unit. The shape of slices is basically arbitrary, slices can even blend together, but usually they form almost the same horizontal strips, as in Figure 3.

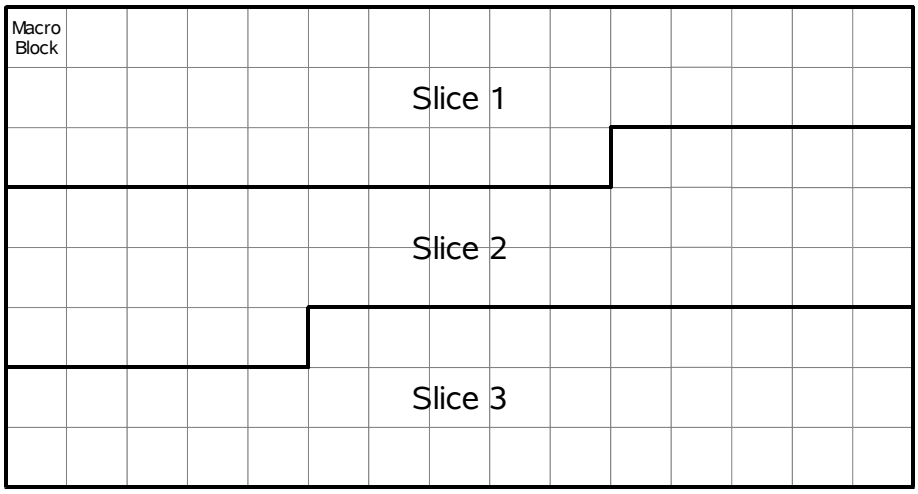


Figure 3: Partitioning of a picture into slices

There are three types of slices: I, P and B. I slices are completely intra coded (no reference pictures are used for prediction) while P and B slices use inter coding, i.e. previous pictures in display order (and in case of B slices, following pictures as well) are used for prediction.

Intra coding may provide access points to the video sequence where decoding can begin and continue correctly, but typically gains only moderate compression efficiency in comparison with inter coding.

The intra prediction process consist in exploiting of spatial statistical dependencies in a single picture while the inter prediction process exploits temporal statistical dependencies between different pictures. The prediction processes are thoroughly described in Section 3.2.

Only the pictures that go in the stream before the current slice can be used for prediction. Thus, even following pictures in display order used for prediction should go before the current slice. The reason is simple: decoders need those pictures to be able to decode predicted slices on-the-fly. Let us assume that each picture consists of a single slice, then the difference between display and stream order is illustrated in Figure 4 and Figure 5 (prediction dependencies are indicated by arrows).

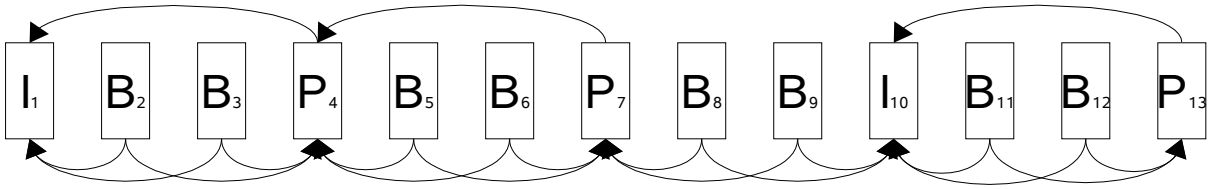


Figure 4: Display order of pictures

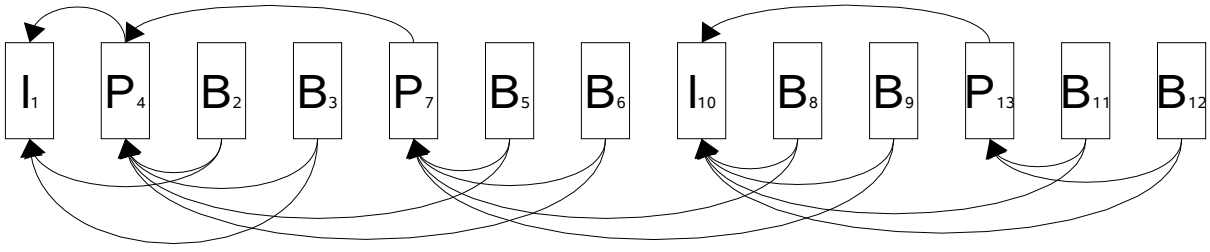


Figure 5: Stream order of pictures

3.1.3 Macroblocks

A slice is a sequence of macroblocks, as depicted in Figure 3. A macroblock, consisting of a 16×16 block of luma samples and two corresponding blocks of chroma samples, is used as the basic processing unit. Luma samples represent luminance of pixels while chroma samples represent chromatic components.

A 16×16 block of luma samples consists of 16 4×4 or 4 8×8 luma sub-blocks, depending on selected frequency transform. This partitioning is also used in a special type of intra prediction process.

Blocks of chroma samples are compounded similarly.

A macroblock can be further partitioned (subsequently halved or quartered) for inter prediction into blocks up to size of 4×4 luma samples.

3.2 Encoding

This section describes a scheme of the H.264 encoding process of a video sequence. The description is restricted to grey-scaled sequences only to avoid talking about chroma blocks which are coded in the completely same way as luma blocks.

Considering one picture of the sequence, encoders may select between intra and inter coding for blocks of the picture. Intra coding is usually selected for pictures just after a scene cut while inter coding for fluently following pictures. Scene-cut pictures typically miss any statistical dependence on previous pictures, thus there is no reason to use inter coding. Fluently following pictures can be imagined as e.g. a static scene without any camera movement, thus such following pictures are very similar and inter coding is the best choice.

In practice, encoders try both ways and choose the one that have better bit-rate to distortion ratio.

Regardless which coding is selected, the encoding process is the same. The process is depicted in Figure 6.

A picture is partitioned into 16×16 blocks of pixel color samples called macroblocks (MB). Then, the prediction process is invoked. Intra coded macroblocks can use intra prediction only while inter coded ones can use both intra and inter prediction. The subtraction of original samples and predicted samples is called prediction residual.

The intra prediction process predicts macroblock samples from edge samples of neighbouring macroblocks within the same picture. A special type of the process can be, in the same way, invoked on 4×4 or 8×8 sub-blocks of the macroblock. The mode of prediction, i.e. which and how neighbouring blocks are used, is encoded into a single number.

The inter prediction process may partition macroblocks into 2 16×8 or 8×16 or 4 8×8 blocks and 8×8 blocks can be further partitioned into 2 8×4 or 4×8 or 4 4×4 sub-blocks. For each block, the most similar block of the same size and shape is found in the reference pictures and its samples are used as predicted samples. The identifier of the reference picture and the relative position of corresponding blocks are encoded into so called motion vector.

The residual is partitioned into 16 4×4 or 4 8×8 blocks, depending on chosen

frequency transform. The choice is made per macroblock. Further, these blocks are transformed to remove spatial correlation inside the blocks.

Basically, the H.264 standard provides 4×4 block transform only but it has been extended to 8×8 blocks. The transform is a very close integer approximation to 2D-DCT transform with pretty much the same features and qualities.

Then, the transform coefficients are quantized (Q), i.e. divided by quantization factors and rounded. This irreversible process typically discards less important visual information while remaining a close approximation to the original samples. After the quantization, many of the transform coefficients are zero or have low amplitude, thus can be encoded with a small amount of data.

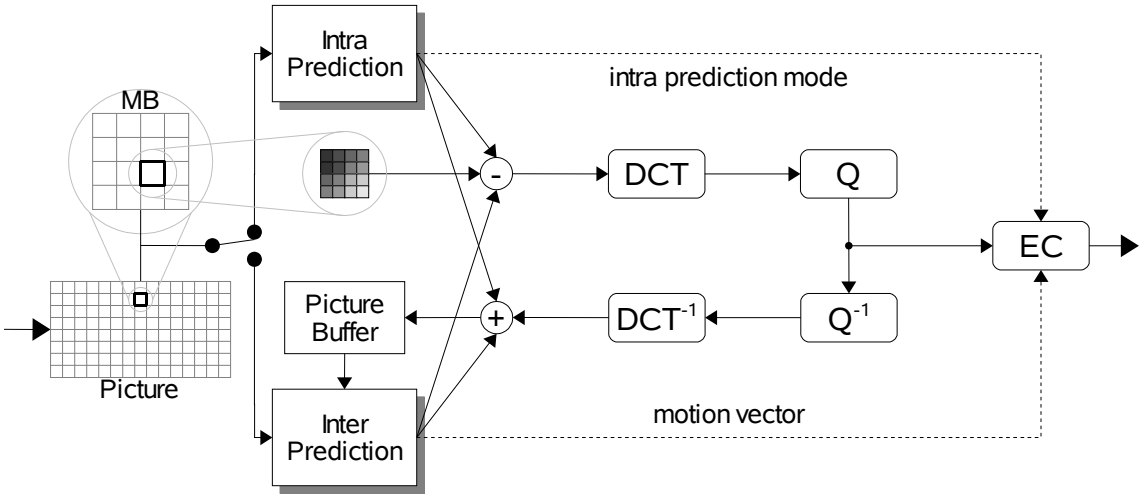


Figure 6: Encoding process scheme

The quantized coefficients are dequantized, inverse transformed and added to the predicted samples to form a block of potentially reference picture.

Finally, the intra prediction modes or the motion vectors are combined with the quantized transform coefficients and encoded using entropy coding (EC). Entropy coding consists in representing more likely values by less amount of data and vice versa.

The standard offers two entropy coding methods: Context-based Adaptive Variable Length Coding (CAVLC) and Context-based Adaptive Binary Arithmetic Coding (CABAC). CABAC is by 5-15% more effective [10] but much more computationally expensive than CAVLC.

Entropy encoded data are enveloped together with header information as a slice into a NAL unit.

3.3 Decoding

The decoding process is reversal process to encoding resulting in visual video data, as depicted in Figure 7.

Incoming slices are decoded, using the same entropy coding as in the encoding process, up to intra prediction modes or motion vectors and quantized transform coefficients.

Macroblock by macroblock, block by block, the quantized transform coefficients are scaled to the former range, i.e. multiplied by dequantization factors, and transformed by inverse frequency transform. Hereby, the prediction residual is obtained.

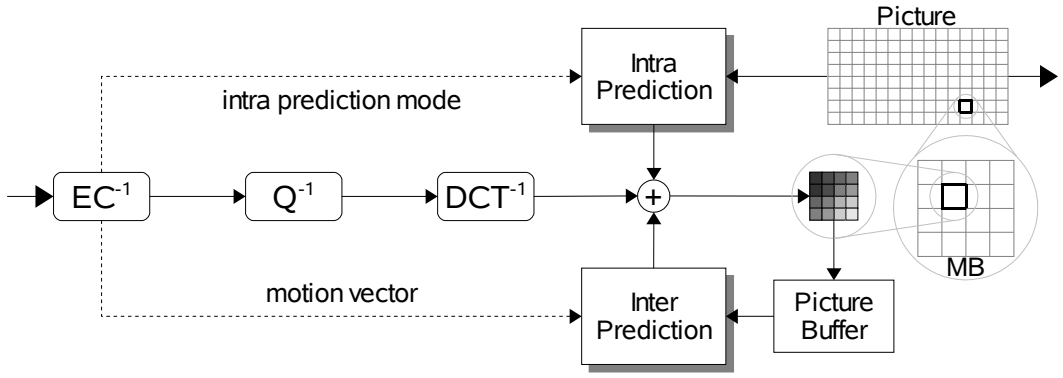


Figure 7: Decoding process scheme

The prediction process is invoked using the intra prediction mode in case of intra prediction, or the motion vector in case of inter prediction. Predicted samples are added to the residual.

Such decoded blocks and macroblocks are joined together to form the visible picture that is stored in the buffer of reference pictures for the inter prediction process in next pictures.

In both encoding and decoding processes, deblocking filter process is invoked over decoded pictures to increase final visual quality. The process eliminates blocking artefacts on block borders, as may be seen in video sequences compressed according to many of previous video coding standards at lower bit-rates.

Chapter 4

Implementation Details

This chapter deals with implementation details of the software framework for watermark embedding and detection.

A partial decoder / encoder (codec), as mentioned in Section 2.2, of H.264 video streams has been implemented in order to obtain transform coefficients for direct watermark embedding in frequency domain and further processing for embedding in spatial domain.

Further, a generic framework for watermarking of H.264 streams in both spatial and frequency domains has been designed and implemented. In this framework, three different watermarking methods have been written. The practical comparison of these methods is presented in Chapter 5.

4.1 The H.264 Codec

The partially decoding part of the codec is implemented according to the H.264 standard [9]. Of course, there are free implementations of the standard but writing an own helps to deeply understand the standard and video compression at all. Moreover, the transform coefficients are needed only, not fully decoded visible pictures.

The decoder produces all syntactical elements of a stream which are relevant for watermarking. In particular, it decodes and parses SPSs, PPSs, slices and macroblocks up to transform coefficients. During the process, it checks whether the decoded elements and the whole stream are correct. When an error occurs, it is reported by a message of particular severity level (critical error, error, warning etc.) and decoding of the current NAL unit ends immediately.

The encoding part of the codec is written as an inverse process to decoding because the standard contains only fragment information about the process. The

encoder is able to handle slices and macroblocks only; neither SPSs nor PPSs are supported because the stream properties are not changed during watermark embedding.

The codec is tested on various H.264 video sequences and even on official tests contained in [11]. But there are still limitations which are listed in Section 4.1.2.

The codec is written in programming language C as a library. Because the names of functions and variables follow labels from the standard and algorithms are rewritten from the standard and only slightly optimized, the source code is commented briefly.

Although the codec has a very limited application, the source code has over 11 000 lines.

4.1.1 Supported Features

The codec is able to decode the following features:

- SPS and PPS,
- both CAVLC and CABAC entropy coding,
- partitioning of pictures into slices,
- both frame and field slices,
- all slice types: I, P and B,
- all syntactical elements of slices: all macroblock types (i.e. partitioning), both 4×4 and 8×8 transform coefficients, intra prediction modes, motion vectors etc.

4.1.2 Known Bugs and Limitations

No bugs are known at the moment but the codec does not support the following features:

- only syntactical elements and several derived values are decoded – no visual data is provided,
- macroblock-adaptive frame-field coded slices, i.e. slices which contain both frame and field macroblocks together, are not supported,
- memory management control is not considered – no reference pictures are buffered,
- reference picture list reordering is not fully decoded and applied,
- unsupported NAL units:
  - Auxiliary Coded Picture (a supplement picture mixed to the primary picture by alpha blending),
  - Sequence Parameter Set Extension (alpha blending parameters for

auxiliary coded pictures),

- Supplemental Enhancement Information (necessary information for correct video playback and other data – timing information, buffer management hints, user data, scene information, pan-scan information, spare picture information, still frames etc.),
- Slice Data Partitions, i.e. partitions of too big slices.

4.2 The Watermarking Framework

The framework is designed for easiness when implementing any particular watermarking method in either spatial or frequency domain of H.264 video streams. Then, implementation of a method consists in writing only two functions, one for watermark embedding and the other for watermark detection.

4.2.1 GStreamer Multimedia Framework

In practice, a H.264 video stream is usually enveloped (multiplexed / muxed) together with an audio stream into a multimedia container format such as Audio Video Interleave (AVI) or Matroska (MKV). In order to avoid implementing of unpacking (demultiplexing / demuxing) various container formats and separating out the video stream, the watermarking framework is implemented as a plugin in the open source multimedia framework called GStreamer [12].

GStreamer is a library that allows the construction of graphs of media-handling components, ranging from simple audio playback to complex audio and video processing.

A graph, also called a pipeline, of a generic audio-video player is illustrated in Figure 8.

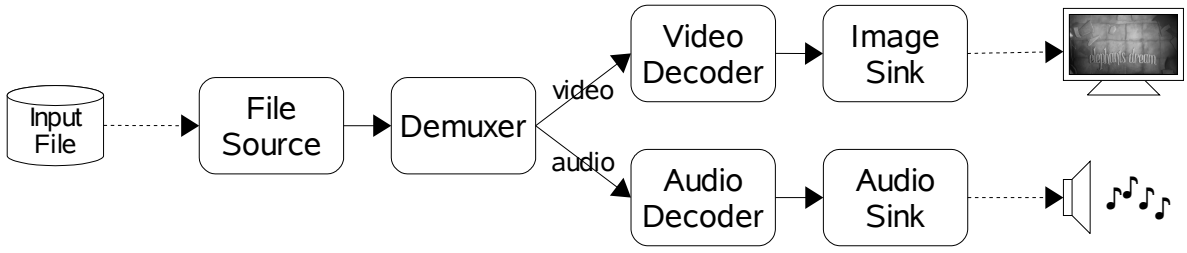


Figure 8: Generic audio-video player pipeline

The file source reads the input file of particular container format and forwards its data to the demuxer. The demuxer demultiplexes the container format resulting in audio and video data blocks. The video decoder decodes video data and forms pictures of the video sequence. Then, pictures are displayed by the video sink on the screen with the correct timing to be a fluently moving video. Audio data are decoded by the audio decoder and reproduced by the audio sink on

loud speakers.

The watermark plugin stands for an element in a suchlike pipeline. The plugin can be divided into two parts: the GStreamer part and the main part, and works in either embedding (see Section 4.2.2) or detection (see Section 4.2.3) mode.

The GStreamer part implements the GStreamer interface which is thoroughly documented on the project's website [12], thus the source code is only briefly commented.

This part parses incoming data blocks of H.264 stream into NAL units which are further decoded using the codec, mentioned in Section 4.1. As soon as a slice is decoded, it is forwarded to the main part of the plugin. Then, in embedding mode, the watermarked slice is encoded again and sent to the output, or in detection mode, detection statistics are given.

The main part does watermark embedding or detection, depending on the mode.

The plugin is written as a library in programming language C and the source code counts about 3 500 lines. The usage of the plugin is described in Appendix B and the documentation is provided in Appendix C.

4.2.2 Embedding

In the embedding mode, the plugin accepts a H.264 stream as the input, invokes the embedding process and outputs the same but possibly watermarked H.264 stream. The embedding pipeline is illustrated in Figure 9.

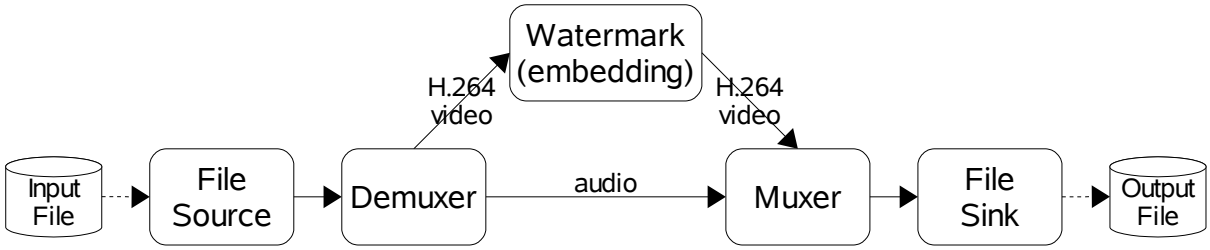


Figure 9: Watermark pipeline in embedding mode

Non-watermarked slices and other NAL units are passed through without any changes.

In the current implementation of the plugin, only intra coded slices are watermarked. This is because inter prediction is quite complicated and is not necessary for objectiveness of the thesis results.

Inputs to the embedding process are:

- an intra coded slice,
- content ID – the identifier of the cover content,
- copy ID – the identifier of particular cover content copy,
- weight – the weight factor specifying the watermark strength.

Output of this process is the watermarked slice.

At the beginning of the entire embedding process, the watermark is generated. The watermark is a pseudo-random noise signal covering one whole picture of the video sequence. The signal sample (i.e. watermark element) values are each either 1 or -1.

The watermark is partitioned into blocks, as the picture is partitioned into macroblocks, thus one block of the watermark is embedded into one macroblock of the picture. Dimension of the blocks depends on particular watermarking method.

The watermark is generated so that the sum of values of the watermark block elements is zero. The reason is to equal number of 1 and -1 in blocks to balance probability of changes caused by an attack. The pseudo-random generator is initialized by the identifier of the cover content copy – copy ID.

Let us denote such generated watermark as pure watermark.

One block of the watermark carries one bit of hidden information. Hidden information in this implementation is the identifier of the cover content – content ID. Content ID is typically represented by much less bits than the number of watermark elements, thus bits of the ID are pseudo-randomly spread over all watermark elements where the usual binary values {0, 1} are replaced by {-1, 1}. The pseudo-random generator is initialized by the ID itself. Another reason why the ID is spread is that the robustness is increased hereby and the spreading stands for a simple self error-correcting code due to redundancy.

Bits of hidden information (spread content ID) modulate the signal. When -1 is to be encoded, values of the block elements are inverted, i.e. from each 1 becomes -1 and vice versa, and when 1 is to be encoded, values of the block elements remain unchanged. This can be expressed like this:

$$W_{ij}^{M} = W_{ij}^{P} * I_i \tag{5}$$

Here, W^M is modulated watermark, W^P is pure watermark, W_{ij} is j-th element value in i-th watermark block and I_i is i-th bit value of hidden information.

The robustness can be improved by multiplying watermark element values by the weight factor a (the weight factor can be locally adjustable to track local spatial characteristics, thus to dynamically balance robustness and perceptibility):

$$W_{ij}^{M} = aW_{ij}^{P} * I_i \tag{6}$$

But the description is restricted to the former values in order to be less confusing; proposed algorithms, processes and calculations do not change.

Figure 10 illustrates content ID spreading, watermark generation and embedding which is described below.

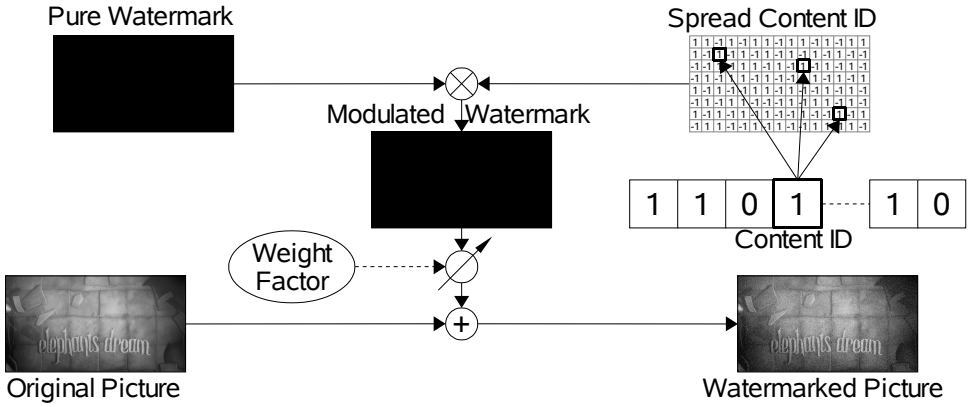


Figure 10: Illustration of watermark generation and embedding

Once the watermark is generated and hidden information is encoded, the embedding process can take place.

Blocks of each macroblock could be watermarked using formula (2) in case of frequency domain watermarks (the transform coefficients of a block are altered to encode one watermark element) or formula (4) in case of spatial domain watermark (corresponding sub-block of watermark block elements is forward transformed and added to the coefficients).

However, it not as simple as it seems. The essence of the problem consists in intra prediction. If watermarked blocks are used for intra prediction of other blocks, distortion caused by watermark embedding spreads into the other blocks. If there is a sequence of predictively dependent blocks, the distortion propagates and accumulates up into the last block of the sequence which probably causes severe, obviously not unobtrusive, fidelity distortion. Therefore, the intra prediction error compensation is implemented to undo the distortion.

In one block of a macroblock, the embedding process proceeds as follows (the scheme is depicted in Figure 11). The residual is obtained using inverse frequency transform on dequantized transform coefficients. Then, the predicted samples of both the original and the watermarked pictures are computed. Thus, both pictures are constructed during the process. The residual is added to predicted samples of the original picture, clipped to allowed range and stored as a block of the original picture. The prediction error as the difference between the watermarked picture predicted samples and the original picture predicted

samples is subtracted from the residual.

Such compensated residual is now ready for direct watermark embedding in the spatial domain. It depends on particular watermarking method whether the embedding process is controlled by the residual only or by the predicted samples as well.

Then, the residual is forward transformed and quantized. Note that the spatial domain watermark can be impaired by the quantization.

The quantized transform coefficients may be directly watermarked in the frequency domain.

The coefficients, watermarked either in the spatial domain or in the frequency domain, are dequantized and inverse transformed again. Such obtained residual is added (and clipped) to predicted samples from the watermarked picture to form a block of the watermarked picture.

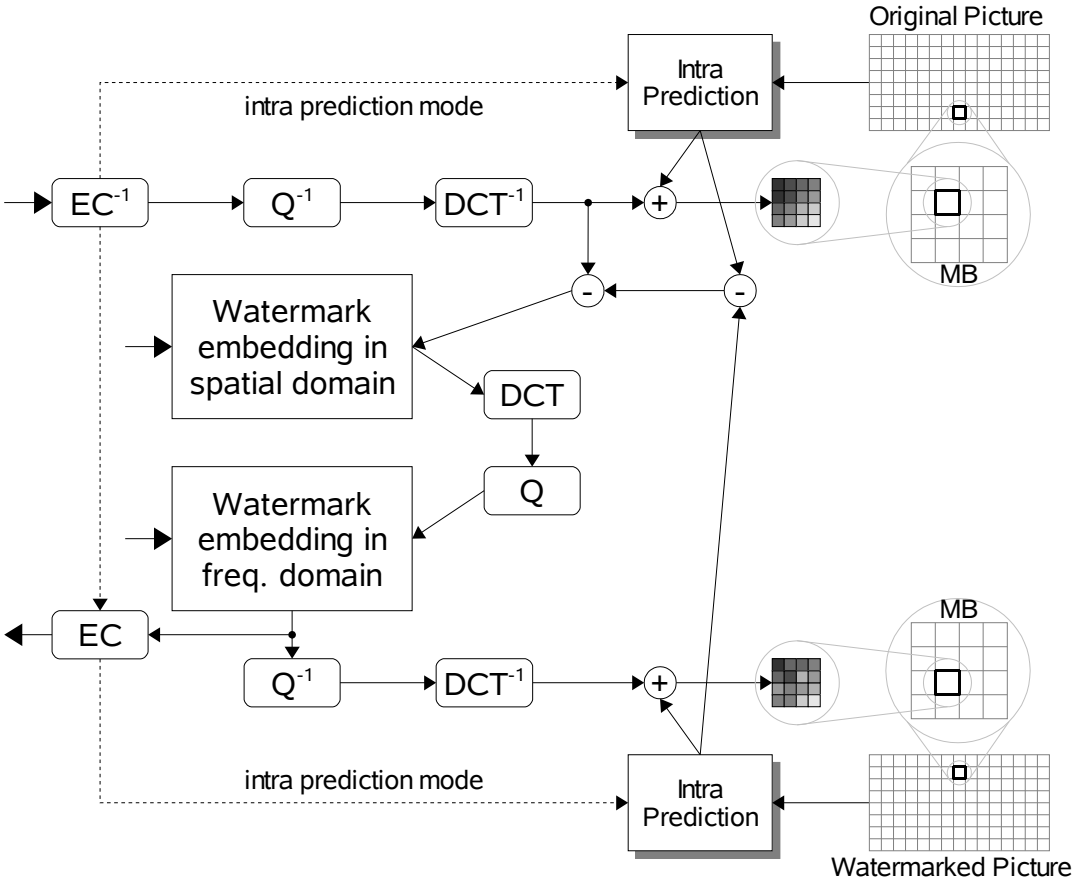


Figure 11: Watermark element embedding scheme with intra prediction error compensation

If the samples were not clipped, the reconstruction of the pictures would not be necessary. The error compensation would be possible by subtracting samples that are intra predicted from the difference in the residual caused by watermark

embedding.

Anyway, the pictures are used for measuring distortion caused by watermark embedding. Distortion in one picture is measured by peak signal-to-noise ratio (PSNR) which is the most commonly measure of quality of reconstruction in image compression:

$$PSNR = 10 * \log_{10}\left(\frac{MAX_I^2}{MSE}\right) = 10 * \log_{10}\left(MAX_I^2 \frac{|P|}{\sum_{i=1}^{|P|}(P_i - P_i^*)^2}\right) \quad (7)$$

where MAX_I is the maximum pixel color sample value (usually 255) of any picture, P is the original picture, P_i is a sample value of the original picture and P^*_i is a sample value of the watermarked picture.

At the end of the entire embedding process, average PSNR over all watermarked pictures is estimated and printed.

Distortion expressed by PSNR relates to perceptibility of the watermark. The practical results are presented in Chapter 5.

4.2.3 Detection

In the detection mode, the plugin accepts a H.264 stream as well, invokes the detection process and outputs detection results as textual data. The pipeline is illustrated in Figure 12.

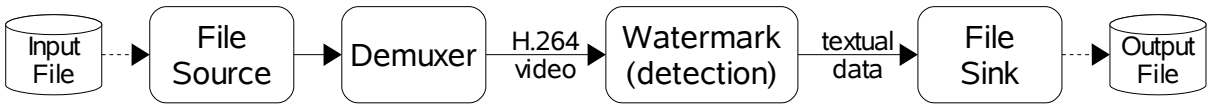


Figure 12: Watermark pipeline in detection mode

Again, only intra coded slices are taken into the detection process.

Inputs for the process are:

- a potentially watermarked intra coded slice,
- content ID,
- copy ID.

Only when whole picture is processed, output of this process is the probability that the cover content copy contains the identifier with value of copy ID.

At the beginning of the entire process, the same pure watermark as in the embedding process is generated. The pure watermark is further used for correlation with the detected watermark to retrieve hidden information.

In each macroblock, watermark block element values carrying one hidden information bit are obtained using particular watermarking method (the scheme is depicted in Figure 13). In case of frequency domain, the transform coefficients are directly accessible. In case of spatial domain, the coefficients have to be dequantized and inverse transformed in order to obtain the residual. It is further added to predicted samples and clipped giving picture samples suitable for detection. In this case, the residual is not enough because it depends on selected intra prediction mode which could change after an attack.

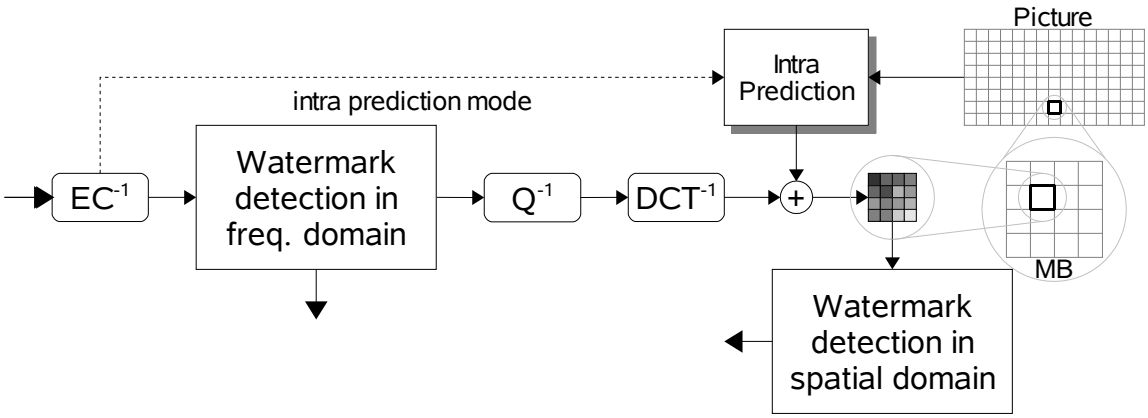


Figure 13: Watermark element detection scheme

Obtained watermark block element values are compared with the corresponding element values of the pure watermark. When the two corresponding values match, 1 has been encoded, while when they differ, -1 has been encoded. Remember the modulation of pure watermark by bits of hidden information in the embedding process: when -1 was to be encoded, values of the watermark block elements are inverted, i.e. each 1 becomes -1 and vice versa (thus differ), and when 1 was to be encoded, values of the block elements remain unchanged (thus match).

But in practice, especially after an attack, the corresponding values in one block need not 100% match or differ. Therefore, some correlation mechanism has to be proceeded. The correlation sum for i-th watermark block is computed:

$$C_i = \sum_j W_{ij}^P * W_{ij}^* \tag{8}$$

where W^P_{ij} is j-th element value of the pure watermark block and W^*_{ij} is j-th element value of the detected watermark block.

When the block encodes 1 (corresponding values match – they are either (1,

1) or (-1, -1)), the sum can get the maximum positive value, while when the block encodes -1 (corresponding values differ – the are either (1, -1) or (-1, 1)), the sum can get the minimum negative value. The middle value between these two extremes is 0. Thus, when the sum is greater than 0, 1 is returned, when the sum is lower then 0, -1 is returned, and when the sum is 0, the value can not be determined and does not participate in the following process.

Once all macroblocks are processed and hidden information bits are retrieved, it is time to merge the bits to form the detected content ID. The merge is done in the reverse way to content ID spreading in the embedding process. One content ID bit value is derived from the hidden information bits from those macroblocks that contain the bit. The spreading determines which macroblocks are taken. The value of the bit is the sign of the sum of the hidden information bits. When the sum is greater than 0, the value is 1, when the sum is lower than 0, the value is -1, and when the sum is 0, the value can not be determined and does not participate in the following probability estimation.

Figure 14 illustrates watermark detection and content ID merging.

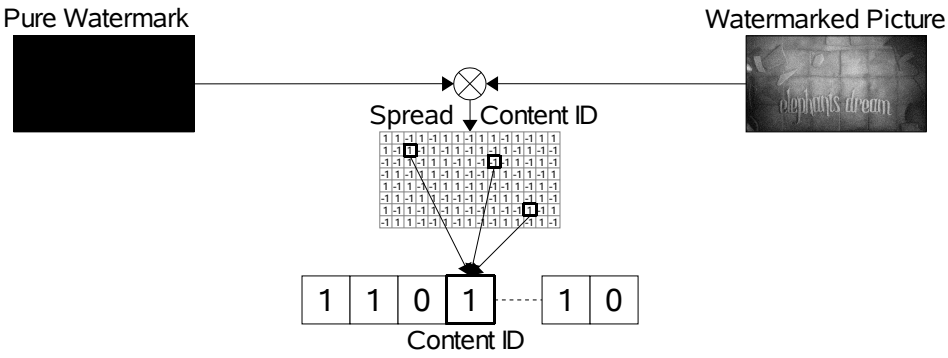


Figure 14: Illustration of watermark detection

The probability of the detection success is expressed by the correlation between the detected content ID and the input content ID. The correlation is computed using formula (8) where watermark values are substituted by ID values. The result is scaled to amplitude with value of 1. Then, when the correlation coefficient is 1, the IDs 100% match and the detection is absolutely successful, when it is -1, the IDs 100% differs, i.e. the detected ID is inverse to input ID, thus the detection is considered successful as well. The correlation coefficient equal to 0 means that the IDs are independent and the detection is considered unsuccessful. The closer the coefficient is to 0 the more independent the IDs are.

Per-picture correlation coefficients are continuously written to the output

file in order to provide detailed results for deeper analysis.

At the end of the entire detection process, average probability as average value of absolute correlation coefficient values over all intra coded pictures is estimated and printed. The probability expresses the detection success rate.

4.2.4 Notes

The generation of the watermark is based on spread spectrum technique presented by Hartung [2]. Spread-spectrum watermarks are described in detail in Section 4.3.1.

The watermark is embedded into luma samples only because human visual system is more sensitive to changes in luminance than to chromatic components, thus the watermark is harder to remove without severe quality degradation of the cover content. Moreover, the chromatic channels of the video stream may be completely removed and the video remains in former quality; the only difference is that the video lacks colors.

To increase the watermark robustness, a different pseudo-random signal can be generated for each picture in the embedding process. But then, a synchronization mechanism must be implemented in the detection process to be able to detect the watermark even if the order of the pictures is changed (or some are missing or extra) by an attack. This is not trivial and is not implemented in the plugin.

The generation of the pseudo-random signal is initialized by copy ID and hidden information is created from content ID intentionally. If a cover content copy contains more watermarks, they are represented by independent pseudo-random signals, thus it is possible to detect each of them. If the pure watermark were generated from content ID and hidden information from copy ID, the advantage would be that the detection result would be just the copy ID but copy IDs in multiple embedded watermarks would overwrite each other.

There is a weakness in the implementation because all macroblocks are watermarked. Especially uniform areas in a picture are encoded by almost none residual. Then, if such area is watermarked, the residual contains the watermark alone, thus the watermark may be completely removed. The solution could be to watermark only non-zero coefficients of residual with prejudice to robustness.

Another problem relates to watermarking of every macroblock. Because of many coefficients that have been zero are altered to non-zero value, the bit-rate is pretty much increased. We will see in Chapter 5 how high the increase is.

With respect to human visual system which is very sensitive to changes in uniform areas, watermarking could be further improved to embed the watermark only into edge features or textured areas. But the goal of the thesis is to compare watermarking methods as they are, therefore no such extensions are implemented.

4.3 Watermarking Methods

Three different watermarking methods have been implemented. One stands for a spatial domain watermarking technique and the other two represent frequency domain techniques.

Each method is implemented in only two functions; one is for embedding into macroblock blocks and the other is for detection. The rest of necessary actions does the watermarking framework.

4.3.1 Pseudo-random Noise Watermark

Pseudo-random noise watermark is inspired by spread-spectrum communication schemes which transmit a narrow-band signal (the watermark) via a wide-band channel (the video sequence) by frequency spreading. This technique was presented by Hartung for uncompressed and MPEG-2 compressed video [2]. In this thesis, it has been implemented for H.264 video streams.

This method belongs to spatial domain techniques, thus the watermark can be impaired during the embedding process by quantization. This is compensated by the technique itself because spread spectrum provides the reliable detection even if the embedded watermark is impaired because of the interference from the video sequence itself and noise arising from subsequent processing or attacks.

Nevertheless, a spread spectrum watermark is vulnerable to synchronization error which occurs when the watermarked sequence undergoes geometric manipulations such as scaling, cropping and rotation.

Furthermore, Stone [13] shows that advanced collusion attacks against spread-spectrum watermarks can be successful with only one to two dozen differently watermarked copies of the same content.

When using this method, the watermark plugin generates the pure watermark blocks with dimension of 16. Macroblocks have the same dimension, thus one watermark element is to be embedded into one pixel of the picture.

The embedding function is called for each block of each macroblock; dimension of the blocks depends on selected frequency transform. The modulated watermark is embedded as it is by simple addition to the residual, thus up to picture samples:

$$P_{ij}^{*} = P_{ij} + W_{ij}^{M} = P_{ij} + aW_{ij}^{P} * I_i \tag{9}$$

The detection function is called for each block of each macroblock as well. The detection process is based on the fact that the pseudo-random signal and the picture are statistically independent while the signal is autocorrelated. This method does not provide detected watermark element values to the framework but uses the correlation sum calculation (see formula (8) above) in the framework

as a part of the whole process. Then substituting detected watermark element values by picture sample values, the evolution of the correlation sum is:

$$C_i = \sum_{j=1}^{16*16} W_{ij}^P * P_{ij}^* = \sum_{j=1}^{16*16} W_{ij}^P * (P_{ij} + aW_{ij}^P * I_i) = \underbrace{\sum_{j=1}^{16*16} W_{ij}^P * P_{ij}}_{A} + \underbrace{a \sum_{j=1}^{16*16} (W_{ij}^P)^2 * I_i}_{B} \quad (10)$$

where A and B stand for contributions to the sum from the picture and from the watermark. Let us assume that A is zero because of independence of the pseudo-random signal and the picture, then:

$$C_i = A + B \approx a \sum_{j=1}^{16*16} (W_{ij}^P)^2 * I_i = a * 16 * 16 * I_i \quad (11)$$

In practice, A is not exactly zero, thus an error is included. The decision process in the framework is invoked – when C_i is greater than 0, the value of the detected hidden information bit is 1, and when C_i is lower than 0, the value is -1. I_i is either -1 or 1 and a is greater than 0, therefore the sign of I_i sets the sign of C_i and the detected hidden information bit is determined correctly. The greater the weight factor a is the greater the tolerance to the error of A is provided.

The probability of detection success may be increased by applying a high-pass filter to the sequence before the detection process in order to filter out the host signal and keep the watermark signal alone.

4.3.2 Block Watermark

Block watermarking method belongs to frequency domain techniques. The method consists in coding one watermark element into one block of a macroblock residual.

Only 4×4 blocks are supported because of the following. The partitioning of macroblock residuals into blocks may change when the video sequence undergoes any video signal processing operation. The simplest example is recompression with different parameters.

The problem occurs when the watermark element has been embedded into a macroblock partitioned into 16 4×4 blocks and the partitioning has changed to 4 8×8 blocks, or vice versa. Changes made by watermark embedding in one partitioning are basically undetectable in the other partitioning because the transforms are not equivalent in terms of transform coefficient values. It would be possible to convert the blocks to the former partitioning before detection but it is not obvious which partitioning is the former one.

Therefore, the conversion to one type of partitioning has to be applied before embedding. After embedding, the partitioning is converted back to the former type in order to preserve macroblock properties. In the detection process, the conversion to the same type as in the embedding process is applied before

detection.

Conversion into 8×8 blocks is out of the question because of intra prediction. The intra prediction process for a 4×4 sub-block within one 8×8 block uses the other 4×4 sub-blocks within that 8×8 block. Therefore, when the 8×8 block is watermarked, the error caused by watermark embedding should be compensated in the 4×4 sub-blocks when using the other 4×4 sub-blocks for prediction. But the compensation may severely impair the already embedded watermark...

There is only conversion into 4×4 blocks left. In this case, intra prediction does not give trouble. The conversion is performed by decoding (i.e. dequantizing and inverse transforming) a 8×8 block, partitioning into 4×4 blocks and encoding (i.e. forward transforming and quantizing) the blocks in order to obtain transform coefficients for watermark embedding. This works pretty well but the quantization causes visible blocking artefacts.

With respect to the reasons above, no conversion is applied and only 4×4 blocks are taken for watermark embedding. 4×4 blocks have been chosen because 4×4 block transform is more usual than 8×8 transform. Video sequences given to both embedding and detection can be converted to required format beforehand at the cost of eventual quality degradation.

The pure watermark blocks are generated with dimension of 4 to cover 16 4×4 macroblock blocks.

Embedding into one block proceeds as follows. Only the half of transform coefficients that represent higher frequencies are taken. Although higher frequencies are more vulnerable to eventual attacks, human visual system is more sensitive to distortion in lower frequencies and modification of low frequency coefficients causes obtrusive blocking artefacts.

When 1 (the weight factor a in fact) is to be embedded, the coefficient with the greatest absolute value is chosen. The coefficient modification keeps the sign of the coefficient but eventually increases its absolute value to required robustness level. If the coefficient is positive but lower than a, the coefficient is increased to a. If the coefficient is negative but greater than $-a$, the coefficient is decreased to $-a$. The coefficient is remained unchanged if it is greater than a in absolute value. If the coefficient is 0, a or $-a$ is randomly assigned. The purpose why all this is done is to enforce a non-zero value in the half while producing to the lowest distortion.

When -1 is to be embedded, all coefficients in the half are set to zero. This causes loss in detail.

Detected watermark element values are obtained directly from transform coefficients. If all transform coefficient values in the half are zero, -1 is returned, otherwise (if there is at least one non-zero coefficient) 1 is returned.

Recompression at lower bit-rate causes more loss in detail, thus zero

coefficients are hardly set to non-zero values. On the other hand, the coefficients set to the weight factor a in absolute value can be zeroed. Therefore, a should be set to such a high value to remain non-zero even if the video sequence undergoes an attack.

Considering multiple embedding attack, this method is quite vulnerable because the watermark elements are directly embedded and thus multiple embedded watermarks overwrite each other.

The watermark can be completely destroyed by zeroing the coefficients in the half in all macroblocks but it results in visible blocking artefacts.

4.3.3 Coefficient Watermark

Coefficient watermarking method belongs to frequency domain techniques as well. The method consists in coding one watermark element into one transform coefficient of a macroblock residual block.

Again, only 4×4 blocks are supported because of the same reasons as in block watermarking method and the pure watermark block has dimension of 4.

The transform coefficient where a watermark element is to be embedded into is pseudo-randomly chosen from the half of coefficients which represent higher frequencies. The pseudo-random generator is initialized for each picture by both content ID and user ID in order to increase robustness against multiple watermark embedding and collusion attacks.

The value of the coefficient is altered in the same way as in block watermarking method, i.e. when 1 is to be embedded, the value is eventually increased to the weight factor a in absolute value, and when -1 is to be embedded, the coefficient is set to zero.

In the detection process, the transform coefficient is pseudo-randomly chosen in the same way as in the embedding process. If the coefficient is zero, -1 is returned, otherwise 1 is returned.

This method should have similar robustness qualities to block watermark method but distortion caused by watermark embedding should be lower because only one coefficient is altered in a block.

Chapter 5

Testing

Proposed watermarking methods have been exposed to several tests in order to check up and compare their qualities and robustness. The test results are summarized in this chapter.

The test environment consists of single test scripts written as Unix shell scripts. If recompression is applied, a free H.264 encoder, x264 [14], is used; it is released under the terms of the GPL license. Video signal processing tests use video filters of MPlayer movie player [15] which is available under the GPL licence as well.

The test scripts have been executed on several video sequences with different characteristics. Most of them have been downloaded from high-definition video gallery [16] on the Apple website. All the sequences have been remuxed to Matroska [17] container format because of easiness of use (there are both the demuxer and the muxer in the GStreamer plugin library). The list of the sequences follows:

Elephants Dream (ED) represents an animated movie. This particular one has been made entirely with open source graphics software, Blender. It has been downloaded from the project's website [18].

Full Bloom (FB) is a sample of 1080p high-definition video.

Kingdom of Heaven (KH) is a trailer of the movie with the same name. The main feature is frequent scene cuts.

Peaceful Warrior (PW) stands for a low-resolution sample.

Renaissance (R) is mostly black-and-white sequence with only a few other hues.

The Simpsons Movie (SM) is the representative of cartoon movies.

Wildlife (W) brings real images from nature with minimum camera movement.

Table 1 outlines characteristics of the sequences.

	Resolution	Length [min:s]	Frame-rate [frames/s]	Bit-rate [kb/s]	Av. I Frame Size [kB]	# I Frames	Description
ED	720×405	10:54	24.000	1667.29	31.34	638	animated
FB	1920×1080	01:41	23.976	8228.74	101.28	102	HD in full resolution
KH	852×360	02:40	23.976	2528.07	34.54	105	frequent scene cuts
PW	320×136	02:20	29.970	239.36	3.87	67	low resolution
R	848×480	01:18	23.976	1701.18	17.02	71	black-and-white
SM	848×352	02:17	23.976	2103.66	39.29	97	cartoon
W	960×540	02:20	29.970	2015.86	45.06	14	nature

Table 1: Characteristics of testing video sequences

Each test script embeds a watermark into each testing video sequence using each proposed watermarking method – block, coefficient or noise – with weight factor from 1 to 5, applies the test itself and obtains the result.

Watermarks are generated with content ID assigned to the sequences subsequently from 1 to 7. If not mentioned otherwise, copy ID is set to 1.

Other scripts are provided to make embedding and detection easier. These scripts contain corresponding GStreamer pipelines. The usage is described in Appendix B.

In the test result tables (see below), the results belonging to one method are grouped into one column set headed by the method name where one column contains results of the test using the weight factor given in the column header.

Row sets represent results for single testing video sequences – ED, FB, KH, PW, R, SM and W. Rows of the sets vary depending on eventual additional test parameter.

5.1 Perceptibility

Perceptibility expresses amount of distortion caused by watermark embedding. In other words, it indicates how visible the watermark is. It is measured by peak signal-to-noise ratio (PSNR) which is mentioned in Section 4.2.2. The less the value of PSNR is the more perceptible the watermark is. We can see in the first row set of Table 2 that the perceptibility grows up with increasing weight factor. It is obvious that block method is the most perceptible method because of the way of embedding.

The second row set of the table contains probabilities of watermark detection success in non-attacked sequences as given by the detector. Note lower probabilities when using noise method with low weight factors caused by the interference from the video sequences and quantization.

		Block					Coefficient					Noise				
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
PSNR [dB]	ED	41.92	38.79	36.23	34.13	32.42	44.16	39.72	36.63	34.27	32.42	49.21	39.75	36.69	34.75	33.23
	FB	43.56	38.40	35.09	32.67	30.78	43.59	38.33	35.01	32.58	30.69	53.71	39.91	36.32	34.41	32.98
	KH	44.54	41.46	38.80	36.65	34.89	46.53	42.08	38.93	36.56	34.72	47.43	40.04	37.12	35.11	33.51
	PW	40.63	37.14	34.41	32.19	30.43	42.47	37.80	34.65	32.25	30.40	54.21	40.52	36.54	34.31	32.84
	R	44.21	40.02	37.09	34.62	32.79	45.02	40.14	36.98	34.48	32.61	49.81	40.33	36.96	34.77	33.19
	SM	35.63	34.15	32.59	31.10	29.74	40.98	37.34	34.46	32.19	30.37	53.35	40.37	36.49	34.39	32.90
	W	40.25	36.03	32.95	30.59	28.72	41.10	36.06	32.78	30.37	28.49	61.14	40.48	36.12	33.84	32.46
Probability	ED	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.00
	FB	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.88	1.00	1.00	1.00	1.00
	KH	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
	PW	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.46	0.92	0.99	1.00	1.00
	R	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.89	0.99	1.00	1.00	1.00
	SM	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.99	1.00	1.00	1.00
	W	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.37	1.00	1.00	1.00	1.00
Bit-rate Ratio over All Slices	ED	104%	107%	109%	111%	112%	106%	109%	111%	113%	115%	104%	116%	124%	130%	135%
	FB	109%	114%	116%	119%	121%	110%	115%	117%	120%	123%	102%	118%	131%	141%	150%
	KH	102%	104%	104%	105%	106%	103%	104%	105%	106%	107%	104%	110%	114%	117%	119%
	PW	103%	104%	105%	106%	107%	103%	105%	106%	107%	108%	102%	107%	111%	114%	117%
	R	109%	113%	115%	117%	119%	110%	115%	117%	119%	121%	109%	126%	138%	146%	152%
	SM	102%	104%	105%	106%	107%	103%	105%	106%	107%	108%	101%	107%	112%	115%	118%
	W	101%	101%	101%	102%	102%	101%	101%	102%	102%	102%	100%	101%	102%	103%	104%
Bit-rate Ratio over I Slices	ED	128%	148%	158%	172%	182%	138%	160%	172%	187%	198%	125%	204%	261%	303%	332%
	FB	190%	237%	260%	287%	309%	196%	246%	272%	301%	325%	120%	278%	411%	509%	590%
	KH	131%	150%	160%	174%	183%	139%	160%	172%	187%	198%	158%	240%	296%	334%	363%
	PW	144%	170%	183%	199%	211%	155%	183%	198%	216%	230%	126%	208%	277%	329%	367%
	R	221%	276%	303%	333%	358%	233%	296%	327%	360%	388%	227%	453%	605%	714%	793%
	SM	122%	137%	144%	153%	160%	132%	149%	158%	168%	175%	111%	164%	207%	239%	263%
	W	142%	168%	181%	199%	212%	150%	178%	194%	214%	229%	102%	157%	220%	271%	310%

Table 2: Perceptibility test results. Probabilities of detection success in non-attacked sequences and bit-rate growth ratios in addition.

The third and the fourth row sets contain the bit-rate growth ratio in percent to the former bit-rate over either all slices or I slices only. Block method increases bit-rate less in comparison with coefficient method because when 0 is embedded, a half of transform coefficients are zeroed in block method while only one coefficient is zeroed in coefficient method. Anyway, bit-rate is increased the most when using noise method. This is mostly obvious in Renaissance because of many uniform areas which are represented by small amount of data in the former compressed video stream.

Each test iteration has been executed with five different copy IDs; values in the table are average values of corresponding five results.

Figure 15 and Figure 16 show the difference between the original picture and the watermarked one using noise method with weight factor of 20 for demonstration.

Figure 15: Original picture

Figure 16: Watermarked picture

Because of inter coded pictures may use watermarked pictures as reference pictures in inter prediction, distortion caused by watermark embedding propagates, as visible in Figure 17 and Figure 18. Therefore, the inter prediction compensation is to be implemented in future work.

Figure 17: Original inter coded picture

Figure 18: Distorted inter coded picture

In practice, weight factor of 2 is a good compromise between robustness and perceptibility.

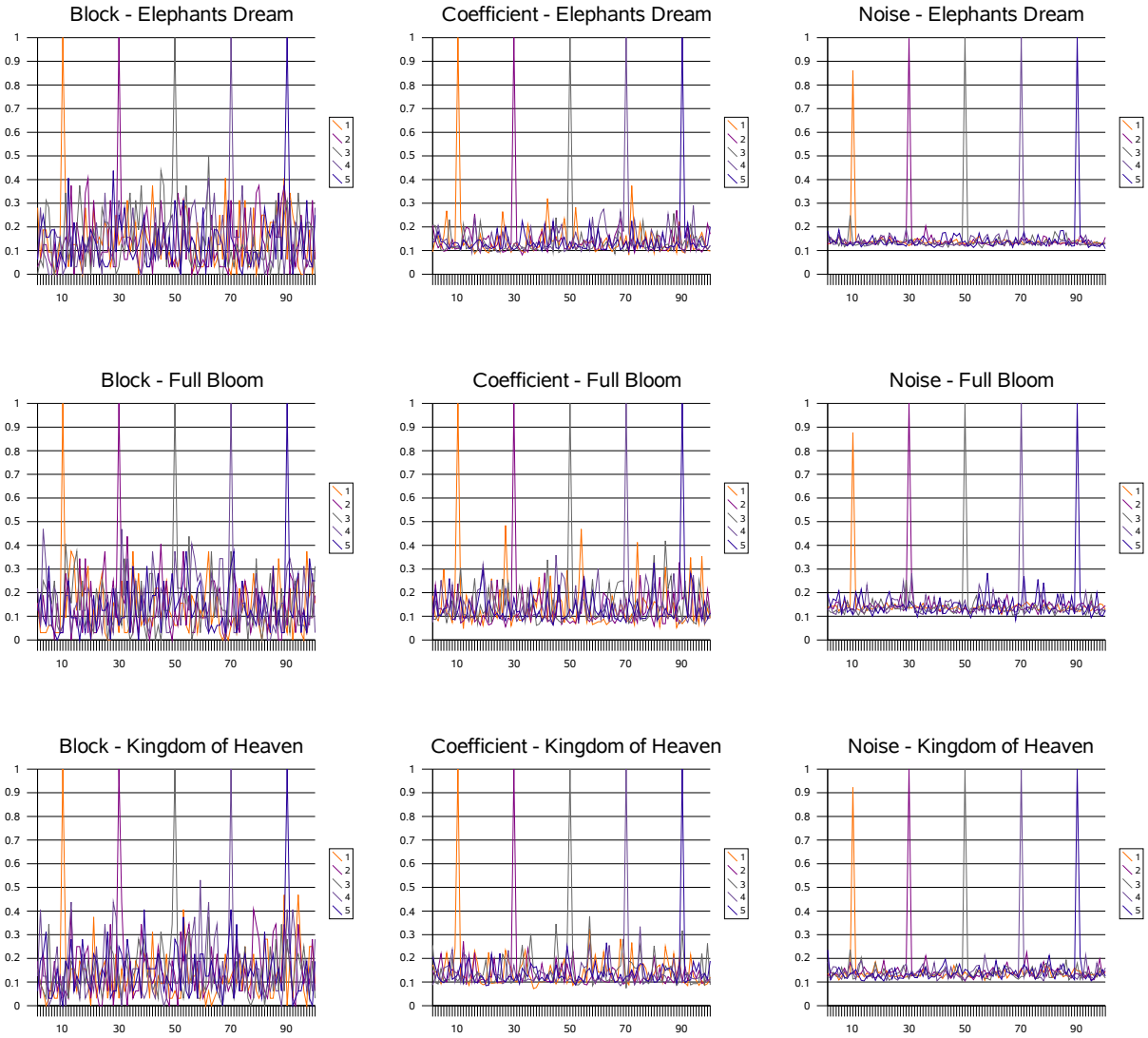
5.2 Uniqueness

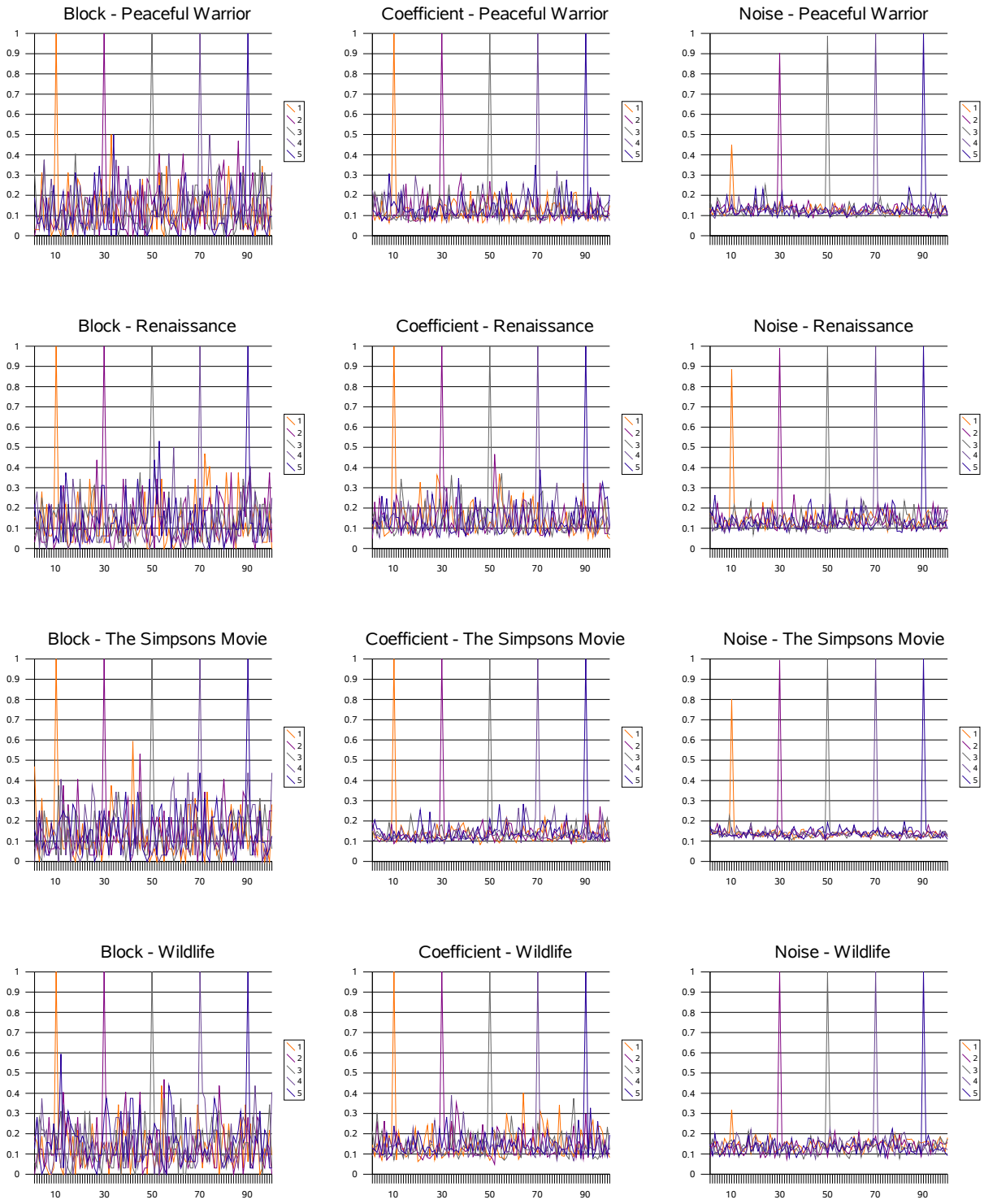
Uniqueness of the watermark means that the detector should return significantly higher probability in case of copy ID which has been embedded than in case of other copy IDs.

In each iteration, the test tries 100 different copy IDs including the correct one – it is 10 for weight factor of 1, 30 for weight factor of 2 etc.

The results are illustrated in the following charts. The horizontal axes represent the 100 different copy IDs and the vertical axes stand for the detector responses.

Although probabilities achieve lower values when using noise method with low weight factors, this method gives the highest distance of the correct copy ID probability from the other values and the narrowest spread of the other values.





Using block method, we cannot consider the detection to be successful if the detector returns value below 0.6. Using coefficient method, the threshold limit is 0.5, and it is below 0.4 in case of noise method. Note that the spread, thus the threshold limit as well, depends on particular video sequence.

5.3 Time Consumption

This section discusses time consumption of both the embedding and the detection pipelines. The time has been measured by standard Unix utility called `time`; the user-space time has been considered only. Average results of three iterations in Table 3 show that all the methods are basically equivalent in embedding but noise method is the worst in detection because of visual data decoding.

The test has been executed on a machine with the following configuration:

- Intel Pentium M (Centrino) processor, 1.60GHz, 3200 bogomips
- 512MB DDR PC2700 memory, 333MHz
- openSUSE 10.1 operating system

	Resolution	# I Frames	Embedding Time [s]			Detection Time [s]		
			Block	Coeff.	Noise	Block	Coeff.	Noise
ED	720×405	638	48.52	49.85	48.22	16.11	17.66	23.38
FB	1920×1080	102	43.77	44.45	44.08	14.83	16.43	25.44
KH	852×360	105	9.18	9.38	9.90	2.98	3.24	4.65
PW	320×136	67	2.03	2.07	2.09	0.35	0.37	0.53
R	848×480	71	6.25	6.38	6.78	2.03	2.25	3.59
SM	848×352	97	8.25	8.52	8.51	2.80	3.02	4.26
W	960×540	14	3.21	3.25	3.92	0.77	0.82	1.84

Table 3: Time consumption test results

The test has proved that the plugin is applicable in practice.

5.4 Robustness

Robustness test scripts simulate real attacks applied either intentionally or unintentionally to watermarked video sequences. In the simulations, they have been executed on pre-filtered watermarked sequences – the sequences have been remuxed in order to contain (besides parameter sets) intra coded slices only because the watermark is embedded into intra coded slices only.

Most of the tests proceeds as follows.

A watermarked pre-filtered sequence is converted using MPlayer to the raw video stream of single images, one image per frame. During the conversion, the video signal processing filter is applied eventually.

Then, the raw stream is compressed by x264 encoder producing H.264 video stream at the former bit-rate with intra coded slices only, and muxed to the Matroska container format.

The recompression at the former bit-rate obviously impairs the embedded watermark but the attacks are simulated more faithfully. The impairment rate of recompression is measured in Section 5.4.1.

Finally, the detection process takes place in such an attacked sequence. The

probabilities of watermark detection success given by the detector are summarized in tables in the following sections.

5.4.1 Recompression

This test uses MPlayer with no filter applied. Recompression is applied at four different bit-rates – at the former bit-rate (100%) and at 75%, 50% and 25% of the former bit-rate. The results are summarized in Table 4 where the bit-rate ratios are listed in column named BR.

		Block					Coefficient					Noise				
	BR	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.79	0.98	1.00	1.00	1.00
	75%	0.99	0.99	1.00	1.00	1.00	0.98	0.99	1.00	1.00	1.00	0.67	0.97	1.00	1.00	1.00
	50%	0.92	0.95	0.96	0.96	0.97	0.84	0.96	0.98	0.97	0.98	0.44	0.91	0.98	1.00	1.00
	25%	0.71	0.73	0.77	0.76	0.78	0.37	0.56	0.76	0.81	0.83	0.22	0.60	0.80	0.89	0.94
FB	100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.75	1.00	1.00	1.00	1.00
	75%	0.98	0.98	0.97	0.94	0.92	1.00	1.00	1.00	0.99	0.99	0.67	1.00	1.00	1.00	1.00
	50%	0.92	0.94	0.91	0.91	0.87	1.00	0.99	0.99	0.97	0.98	0.51	1.00	1.00	1.00	1.00
	25%	0.42	0.75	0.77	0.74	0.72	0.28	0.88	0.88	0.88	0.84	0.28	0.93	0.99	1.00	0.99
KH	100%	0.99	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	0.84	1.00	1.00	1.00	1.00
	75%	0.95	0.97	0.97	0.99	1.00	0.91	0.95	0.97	0.98	1.00	0.71	0.99	1.00	1.00	1.00
	50%	0.90	0.89	0.91	0.91	0.93	0.78	0.87	0.90	0.90	0.91	0.50	0.91	0.98	1.00	1.00
	25%	0.70	0.70	0.71	0.71	0.72	0.38	0.50	0.62	0.68	0.72	0.30	0.67	0.79	0.87	0.91
PW	100%	0.86	0.98	0.99	1.00	1.00	0.83	0.96	0.99	0.99	1.00	0.31	0.77	0.89	0.96	0.99
	75%	0.68	0.79	0.90	0.91	0.97	0.62	0.77	0.87	0.91	0.95	0.13	0.52	0.74	0.87	0.93
	50%	0.50	0.59	0.67	0.68	0.70	0.33	0.55	0.66	0.68	0.71	0.09	0.26	0.49	0.61	0.72
	25%	0.23	0.24	0.27	0.31	0.36	0.08	0.12	0.24	0.28	0.33	0.10	0.12	0.19	0.26	0.33
R	100%	0.80	0.79	0.81	0.82	0.85	0.75	0.76	0.80	0.78	0.79	0.46	0.88	0.96	0.98	1.00
	75%	0.71	0.69	0.70	0.71	0.72	0.63	0.62	0.66	0.66	0.69	0.30	0.69	0.86	0.94	0.96
	50%	0.55	0.59	0.59	0.60	0.59	0.44	0.49	0.50	0.53	0.53	0.22	0.51	0.64	0.71	0.78
	25%	0.27	0.25	0.23	0.23	0.24	0.10	0.13	0.15	0.19	0.19	0.11	0.20	0.30	0.39	0.48
SM	100%	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.44	0.88	0.99	1.00	1.00
	75%	1.00	1.00	1.00	1.00	1.00	0.98	0.99	1.00	1.00	1.00	0.24	0.69	0.94	0.98	1.00
	50%	0.98	0.99	0.98	0.98	0.98	0.93	0.96	0.98	0.98	0.98	0.18	0.53	0.80	0.90	0.95
	25%	0.93	0.92	0.93	0.94	0.93	0.63	0.65	0.73	0.76	0.81	0.15	0.29	0.49	0.63	0.72
W	100%	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.23	0.95	1.00	1.00	1.00
	75%	0.85	1.00	1.00	0.99	1.00	0.86	1.00	1.00	1.00	1.00	0.15	0.87	0.99	0.98	1.00
	50%	0.78	0.77	0.83	0.95	1.00	0.62	0.70	0.92	0.98	1.00	0.17	0.70	0.90	0.96	0.97
	25%	0.45	0.33	0.35	0.37	0.46	0.22	0.31	0.33	0.40	0.48	0.09	0.49	0.75	0.87	0.92

Table 4: Recompression test results

All three methods are robust at similar level. Watermarks from all video sequences have been successfully detected after recompression at up to 50% of the former bit-rate; from some sequences even after recompression at 25% of the former bit-rate. Only the recompression of Wildlife using noise method with weight factor of 1 can be considered to be a successful attack. The watermark is impaired the most in Renaissance because of the greatest bit-rate growth during watermark embedding.

Note that the watermark quite resists to recompression at the former bit-rate, thus the results of the other tests using recompression are distorted only a bit.

5.4.2 Scaling

The scaling test scales down the watermarked video sequences to the specified resolution using MPlayer bicubic "scale" filter. The resolution is given by scaling factor (column in Table 5 named SF) which determines how much the images of the output raw stream are scaled down – e.g. scaling factor of 1/4 means that the image area size is reduced 4-times, i.e. both width and height are halved.

The raw stream is compressed at the scaling factor fragment of the former bit-rate, i.e. for example scaling factor of 1/4 means 1/4 of the former bit-rate.

Then, the compressed stream is scaled up back to the former resolution and recompressed at the former bit-rate because the synchronization of the pure watermark with the tested video sequence in the detection process is out of scope of this thesis. Moreover, the human operator which would convert the sequence to the former stadium is better than any artificial intelligence automaton.

		Block					Coefficient					Noise				
	SF	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	1/2	0.34	0.64	0.90	0.97	0.99	0.15	0.30	0.59	0.78	0.88	0.28	0.81	0.96	0.99	1.00
	1/3	0.19	0.23	0.39	0.59	0.76	0.12	0.14	0.17	0.24	0.34	0.21	0.62	0.87	0.96	0.99
	1/4	0.15	0.15	0.17	0.23	0.34	0.12	0.13	0.13	0.15	0.17	0.18	0.49	0.73	0.87	0.95
	1/5	0.14	0.14	0.14	0.16	0.17	0.12	0.13	0.14	0.13	0.13	0.16	0.42	0.62	0.78	0.88
FB	1/2	0.44	0.98	1.00	1.00	1.00	0.27	0.80	0.97	1.00	1.00	0.33	0.98	1.00	1.00	1.00
	1/3	0.21	0.52	0.92	0.99	1.00	0.13	0.24	0.59	0.82	0.93	0.27	0.90	0.99	1.00	1.00
	1/4	0.14	0.13	0.15	0.18	0.20	0.11	0.13	0.15	0.14	0.14	0.24	0.82	0.97	1.00	1.00
	1/5	0.13	0.16	0.21	0.31	0.45	0.12	0.13	0.14	0.18	0.22	0.21	0.74	0.93	0.98	1.00
KH	1/2	0.42	0.65	0.82	0.90	0.94	0.15	0.30	0.46	0.63	0.75	0.39	0.85	0.98	1.00	1.00
	1/3	0.22	0.35	0.49	0.59	0.70	0.12	0.16	0.18	0.26	0.31	0.32	0.71	0.88	0.96	0.99
	1/4	0.15	0.15	0.16	0.17	0.17	0.13	0.13	0.12	0.13	0.12	0.28	0.59	0.77	0.88	0.94
	1/5	0.16	0.15	0.17	0.19	0.22	0.12	0.12	0.13	0.14	0.14	0.26	0.55	0.71	0.81	0.88
PW	1/2	0.13	0.21	0.41	0.60	0.71	0.08	0.09	0.15	0.23	0.31	0.12	0.26	0.41	0.58	0.70
	1/3	0.08	0.11	0.14	0.17	0.26	0.08	0.09	0.09	0.09	0.10	0.12	0.19	0.30	0.42	0.51
	1/4	0.11	0.10	0.09	0.09	0.11	0.08	0.10	0.08	0.09	0.09	0.12	0.15	0.23	0.31	0.34
	1/5	0.08	0.10	0.10	0.10	0.10	0.08	0.09	0.08	0.09	0.09	0.11	0.17	0.22	0.27	0.30
R	1/2	0.20	0.41	0.51	0.65	0.69	0.11	0.23	0.33	0.43	0.50	0.29	0.56	0.70	0.79	0.86
	1/3	0.13	0.19	0.30	0.41	0.48	0.10	0.10	0.14	0.20	0.24	0.21	0.42	0.57	0.66	0.72
	1/4	0.09	0.09	0.09	0.09	0.12	0.10	0.08	0.09	0.09	0.07	0.14	0.28	0.39	0.49	0.56
	1/5	0.08	0.11	0.10	0.10	0.14	0.10	0.08	0.09	0.11	0.09	0.16	0.24	0.35	0.46	0.53
SM	1/2	0.33	0.49	0.70	0.83	0.92	0.15	0.21	0.32	0.47	0.61	0.19	0.44	0.67	0.82	0.92
	1/3	0.19	0.24	0.31	0.42	0.52	0.12	0.13	0.17	0.19	0.21	0.17	0.36	0.55	0.69	0.80
	1/4	0.14	0.14	0.14	0.15	0.16	0.13	0.13	0.13	0.13	0.13	0.17	0.33	0.47	0.59	0.69
	1/5	0.13	0.16	0.16	0.18	0.20	0.12	0.13	0.12	0.12	0.13	0.17	0.30	0.42	0.53	0.64
W	1/2	0.55	0.69	0.83	0.92	0.97	0.21	0.38	0.49	0.58	0.75	0.15	0.60	0.79	0.92	0.95
	1/3	0.15	0.37	0.52	0.62	0.72	0.10	0.25	0.27	0.33	0.37	0.11	0.52	0.70	0.83	0.90
	1/4	0.16	0.15	0.16	0.25	0.19	0.15	0.13	0.09	0.16	0.13	0.13	0.48	0.68	0.82	0.82
	1/5	0.19	0.17	0.21	0.20	0.26	0.12	0.13	0.16	0.12	0.19	0.10	0.46	0.59	0.69	0.80

Table 5: Scaling test results

Looking at the results, we can say that noise method is more robust than the other two methods, especially for lower scaling factors. Anyway, the higher resolution the sequence has the less impaired the watermark is.

5.4.3 Cropping

In the cropping test, the tested video sequences are cropped to the resolution given by the cropping factor (column in Table 6 named CF) which is the same as scaling factor in the scaling test.

The cropped raw stream is compressed at the cropping factor fragment of the former bit-rate as well as in the scaling test.

The compressed stream is black boxed to the former resolution using MPlayer "expand" filter, and recompressed at the former bit-rate. The expansion is applied because of the same synchronization reason as in the scaling test.

High resistance to this attack could be expected because the hidden information bits are duplicated and randomly spread over whole frames. Thus, even a small part of the frames should be enough for successful detection. Anyway, the redundancy falls down with decreasing resolution, therefore the detection success falls down too.

		Block					Coefficient					Noise				
	CF	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	1/2	0.88	1.00	1.00	1.00	1.00	0.77	0.98	1.00	1.00	1.00	0.18	0.34	0.47	0.45	0.43
	1/3	0.73	0.95	0.97	0.98	0.98	0.57	0.89	0.94	0.96	0.96	0.35	0.88	0.96	0.98	0.99
	1/4	0.64	0.91	0.95	0.97	0.97	0.50	0.83	0.90	0.93	0.94	0.28	0.81	0.94	0.98	0.99
	1/5	0.52	0.84	0.90	0.93	0.95	0.45	0.80	0.88	0.92	0.93	0.23	0.29	0.33	0.33	0.37
FB	1/2	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.34	0.82	0.88	0.88	0.84
	1/3	0.98	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.40	0.98	1.00	1.00	1.00
	1/4	0.96	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	0.40	0.97	1.00	1.00	1.00
	1/5	0.76	0.99	1.00	1.00	1.00	0.75	1.00	1.00	1.00	1.00	0.21	0.73	0.68	0.67	0.68
KH	1/2	0.79	0.97	1.00	1.00	1.00	0.68	0.94	0.99	1.00	1.00	0.17	0.27	0.31	0.37	0.37
	1/3	0.87	0.98	0.98	1.00	1.00	0.66	0.93	0.96	0.98	0.98	0.60	0.94	0.99	1.00	1.00
	1/4	0.39	0.83	0.92	0.94	0.96	0.36	0.81	0.90	0.93	0.95	0.21	0.35	0.42	0.41	0.43
	1/5	0.26	0.62	0.76	0.84	0.87	0.21	0.56	0.76	0.83	0.87	0.18	0.29	0.33	0.36	0.37
PW	1/2	0.33	0.69	0.79	0.85	0.88	0.21	0.46	0.56	0.60	0.63	0.13	0.13	0.13	0.14	0.14
	1/3	0.32	0.69	0.80	0.84	0.87	0.21	0.55	0.68	0.70	0.70	0.10	0.12	0.12	0.16	0.17
	1/4	0.17	0.45	0.58	0.63	0.65	0.11	0.29	0.40	0.45	0.46	0.11	0.24	0.38	0.49	0.54
	1/5	0.14	0.32	0.42	0.48	0.49	0.12	0.26	0.31	0.35	0.35	0.19	0.31	0.44	0.51	0.57
R	1/2	0.53	0.76	0.88	0.93	0.95	0.44	0.67	0.80	0.89	0.92	0.36	0.59	0.78	0.90	0.94
	1/3	0.36	0.62	0.72	0.86	0.91	0.32	0.59	0.70	0.81	0.87	0.12	0.17	0.19	0.24	0.23
	1/4	0.51	0.62	0.69	0.68	0.72	0.36	0.53	0.62	0.62	0.64	0.38	0.61	0.75	0.86	0.92
	1/5	0.29	0.58	0.65	0.76	0.81	0.28	0.58	0.67	0.75	0.82	0.16	0.23	0.30	0.34	0.40
SM	1/2	0.95	0.99	1.00	1.00	1.00	0.55	0.93	1.00	1.00	1.00	0.23	0.51	0.77	0.92	0.98
	1/3	0.26	0.58	0.81	0.92	0.95	0.25	0.58	0.79	0.90	0.95	0.13	0.18	0.20	0.20	0.25
	1/4	0.70	0.93	0.99	1.00	1.00	0.36	0.81	0.93	0.95	0.94	0.18	0.40	0.62	0.76	0.88
	1/5	0.22	0.58	0.75	0.83	0.89	0.21	0.58	0.79	0.87	0.89	0.12	0.16	0.20	0.26	0.29
W	1/2	0.48	0.92	1.00	1.00	1.00	0.41	0.89	0.96	0.99	1.00	0.10	0.27	0.36	0.38	0.44
	1/3	0.49	0.66	0.84	0.89	0.97	0.40	0.65	0.81	0.91	0.97	0.15	0.36	0.49	0.55	0.63
	1/4	0.49	0.90	0.99	1.00	1.00	0.45	0.83	0.96	0.98	0.98	0.14	0.27	0.38	0.48	0.50
	1/5	0.45	0.90	0.98	1.00	1.00	0.47	0.87	1.00	1.00	1.00	0.16	0.23	0.31	0.37	0.42

Table 6: Cropping test results

The test has finished as expected. The inconsistencies in monotonicity of the results when changing the cropping factor may be caused by non-uniform spreading of the content ID bits. Noise method is the least robust one.

5.4.4 Denoising

Denoising is an attack especially against noise watermarking method. It consists in removing noise from the video sequence which could cause noise watermark removal. MPlayer high quality denoise 3D filter ("hqdn3d") is used with "spatial luma strength" set to 16 and other parameters set to 0.

The test results are summarized in Table 7.

	Block					Coefficient					Noise				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	0.84	0.91	0.92	0.92	0.97	0.91	0.96	0.97	0.98	0.99	0.26	0.85	0.98	1.00	1.00
FB	0.95	0.97	0.97	0.99	0.99	0.97	0.98	1.00	1.00	1.00	0.30	1.00	1.00	1.00	1.00
KH	0.77	0.87	0.90	0.92	0.93	0.85	0.91	0.93	0.94	0.95	0.38	0.89	0.97	0.99	1.00
PW	0.51	0.66	0.73	0.76	0.80	0.59	0.72	0.75	0.77	0.80	0.11	0.30	0.61	0.80	0.91
R	0.57	0.62	0.65	0.72	0.78	0.61	0.66	0.70	0.75	0.77	0.21	0.70	0.89	0.98	0.99
SM	0.89	0.95	0.97	0.99	1.00	0.91	0.98	0.99	1.00	1.00	0.12	0.57	0.89	0.98	1.00
W	0.93	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.17	0.76	1.00	1.00	1.00

Table 7: Denoising test results

Despite the expectations, all the methods have gone well.

5.4.5 Noising

Noising is the opposite process to denoising, namely adding noise to the video sequence. MPlayer "noise" filter is used with parameters equal to "10t:0", i.e. only luma samples are affected by Gaussian noise changing in time with amplitude of 10.

No significant influence is expected in case of noise method because another noise does not interfere with the noise watermark. Lesser influence is expected in case of coefficient method because the method alters only one coefficient per macroblock. The coefficient is hardly impaired by noise due to quantization. The quantization effect is expected when using block method as well.

	Block					Coefficient					Noise				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.73	0.99	1.00	1.00	1.00
FB	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.61	1.00	1.00	1.00	1.00
KH	0.84	0.97	0.98	0.98	0.98	0.98	1.00	1.00	1.00	1.00	0.84	1.00	1.00	1.00	1.00
PW	0.74	0.96	0.98	0.98	0.98	0.90	1.00	1.00	1.00	1.00	0.31	0.81	0.95	0.98	0.99
R	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.67	0.95	1.00	1.00	1.00
SM	0.98	0.99	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.41	0.97	1.00	1.00	1.00
W	0.95	0.96	0.97	0.97	0.96	0.98	1.00	1.00	1.00	1.00	0.16	0.97	1.00	1.00	1.00

Table 8: Noising test results

The results in Table 8 are as expected. Moreover, the probability grows up in case of noise method with weight factor of 2 in comparison with results of the recompression at the former bit-rate test.

5.4.6 Blurring

Blurring can be considered as a kind of denoise filter. MPlayer “unsharp” filter is used affecting only luma samples. Three differently sized convolution blur masks are applied (column in Table 9 named BM): 3×3, 5×5 and 7×7.

Because this filter is simpler than the denoise filter and blurs macroblocks into each other, higher impairment is expected.

		Block					Coefficient					Noise				
	BM	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	3×3	0.75	0.99	1.00	1.00	1.00	0.74	0.99	1.00	1.00	1.00	0.67	0.96	1.00	1.00	1.00
	5×5	0.30	0.51	0.81	0.95	0.99	0.20	0.54	0.86	0.97	1.00	0.61	0.94	0.99	1.00	1.00
	7×7	0.18	0.20	0.29	0.45	0.64	0.13	0.17	0.31	0.52	0.74	0.56	0.91	0.98	0.99	1.00
FB	3×3	0.83	1.00	1.00	1.00	1.00	0.80	1.00	1.00	1.00	1.00	0.62	1.00	1.00	1.00	1.00
	5×5	0.26	0.62	0.94	1.00	1.00	0.23	0.61	0.95	1.00	1.00	0.57	1.00	1.00	1.00	1.00
	7×7	0.16	0.21	0.32	0.48	0.70	0.12	0.18	0.31	0.53	0.79	0.54	1.00	1.00	1.00	1.00
KH	3×3	0.71	0.93	0.98	1.00	1.00	0.60	0.91	0.98	1.00	1.00	0.74	0.99	1.00	1.00	1.00
	5×5	0.30	0.47	0.70	0.85	0.92	0.19	0.44	0.70	0.86	0.93	0.68	0.98	1.00	1.00	1.00
	7×7	0.18	0.20	0.29	0.39	0.50	0.12	0.17	0.26	0.40	0.55	0.63	0.97	0.99	1.00	1.00
PW	3×3	0.25	0.66	0.92	0.97	0.98	0.18	0.66	0.93	0.98	0.99	0.22	0.61	0.80	0.89	0.93
	5×5	0.13	0.14	0.29	0.50	0.69	0.07	0.13	0.30	0.53	0.73	0.20	0.54	0.76	0.84	0.88
	7×7	0.08	0.08	0.09	0.12	0.16	0.06	0.05	0.08	0.10	0.19	0.20	0.52	0.70	0.80	0.84
R	3×3	0.52	0.77	0.93	0.97	0.98	0.44	0.74	0.92	0.97	0.99	0.58	0.91	0.98	1.00	1.00
	5×5	0.19	0.38	0.55	0.70	0.78	0.12	0.35	0.51	0.67	0.78	0.59	0.87	0.99	1.00	1.00
	7×7	0.11	0.15	0.21	0.34	0.41	0.07	0.12	0.20	0.33	0.43	0.58	0.85	0.97	1.00	1.00
SM	3×3	0.73	0.94	1.00	1.00	1.00	0.60	0.94	1.00	1.00	1.00	0.39	0.92	1.00	1.00	1.00
	5×5	0.33	0.46	0.67	0.84	0.95	0.21	0.41	0.69	0.87	0.97	0.36	0.90	0.99	1.00	1.00
	7×7	0.19	0.19	0.23	0.34	0.44	0.12	0.19	0.27	0.41	0.55	0.33	0.87	0.98	1.00	1.00
W	3×3	0.85	0.97	1.00	1.00	1.00	0.67	0.94	1.00	1.00	1.00	0.21	0.88	0.99	1.00	1.00
	5×5	0.31	0.52	0.72	0.90	0.97	0.23	0.49	0.65	0.79	0.97	0.13	0.85	0.97	1.00	1.00
	7×7	0.20	0.27	0.33	0.47	0.57	0.13	0.16	0.33	0.40	0.55	0.14	0.81	0.97	1.00	1.00

Table 9: Blurring test results

It is interesting that block and coefficient methods are more vulnerable than the noise method. This is the most perceptible when using 7×7 mask.

It is probably caused by higher liability of the transform coefficients to blurring into each other than of the noise pattern to smoothing. Namely, the local extremes in the noise pattern, which are important in the detection process, remain extremes even if the pattern undergoes smoothing.

5.4.7 Sharpening

Sharpening is a kind of high-pass filter mentioned in Section 4.3.1, thus high probabilities are expected in case of noise method. The test uses MPlayer "unsharp" filter with opposite coefficient than in the blurring test. Again, three convolution sharpening masks are applied (see column in Table 10 named SM).

		Block					Coefficient					Noise				
	SM	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	3×3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	0.98	1.00	1.00	1.00
	5×5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	0.98	1.00	1.00	1.00
	7×7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	0.98	1.00	1.00	1.00
FB	3×3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.82	1.00	1.00	1.00	1.00
	5×5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.82	1.00	1.00	1.00	1.00
	7×7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00	1.00	1.00	1.00
KH	3×3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
	5×5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
	7×7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
PW	3×3	0.96	1.00	1.00	1.00	1.00	0.94	0.99	1.00	1.00	1.00	0.36	0.87	0.94	0.98	1.00
	5×5	0.94	0.99	1.00	1.00	1.00	0.93	0.99	1.00	1.00	1.00	0.36	0.87	0.93	0.97	1.00
	7×7	0.94	0.99	1.00	1.00	1.00	0.92	0.98	1.00	1.00	1.00	0.38	0.86	0.93	0.97	1.00
R	3×3	0.82	0.85	0.85	0.86	0.89	0.81	0.84	0.84	0.84	0.85	0.58	0.94	0.98	0.99	1.00
	5×5	0.83	0.86	0.84	0.87	0.90	0.79	0.83	0.82	0.82	0.83	0.56	0.94	0.98	1.00	1.00
	7×7	0.83	0.84	0.84	0.86	0.88	0.78	0.81	0.82	0.81	0.82	0.51	0.95	0.98	1.00	1.00
SM	3×3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	0.96	1.00	1.00	1.00
	5×5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.60	0.96	1.00	1.00	1.00
	7×7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.59	0.96	1.00	1.00	1.00
W	3×3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.26	0.98	1.00	1.00	1.00
	5×5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.22	0.97	1.00	1.00	1.00
	7×7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.26	0.98	1.00	1.00	1.00

Table 10: Sharpening test results

The sharpening filter works pretty well not only when using noise method but also when using both block and coefficient methods. The test results show that it does not matter which size of the convolution mask is used.

5.4.8 Multiple Watermark Embedding

Multiple watermark embedding test measures influence of watermarking already watermarked video sequences. Five watermarks generated from five different copy IDs have been subsequently embedded. Sequence numbers of the copy IDs used in the detection process are listed in Table 11 in column named C#.

In case of block method, the test proves overwriting of previously embedded watermarks, as supposed in Section 4.3.2.

Coefficient method chooses one of 8 coefficients for watermark element embedding. Therefore, the overwriting is expected when embedding more than 8 watermarks. This hypothesis has been proved by an additional test with 20 watermarks.

No impairment is expected in case of noise method because different noise patterns are statistically independent.

		Block					Coefficient					Noise				
	C#	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	1	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00	1.00
	2	0.28	0.28	0.28	0.28	0.28	1.00	1.00	1.00	1.00	1.00	0.86	1.00	1.00	1.00	1.00
	3	0.13	0.13	0.13	0.13	0.13	1.00	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00	1.00
	4	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.86	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.00
FB	1	0.13	0.13	0.13	0.13	0.13	1.00	1.00	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.00
	2	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.86	1.00	1.00	1.00	1.00
	3	0.25	0.25	0.25	0.25	0.25	1.00	1.00	1.00	1.00	1.00	0.87	1.00	1.00	1.00	1.00
	4	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.89	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.88	1.00	1.00	1.00	1.00
KH	1	0.22	0.22	0.22	0.22	0.22	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
	2	0.22	0.22	0.22	0.22	0.22	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
	3	0.22	0.22	0.22	0.22	0.22	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
	4	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00
PW	1	0.16	0.16	0.16	0.16	0.16	1.00	1.00	1.00	1.00	1.00	0.41	0.90	0.99	1.00	1.00
	2	0.09	0.09	0.09	0.09	0.09	1.00	1.00	1.00	1.00	1.00	0.45	0.91	0.99	1.00	1.00
	3	0.06	0.06	0.06	0.06	0.06	1.00	1.00	1.00	1.00	1.00	0.43	0.91	0.99	1.00	1.00
	4	0.06	0.06	0.06	0.06	0.06	1.00	1.00	1.00	1.00	1.00	0.49	0.91	0.99	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.42	0.92	0.99	1.00	1.00
R	1	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.87	0.99	1.00	1.00	1.00
	2	0.22	0.22	0.22	0.22	0.22	1.00	1.00	1.00	1.00	1.00	0.88	0.99	1.00	1.00	1.00
	3	0.28	0.28	0.28	0.28	0.28	1.00	1.00	1.00	1.00	1.00	0.87	0.98	1.00	1.00	1.00
	4	0.03	0.03	0.03	0.03	0.03	1.00	1.00	1.00	1.00	1.00	0.88	0.99	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.88	0.99	1.00	1.00	1.00
SM	1	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.76	0.99	1.00	1.00	1.00
	2	0.19	0.19	0.19	0.19	0.19	1.00	1.00	1.00	1.00	1.00	0.78	0.99	1.00	1.00	1.00
	3	0.06	0.06	0.06	0.06	0.06	1.00	1.00	1.00	1.00	1.00	0.77	0.99	1.00	1.00	1.00
	4	0.06	0.06	0.06	0.06	0.06	1.00	1.00	1.00	1.00	1.00	0.78	0.99	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.76	0.99	1.00	1.00	1.00
W	1	0.19	0.19	0.19	0.19	0.19	1.00	1.00	1.00	1.00	1.00	0.39	1.00	1.00	1.00	1.00
	2	0.22	0.22	0.22	0.22	0.22	1.00	1.00	1.00	1.00	1.00	0.38	1.00	1.00	1.00	1.00
	3	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	0.34	1.00	1.00	1.00	1.00
	4	0.09	0.09	0.09	0.09	0.09	1.00	1.00	1.00	1.00	1.00	0.36	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.34	1.00	1.00	1.00	1.00

Table 11: Multiple watermark embedding test results

5.4.9 Collusion

The collusion attack consists in combining several differently watermarked copies to destroy the watermark.

The attack is simulated in the plugin itself during the embedding process. There are two types of collusion attacks, thus two modes of the simulation has been implemented:

Collusion by averaging

This mode is based on averaging of corresponding pixel color samples of participating copies. In case of block and coefficient methods, it may cause appearance of non-zero coefficients where they have not been and vice versa resulting in invalid detection of watermark element values. In case of noise method, the attack causes averaging of the noise patterns. Lesser impairment is expected in this case because the average pattern contains all the single patterns which are statistically independent.

The simulation takes place in the embedding process. Required number of watermarks is generated. The same number of differently watermarked versions is created when watermarking single macroblocks. Then, the average macroblocks are estimated.

The results in Table 12 are average values of probabilities given by the detector from the corresponding number of copies. The numbers of copies are listed in column named #C.

		Block					Coefficient					Noise				
	#C	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.99	1.00	1.00	1.00
	5	0.98	1.00	1.00	1.00	1.00	0.97	1.00	1.00	1.00	1.00	0.55	0.96	1.00	1.00	1.00
	10	0.62	0.86	0.84	0.84	0.81	0.27	0.98	1.00	1.00	1.00	0.29	0.87	0.97	0.99	1.00
FB	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.82	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.30	1.00	1.00	1.00	1.00
	10	0.77	1.00	1.00	1.00	1.00	0.85	1.00	1.00	1.00	1.00	0.17	0.96	1.00	1.00	1.00
KH	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00
	5	0.99	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	1.00	0.78	0.99	1.00	1.00	1.00
	10	0.65	0.89	0.88	0.87	0.84	0.24	0.99	1.00	1.00	1.00	0.58	0.93	0.99	1.00	1.00
PW	3	0.94	0.99	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.40	0.83	0.94	0.98	0.99
	5	0.60	0.83	0.82	0.76	0.76	0.67	1.00	1.00	1.00	1.00	0.31	0.68	0.89	0.95	0.97
	10	0.21	0.42	0.39	0.41	0.39	0.12	0.72	0.80	0.98	0.98	0.22	0.48	0.71	0.84	0.88
R	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.85	0.98	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.96	0.99	1.00	1.00
	10	0.51	0.94	0.91	0.93	0.92	0.42	1.00	1.00	1.00	1.00	0.55	0.90	0.97	0.99	1.00
SM	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	0.99	1.00	1.00	1.00
	5	0.97	1.00	1.00	1.00	1.00	0.96	1.00	1.00	1.00	1.00	0.33	0.95	1.00	1.00	1.00
	10	0.52	0.85	0.83	0.84	0.82	0.20	0.98	1.00	1.00	1.00	0.20	0.84	0.97	0.99	1.00
W	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.32	1.00	1.00	1.00	1.00
	5	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.14	0.91	1.00	1.00	1.00
	10	0.66	0.96	0.94	0.94	0.93	0.30	1.00	1.00	1.00	1.00	0.14	0.59	0.95	1.00	1.00

Table 12: Collusion by averaging test results

Despite the expectations, all the methods have gone pretty well.

Collusion by swapping macroblocks

Swapping macroblocks consists in picking out macroblocks from participating copies producing one video sequence with differently watermarked macroblocks. When obtaining hidden information bit from swapped macroblocks, the pure watermark block does not correlate with the detected watermark block and the hidden information bit value is not determined at all (the correlation sum is 0) in the ideal case. In practice, the bit values oscillate uniformly around zero, thus eliminate each other in the correlation sum. Only the rest of the right macroblocks remains. Thereby, similar results to the cropping test (number of copies should correspond to the cropping factor) are expected.

The simulation takes place in the embedding process as well. Required number of watermarks is generated and swapped producing a single watermark. This watermark is then embedded in an usual way.

The results are summarized in Table 13.

		Block					Coefficient					Noise				
	#C	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
ED	3	1.00	1.00	1.00	1.00	1.00	0.92	0.91	0.91	0.90	0.90	0.65	0.92	0.96	0.97	0.97
	5	0.87	0.87	0.87	0.87	0.87	0.67	0.67	0.66	0.66	0.65	0.47	0.72	0.77	0.78	0.78
	10	0.51	0.51	0.51	0.51	0.51	0.40	0.39	0.39	0.38	0.38	0.27	0.43	0.47	0.48	0.48
FB	3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.70	1.00	1.00	1.00	1.00
	5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.59	1.00	1.00	1.00	1.00
	10	0.96	0.96	0.96	0.96	0.96	0.87	0.87	0.86	0.86	0.85	0.41	0.87	0.89	0.89	0.89
KH	3	0.99	0.99	0.99	0.99	0.99	0.85	0.84	0.84	0.83	0.83	0.76	0.93	0.95	0.95	0.96
	5	0.90	0.90	0.90	0.90	0.90	0.69	0.68	0.68	0.67	0.66	0.56	0.74	0.78	0.79	0.79
	10	0.47	0.47	0.47	0.47	0.47	0.33	0.34	0.33	0.32	0.32	0.35	0.44	0.46	0.47	0.47
PW	3	0.72	0.72	0.72	0.72	0.72	0.51	0.51	0.51	0.51	0.51	0.24	0.43	0.50	0.52	0.51
	5	0.48	0.48	0.48	0.48	0.48	0.31	0.32	0.32	0.31	0.31	0.19	0.30	0.35	0.37	0.38
	10	0.30	0.30	0.30	0.30	0.30	0.17	0.18	0.18	0.18	0.18	0.16	0.20	0.23	0.23	0.23
R	3	1.00	1.00	1.00	1.00	1.00	0.97	0.97	0.97	0.96	0.96	0.77	0.93	0.96	0.97	0.98
	5	0.93	0.93	0.93	0.93	0.93	0.77	0.77	0.77	0.77	0.77	0.61	0.75	0.79	0.82	0.84
	10	0.62	0.62	0.62	0.62	0.62	0.44	0.44	0.44	0.44	0.44	0.38	0.46	0.49	0.50	0.49
SM	3	1.00	1.00	1.00	1.00	1.00	0.89	0.89	0.89	0.88	0.88	0.50	0.86	0.94	0.96	0.96
	5	0.91	0.91	0.91	0.91	0.91	0.64	0.64	0.64	0.64	0.63	0.37	0.64	0.72	0.75	0.76
	10	0.62	0.62	0.62	0.62	0.62	0.32	0.32	0.32	0.32	0.32	0.22	0.37	0.42	0.44	0.45
W	3	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.99	0.98	0.98	0.23	0.95	1.00	1.00	1.00
	5	0.89	0.89	0.89	0.89	0.89	0.77	0.76	0.76	0.75	0.74	0.17	0.77	0.86	0.89	0.90
	10	0.72	0.72	0.72	0.72	0.72	0.51	0.50	0.49	0.48	0.46	0.16	0.46	0.54	0.55	0.57

Table 13: Collusion by swapping macroblocks test results

Comparing the results with cropping test results, the cropping attack is more successful. Nevertheless, the results are quite similar including the fact that noise method is the least robust one if lower number of the copies participate in the attack.

Chapter 6

Conclusion

Watermarking is a copy protection system that allows tracking back illegally produced copies of the protected multimedia content. Compared with other copy protection systems like Digital Rights Management, the main advantage of watermarking is that the watermark is embedded permanently in visual data of the content but at the cost of slight loss in fidelity.

In this thesis, three different watermarking methods have been designed and implemented. Block and coefficient methods belong to watermarking techniques in frequency domain while pseudo-random noise method represents watermarking in spatial domain. Frequency domain techniques modify the coefficients obtained by the application of some frequency transform to visual data of the content. Spatial domain techniques apply the watermark directly to visual data of the content.

A generic watermarking framework has been designed and implemented as a plugin for an existing open source multimedia streaming library. The framework provides the interface for easy implementation of particular watermarking methods in both frequency and spatial domain.

The watermark embedding process is performed on a compressed video stream. The H.264 video coding standard has been chosen as the particular video compression technique. The standard uses a kind of the frequency transform mentioned above, thus frequency domain watermarking is implemented using coefficients of the compressed stream. The spatial domain watermark is transformed to frequency domain using the transform before embedding.

The watermarking methods have been compared with each other in terms of their perceptibility and robustness. The methods have been exposed to several simulation tests checking up their resistance to various types of attacks.

All the methods are more or less resistant to simple attacks such as

recompression and noising, and to some removal attacks such as denoising and collusion by averaging.

Noise method is the most resistant method to scaling. The watermark is successfully detected even if the video is scaled down up to 1/5 of the former resolution. Using any of the frequency domain methods, the watermark is destroyed when scaling down the video to 1/3 of the former resolution.

On the other hand, noise method is the most vulnerable method to cropping. The frequency domain methods withstand cropping the video up to 1/5 of the former resolution while the watermark may be severely impaired by cropping the video to 1/4 of the former resolution in case of noise method.

Concerning blurring, the noise method watermark is robust using any size of the convolution blur mask. In case of both block and coefficient methods, blurring with the 7×7 mask may destroy the watermark but the video quality is severely degraded as well.

Sharpening even increases the watermark detection success probability in all the methods.

When using the frequency domain methods, the multiple watermark embedding test has shown that limited number of transform coefficients enables overwriting of previously embedded watermarks. Thereby, an attacker may completely destroy the former watermark.

On the other hand, the frequency domain methods are more resistant to collusion by swapping macroblocks. Anyway, the watermark may be destroyed with sufficient number of copies participating in the collusion attack.

Although noise method is more vulnerable to cropping, it is equally or more resistant to the other attacks than the frequency domain methods. Moreover, there is only few visual data left in the video cropped to 1/4 of the former resolution.

Further, the noise method watermark is the least perceptible one in comparison with the other method watermarks.

Unfortunately, there is a trade-off between benefits and much more bit-rate growth when using noise method. Noise method increases the video bit-rate up to two times more than the other methods, using reasonable weight factors. The ratio grows up with increasing weight factor values.

With respect to the reasons above, noise watermarking method is recommended despite the bit-rate growth. Further, weight factor of 2 is recommended as a good compromise between robustness and perceptibility.

For practical use, several improvements should be made.

Firstly, the embedding process should be optimized to preserve the former bit-rate of the video sequences.

In order to increase robustness against direct removal attack, the watermark should be embedded into textured areas only. Textured areas provide more non-zero coefficients in the residual than uniform areas do, thus the watermark may be hidden more safely. Moreover, less distortion would be produced.

Therefore, an adaptive embedding algorithm which would adjust the weight factor per macroblock according to its complexity and spatial characteristics should be implemented.

Furthermore, the distortion in inter predicted slices caused by prediction from watermarked intra slices should be compensated. Among others, complete inter prediction has to be implemented in order to accomplish this task.

As soon as the inter prediction error compensation is implemented, there is only a small step left to implementation of the embedding process into inter coded slices as well.

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Appendix A

Enclosed CD & Installation

The source codes of the H.264 codec and of the watermarking plugin as well as the third party software are provided on the enclosed CD. In particular, the CD contains the following data:

`detect`	Unix shell script that contains the detection GStreamer pipeline
`doxydoc/`	programming documentation in the HTML format generated by Doxygen from the source code of the plugin
`embed`	Unix shell script that contains the embedding GStreamer pipeline
`gst-plugin`	source code of the watermarking plugin
`h264`	source code of the partial H.264 codec
`installs/`	source codes of GStreamer, MPlayer and x264
`params`	additional Unix shell script used by the other scripts to parse given command-line parameters
`prepare`	Unix shell script that remuxes a video sequence in order to contain intra coded slices only; the script is used by test scripts
`tests/`	Unix shell scripts that contain the simulation tests
`thesis/`	sources of the thesis
`thesis.pdf`	the thesis in Acrobat PDF format
`thesis.ps`	the thesis in PostScript format
`video/`	testing video sequences where the licence permits copying

All programs and libraries, provided in source code, may be installed on Unix platforms in the following way. Copy the source code or the tarball to some location where you have writing rights, and change the working directory to that location. If the program is compressed as a tarball, type the following command to obtain the source code:

```
tar xjvf <tarball.tar.bz2>
```

All the programs use the standard Unix build system, thus type subsequently in the directories containing the programs:

```
./autogen.sh      (in case there is no configure script)
./configure
make
make install
```

Some of the programs may require newer versions of libraries you have installed. The `configure` script should detect this and report a message. In such a case, please update the reported library.

Nevertheless, install the programs in the following order:

- GStreamer (tarball `gstreamer-0.10.11.tar.bz2`)
- GStreamer Base Plugins (tarball `gst-plugins-base-0.10.11.tar.bz2`)
- GStreamer Good Plugins (tarball `gst-plugins-good-0.10.5.tar.bz2`)
- the H.264 codec
- the watermarking plugin

And if you intend to execute the test scripts, install in addition:

- MPlayer (tarball `MPlayer-1.0rc1.tar.bz2`)
- x264 encoder (tarball `x264-645.tar.bz2`)

Appendix B

The plugin usage

The watermarking plugin can be used as an element queued in a GStreamer pipeline. The construction of the pipelines is described in the documentation on the project's website [12]. The name of the plugin is `h264watermark`.

The plugin behaviour is controlled by several parameters. The list of the parameters follows:

`mode` specifies the working mode of the plugin. Three values may be assigned: `prepare` (everything except parameter set NAL units and intra coded slices is dropped), `embed` (activates the embedding process) and `detect` (activates the detection process).

`method` selects the watermarking method: `block`, `coeff` (stands for coefficient) and `noise`.

`weight` sets the weight factor.

`content-id` stands for the identifier of the video content.

`copy-id` is the identifier of the content copy.

It is possible to obtain the parameter list by using one of GStreamer utilities as well – type:

```
gst-inspect h264watermark
```

There are three scripts, containing complete GStreamer pipelines, provided on the enclosed CD – `embed`, `detect` and `prepare` – using the plugin in the corresponding mode. The required arguments are listed if the scripts are executed without any arguments. The first two arguments stand for the input and the output files. Only Matroska muxed video sequences are accepted. The other arguments represent the plugin parameters.

Appendix C

Programming Documentation

There is the programming documentation, generated from the source code of the plugin, on the enclosed CD but lacks description of adding another watermarking method.

In order to add a new watermarking method into the watermarking framework, several actions have to be taken:

- The identifier of the method has to be inserted into the list of available methods. The list, named `WatermarkMethod`, is located in file `watermark.h`.
- The name and the description of the method have to be inserted into the list of possible values of the plugin's parameter `method`. The list is located in file `gsth264watermark.c` and its name is `mode_types`.
- Both embedding and detection functions have to be implemented. The file that contains the functions should be listed in file `Makefile.am` and the header file with the function declarations should be included in file `watermark.c`.

  The embedding and the detection functions have to be specified as the second and the third item in the defining structure in the list of defining structures. The list, named `methods`, is located in file `watermark.c`. The first item of the structure is the type of watermarking domain that the method uses; it is either `WATERMARK_DOMAIN_FREQUENCY` or `WATERMARK_DOMAIN_SPATIAL`.

Both the embedding and the detection functions in frequency domain have the same arguments in the following order:

`watermark` is pointer to the framework context.

`coefficients` is pointer to the list of transform coefficients of one block. The list contains zig-zag scan of the coefficients in case of frame macroblocks, or field scan in case of field macroblocks.

`length` is the length of the list of coefficients.

`CurrMbAddr` is address of the macroblock that contains the block. The address is the index of the macroblock in macroblock raster scan.

`y` is row index of the top-left pixel of the block within the picture.

`x` is column index of the top-left pixel of the block within the picture.

The embedding function in spatial domain has the same arguments but there are `residual` and `dimension` arguments instead of `coefficients` and `length`:

`residual` is 2-dimensional array of residual values of one block.

`dimension` is dimension of the block.

Finally, there is a `picture` argument instead of `residual` in case of the detection function in spatial domain. The `picture` argument stands for a block of luma samples located at the position specified by `x` and `y`.

In case the embedding function in spatial domain requires luma samples of the block besides the residual, the whole picture is available in item `picture_original` in the framework context.