Digital Watermark Detection in Visual Multimedia Content

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Abstract

Digital watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in visual multimedia content such as images or video. Watermark detection is an integral component of a watermarking system.

This cumulative thesis addresses watermark detection problems in important application domains such as scalable multimedia, raw/demosaicked digital camera images, and 2D vector graphics with a distortion constraint. Generally, we rely on spread-spectrum watermark embedding and aim to improve performance of the system on the receiving side by taking into account peculiarities of the embedding domain and host signal modelling.

A watermarked, scalable multimedia bitstream can be decoded in several quality and resolution layers to meet the demand of different devices. The watermark should be detectable in each layer, with increased detection performance in higher layers, yet without impairing the coding efficiency. We investigate watermarking of scalable JPEG2000, H.264/SVC and MZ-EZBC bit streams.

A system for watermarking the raw image sensor data is constrained by the processing resources of the camera. We implement a spatial-domain embedding in camera firmware and propose a watermark detector exploiting the structure of the interpolated, demosaicked image.

The computational effort for blind, spread-spectrum watermark detection is analyzed including the determination of the detection threshold and accuracy versus runtime trade-offs for the parameter estimation of the host signal model. We propose two novel detectors with runtime efficiency in mind that show competitive detection performance with state-of-the-art blind watermarking detection approaches. A novel watermark detector based on a joint statistical model for color images is proposed.

Further, we investigate watermarking in the dual-tree complex wavelet domain and study the security of several quantization-based watermarking schemes.

Digitale Wasserzeichen wurden als eine technische Lösung zum Schutz von Urheberrechten vorgeschlagen. Dabei wird ein nicht wahrnehmbares, jedoch detektierbares Signal in visuelle

Multimedia-Inhalte wie digitale Bilder oder Videos eingebettet (Watermarking). Der Nachweis des Wasserzeichens ist eine integraler Komponente eines solchen Systems.

Diese kumulative Dissertation widmet sich mehreren Problemen der Detektion von Wasserzeichen in wichtigen Anwendungsfeldern wie der skalierbaren Multimedia-Kodierung, der Erkennung von Wasserzeichen in den unverarbeiteten und verarbeiteten Sensordaten von Digitalkameras, sowie dem Einbetten und der Erkennung von Wasserzeichen in 2D Vektor-Grafiken unter Erhalt von geometrischen Eigenschaften. Dabei wird generell von einfachen Bandspreizverfahren (Spread Spectrum) für die Einbettung ausgegangen. Ziel ist es, die Detektion des Wasserzeichens auf der Empfängerseite durch Modellierung des Trägersignals sowie durch Ausnutzung der spezifischen Eigenschaften der Multimediadaten zu verbessern.

Ein mit einem Wasserzeichen versehener, skalierbar kodierter Datenstrom kann einfach auf verschiedene Arten dekodiert werden, um die Anforderungen von unterschiedlichen Darstellunggeräten bezüglich Qualität und Auflösung zu erfüllen. Das Wasserzeichen soll dabei in jeder gewählten Repräsentation nachweisbar sein, ohne die Kodiereffizienz zu beeinträchtigen. Wir untersuchen Watermarking von skalierbaren JPEG2000, H.264/SVC und MZ-EZBC Datenströmen.

Ein System zum Einbetten eines Wasserzeichens in die Sensordaten einer Digitalkamera ist durch die Verarbeitungsgeschwindigkeit der Kamera eingeschränkt. Wir entwickeln ein Einbettungsverfahren als Firmware-Erweiterung einer Digitalkamera und stellen ein Methode zur Erkennung des Wasserzeichens vor, die die spezielle Struktur der verarbeiteten Sensordaten (Interpolation, Demosaicking) ausnutzt.

Wir untersuchen den Rechenaufwand für die Erkennung von Spread-Spectrum Wasserzeichen ohne Bezugnahme auf die Ausgangsdaten. Dabei wird neben der Bestimmung des Schwellwertes für die Erkennung auch auf das Schätzverfahren zur Gewinnung der Modellparameter des Trägersignals eingegangen; von besonderem Interesse ist der Kompromiss zwischen der Genauigkeit der Modellparameter und der erzielten Laufzeit. Ausgehend von Effizienzüberlegungen stellen wir zwei neue Detektoren für Wasserzeichen vor, die mit dem derzeitigen Stand der Technik vergleichbare Detektionsergebnisse erzielen, aber einfacher zu implementieren sind.

Weitere Ergebnisse umfassen einen neuartigen Detektor basierend auf einem multivariaten Modell für Farbbilder, ein Verfahren zur Einbettung von Wasserzeichen unter Verwendung der Dual-Tree Complex Wavelet-Transformation, sowie eine Angriffsstudie auf eine Reihe von bekannten Wasserzeichen-Verfahren, die mittels Koeffizienten-Quantisierung einbetten.

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Contents

Chapter 1

Introduction and Overview

Digital watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in digital multimedia content such as images or video [46, 6, 199]. The embedded signal can be used to identify the legitimate owner holding the copyright of the content.

Many other related application scenarios are also conceivable, but are not thoroughly treated in this work. For example, a watermark signal associated with an authorized user can be embedded and used to track a particular copy of the content, i.e. fingerprinting or traitor tracing applications [109, 88]. Further, watermarking allows detection of malicious tampering of a document and makes it possible to establish the authenticity of the content [87], even if the multimedia data is, for instance, subjected to lossy compression. Data hiding and annotation watermarking [49] enable mobile and electronic commerce applications as the embedded watermark signal can be used to bridge the gap between physical and digital media. The key element distinguishing digital watermarking from other multimedia security techniques such as forensics [156, 33], biometrics, steganography [56], perceptual hashing [78] or cryptographic hashing and encryption is that the content itself is purposefully altered to encode additional information about the multimedia content.

With the growing availability of the Internet as a distribution platform for multimedia data, technical means for the protection of intellectual property rights of digital commodities are perceived as a requirement to perpetuate the established business models of the non-digital era. Digital watermarking technology has been heavily researched during the late 1990s and early 2000s. So far, however, the technology has not found widespread adoption[1]. It remains to be seen if technical immaturity or legal obstacles encumber the deployment.

In this work, we pick up on a number of watermark detection problems which have not been thoroughly addressed but seem of great practical interest.

This thesis is presented in cumulative form. After a brief outline of the topics in the following

[1] . . . as far as one can see :-)

sections, we reprint the corresponding papers as published in Chapter 2 and provide discussion and concluding remarks in Chapter 3.

Section 1.1 discusses watermarking of scalable multimedia formats such as the JPEG2000 standard for images and H.264/SVC for video content. Section 1.2 focuses on efficient, blind watermark detection with regard to the computation of the host signal parameter model, the detection statistic itself and determination of the detection threshold. In Sections 1.4 and 1.5 watermark detection in the Dual-Tree Complex Wavelet Domain (DT-CWT) and watermark detection with a multivariate model of an color image is discussed. Section 1.3 explores watermark detection in raw and demosaicked images captured by a digital camera. Watermark detection in 2D vector graphics data under a distortion constraint is treated in Section 1.6. Attack results on a number of quantization-based watermarking schemes are described in Section 1.7.

1.1 Watermark Detection in Scalable Multimedia Formats

Distribution of multimedia content has become ubiquitous and targets small, low-power mobile to high fidelity digital television devices. Scalable multimedia formats such as the JPEG2000 standard [75, 176] for images and H.264/SVC [74, 164, 165, 161] for video content have been proposed to enable the formation of a single bit stream containing the same content in multiple spatial resolutions, quality levels and – for video – temporal resolutions. A scalable bit stream can be efficiently adapted to meet the display resolution and transmission bandwidth capabilities of a wide range of presentation devices, without re-encoding the content. Scalable multimedia formats pose new challenges for watermarking [107] that need to be addressed to achieve full protection of the scalable content while maintaining low bitrate overhead due to watermarking. Challenges that complicate watermark detection include the very different statistics of the transform domain coefficients of scalable base- and enhancement layers, the combination of multi-channel detection results for incremental detection performance [153], as well as the prediction of data between scalability layers which complicates the modelling of the embedding domain.

For video coding, the H.264 standard [74] has been amended in 2007 with Annex G which addresses resolution, temporal and quality scalability by adding a small number of new coding tools to the bitstream syntax. The previous MPEG video coding standards inherently support temporal scalability due to the P-/B-frame prediction structure and quality scalability via coarse-grain scalability (CGS) layers; MPEG-4 adds fine-grain scalability (FGS) [72, 102]. Scalability, however, came at a significant reduction in coding efficiency and increased coding complexity compared to non-scalable coding. H.264/SVC employs inter-layer prediction and can perform within 10% bit rate overhead for a two-layer resolution scalable bitstream compared to coding a single layer with H.264 [164]. Although H.264/SVC is specified for up to 7 CGS quality- or resolution enhancement layer, the coding complexity increases with each layer and constrains the number of scalability options that can be provided due to the 'closed-loop' encoder design [143].

A different approach to video coding is based on motion-compensated temporal filtering (MC-TF) in combination with wavelet-based subband coding ('open-loop' design) and promises superior coding and scalability performance [143].

Despite intense research in the area of image and video watermarking, the peculiarities of watermarked scalable multimedia content have received limited attention and a number of challenges remain [107]. One limited point of view is to simply consider scalable compression as a robustness attack on watermarking. In [122], we identify, refine and categorize several aspects in protecting scalable video content and review related work.

As a starting point, we propose a frame-by-frame watermarking scheme as a vehicle for robustness experiments with scalable video coding [122]. Separate watermarks are embedded in the Discrete Wavelet Transform (DWT) approximation and detail subband coefficients using different embedding strategies, Spread-Transform Scalar Costa Scheme (ST-SCS) and additive spread-spectrum, respectively, due to the different host signal statistics. The quantization-based ST-SCS rejects the host interference; high-pass filtering is applied before correlation of the spread-spectrum signal in the DWT detail subbands. The design goal is to provide individual protection for the lowest resolution layer and the incremental resolution layers inherent to the pyramidal DWT. A shortcoming is that the detection results cannot be easily combined.

The watermarked video is coded with H.264/SVC with two resolution layers (QCIF and CIF, 176×144 and 352×288 pixels, respectively, with YCbCr $4:2:0$ color coding) and a group-of-picture (GOP) size of 16, and MC-EZBC [66] with 4 decomposition levels. The resulting scalable bit streams are adapted for different bit rates, resolutions and frame rates. Blind watermark detection is performed on the decoded video. Several important observations can be made based on the experimental results:

- Scalable video coding broadens the range of unintentional, non-malicious attacks on the embedded watermark. Downsampling in the spatial and temporal domain becomes part of the multimedia encoding, although implemented differently depending on the codec.
- The temporal motion-compensated filtering of the MC-EZBC codec acts as a temporal frame-averaging attack [144] when adapting the bitstream for a lower frame rate.
- Although using different watermark embedding methods and two video coding paradigms, the watermark proofed to be robust and was detectable in all cases to some extent.

The experiments triggered further research in signal detection and modelling of the host signal as the coefficient statistics are drastically different for low-pass approximation or detail subbands. In order to incorporate the two requirements for scalable watermark detection pointed out by Piper et al. [153], namely (i) detection in the base layer, and (ii) incremental improvement of detection performance as more content data becomes available, it is necessary to somehow combine the detection results obtained for each layer. The experimental setup is very time consuming as the estimation of the detection statistic parameters requires many detection experiments for which in turn the multimedia content has to be re-encoded each time. These issues are addressed in the next section: we propose the Rao-Cauchy watermark detector [91] which (i) employs the Cauchy distribution to model subband coefficients and thus benefits from fast (approximate) model parameter estimation [181], (ii) allows to combine detection results from hierarchical subbands in a straightforward way, (iii) facilitates the experimental step being a constant false-alarm rate (CFAR) detector, (iv) is efficient to implement [94, 96].

In [120], we turn to the problem of watermark embedding and detection in a motion-compensated temporally filtered (MC-TF) host video signal [144, 145]. Adjacent video frames are typically highly correlated along the temporal axis [173, 172] which can be exploited for inter-frame collusion attacks [51] or watermark estimation and remodulation attacks [187] to remove a per-frame watermark. As a countermeasure, the embedded watermark should exhibit correlation similar to the host signal frames [173, 52]. Our contribution [120] is a blind detection scheme for a MC-TF domain watermark and the assessment of its robustness with regard to H.264 and MC-EZBC compression attacks, blind motion estimation, and temporal filtering attacks.

For image coding, JPEG2000 [75, 176] addresses scalability by relying on a pyramidal wavelet transformation and embedded, rate-distortion optimal coding [175]. The previous JPEG standard [76, 147] provides only limited support for sequential and progressive quality scalability (Annex F and G, respectively) and resolution scalability (Annex J) which is rarely implemented. Piper et al. [152] evaluate the robustness of different coefficient selection methods with regards to quality and resolution scalability in the context of the basic non-blind spread-spectrum watermarking approach proposed by Cox et al. [44]. Later they also consider combined scalability and argue that by exploiting human visual system (HVS) characteristics in the transform domain coefficient selection for watermark embedding, the goal can be achieved. However, only non-blind watermarking schemes are addressed and consequently the host signal interference can be completely cancelled in the detection process. In [121], we propose two watermarking schemes with blind detection. An additive spread-spectrum watermark is embedded in multiple, diverse host signal components obtained by Discrete Cosine Transform (DCT) and DWT. The individual channels are modelled by Generalized Gaussian Distributions (GGD) and detection results from different channels are combined in order to enable increasingly reliable detection – one of the set requirements for scalable watermarking [153].

Two-layer resolution- and quality adaptation of the scalable JPEG2000 bit stream as well as JPEG compression and scaling are considered in the performance evaluation. The experimental results lead to the following statements:

- DCT as well as DWT embedding fulfill the properties of scalable watermarking, thus the embedding domain does not necessarily have to match the of transform used by the codec. DCT embedding does not require a multi-resolution decomposition of the host content, but fails to protect the base resolution layer after JPEG coding.
- The DWT-based watermarking scheme fails to gain in detection reliability when making the second resolution enhancement layer available.
- The proposed multi-channel host signal modelling and detection approach permits experimental investigation of blind, scalable watermark detection.

Noorkami et al. [140, 141] propose a framework for robust watermarking of H.264 encoded video. In [125, 126] we extend the framework with the aim to provide a single scalable, watermarked H.264/SVC bit stream where the watermark is detectable in the compressed domain and the decoded video without reference to the original content. We show that watermarking the only base layer within the framework of Noorkami et al. can not reliably protect a resolution-scalable H.264/SVC encoded video. Further, watermarking the base and enhancement layer separately with independent watermarks severely increases the bit rate of the coded video. The reason is a new coding tool introduced with H.264/SVC which adaptively enables inter-layer intra prediction using the upsampled reconstructed reference signal of intra-coded macroblocks.

To mitigate these issues, we propose to upsample the base layer watermark information to the resolution enhancement layer and embed the upsampled watermark signal in the higher resolution layer. This strategy has two advantages: (i) it reduces the enhancement layer residual signal that must be encoded which translates into a bit rate saving of the watermarked resolution scalable bitstream, (ii) enables reliable watermark detection in both, the decoded low and full resolution video.

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1.2 Efficient Watermark Detection

For blind watermarking, i.e. when detection is performed without reference to the unwatermarked host signal, the host interferes with the watermark signal. Several strategies have been devised for host noise suppression [43, 160, 32, 55, 116]. In the case of (additive) spread-spectrum watermark embedding and correlation detection, detection performance benefits from an accurate model of the host signal [79].

If Gaussian noise is assumed, it is well known that the optimal detector is the straightforward linear correlation (LC) detector [79]. For watermarking embedding often DCT or DWT domain coefficients are employed in order to facilitate shaping of the embedding power according to human perception constraints and to permit selection of significant signal components [46]. DCT and DWT coefficient of natural images do not obey a Gaussian law in general [16].

Different statistical models for transform domain coefficients of images and video have been proposed which determine the watermark detection statistic; among them are the GGD and Cauchy distribution model for DCT and DWT domain coefficients [16, 1, 63, 138, 36, 18], and the Weibull and Rayleigh distribution model for Discrete Fourier Transform magnitudes [168].

The correlated components of color image can be modelled by multivariate distributions, such as multivariate Gaussian [7] or Multivariate Power Exponential (MPE) distribution [60]. The trade-off between detection performance and host model complexity in terms of computational effort (e.g. for model parameter estimation) is certainly an important aspect for efficient watermark detection.

In [91], we derive a Rao test for additive spread-spectrum watermark detection under the assumption that the host signal can be modelled by a Cauchy distribution. A Rao test for watermark detection was first proposed by Nikolaidis et. al [138] for DWT domain coefficients modelled by a GGD. For large data records, the Rao hypothesis test is asymptotically equivalent to the Likelihood Ratio Test (LRT) [79]. The Cauchy host signal model has been proposed by Briassouli et. al [18] for the DCT domain coefficients and earlier by Sayrol et al. [162] for high-pass filtered spatial domain color image data. In video coding, the Cauchy distribution has been applied to model quantized DCT coefficients [1]. Using Quantile-Quantile (QQ) plots, we demonstrate that the Cauchy distribution is a reasonable model for DWT detail subband coefficients.

The Rao-Cauchy watermark detector has a number of advantages over previous approaches, including:

- Knowledge of watermark embedding strength is not required to compute the detection statistic.
- The detection threshold can be stated without estimation of the detection statistic parameters under the null hypothesis ($\mathcal{H}_0$), i.e the detector is a CFAR detector [79]. This greatly simplifies the experimental setup for detection performance evaluation and reduces the computational effort to make the detection decision compared to the detectors based on a LRT.
- Fast, approximate methods are available for the estimation of the Cauchy host signal parameter [181].
- The detection statistic computation is more efficient in terms of runtime and number of arithmetic operations.
- Detection performance has been found competitive with the LRT-GGD, LRT-Cauchy and Rao-GGD detector and superior to the simpler LC detection, also considering JPEG and JPEG2000 compression attacks.

The computational detection effort and the host signal model parameter estimation process is further investigated in [94]. Hernandez et al. [63] first suggested to use a fixed parameter setting for the GGD shape parameter and assessed the impact on watermark detection performance, avoiding the computationally cumbersome Maximum Likelihood Estimation (MLE) procedure [186, 50]. Also approximate methods for computing an estimate of the GGD parameters can be employed, e.g. the method of moments [115], fast moment matching [85], or convex maximum likelihood estimation [170]. For the Cauchy distribution, we can resort to estimation based on sample quantiles [84] with runtime complexity improvements [202], lower-order moments [137] or fast estimation procedures for the more general alpha-stable model [181].

In [96] and [97], we extend the experimental assessment of our previous work by comparing the watermark detection performance obtained using the ML estimate, approximate estimates and fixed settings for the GGD and Cauchy host signal model on the 1338 image of the UCID database [163]. We find that MLE performs only sightly better than approximative estimation. Choosing fixed parameter settings also yields competitive detection results. Separate runtime measurements for model parameter estimation, computation of the detection statistic and threshold determination of the five different detectors investigated (LC, LRT-GGD [63], LRT-Cauchy [18], Rao-GGD [138], Rao-Cauchy [91]) complete the analysis.

In [128], we pick up the idea of a simplistic distribution model for quantized transform coefficients recently proposed by Pi et al. [151, 40] for DWT subband characterization in texture retrieval applications. The joint probability distribution of the absolute, quantized coefficients can be written as a product of Bernoulli distributions (PBD). The model parameters can be determined by simply counting the number of 1 bits in each bit plane of the quantized transform coefficients. We derive a novel, blind watermark detector for additive, spread-spectrum watermarking based on a likelihood ratio test conditioned on the PBD and compare the detection performance against the LC and LRT-GGD detector. The detection statistic of the proposed LRT-PBD detector can essentially be implemented by counting occurrences of 1 bits in each bit plane. Nevertheless, experimental results on the UCID image database show that watermark detection performance of LRT-PBD is clearly superior compared to the LC detector and competitive with the LRT-GGD detector while runtime requirements are in between the LC and LRT-GGD detector. We consider two embedding scenarios, (i) adding the watermark to all host signal coefficients, and (ii) embedding in only non-zero coefficients. The later case is relevant for bit rate aware watermarking integrated in a image or video codec – and closely related to the watermarking framework described by Noorkami et al. [141] that we built upon in the previous section (cf. [125]). In this second embedding scenario, LRT-PBD achieves better detection performance than the considerable more complex LRT-GGD approach.

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1.3 Watermark Detection in Raw and Demosaicked Camera Images

Digital cameras are in ubiquitous use and most popular digital cameras employ a single, monochrome image sensor with a color filter array (CFA) on top. In order to provide a full-resolution RGB image, the sensor data has to be interpolated – a process called demosaicking – as well as color, gamma and white point corrected [159]. Many different demosaicking techniques exist, see [103, 10], yet the basic processing steps are shared by most camera implementations. While the JPEG image format is widely use to store the processed image data, most cameras also allow to store the unprocessed, raw sensor data which can be considered the most valuable image asset and the digital equivalent of the analog film negative. Surprisingly, watermarking is generally not integrated in the early stages of the image acquisition processes but added later-on e.g. during JPEG compression. Blythe et al. [17] discuss a secure digital camera which uses lossless watermarking to embed a biometric identifier of the photographer together with a cryptographic hash of the image data. Their embedding method efficiently changes the JPEG quantization tables and DCT coefficients but precludes watermarking of raw images. A CMOS image sensor with DCT domain watermarking and JPEG compression capabilities is presented by Shoshan et al. [166]. Very limited research has been published on watermark protection of the sensor data itself. It is not clear how the image processing pipeline and the demosaicking step in particular affect a watermark embedded in the sensor data [135]. We consider watermarking the raw CFA sensor data, detection after demosaicking, the processing steps of a digital camera and try to exploit the inherent interpolated structure of the image to improve detection performance.

In order to get access to the image processing pipeline of a consumer digital camera, we implement a watermarking add-on [124] for Canon IXUS cameras[2] based on the open-source CHDK extension firmware[3]. The injected firmware code is executed after image capture and can manipulate the raw, packed 10 bits per pixel CFA sensor data buffer before subsequent processing such as demosaicking and JPEG compression is performed. We implement additive, spread spectrum watermarking of one color component. Nelson et al. [135] propose a hardware-based solution and describe a CMOS imaging sensor with watermarking capabilities with essentially performs the same operation.

The camera has to upsample the CFA sensor data and interpolate the missing color information using a low-pass filter. Giannoula et al. [59] propose a watermark detection strategy for interpolated, noisy images which we apply to the detection problem at hand. The received demosaicked and likely JPEG compressed image is split into its polyphase components [183]. The components are used to compute estimates of the original host signal that can be *fused* into one signal are according to their estimated noise variance. Linear correlation watermark detection is then performed on the *fused* signal, obtaining better detection performance compared to detection using just one polyphase component or the downsampled image. Further, the impact of different demosaicking techniques (AHD [64], VNG [30], PPG [4]) on detection performance is assessed using synthetic CFA data. In [123, 129], we extend the results by considering watermarking of blue versus green CFA components and a component fusion technique which incor-

[2] Canon IXUS is the product name in Europe; the camera is called PowerShot ELPH or IXY in North America and Japan, respectively.

[3] Available at `http://chdk.wikia.com`.

[4] By Chuan-kai Lin, described at `http://web.cecs.pdx.edu/~cklin/demosaic/` and implemented in `dcraw`, `http://www.cybercom.net/~dcoffin/dcraw/`.

porates all color channels. In [123], extensive results on synthetic CFA data with demosaicking methods based on two intra- and twenty sequential inter channel interpolation techniques (fifteen in the spatial- and five in the frequency domain) are provided, confirming the detection performance improvements reported earlier.

In [127] we investigate a watermarking application where a content identifier and time-stamp information are embedded in individual video frames and decoded from a single frame captured from a display device using a mobile phone camera. This allows to remember ('bookmark') scenes in the video by means of decoding the embedded time-stamp and content id information. Since the watermark information is embedded in the visual data itself, the information is retained even when the content passes the digital-to-analog-to-digital conversion from screen to camera. Pramila et al. [157] survey the challenges in bridging the analog/digital gap using camera-based watermark extraction; Stach et al. [171] investigate the use of web cams for the same purpose and identify similar requirements. Data hiding and annotation watermarking is an enabling technology for electronic and mobile commerce applications [49] such as Related Service Introduction Systems (RSIS) [133]. Bookmarking of video content using a mobile phone's camera is a watermarking application outside the context of copyright protection and security.

The key challenge of the application is the inherent geometric distortion resulting from free-hand shooting and the comparatively low quality of the optics and image sensor employed for mobile phone cameras. Watermarking robust to complex geometric distortion has been studied in the context of digital cinema applications [99, 48, 113] with the aim to identify the content in so-called 'screener' copies. For correlation-based watermark detection, synchronization between the received signal and the watermark sequence is a precondition. A dedicated synchronization pattern (also called pilot or template watermark) [2] or an auto-correlation function [89, 99] can be used to estimate the geometric distortion and permit perspective correction.

Our approach builds up the Rao-Cauchy [91] watermark detector introduced in Section 1.2 in combination with implicit synchronization using the corner points of the watermarked target frame in the captured image and exhaustive search. Compared to previous approaches [133, 134], the proposed method [127] combines high temporal resolution (per-frame watermark detection) with considerable better image fidelity of the watermarked image.

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1.4 Watermark Detection in Dual-Tree Complex Wavelet Domain

Loo et al. [111] first proposed to use Kingsbury's dual-tree complex wavelet transform (DT-CWT) [82] for blind watermarking. The DT-CWT is a complex wavelet transform variant which is only four-times redundant in 2-D and offers approximate shift invariance together with the property of directional selectivity. Thus, it remedies two commonly-known shortcomings of the classic, maximally decimated DWT. For these reasons, the DT-CWT domain has become a very popular choice for watermark embedding recently [111, 67, 98, 195, 54, 189, 42, 114, 178, 205]. Accurate modelling of the host signal is crucial for the overall performance of a blind watermarking scheme.

In [92, 95], we argue that the concatenated real and imaginary parts of DT-CWT subband coefficients can be accurately modeled by a GGD. Based on this finding, we adopt the LRT [63] and Rao detector [138]

We experimentally compare the detection performance of the proposed schemes under JPEG and JPEG2000 attacks and assess the perceptual quality of DT-CWT embedding versus DWT embedding by relying on several objective image quality measures: wPSNR/PQS [130], Komparator [4], C4 [23], VSNR [28]. A subjective quality assessment experiment was performed [3] comparing DWT and DT-CWT embedding and the watermarked images were used in the development of a simplified perceptual metric for watermarking applications [24].

Publications

[92] R. Kwitt, P. Meerwald, and A. Uhl. Blind DT-CWT domain additive spread-spectrum watermark detection. In *Proceedings of the 16th International Conference on Digital Signal Processing (DSP '09)*, Santorini, Greece, July 2009

[95] R. Kwitt, P. Meerwald, and A. Uhl. Blind detection of additive spread-spectrum watermarking in the dual-tree complex wavelet domain. *International Journal of Digital Crime and Forensics*, 2(2):34–46, Apr. 2010

1.5 Watermark Detection in Color Images

Most of the watermarking research focuses on grayscale images. The extension to color image watermarking is usually accomplished by marking only the luminance channel or by processing each color channel separately [9]. Alternatively, the watermark can be embedded only in certain bands such as the blue channel since the human eye is less sensitive to this frequency range [162, 182]. Nevertheless, for best detection performance all color channels should contribute to the watermark signal. Expressing the joint statistical distribution of transform coefficients across correlated color channels for watermark detection is tedious and has so far been proposed for the Gaussian host signal case only [7, 136].

In [93], we propose to use a multivariate statistical model to accurately capture wavelet detail subband statistics and dependencies across RGB color channels and derive a LRT conditioned on the Multivariate Power-Exponential (MPE) distribution [60, 131] for additive spread-spectrum watermark detection in the DWT domain.

We observe that watermark detection performance is improved compared to watermarking the luminance channel only [63], decorrelating the color bands [9], or relying on a joint Gaussian host signal model [7]. More extensive results obtained comparing the proposed DWT domain LRT-MPE detector [93] with a DCT domain [7] and a DFT domain [8, 9] watermarking scheme on all images of the UCID color image database [163] can be found in [90].

Publication

[93] R. Kwitt, P. Meerwald, and A. Uhl. Color-image watermarking using multivariate power-exponential distribution. In *Proceedings of the IEEE International Conference on Image Processing (ICIP '09)*, pages 4245–4248, Cairo, Egypt, Nov. 2009

1.6 Watermark Detection in 2D Vector Graphics Data under Distortion Constraint

Watermarking research has primarily focused on raster data (audio and video content). However, increasingly more complex models of computer-aided design (CAD) or huge maps and infrastructure data stored in geographical information systems (GIS) also constitute valuable digital assets and make the protection of vector data more important. Watermarking of vector data has been proposed for 2D polygons and 3D meshes [12, 142, 26, 53, 38, 39]. Zheng et al. [204] provide an overview of the state-of-the-art in vector watermarking and Li et al. [101] as well as Lopez at al. [112] review technical and legal copyright issues with watermarking of geo-spatial datasets.

When embedding watermark information in a collection of geometric primitives not only perceptional constraints [155, 191] have to be met but also geometrical properties must be preserved. In [70], we propose a geometric distortion constraint framework which guarantees that no line segments cross due to vertex perturbation. For each vertex, the *Maximum Perturbation Region* (MPR) is efficiently computed with the help of Voronoi diagrams [62]. The MPR is conceptually similar to the Just Noticeable Difference (JND) constraint proposed for raster image data [155].

Depending on the watermarking application, the MPR constraint can be either enforced on all watermarked vertices outside their corresponding MPR by projecting the vertices on the MPR boundary, or on just those vertices which actually cause line segments to cross. We assess the impact of the MPR constraint on the watermark detection performance of a prominent 2D vector watermarking scheme proposed by Solachidis et al. [169, 53]. A spread-spectrum watermark is multiplicatively added to coefficient magnitudes in the complex DFT domain; watermark detection is performed using a linear correlation detector [169] and a LRT conditioned on the Rayleigh distribution of the complex-valued host signal [53].

Results indicate that the geometric distortion constraint can be efficiently applied on large vector data sets with little impact on the detection performance. We are working on extending the approach to 3D vector data by means of conforming Delaunay triangulations.

Publication

[70] S. Huber, R. Kwitt, P. Meerwald, M. Held, and A. Uhl. Watermarking of 2D vector graphics with distortion constraint. In *Proceedings of the IEEE International Conference on Multimedia & Expo (ICME '10)*, pages 480–485, Singapore, July 2010

1.7 Attack on Quantization-Based Watermarking Schemes

Quantization-based watermarking is an attractive choice as it combines high watermark capacity with robustness against manipulation of the cover data. The ability to embed many watermark bits (in the range of 256 to 1024 bits) allows to hide a small black-and-white logo image. However, in the copyright protection scenario, a watermarking method must not only withstand unintentional processing of the cover data but also intentional, targeted attack by a malicious adversary.

In [118], we describe an attack on the recently proposed 'Watermarking Method Based on Significant Difference of Wavelet Coefficient Quantization' [108]. While the method is shown to be robust against many signal processing operations, security of the watermarking scheme under intentional attack exploiting knowledge of the implementation (Kerckhoffs' principle [80]) has been neglected. We assume that we have access to only a single watermarked image but possess full knowledge of the implementation details of the watermarking scheme. According to the classification suggested by Cayre et. al [25], this constitutes a watermark-only-attack (WOA).

We demonstrate a straightforward attack by guessing the embedding location and perturbing the related subband coefficients. The attack retains the fidelity of the image. The method [108] is therefore not suitable for copyright protection applications. Further, we propose a countermeasure which mitigates the shortcoming.

Similar vulnerabilities can also be exploited in a number of other quantization-based watermarking schemes. In [119], we present targeted attacks on five other methods[86, 35, 190, 196, 179], one of which [179] taking into account a previous targeted attack demonstrated by Das and Maitra [47] on [190]. All discussed schemes violate Kalker's security principle [77] which states that 'security refers to the inability by unauthorized users to have access to the raw watermarking channel' and thus allow the attacker to concentrate the attack on a small set of coefficients or permits finely tuned attack vectors resulting in low overall attack energy.

Publications

[119] P. Meerwald, C. Koidl, and A. Uhl. Targeted attacks on quantization-based watermarking schemes. In *Proceedings of the 6th International Symposium on Image and Signal Processing and Analysis, ISPA '09*, pages 465–470, Salzburg, Austria, Sept. 2009

[118] P. Meerwald, C. Koidl, and A. Uhl. Attack on 'Watermarking Method Based on Significant Difference of Wavelet Coefficient Quantization'. *IEEE Transactions on Multimedia*, 11(5):1037–1041, Aug. 2009

Chapter 2

Publications

This online version of the thesis provides hypertext links to the publishers' web sites where available as well as links to local copies of the respective PDF documents where permitted. The submitted thesis contains reprints of the publications. [126] – and extended version of [125] – was accepted after submitting the thesis and is included only in the thesis's online version. The references have been updated to include the bibliographic data of publications that became available after thesis submission. Errata can be found in Appendix B.

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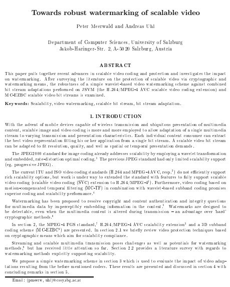
P. Meerwald, A. Uhl. Toward robust watermarking of scalable video. In *Proceedings of SPIE, Security, Forensics, Steganography, and Watermarking of Multimedia Contents X*, volume 6819, San Jose, CA, USA, Jan. 2008.



Towards robust watermarking of scalable video

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ABSTRACT

This paper pulls together recent advances in scalable video coding and protection and investigates the impact on watermarking. After surveying the literature on the protection of scalable video via cryptographic and watermarking means, the robustness of a simple wavelet-based video watermarking scheme against combined bit stream adaptations performed on JSVM (the H.264/MPEG-4 AVC scalable video coding extension) and MC-EZBC scalable video bit streams is examined.

Keywords: Scalability, video watermarking, scalable bit stream, bit stream adaptation.

1. INTRODUCTION

With the advent of mobile devices capable of wireless transmission and ubiquitous presentation of multimedia content, scalable image and video coding is more and more employed to allow adaptation of a single multimedia stream to varying transmission and presentation characteristics. Each individual content consumer can extract the best video representation fitting his or her application from a single bit stream. A scalable video bit stream can be adapted to fit resolution, quality, and well as spatial or temporal presentation demands.

The JPEG2000 standard for image coding already addresses scalability by employing a wavelet transformation and embedded, rate-distortion optimal coding.[1] The previous JPEG standard had only limited scalability support (eg. progressive JPEG).

The current ITU and ISO video coding standards (H.264 and MPEG-4 AVC, resp.[2]) do not efficiently support rich scalability options, but work is under way to extended the standard with features to fully support scalable video coding (scalable video coding (SVC) extension to H.264/MPEG-4[3]). Furthermore, video coding based on motion-compensated temporal filtering (MC-TF) in combination with wavelet-based subband coding promises superior coding and scalability performance.[4]

Watermarking has been proposed to resolve copyright and content authentication and integrity questions for multimedia data by imperceptibly embedding information in the content.[5] Watermarks are designed to be detectable, even when the multimedia content is altered during transmission – an advantage over 'hard' cryptographic methods.[6]

In section 2, the MPEG-4 FGS standard,[7] H.264/MPEG-4 AVC scalability extension[3] and a 3D subband coding scheme (MC-EZBC[8]) are presented. In section 2.1 we briefly review video protection techniques based on cryptographic means which aim for scalability compliance.

Streaming and scalable multimedia transmission poses challenges as well as potentials for watermarking methods,[9] but has received little attention so far. Section 2.2 provides a literature survey with regards to watermarking methods explicitly supporting scalability.

We propose a simple watermarking scheme in section 3 which is used to evaluate the impact of video adaptations resulting from the before mentioned codecs. These results are presented and discussed in section 4 with concluding remarks in section 5.

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Scalability evaluation of blind spread-spectrum image watermarking

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Abstract. In this paper, we investigate the scalability aspect of blind watermark detection under combined quality and resolution adaption of JPEG2000 and JPEG coded bitstreams. We develop two multi-channel watermarking schemes with blind detection, based on additive spread-spectrum watermarking: one employs the DCT domain, the other the DWT domain. We obtain watermark scalability by combining detection results from multiple channels modeled by Generalized Gaussian distributions. Both schemes achieve incremental improvement of detection reliability as more data of a scalable bitstream becomes available.

1 Introduction

Watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in digital multimedia content such as images or video [1]. Watermarks are designed to be detectable, even when the multimedia content is altered during transmission and provide a level of protection after presentation – an advantage over cryptographic methods [2].

With the advent of mobile devices capable of wireless transmission and ubiquitous presentation of multimedia content, scalable image coding is more and more employed to allow adaptation of a single multimedia stream to varying transmission and presentation characteristics. A scalable image bitstream can be adapted to fit different resolution and quality presentation demands.

The JPEG2000 standard for image coding already addresses scalability by relying on a wavelet transformation and embedded, rate-distortion optimal coding [3]. The previous standard, JPEG [4], provides only limited support for sequential and progressive quality scalability (Annex F and G, resp.) and resolution scalability (Annex J), which is rarely implemented.

Streaming and scalable multimedia transmission poses challenges as well as potentials for watermarking methods [5], but has received little attention so far. An explicit notion of scalability first appears in the work of Piper et al. [6]. They evaluate the robustness of different coefficient selection methods with regards to quality and resolution scalability in the context of the basic spread-spectrum scheme proposed by Cox et al. [7]. Later, Piper et al. [8] combine resolution and quality scalability and argue that both goals can be achieved by exploiting the

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BLIND MOTION-COMPENSATED VIDEO WATERMARKING

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ABSTRACT

The temporal correlation between adjacent video frames poses a severe challenges for video watermarking applications. Motion-coherent watermarking has been recognized as a strategy to embed watermark information in video frames, resistant to collusion attacks. The motion-compensated temporal wavelet transform (MC-TWT) provides an efficient tool to separate static and dynamic components of a video scene and enables motion-coherent watermarking.

In this paper, we extend a MC-TWT domain watermarking scheme with blind detection, i.e. motion estimation and watermark detection is performed without reference to the unwatermarked video. Our results show that motion-coherent watermarking can be combined with a blind detector, widening the applicability of MC-TWT domain watermarking beyond forensics (where the unwatermarked content is assumed to be available).

Index Terms— motion-coherent, blind watermarking

1. INTRODUCTION

Watermarking has been proposed as a technology to ensure copyright protection by embedding a signal in digital multimedia content such as video [1]. Direct application of image watermarking schemes on the individual video frame gives rise to inter-frame attacks [2]. Adjacent video frames are typically highly correlated along the temporal axis. This fact can be exploited by averaging frames in case of an uncorrelated watermark or by performing perceptual remodulation of the averaged per-frame watermark estimate (WER attack [3]). To counter above attacks, the embedded watermark should exhibit correlation similar to the host signal frames [4], i.e. the watermark should be motion-coherent [5].

Frame registration and temporal transforms employing motion-compensation (MC) have been proposed as tools to align components of a video scene [6]. While the temporal transform approach uses block-based motion estimation (ME) to track motion of background and foreground objects, the frame registration technique merely separates and aligns the background. Motion-compensated frame prediction and evaluation of the local variance statistics of the residual frame has been proposed to assess the motion-coherency of a video watermarking scheme [7].

In this paper, we propose a blind video watermarking scheme based on a motion-compensated temporal wavelet transform. It extends the work of Pankajakshan et al. [6] by employing blind ME and blind watermarking detection, i.e. without reference to the unwatermarked content.

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In section 2 we review motion-compensated watermarking and propose our novel blind detection scheme. Experimental results are presented in section 3, followed by concluding remarks in section 4.

2. MOTION-COHERENT WATERMARKING

Early video watermarking schemes simply adopted image watermarking techniques on a per-frame basis. Two prototypical key schedules, repetitive and independent watermarking, can be distinguished, i.e. the same key is used for all frames or a different key is used to generate the watermark signal for each frame. In case of independent frame watermarking, flickering may become noticeable even when the watermark is imperceptible for each frame.

Furthermore, the redundancy between video frames permits to drop or swap frames to hinder synchronization, but also gives rise to powerful watermark estimation and collusion attacks which threaten the security of the watermarking scheme by revealing information on the secret watermark signal. Only recently, the notion of watermark security has been established alongside watermark robustness. In this paper we do not consider synchronization or inter-video attacks but concentrate on inter-frame attacks.

A repetitive video watermark can be attacked by estimating and remodulating the watermark's high-frequency components in each frame (e.g. via Wiener filtering [3]). The watermark estimate can be refined by combining estimates derived from dissimilar frames thus exploiting the redundancy of the watermark signal.

An independent video watermark is susceptible to the frame temporal filtering (FTF) or collusion attack: representing adjacent video frames by their temporal low-pass approximation averages out the uncorrelated watermark in the high frequency components. This attack's effectiveness can be greatly increased by employing MC-FTF [6] or FTF after frame registration [5].

Watermarking schemes aim to cope with the redundancy between the host frames using temporal transforms: Swanson et al. [8] apply temporal wavelet filtering to separately mark static (low-pass approximation) and dynamic (detail subbands) components of the video. 3D DCT [9] and DFT [10] transforms have also been proposed. Recently, watermarking schemes have been presented which explicitly take video motion into account to resist MC-FTF attacks. Kundur et al. [4] depend on anchor points to embed a correlated watermark in similar host video components, Doërr et al. use frame registration to align the video's background component before watermarking. Pankajakshan et al. [6] embed the watermark in the low-pass approximation obtained by a motion-compensated temporal wavelet transform (MC-TWT) [11]. Figure 1 shows the temporal low-pass frame with and without MC of the first 16 Foreman sequence frames.

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Robust watermarking of H.264-encoded video: Extension to SVC

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Abstract

In this paper we extend a framework for robust watermarking of H.264-encoded video to scalable video coding (SVC) as defined in Annex G of the standard. We focus on spatial scalability and show that watermark embedding in the base resolution layer of the video is insufficient to protect the decoded video of higher resolution. This problem is mitigated by a proposed upsampling technique of the base layer watermark signal when encoding the enhancement layer. We demonstrate blind watermark detection in the full- and low-resolution decoded video and, surprisingly, can report bit rate savings when extending the base layer watermark to the enhancement layer.

1. Introduction

Distribution of video content has become ubiquitous and targets small, low-power mobile to high fidelity digital television devices. The Scalable Video Coding (SVC) extension of the H.264/MPEG-4 Advanced Video Coding standard describes a bitstream format which can efficiently encode video in multiple spatial and temporal resolutions at different quality levels [7]. Scalability features have already been present in previous MPEG video coding standards. They came, however, at a significant reduction in coding efficiency and increased coding complexity compared to non-scalable coding. H.264/SVC employs inter-layer prediction and can perform within 10% bit rate overhead for a two-layer resolution scalable bitstream compared to coding a single layer with H.264.

In this work we extend a well-known robust watermarking framework proposed by Noorkami et al. [5,6] for copyright protection and ownership verification applications of H.264-encoded video content. The aim is to provide a single scalable, watermarked bitstream which can be distributed to diverse clients without the need to re-encode the video material. Scalability is provided at the bitstream level. A bitstream with reduced spatial and/or temporal resolution can be obtained by discarding NAL units [7]. The watermark should be detectable in the compressed domain *and* the decoded video without reference to the original content.

In Section 2 we briefly review the H.264 watermarking framework and investigate its applicability for protecting resolution-scalable video encoded with H.264/SVC. We propose an upsampling step of the base-layer watermark signal in Section 3 in order to extend the framework to SVC. Experimental results are provided in Section 4 followed by discussion and concluding remarks in Section 5.

2. Watermarking of H.264-encoded video

Several strategies have been proposed for embedding a watermark in H.264-encoded video. Most commonly, the watermark signal is placed in the quantized AC coefficients of intra-coded macroblocks. Noorkami et al. [5] present a framework where the Watson perceptual model for 8×8 DCT coefficients blocks [9] is adapted for the 4×4 integer approximation to the DCT which is predominantly used in H.264. Other embedding approaches include the modification of motion vectors or quantization of the DC term of each DCT block [2], however, the watermark can not be detected in the decoded video sequence or the scheme has to deal with prediction error drift.

Figure 1 illustrates the structure of the watermarking framework integrated in the H.264 encoder; each macroblock of the input frame is coded using either intra- or inter-frame prediction and the difference between input pixels and prediction signal is the residual[1]. We denote by $r_{i,j,k}$ the coefficients of 4×4 residual block k with $0 \leq i,j < 4$ and similarly by $o_{i,j,k}$ and $p_{i,j,k}$ the values of the original pixels and the prediction signal, resp. Each block is transformed and quantized, T denotes the DCT and Q the quantization operation in the figure. Let $R_{i,j,k}$ represent the corresponding quantized DCT coefficients obtained by

[1]Other modes are possible, e.g. *PCM* or *skip* mode, but rarely occur or are not applicable for embedding an imperceptible watermark due to lack of texture.

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Robust watermarking of H.264/SVC-encoded video: quality and resolution scalability

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Abstract. In this paper we investigate robust watermarking integrated with H.264/SVC video coding and address coarse-grain quality and spatial resolution scalability features according to Annex G of the H.264 standard. We show that watermark embedding in the base layer of the video is insufficient to protect the decoded video content when enhancements layers are employed. The problem is mitigated by a propagation technique of the base layer watermark signal when encoding the enhancement layer. In case of spatial resolution scalability, the base layer watermark signal is upsampled to match the resolution of the enhancement layer data. We demonstrate blind watermark detection in the full- and low-resolution decoded video for the same adapted H.264/SVC bitstream and, surprisingly, can report bit rate savings when extending the base layer watermark to the enhancement layer.

Keywords: Watermarking, scalable video coding

1 Introduction

Distribution of video content has become ubiquitous and targets small, low-power mobile to high fidelity digital television devices. The Scalable Video Coding (SVC) extension of the H.264/MPEG-4 Advanced Video Coding standard describes a bit stream format which can efficiently encode video in multiple spatial and temporal resolutions at different quality levels [14, 15]. Scalability features have already been present in previous MPEG video coding standards. They came, however, at a significant reduction in coding efficiency and increased coding complexity compared to non-scalable coding. H.264/SVC employs inter-layer prediction and can perform within 10% bit rate overhead for a two-layer resolution scalable bitstream compared to coding a single layer with H.264.

In this work we investigate a well-known robust watermarking framework proposed by Noorkami et al. [10, 11] for copyright protection and ownership verification applications of H.264-encoded video content. The aim is to provide

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R. Kwitt, P. Meerwald, A. Uhl. A lightweight Rao-Cauchy detector for additive watermarking in the DWT-domain. In *Proceedings of the ACM Multimedia and Security Workshop, MMSEC '08*, pages 33–41, Oxford, UK, Sept. 2008.


A Lightweight Rao-Cauchy Detector for Additive Watermarking in the DWT-Domain

Roland Kwitt, Peter Meerwald and Andreas Uhl

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R. Kwitt, P. Meerwald, A. Uhl. Efficient detection of additive watermarking in the DWT-domain. In *Proceedings of the 17th European Signal Processing Conference, EUSIPCO '09*, pages 2072–2076, Glasgow, UK, Aug. 2009.


EFFICIENT DETECTION OF ADDITIVE WATERMARKING IN THE DWT-DOMAIN

Roland Kwitt, Peter Meerwald, Andreas Uhl

http://www.eurasip.org/Proceedings/Eusipco/Eusipco2009/Start.html

R. Kwitt, P. Meerwald, A. Uhl. Lightweight Detection of Additive Watermarking in the DWT–Domain. Dept. of Computer Sciences, University of Salzburg, Technical Report 2010–04, May 2010.

Lightweight Detection of Additive Watermarking in the DWT–Domain

Roland Kwitt, Peter Meerwald, and Andreas Uhl

http://www.cosy.sbg.ac.at/research/tr.html

R. Kwitt, P. Meerwald, A. Uhl. Lightweight Detection of Additive Watermarking in the DWT–Domain. IEEE Transaction on Image Processing, 20(2):474–484, Feb. 2011.

Lightweight Detection of Additive Watermarking in the DWT–Domain

Roland Kwitt, Peter Meerwald*, and Andreas Uhl

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P. Meerwald, A. Uhl. Watermark Detection on Quantized Transform Coefficients using Product Bernoulli Distributions. In *Proceedings of the ACM Multimedia and Security Workshop, MM&Sec '10*, pages 175–180, Rome, Italy, Sept. 2010.

Watermark Detection on Quantized Transform Coefficients Using Product Bernoulli Distributions

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ABSTRACT

Detection performance of additive spread-spectrum watermarks depends on the statistical host signal model employed to derive the detection statistic. When transform coefficients are heavily quantized, the assumption of a Cauchy or Generalized Gaussian Distribution (GGD) is hard to justify and the estimation of model parameters becomes inaccurate. In this paper we derive a Likelihood-Ratio Test (LRT) based on the product of Bernoulli distributions. The watermark detector is designed to operate on quantized (integer) transform coefficients and therefore permits straightforward integration of the watermarking scheme in popular image and video codecs. Detection performance surpasses the linear correlation detector and is competitive with the computationally more demanding LRT based on a GGD.

Categories and Subject Descriptors

I.4.10 [**Image Processing and Computer Vision**]: Statistical

General Terms

Algorithms, Performance, Security

Keywords

Watermarking, Spread-spectrum, Generalized Gaussian, Likelihood Ratio Test

1. INTRODUCTION

Watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in digital multimedia content such as images or video [5]. For blind watermarking, i.e. when detection is performed without reference to the unwatermarked host signal, the host interferes with the watermark signal.

Transform domains – such as the Discrete Cosine Transformation (DCT) or the Discrete Wavelet Transformation (DWT) domain – facilitate modeling human perception and permit selection of significant signal components for multimedia coding and watermark embedding. The perceptual characteristics and distributions of transform domain coefficients has been extensively studied for image compression [2, 1]. If we assume a Gaussian host signal, it is known that the optimal detector is the straightforward linear-correlation (LC) detector [8].

Unfortunately, DCT and DWT coefficients do not obey a Gaussian law in general, which renders the LC detector suboptimal in these situations. A first approach, exploiting the fact that DCT or DWT coefficients are not Gaussian, is proposed in [7] where the authors derive an optimal detector for an additive bipolar watermark sequence in DCT transform coefficients following a Generalized Gaussian Distribution (GGD). Many approaches for optimal detection of additive watermarks embedded in transform coefficients have been proposed in literature so far [7, 13, 3].

In this work we propose we novel watermark detector derived from on a simple model for quantized (integer) DWT or DCT coefficient values based on the bit-plane probability signatures recently introduced for texture retrieval applications [16, 4]. The advantages of the proposed watermark detector include the reliable estimation of the model parameters even on heavily quantized data, straightforward integration of the method in multimedia codecs as the computation of the detection statistic can be implemented using integer arithmetic only, thus permitting efficient implementation. We show that detection performance surpasses the LC detector, and – in certain embedding scenarios relevant for integrated coding and watermarking – also the LRT-GGD approach [7].

The remainder of the paper is structured as follows: In Section 2 we discuss the statistical model of our approach, followed by the derivation of the detection statistic in Section 3. In Section 4, we present experimental detection results and evaluate the performance of our detector under JPEG compression attacks. Section 5 concludes the paper with a discussion on open problems and an outlook on further research.

2. MODELING QUANTIZED TRANSFORM COEFFICIENTS

It is commonly accepted that the marginal distributions of the DWT detail subband coefficients or DCT coefficients of natural images are highly non–Gaussian but can be well modeled by the GGD [11, 2] or Cauchy distribution [1, 3]. Employing the parametrization of [12], the PDF of the GGD

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P. Meerwald, A. Uhl. Watermarking of raw digital images in camera firmware: embedding and detection. In *Advances in Image and Video Technology: Proceedings of the 3rd Pacific-Rim Symposium on Image and Video Technology, PSIVT '09*, volume 5414 of *Lecture Notes in Computer Science*, Springer, pages 340–348, Tokyo, Japan, Jan. 2009.

Watermarking of raw digital images in camera firmware: embedding and detection

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Abstract. In this paper we investigate 'real-time' watermarking of single-sensor digital camera images (often called 'raw' images) and blind watermark detection in demosaicked images. We describe the software-only implementation of simple additive spread-spectrum embedding in the firmware of a digital camera. For blind watermark detection, we develop a scheme which adaptively combines the polyphase components of the demosaicked image, taking advantage of the interpolated image structure. Experimental results show the benefits of the novel detection approach for several demosaicking techniques.

Key words: watermarking, demosaicking, signal detection, firmware

1 Introduction

Digital cameras are in ubiquitous use. Most popular digital cameras use a single, monochrome image sensor with a color filter array (CFA) on top, often arranged in the Bayer pattern, see Figure 1. In order to provide a full-resolution RGB image, the sensor data has to be interpolated – a process called demosaicking – as well as color, gamma and white point corrected. Different demosaicking techniques exist, e.g. [1, 2], yet the basic processing steps are shared by most camera implementations.

The digital nature of the recorded images which allows for easy duplication and manipulation, poses challenges when these images are to be used as evidence in court or when resolving ownership claims. Active techniques, such as watermarking [3], as well as passive or forensic approaches have been suggested to address image integrity verification, camera identification and ownership resolution. Many different forensic techniques have been proposed to detect image forgeries. For example, Chen et al. [4] exploit the inherent Photo-Response Non-Uniformity (PRNU) noise of the image sensor for camera identification and image integrity verification. Interpolation artefacts due to demosaicking are used by Popescu et al. [5] to verify the integrity of the image. Passive techniques have the disadvantage that camera characteristics such as PRNU have to be estimated before use.

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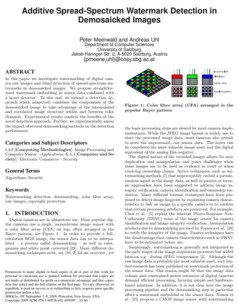
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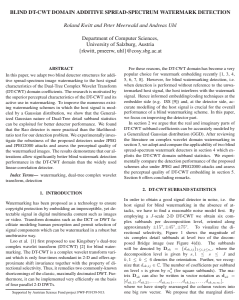
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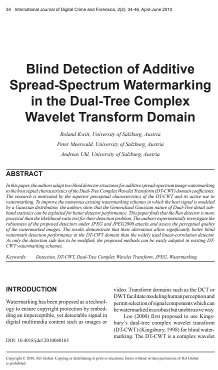

34 International Journal of Digital Crime and Forensics, 2(2), 34-46, April-June 2010

Blind Detection of Additive Spread-Spectrum Watermarking in the Dual-Tree Complex Wavelet Transform Domain

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ABSTRACT

In this paper, the authors adapt two blind detector structures for additive spread-spectrum image watermarking to the host signal characteristics of the Dual-Tree Complex Wavelet Transform (DT-CWT) domain coefficients. The research is motivated by the superior perceptual characteristics of the DT-CWT and its active use in watermarking. To improve the numerous existing watermarking schemes in which the host signal is modeled by a Gaussian distribution, the authors show that the Generalized Gaussian nature of Dual-Tree detail subband statistics can be exploited for better detector performance. This paper finds that the Rao detector is more practical than the likelihood-ratio test for their detection problem. The authors experimentally investigate the robustness of the proposed detectors under JPEG and JPEG2000 attacks and assess the perceptual quality of the watermarked images. The results demonstrate that their alterations allow significantly better blind watermark detection performance in the DT-CWT domain than the widely used linear-correlation detector. As only the detection side has to be modified, the proposed methods can be easily adopted in existing DT-CWT watermarking schemes.

Keywords: *Detection, DT-CWT, Dual-Tree Complex Wavelet Transform, JPEG, Watermarking*

INTRODUCTION

Watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in digital multimedia content such as images or video. Transform domains such as the DCT or DWT facilitate modeling human perception and permit selection of signal components which can be watermarked in a robust but unobtrusive way.

Loo (2000) first proposed to use Kingsbury's dual-tree complex wavelet transform (DT-CWT) (Kingsbury, 1998) for blind watermarking. The DT-CWT is a complex wavelet

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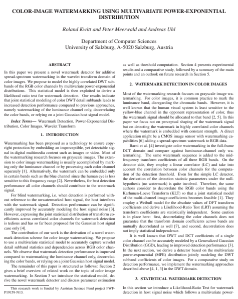

COLOR-IMAGE WATERMARKING USING MULTIVARIATE POWER-EXPONENTIAL DISTRIBUTION

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ABSTRACT

In this paper we present a novel watermark detector for additive spread-spectrum watermarking in the wavelet transform domain of color images. We propose to model the highly correlated DWT subbands of the RGB color channels by multivariate power-exponential distributions. This statistical model is then exploited to derive a likelihood ratio test for watermark detection. Our results indicate that joint statistical modeling of color DWT detail subbands leads to increased detection performance compared to previous approaches, namely watermarking of the luminance channel only, decorrelating the color bands, or relying on a joint Gaussian host signal model.

***Index Terms*—** Watermark Detection, Power-Exponential Distribution, Color Images, Wavelet Transform

1. INTRODUCTION

Watermarking has been proposed as a technology to ensure copyright protection by embedding an imperceptible, yet detectable signal in digital multimedia content such as images or video. Most of the watermarking research focuses on grayscale images. The extension to color image watermarking is usually accomplished by marking only the luminance channel or by processing each color channel separately [1]. Alternatively, the watermark can be embedded only in certain bands such as the blue channel since the human eye is less sensitive to this frequency range [2]. Nevertheless, for best detection performance all color channels should contribute to the watermark signal.

For blind watermarking, i.e. when detection is performed without reference to the unwatermarked host signal, the host interferes with the watermark signal. Detection performance can be significantly improved by accurately modeling the host signal noise [3]. However, expressing the joint statistical distribution of transform coefficients across correlated color channels for watermark detection is tedious and has so far been proposed for the Gaussian host signal case only [4].

The contribution of our work is the derivation of a novel watermark detection scheme for color image watermarking. We propose to use a multivariate statistical model to accurately capture wavelet detail subband statistics and dependencies across RGB color channels. We observe that watermark detection performance is improved compared to watermarking the luminance channel only, decorrelating the color bands, or relying on a joint Gaussian host signal model.

The remainder of this paper is structured as follows: Section 2 gives a brief overview of related work on the topic of color image watermarking. In Section 3 we introduce the statistical model, derive the novel watermark detector and discuss parameter estimation as well as threshold computation. Section 4 presents experimental results and a comparative study, followed by a summary of the main points and an outlook on future research in Section 5.

2. WATERMARK DETECTION IN COLOR IMAGES

Most of the watermarking research focuses on grayscale image watermarking. For color images, it is common practice to mark the luminance band, disregarding the chromatic bands. However, it is well known that the human visual system is least sensitive to the yellow-blue channel in the opponent representation of color, thus the watermark signal should be allocated to that band [2, 5]. In this paper we focus not on perceptual shaping of the watermark signal but on detecting the watermark in highly correlated color channels where the watermark is embedded with constant strength. A direct application might be a CMOS image sensor with watermarking capabilities [6] adding a spread-spectrum watermark to RGB data.

Barni et al. [4] investigate color watermarking in the full-frame DCT domain and compare against luminance-channel only watermarking. The same watermark sequence is added to the mid-frequency transform coefficients of all three RGB bands. On the detector side, they employ a linear correlator (LC) and take into account the correlation between color channels for the computation of the detection threshold. Even for the simple LC detector, the derivation of the detection statistic parameters under the null-hypothesis (no watermark) is quite involved. Therefore, the same authors consider to decorrelate the RGB color bands using the Karhunen-Loeve Transform (KLT) so that a joint statistical model of the multi-channel image coefficients becomes feasible [1]. They employ a Weibull model for the absolute values of DFT transform coefficients and derive a Likelihood-Ratio Test (LRT) assuming the transform coefficients are statistically independent. Some caution is in place here: first, decorrelating the color channels does not guarantee that the transform domain coefficients across bands are mutually decorrelated as well [7], and second, decorrelation does not imply statistical independence.

It is well known that DWT and DCT coefficients of a single color channel can be accurately modeled by a Generalized Gaussian Distribution (GGD), leading to improved detection performance [3]. In the next section, we derive a detector based on the multivariate power-exponential (MPE) distribution jointly modeling the DWT subband coefficients of color images. For a comparative study on detection performance, we implement the watermarking approaches described above [4, 1, 3] in the DWT domain.

3. STATISTICAL WATERMARK DETECTION

In this section we introduce a Likelihood-Ratio Test for watermark detection in host signal noise which follows a multivariate power-

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Watermark Detection for Video Bookmarking Using Mobile Phone Camera

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Abstract. In this paper we investigate a watermarking application for bookmarking of video content using a mobile phone's camera. A content identifier and time-stamp information are embedded in individual video frames and decoded from a single frame captured from a display device, allowing to remember ('bookmark') scenes in the video. We propose a simple watermarking scheme and blind image registration to combat the inherent geometric distortion due to digital/analog conversion. The work-in-progress shows promising results over previous approaches.

Keywords: Watermarking, image registration, geometric distortion.

1 Introduction

Watermarking has been proposed as a technology to embed an imperceptible, yet detectable signal in digital multimedia content such as images or video [1]. Since the watermark information is embedded in the video data itself and not a particular file format, the embedded information is retained even if the content undergoes transformation such as re-encoding or presentation on a monitor and capturing with a camera. Pramila et al. [2] survey the challenges in bridging the analog/digital gap using camera-based watermark extraction. Transmission of watermark information over the print/scan channel has been studied for applications including document authentication and copyright protection [3,4,5].

Nakamura et al. [6,7] present two watermark detection schemes for camera-equipped cellular phones: in [6], the authors aim to decode information such as an imperceptible content identifier analogous to a visible bar code in printed material while in [7], a content id is decoded from a sequence of video frames. Both methods rely on extraction of the target content region in the captured image and image sequence before applying projective correction to combat geometric distortion which inevitably results from freehand shooting. The side trace algorithm (STA) [8] employed requires a smooth background or an artificial border marker in order to identify the target region.

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WATERMARKING OF 2D VECTOR GRAPHICS WITH DISTORTION CONSTRAINT

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ABSTRACT

We study the watermarking of 2D vector data and introduce a framework which preserves topological properties of the input. Our framework is based on so-called maximum perturbation regions (MPR) of the input vertices, which is a concept similar to the just-noticeable-difference constraint. The MPRs are computed by means of the Voronoi diagram of the input and allow us to avoid (self-)intersections of input objects that might result from the embedding of the watermark. We demonstrate and analyze the applicability of this new framework by coupling it with a well-known approach to watermarking that is based on Fourier descriptors. However, our framework is general enough such that any robust scheme for the watermarking of vector data can be applied.

1. MOTIVATION

Watermarking is a technology to enable copyright protection by embedding an imperceptible, yet detectable signal in digital content [1]. Watermarking research has primarily focused on raster data (audio and video content). However, increasingly more complex models of computer-aided design (CAD) or huge maps and infrastructure data stored in geographical information systems (GIS) also constitute valuable digital assets and make the protection of vector data more important.

When embedding watermark information in a collection of geometric primitives not only perceptional constraints have to be met but also geometrical properties must be preserved: For example, the banks of a river in a geographic map should not cross due to the embedding. Similarly, the pads of a printed circuit board should not overlap afterwards. This is particularly important for industrial 2D vector data, where copyright protection has not received much attention.

Watermarking of vector data has been proposed for 2D polygons and 3D meshes. In this work, we focus on 2D polygonal data. Zheng et al. [2] provide an overview of the state-of-the-art in vector watermarking and Li et al. [3] review technical and legal copyright issues with watermarking of geo-spatial datasets.

Although fidelity of the watermarked data is generally considered (if only by visual inspection), distortion constraints and preservation of geometrical properties of the watermarked data received only very limited attention so far: Ohbuchi et al. [4] report an acceptable error of 75 cm in the real world on a 1:2500-scale geographical map. Doncel et al. [5] consider polygonal chains sharing a number of points such as the border of neighboring countries; the chains must be kept coincident at the corresponding locations after watermark insertion.

2. OVERVIEW

We introduce a general distortion constraint framework for geometric data watermarking which preserves essential geometric properties after the embedding: it guarantees that no line segments cross due to vertex perturbation. Hence, the input topology is preserved. For each vertex we compute a radius which bounds the allowed perturbation. By deliberately choosing a smaller radius, the error bound mentioned by Ohbuchi et al. [4] can be implemented.

Let us define a (simple) polygonal chain as a (possibly closed) sequence of adjacent straight line segments where non-consecutive segments are not allowed to intersect. We represent such a polygonal chain by the series of its vertices; if the chain is closed, the first and last vertex coincide. The input of our framework is a set of polygonal chains where two chains may only intersect at their endpoints.

The proposed framework consists of three parts as depicted in Fig. 1: (i) a geometric pre-processing step computing the so-called maximum perturbation region (MPR) of each input vertex; (ii) the watermark embedding process; and (iii) the correction step which outputs the watermarked polygonal chains subject to the distortion constraint.

The remainder of this work is organized as follows. In Section 3, we describe the computation of the maximum perturbation regions. We exemplary show how to apply the MPR distortion constraint on a well-known vector graphics watermarking approach based on Fourier descriptors [6, 5] in Section 4. In Section 5, we investigate the impact on detection performance when adopting the MPR framework and finally summarize our results in Section 6.

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Attack on 'Watermarking Method Based on Significant Difference of Wavelet Coefficient Quantization'

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Targeted Attacks on Quantization-based Watermarking Schemes

Chapter 3

Discussion and Conclusion

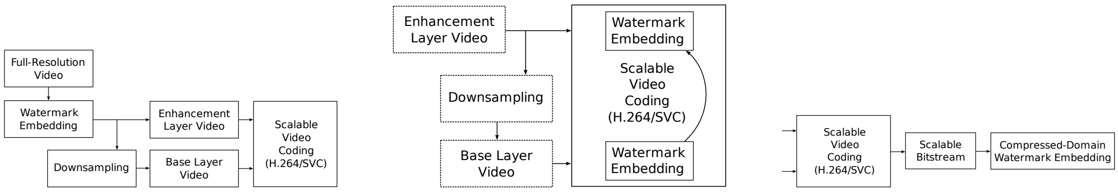
In this final chapter we try to collect the results obtained on the various research topics and put them in perspective with the state-of-the-art in the field. In Section 3.2 we discuss research methodology. Section 3.3 concludes with remarks and open issues closely related to the investigated topics.

3.1 Contribution

Watermark detection in scalable multimedia formats. Lin et al. [106, 107] speculated about the impact of streaming video data and rate-scalable compressing on watermarking in 2001. Video streaming is certainly a commodity service nowadays and scalable multimedia formats begin to gain wider attention. Surprisingly, the questions put forward received only little attention so far. For robust watermarking, one possible explanation is that rate-scalable compression after watermark embedding can be seen as just another processing step (unintentional 'attack') the watermark has to withstand. Quantization due to lossy compression as well as spatial and temporal domain scaling – constituent to the formation of a scalable bitstream – have been considered early-on in watermark robustness evaluation experiments [149, 150]. On the other hand, watermarking in a hierarchical, multi-resolution domain (such as a pyramidal DWT decomposition for example) easily gains properties related to scalability such as progressive detection.

As a first step, the impact of scalable H.264 video coding and JPEG2000 image coding on watermarking schemes is experimentally assessed in [122] and [121]. Experiments in the same direction are also reported in [152, 153, 14, 15]. Further, we identify six aspects of scalable watermarking [122]: complexity scalability, detection progressiveness, watermarking integrated with scalable coding, distribution scalability, new application scenarios, and, obviously, watermark robustness to scalable coding. When taking a closer look, the peculiarities of scalable watermarking become apparent.

Detection progressiveness was introduced by Lin et. [106] as a requirement for scalable wa-



(a) Embedding before encoding **(b)** Integrated embedding **(c)** Compressed-domain embedding

Figure 3.1: Embedding scenarios for watermarking resolution-scalable H.264/SVC video content

termarking, and later refined by Piper et al. [153]. The issue is to combine detection responses obtained on different parts of the host signal. Under the i.i.d. assumption we derive a global LRT-GGD detection statistic [121] as well as a multi-channel Rao-Cauchy detector [91].

Cox et al. [45] assert that computational cost is important for commercial applications. Given the increasing availability of computing resources, it makes sense to design a simple and efficient decoder first which can be replaced by a more sophisticated version as more resources become affordable – the watermark detection performance scales with processing power. Our results on efficient watermark detection show that complexity scalability can be obtained for spread-spectrum watermarking schemes.

Video watermarking integrated with MC-EZBC and H.264/SVC coding is addressed in [120] and [128], respectively. In Fig. 3.1 we distinguish three embedding scenarios for producing a watermarked, resolution-scalable H.264/SVC bitstream: (a) embedding before encoding, (b) embedding integrated in the coding process, (c) altering the scalable bit stream (embedding in the compressed domain). Our proposal for integrated H.264/SVC watermarking [125] achieves to detect the watermark in the base and enhancement resolution layer while reducing the bitrate by embedding an upsampled watermark signal in the enhancement layer.

The first embedding scenario offers little control over the resulting bitstream and thus makes detection in the compressed domain difficult. In principle, most video watermark schemes operating on uncoded video data could be adopted in this scenario, yet the coding process (i.e. scaling, prediction, lossy compression) interferes with the embedded watermark signal. Caenegem et al. [184] design a H.264/SVC resilient watermark by embedding in the scaling invariant Fourier-Mellin transform domain. The scheme relates to the first embedding scenario (cf. 3.1) and therefore treats the video encoding simply as a robustness attack on the embedded watermark.

The third scenario appears to be overly complex from an implementation point of view given the prediction structure of H.264/SVC. Compressed-domain replacement watermarking techniques are known for H.264's context adaptive variable length and binary arithmetic coding methods (CAVLC and CABAC, respectively) [206, 207], however, a large amount of video data is required to embed a robust watermark and multiple layers are not considered.

Watermarking explicitly addressing scalable media has received some attention in the literature. A combined encryption and watermarking-based authentication method for H.264/SVC has been proposed by Park and Shin [146]. Authentication information is encoded in the bits signalling the intra prediction mode and thus cannot be verified on the decoded video. Kim et al. [81] perform embedding experiments with H.264/SVC but do not consider any scalability options. Chang et al. [31] consider a layered encryption scheme and use watermarking to simplify key management. Zhao and Liu [203] analyze the resistance of a fingerprinting system for scalable video data under fair collusion attacks; colluders are assumed to possess fingerprinted copies of the same content at different resolutions. Iqbal et al. [71] describe an authentication component for compressed domain processing in an video bit stream adaptation engine conforming to MPEG-21 part 7 (Digital Item Adaptation) [73]. The watermark is applied by inserting bits in the H.264 slice header, consequently the watermark is fragile and extractable only in the compressed domain. The discussion of robust watermarking with regard to scalability is often limited to progressive detection approaches and quality scalability [197, 34, 167, 174, 177, 153].

Efficient watermark detection. Blind detection performance for additive, spread-spectrum watermarking of visual multimedia content can be greatly improved by incorporating an appropriate model of the host signal [63, 18, 36, 138, 158], thus permitting to derive an 'optimal' detector (under simplifying assumptions). The most commonly used models (GGD [16], Cauchy [180]) require estimation of the model parameters which (i) significantly increases the computational effort for implementing the watermark detector, and (ii) raises the question how detection performance depends on the accuracy of the estimates, a problem first stated by Hernandez et al. [63].

We address the first issue in [91, 94, 96, 128] and try to answer the second question in [94, 96]. Results include:

- Based on the Cauchy host signal model and the Rao test, the Rao-Cauchy watermark detector [91] is proposed which compares favorable in terms of detection performance and computational effort and – being a CFAR detector – simplifies the experimental setup.
- Five watermark detectors are compared with regard to detection performance and runtime efficiency from the viewpoint of host signal model parameter estimation [94, 96]. We contrast Maximum Likelihood Estimation with fast, approximative methods and fixed parameter setting. Detection performance degrades only marginally using the approximative estimates and also fixed settings achieve to outperform the linear correlation detector on a large number of images. The results indicate that peak detection performance can not be obtained in the watermarking setting even employing ML estimates.
- For quantized transform domain coefficients, we propose a LRT watermark detector [128] based on the Product Bernoulli distribution [151, 40]. The novel detector can largely be implemented with integer arithmetic and achieves performance comparable to the LRT-GGD detector; yet it is based on a simple host signal model whose parameters can be efficiently estimated in a ML sense. The LRT-PBD detector is well-suited for watermarking applications integrated in a multimedia codec such as JPEG2000 or H.264 where the detector operates on quantized transform coefficients (cf. the video watermarking framework proposed by Noorkami et al. [140]).

The work presented is to our knowledge the first attempt to incorporate the aspect of computational efficiency in the design of a watermark detector. We believe this to be a valuable contribution given the increasing importance of content distribution to mobile, power-aware applications. In Fig. 3.2 we plot the relative runtimes for performing different single-precision

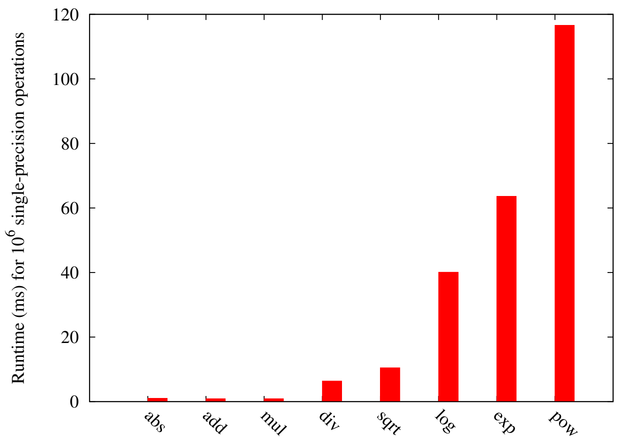


Figure 3.2: Runtime (in milliseconds) for several single-precision floating point operations on Intel Core2 2.6 GHz GPU.

floating point operations on a contemporary Intel Core2 2.6 GHz CPU – computation of the logarithm or power function is 50 to 100 times slower than floating-point addition or multiplication. Clearly, the type of floating point operations the detector makes use of determines the runtime.

In case synchronization of the received signal with the watermark signal requires an extensive search to determine the correct parameters [5, 104], computational efficiency is highly desirable. An alternative approach to efficiency is sequential detection [29] where the decision is not made after correlating a fixed-length signal, but incrementally, after processing each signal sample.

Watermark detection in raw sensor data. Most digital cameras support storing the raw, unprocessed sensor data in addition to the JPEG-compressed image. Although the sensor data is the most valuable digital asset and equivalent to the analog film negative, watermarking of raw image sensor data has received little attention. In [124, 129] a firmware extension for a range of camera models is proposed to enable additive, spread-spectrum watermarking in the camera. The implementation allows to study the impact of the camera's processing pipeline on the watermark signal. The following results have been obtained:

- By incorporating the interpolated structure of the demosaicked image using the polyphase component model of Giannoula et al. [59], the watermark detection performance is improved.
- The impact of several spatial- and frequency domain demosaicking algorithms on the watermark embedded in the green and blue CFA sensor data is experimentally assessed [123]. It is shown that due to the iterative demosaicking steps, the green channel preserves the watermark signal better than the blue channel.

Many passive, forensic techniques based on the properties of image sensors or the image processing pipeline are known [21, 11, 83]. The present work [124, 129, 123] is to the best of our knowledge the first attempt to investigate the impact of demosaicking on watermarking. Naeeni et al. [132] consider combined watermarking and demosaicking, however, the approach still renders the raw image data unprotected.

Watermark detection in color images and the DT-CWT domain. In [93], we derive a LRT for spread-spectrum watermark detection based on the Multivariate Power Exponential (MPE) distribution to jointly model the correlated RGB color channel subbands. In [92, 95], we adapt the LRT-GGD host signal model to the complex coefficient DT-CWT subband data. Both approaches demonstrate a substantial detection performance improvement over the LC detector thanks to the use of a more accurate host signal model.

Watermark detection in 2D vector graphics data under distortion constraint. In [70] we propose a distortion constraint for 2D vector data, the Maximum Perturbation Region (MPR). The novel MPR framework can be efficiently computed using Voronoi diagrams and is conceptually similar to the perceptual JND constraint for visual raster data. The MPR bounds the watermark strength for each vertex such that no polygon line segments cross due to watermark embedding. Applications include the watermarking of GIS [101, 142] or industrial 2D vector data which constitute valuable digital assets – crossing electric wires or overlapping national borders due to data perturbation are disastrous in these scenarios. Prior work only applied a maximum acceptable error for GIS data without considering the actual geometric constraints [142] or just considered multiple polygonal chains with coincident vertices [53]. Both constraints can be easily accommodated in the proposed MPR framework.

Targeted attack on quantization-based watermarking schemes. While general signal processing, geometric and protocol level attacks [149, 188, 41] have received ample attention in the literature, only few works (e.g. [47]) investigate targeted attack directed towards the weakness of a particular watermarking algorithm. The attacks mounted during the first and second edition of the 'Break Our Watermarking System' (BOWS) contest[1] [154, 13, 61, 192, 193, 194] exposed vulnerabilities and indicate design guidelines for robustness and security to be incorporated in future watermarking schemes. It is thus worthwhile to consider attacking a particular watermarking method. Benchmarking may provide a robustness evaluation [150], however in the copyright protection scenario a detailed analysis for potential weaknesses is required.

Our own attacks [118, 119] highlight that robustness attacks are indeed very different from security attacks crafted for a particular watermarking scheme. The attack scenario assumes knowledge of the implementation but not access to a detector, and requires just a single watermarked image. In particular, a family of wavelet-domain quantization based watermarking approaches which group coefficients across subbands or form tree structures spanning several decomposition hierarchies has been found vulnerable. The schemes leak enough information to permit statistical analysis on a single image and reveal potential embedding locations. The connection to steganalysis is apparent, yet the security analysis of watermarking schemes is only about to emerge [25, 148].

[1] BOWS and BOWS 2nd Ed. is accessible at http://lci.det.unifi.it/BOWS/ and http://bows2.gipsa-lab.inpg.fr, respectively.

3.2 Methodology

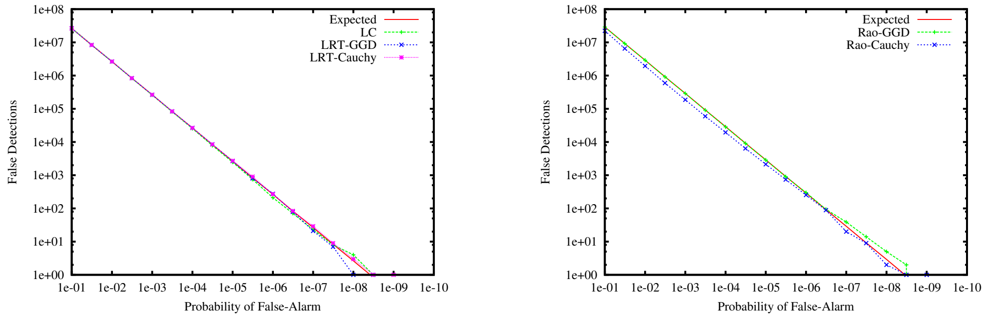
It is well-known that the statistics of natural images vary dramatically. Therefore, performance evaluation should be conducted on a large body of images such as the UCID database [163] (1338 color images with 512×384 pixels) or the 10000 grayscale images (512×512 pixels) that have been made available during the BOWS-2 ('Break Our Watermarking System', 2nd Edition) contest [57]. Large-scale test results have been published in [96, 128]. In [124, 123, 129, 93], the 24 Kodak lossless true color test images (768×512)[2] have been used since this image set is popular in image demosaicking research.

Comparison of watermark detection performance is a controversial issue. For copyright protection applications, it is of crucial importance to meet the required probability of false-alarm (e.g. $P_f = 10^{-6}$ or $P_f = 10^{-9}$). Generally, we establish the detection threshold in a Neyman-Pearson sense by assuming that the detection statistic adheres to a Gaussian law in case of the LRT detectors and a Chi-Square distribution in case of the Rao detectors. For the LRT detectors, the parameters of the Gaussian have to be determined under the null-hypothesis $\mathcal{H}_0$ by either using the (theoretical) expressions for the expectation of the detection statistic's mean and variance, or by experimentally estimating the parameters based on a large number of detection experiments. Obviously, no parameters are necessary for the CFAR detectors [79, 91, 96]. Given the low desired false-alarm probabilities, it is difficult to verify the reliability of watermarking schemes experimentally [27, 58] – fast methods are known only for the Gaussian noise model. In Figs. 3.3 and 3.4, we plot the given probability of false-alarm against the number of false detections that are observed in large-scale experiments, performing in the order of 10^8 and 10^7 detector calls on uncompressed and JPEG-compressed images, respectively. The expressions for the detection statistics, fast (approximative) host image parameter estimation, and threshold determination can be found in [96]; the DWT detail subbands of the BOWS-2 grayscale images were used. It can be seen that the observed number of false detections is in good agreement with their expected number. Only in case of the Rao-Cauchy detector, the observed number is somewhat lower, especially when the test images are subjected to JPEG compression. Hence, the determined detection threshold is slightly too conservative.

Detection performance of single (or zero) bit watermarks is generally presented and compared in terms of probability of miss under the assumption that the detection statistic under the alternative hypothesis $\mathcal{H}_1$ follows a Gaussian or Chi-Square distribution. The parameter(s) of the distribution are estimated performing a large number of detection experiments employing different, pseudo-random watermarks. The aim is to have a measure applicable to diverse detection approaches for comparison. Clearly, a very low probability of error is difficult to estimate given a limited number of experiments. An alternative approach would be to state the number of detection errors that actually occur in the experiments. However, unless the watermark strength is unrealistically low or the host signal length severely constrained, all detection schemes would produce zero detection misses. Caution is recommended with regard to the individual probability values determined; however, in comparison the observed performance differences are often quite large and consistent over a large number of images.

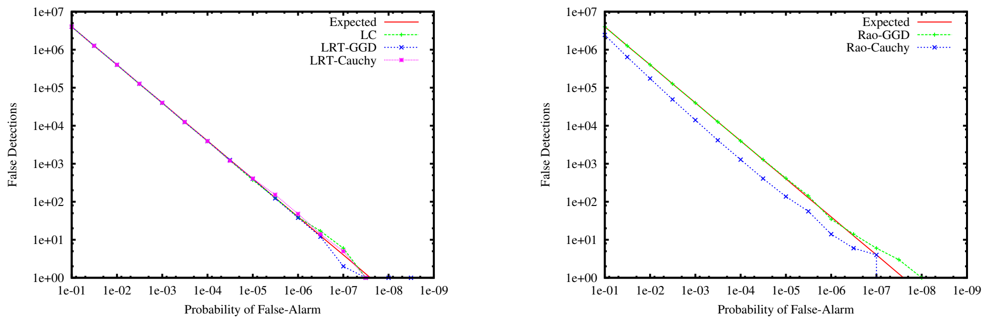
Where possible [91, 92, 94, 93, 96, 124, 129, 123, 128, 70], we tried to compare watermarking schemes by solely altering the detection side and embedding with high PSNR (dB) since the objective assessment of the perceptual quality of watermarked images is still in its infancy [117,

[2] Made available by Rich Franzen at `http://r0k.us/graphics/kodak/`.

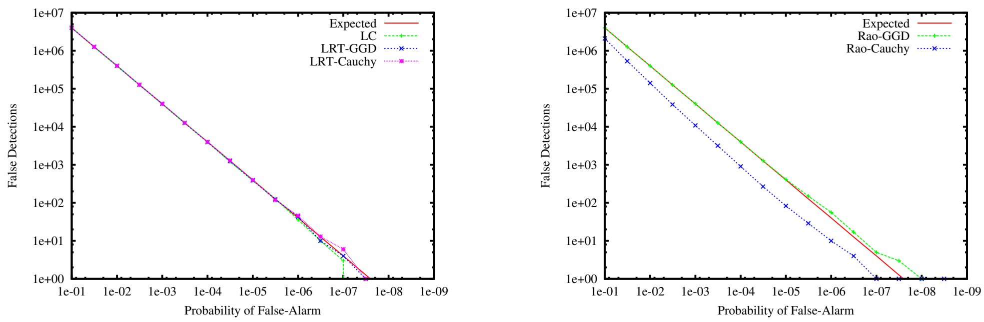


(a) LRT **(b)** Rao

Figure 3.3: Experimental verification of the threshold for (a) the LRT and (b) the Rao detectors (performing $2.9 \cdot 10^8$ detector calls).



(a) LRT, JPEG ($Q = 60$) **(b)** Rao, JPEG ($Q = 60$)



(c) LRT, JPEG ($Q = 30$) **(d)** Rao, JPEG ($Q = 30$)

Figure 3.4: Experimental verification of the threshold for the LRT (a,c) and Rao (b,d) detectors ($4.0 \cdot 10^7$ detector calls) under JPEG compression ($Q = 60$ and $Q = 30$).

24], thus precluding a fair comparison of different embedding strategies without large-scale subjective testing.

In consideration of a recent opinion article by Vandewalle et al. [185] on reproducible research, the full source code will become available (see Appendix C) to reproduce the experimental results and provide a basis for further research. Description of the implementation details and the experimental setup (especially in the area of video coding) are a prerequisite for security and comparative performance analysis, yet often missing. Only the availability of source code and the automated test procedure can fill this gap.

3.3 Concluding Remarks and Open Issues

To summarize, blind detection performance for additive spread-spectrum watermarking highly depends on the characteristics of the host signal. Particular relevant embedding domains such as scalable image and video formats, raw image sensor data or 2D vector data pose interesting application problems that should be addressed with a dedicated detection approach.

Modelling of a multi-component visual multimedia signal with regard to color channels and multiple layers in scalable coding remains a challenging topic for watermarking detection for many practical reasons. Especially robust watermarking integrated in closed-loop video codecs such as H.264/SVC poses several interesting problems due to the prediction structure. Video watermarking is only part of a larger video content distribution system that sets the requirements.

Data hiding of authentication information in scalable media received some attention [146, 71] in conjunction with multimedia encryption, however the embedded data is added to the bitstream format (e.g. the intra prediction mode choice or the H.264 slice header) rather than the multimedia data itself. In contrast, this work focuses on methods where the embedded signal can be detected in the decoded video. Our own design of a robust watermarking scheme with the explicit treatment of scalability requirements [125] only considers one resolution enhancement layer, yet the approach should also be applicable to CGS enhancement layers providing quality scalability.

The choice of the Rao-Cauchy detector [91, 125] was mainly motivated by the simplified experimental setup due to the CFAR detector. It is not clear how to perform 'optimal' blind detection on heavily quantized 4×4 DCT coefficients, in particular in the Location Unaware Detection (LUD) scenario [141] where the embedder selects non-zero coefficients and the detector has only incomplete information about the selection made. As a first step, applying the LRT-PBD detector [128] on quantized transform coefficients yields promising results, but the novel detector has not been employed in the DCT domain yet. Several 'optimal' detection approaches have been devised for spread-spectrum watermarking, yet the ideal host signal models put forward deviate notably from the actual predicted and quantized coefficients observed especially in the context of scalable coding. The problem could be addressed building upon robust hypothesis testing theory [68, 69].

Watermarking temporally predicted (P) frames within the framework of Noorkami et al. [139, 141] is often neglected and, following the original proposal, tedious due to the long-term accumulation of frame data and iterative determination of the detection threshold. Several proposals decorrelate the video frames along the temporal axis using before embedding [105, 100, 198, 19, 20, 22], yet these approaches are applicable only to embedding before encoding, not for the intended integrated coding and watermarking scenario (cf. Fig. 3.1).

For watermark detection in demosaicked image data, linear correlation detection on the fused image [124, 129] was proposed. A more accurate spatial domain detector for color images, such as the detector put forward by Sayrol et al. [162] based on the Cauchy model, might further improve detection performance. While we have investigated the impact of demosaicking on the embedding watermark, the watermark signal as an additional noise source certainly has an impact on the demosaicking process and hence the quality of full-resolution color image – certain demosaicking methods [65, 200, 201] perform joint denoising and demosaicking. A better understanding of the interplay between these components might lead to an improved image quality and watermark effectiveness.

The MPR distortion constraint [70] permits to efficiently incorporate geometric and perceptual restrictions into watermarking schemes for 2D vector graphics, similar to the JND constraint for raster data. Instead of using the Voronoi diagram as the basis for the MPR computation, a Delaunay triangulation could be employed in order to enable an extension of the proposed framework to 3D data. So far the framework handles only the problem of polygon line segments intersecting due to the vertex perturbation of the watermark signal. Other geometric constraints, such as the preservation of a particular alignment of line segments, e.g. parallelism, are essential for certain application areas but remain open work.

Our runtime performance analysis [96, 125] covers several major components of the detection process for additive spread-spectrum watermarking. Perceptual shaping of the watermark or multiplicative embedding [37] complicate the formulation of the detection statistics. Liu et al. [110] propose to transform the cover signal into a perceptually uniform domain where simple additive embedding can be employed and derive a locally-optimum detector for the GGD host signal model. The computational effort for perceptual modelling needs to be dissected in order to complete the picture of lightweight watermark detection approaches.

We have limited our investigations to additive spread-spectrum watermarking and largely ignored quantization-based embedding methods [32] which overcome the host signal interference problem [116]. Given the set of application problems investigated in this thesis, we belief that new, challenging topics arise when addressed from the angle of a different information modulation technique.

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Appendix A

Appendix

A.1 Breakdown of Authors' Contribution

Breakdown of authors' contribution for publications with more than one author. In case of equal contribution, the author names appear in alphabetical order on the publications. Andreas Uhl is thesis advisor/project leader of Roland Kwitt and Peter Meerwald, Martin Held is thesis advisor/project leader of Stefan Huber. Since the explicit contribution of an advisor and project leader cannot be stated for a single paper, it is omitted in the following breakdown.

	Contribution (in %)					
Publication	Stefan Huber	Christian Koidl	Roland Kwitt	Peter Meerwald	Martin Held	Andreas Uhl
P. Meerwald and A. Uhl. Toward robust watermarking of scalable video. In *Proceedings of SPIE, Security, Forensics, Steganography, and Watermarking of Multimedia Contents X*, volume 6819, page 68190J ff., San Jose, CA, USA, Jan. 2008				100		
P. Meerwald and A. Uhl. Blind motion-compensated video watermarking. In *Proceedings of the 2008 IEEE Conference on Multimedia & Expo, ICME '08*, pages 357–360, Hannover, Germany, June 2008				100		

Publication	Contribution (in %)					
	Stefan Huber	Christian Koidl	Roland Kwitt	Peter Meerwald	Martin Held	Andreas Uhl
P. Meerwald and A. Uhl. Scalability evaluation of blind spread-spectrum image watermarking. In *Proceedings of the 7th International Workshop on Digital Watermarking, IWDW '08*, volume 5450 of *Lecture Notes in Computer Science*, pages 61–75, Busan, South Korea, Nov. 2008. Springer				100		
R. Kwitt, P. Meerwald, and A. Uhl. A lightweight Rao-Cauchy detector for additive watermarking in the DWT-domain. In *Proceedings of the ACM Multimedia and Security Workshop (MMSEC '08)*, pages 33–41, Oxford, UK, Sept. 2008			50	50		
R. Kwitt, P. Meerwald, and A. Uhl. Efficient detection of additive watermarking in the DWT-domain. In *Proceedings of the 17th European Signal Processing Conference (EUSIPCO '09)*, pages 2072–2076, Glasgow, UK, Aug. 2009			50	50		
R. Kwitt, P. Meerwald, and A. Uhl. Lightweight detection of additive watermarking in the DWT–domain. Technical Report 2010–04, Dept. of Computer Sciences, University of Salzburg, Salzburg, Austria, May 2010. Available at `http://www.cosy.sbg.ac.at/research/tr.html`			50	50		
R. Kwitt, P. Meerwald, and A. Uhl. Lightweight detection of additive watermarking in the DWT-domain. *IEEE Transactions on Image Processing*, 20(2):474–484, Feb. 2011			50	50		
P. Meerwald and A. Uhl. Watermark detection on quantized transform coefficients using product Bernoulli distributions. In *Proceedings of the ACM Multimedia and Security Workshop, MM&Sec '10*, pages 175–180, Rome, Italy, Sept. 2010				100		
P. Meerwald and A. Uhl. Robust watermarking of H.264-encoded video: Extension to SVC. In *Proceedings of the Sixth International Conference on Intelligent Information Hiding and Multimedia Signal Processing, IIH-MSP '10*, pages 82–85, Darmstadt, Germany, Oct. 2010				100		
P. Meerwald and A. Uhl. Robust watermarking of H.264/SVC-encoded video: quality and resolution scalability. In H.-J. Kim, Y. Shi, and M. Barni, editors, *Proceedings of the 9th International Workshop on Digital Watermarking, IWDW '10*, volume 6526 of *Lecture Notes in Computer Science*, pages 159–169, Seoul, Korea, Oct. 2010. Springer				100		

Publication	Contribution (in %)					
	Stefan Huber	Christian Koidl	Roland Kwitt	Peter Meerwald	Martin Held	Andreas Uhl
R. Kwitt, P. Meerwald, and A. Uhl. Blind DT-CWT domain additive spread-spectrum watermark detection. In *Proceedings of the 16th International Conference on Digital Signal Processing (DSP '09)*, Santorini, Greece, July 2009			50	50		
R. Kwitt, P. Meerwald, and A. Uhl. Blind detection of additive spread-spectrum watermarking in the dual-tree complex wavelet domain. *International Journal of Digital Crime and Forensics*, 2(2):34–46, Apr. 2010			50	50		
R. Kwitt, P. Meerwald, and A. Uhl. Color-image watermarking using multivariate power-exponential distribution. In *Proceedings of the IEEE International Conference on Image Processing (ICIP '09)*, pages 4245–4248, Cairo, Egypt, Nov. 2009			50	50		
P. Meerwald and A. Uhl. Watermarking of raw digital images in camera firmware: embedding and detection. In *Advances in Image and Video Technology: Proceedings of the 3rd Pacific-Rim Symposium on Image and Video Technology, PSIVT '09*, volume 5414 of *Lecture Notes in Computer Science*, pages 340–348, Tokyo, Japan, Jan. 2009. Springer				100		
P. Meerwald and A. Uhl. Watermarking of raw digital images in camera firmware and detection. *IPSJ Transactions on Computer Vision and Applications*, 2:16–24, Mar. 2010				100		
P. Meerwald and A. Uhl. Additive spread-spectrum watermark detection in demosaicked images. In *Proceedings of the ACM Multimedia and Security Workshop, MMSEC '09*, pages 25–32, Princeton, NJ, USA, Sept. 2009. ACM				100		
P. Meerwald and A. Uhl. Watermark detection for video bookmarking using mobile phone camera. In B. D. Decker and I. Schaumüller-Bichl, editors, *Proceedings of the 11th Joint IFIP TC6 and TC11 Conference on Communications and Multimedia Security, CMS '10*, volume 6109 of *Lecture Notes in Computer Science*, pages 64–74, Linz, Austria, May 2010. Springer				100		

Publication	Contribution (in %) Stefan Huber	Christian Koidl	Roland Kwitt	Peter Meerwald	Martin Held	Andreas Uhl
S. Huber, R. Kwitt, P. Meerwald, M. Held, and A. Uhl. Watermarking of 2D vector graphics with distortion constraint. In *Proceedings of the IEEE International Conference on Multimedia & Expo (ICME '10)*, pages 480–485, Singapore, July 2010	33		33	33		
P. Meerwald, C. Koidl, and A. Uhl. Targeted attacks on quantization-based watermarking schemes. In *Proceedings of the 6th International Symposium on Image and Signal Processing and Analysis, ISPA '09*, pages 465–470, Salzburg, Austria, Sept. 2009		20		80		
P. Meerwald, C. Koidl, and A. Uhl. Attack on 'Watermarking Method Based on Significant Difference of Wavelet Coefficient Quantization'. *IEEE Transactions on Multimedia*, 11(5):1037–1041, Aug. 2009		20		80		

A.2 Curriculum Vitae

PETER MEERWALD

Personal Data	Date and place of birth: 18th April 1975, Salzburg, Austria Citizenship: Austrian	
Education	UNIVERSITY OF SALZBURG March 2007 - September 2010 PhD Program in Computer Science.	Salzburg, Austria
	UNIVERSITY OF SALZBURG September 1999 - May 2001 Graduate Program, Engineering Diploma in Applied Computer Science (with distinction).	Salzburg, Austria
	BOWLING GREEN STATE UNIVERSITY August 1998 - August 1999 Master of Science in Computer Science, GPA 4.0.	Bowling Green, Ohio
	UNIVERSITY OF SALZBURG September 1994 - June 1998 Undergraduate Program, Major: Computer Science, Minor: Legal Studies (Law).	Salzburg, Austria
	BUNDESHANDELSAKADEMIE II SALZBURG September 1989 - July 1994 Commercial High School, Matura passed with distinction.	Salzburg, Austria
Work Experience	POSTDOC RESEARCHER, INRIA BRETAGNE-ATLANTIQUE October 2010 - August 2011	Rennes, France
	SOFTWARE DEVELOPER, BCT ELECTRONIC GMBH September 2008 - August 2010	Salzburg, Austria
	LECTURER, SALZBURG UNIVERSITY OF APPLIED SCIENCES September 2007 - July 2010	Puch, Austria
	SENIOR RESEARCHER, UNIVERSITY OF SALZBURG March 2007 - September 2010	Salzburg, Austria
	LEAD SOFTWARE ENGINEER, SONY DADC AUSTRIA AG September 2001 - March 2007	Anif, Austria
	RESEARCH ASSISTANT, UNIVERSITY OF SALZBURG May 2001 - August 2001	Salzburg, Austria
	RESEARCH ASSISTANT, GERMAN DEPARTMENT August 1998 - August 1999	Bowling Green, Ohio
	APPLICATION DEVELOPER, ATOMIC AUSTRIA GMBH June 1996 - September 1997	Altenmarkt, Austria
	SOCIAL WORK (ZIVILDIENST), LEBENSHILFE SALZBURG February 1995 - December 1995	Salzburg, Austria

Appendix B

Errata

Unfortunately, a few minor errors regarding notation have been discovered after the papers reprinted in Chapter 2 have been published. Corrections are given below.

Table 1 in [94] and Table 3 in [91] containing the number of arithmetic operations for the computation of various detection statistics is incorrect; a correct version can be found in [96], Table II.

The initialization of the summation index in Eq. (10) of [91] should read $t = 1$, the correct equation thus is

$$\rho(\mathbf{y}) = \left[\sum_{t=1}^{N} \left. \frac{\partial \log p(y[t] - \alpha w[t], \hat{\gamma})}{\partial \alpha} \right|_{\alpha=0} \right]^2 \mathbf{I}_{\alpha\alpha}^{-1}(0, \hat{\gamma}). \tag{B.1}$$

The size of the UCID images is incorrectly stated as 768×512 pixels in [96]; the correct size is 512×384 pixels.

Appendix C

Implementation

Implementations of watermarking methods and scripts to regenerate results are available for download at `http://www.wavelab.at/sources`. Please consult the README files in the download packages for further information on the software dependencies and instructions how to run the code.