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 human visual system (HVS) characteristics appropriately in order to maximize the watermark energy in the low-frequency components of the images which are typically best preserved by image coding methods. However, only non-blind watermarking was considered so far [9, 8] . In this case, the original host signal can be used to completely suppress the interference of the host noise during watermark detection, thus a relatively small number of coefficients suffices for reliable detection.

In this paper we revisit the scalable watermarking problem. We aim for blind scalable watermark detection and design two schemes where the watermark information is embedded into multiple, diverse host signal components which are roughly aligned with resolution or quality enhancement layer components of a scalable bitstream. As the scalable bitstream of the watermarked image is transmitted, more and more host signal channels become available. We propose a multi-channel watermark detector which combines the detection results of the independent watermarks that are embedded in the different channels. The detection reliability should increase as more channels are transmitted. This allows to explicitly investigate the scalability of the watermark.

We propose to split the host image into independent subbands obtained using the DWT and $8 \times 8-$block DCT and model the different characteristics of the resulting host signal channels separately using Generalized Gaussian distributions (GGDs) [10]. We investigate the impact of scalable JPEG2000 bitstream adaption and JPEG coding on the global detection performance and present results for blind spread-spectrum watermarking.

In section 2, we discuss the application scenario for scalable watermarking, then turn to the multi-channel watermark detection problem in section 3. Based on this foundation, we design two blind spread-spectrum watermarking schemes with scalable detection in section 4. In section 5, we present experimental results and offer concluding remarks in section 6.

2 Application Scenario

In this paper we study the scenario that a watermark is embedded in the host image during content creation to denote the copyright owner before it is distributed. A single bit watermarking method can be employed to this end where the seed used to generate the watermark identifies the copyright owner. Before distribution, the watermarked content is compressed. Primarily, we are interested in JPEG2000 as a vehicle for image coding and bitstream adaption. Depending on the capabilities of the content consumer's presentation device, the compressed bitstream may undergo adaption before or during transmission in order to save bandwidth or processing time on the presentation device. Adaption of the coded bitstream might reduce the quality and/or resolution of the coded image, yet the watermark shall remain detectable [9]. See Figure 1 for an overview of the scenario. For comparison, we also examine JPEG coding. However, we do not use JPEG's scalability features but rather simulate adaption by coding separate bitstreams for the required resolution and quality settings since JPEG's hierarchical scalability (Annex J) shows poor performance.

Alternatively, in a different scenario, the watermark could also be embedded in the bitstream either at the distribution stage, during transmission or before presentation of the content. In all of these cases, the secret watermark key must be exposed to areas which are not under the control of the content creator. Hence, the problem of watermark key distribution must be addressed in technical ways or by assuming trust between the involved entities [11].

The presentation device tries to make a fast decision on the presence or absence of the watermark. If possible, the watermark should be detectable from the base layer. In addition, we expect an increase in detection reliability as more data is transmitted, improving the quality and resolution of the image. A blind watermark detector that can incrementally provide more reliable detection results when decoding scalable image data has not been discussed in the literature so far but seems highly desirable for resource-constraint multimedia clients, such as mobile devices.

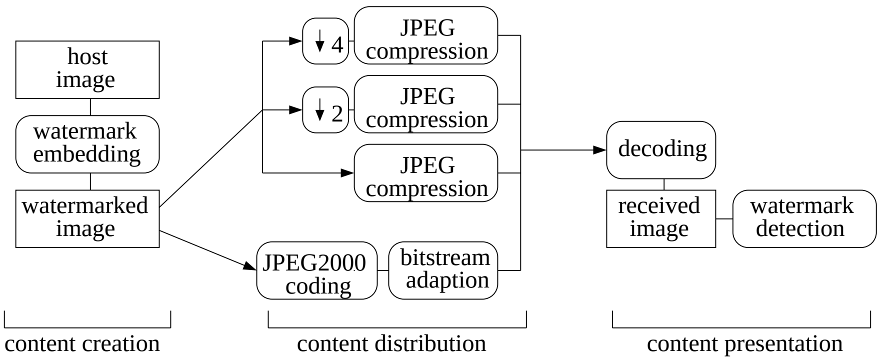


Fig. 1. The application scenario

2.1 Scalable watermarking

Lu et al. [12] claim that a watermark is scalable if it is detectable at low quality or low resolution layers. A number of watermarking methods have been proposed which allow for progressive detection [13–16, 8]. However, they either are non-blind [16, 8], or do not consider resolution scalability [13–15]. The impact of fully scalable image coding as enabled by JPEG2000 has not been investigated as far.

Piper et al. [8] refine Lu et al.'s definition and put forward two properties for scalable watermarking along with numeric measures: detectability and graceful improvement. The detectability property states that a watermark shall be detectable in any version of the scaled content which is of acceptable quality. Graceful improvement refers to the desirable property that as increased portions of the content data become available, the watermark detection shall become more reliable. Note that detection reliability may also be traded for faster detection [15], i.e. watermark detection utilizing a minimum number of host coefficients. Chandramouli et al. [17] have proposed a sequential watermark detection framework offering faster detection than fixed sample size detectors.

We distinguish between quality scalability on the one, and resolution scalability on the other hand. The robustness of a watermark to lossy coding at different bit rates, which is in most instances equivalent to a quantization attack in the transform domain, is very well studied. Resolution scalability poses more of a problem as spatial up- and down-sampling imposes also a synchronization issue. Scalable image coding must encode and transmit the perceptually most significant information first. To this end, the image data is decorrelated with a transform that concentrates the signal's energy. It is well known that the statistics can be drastically different, e.g. between the approximation and details subbands for the DWT or between DC and AC coefficients for the DCT, see Figure 2. Therefore, it is imperative to accurately model the host signal statistics per channel for effective blind watermark detection which we address in the next section relying on the GGD.

3 Watermark detection

We review optimal blind detection of an additive spread-spectrum watermark with the assumption that the transform domain host signal coefficients can be modeled with i.i.d Generalized Gaussian distributions [18, 10]. The next section extends the results to the multi-channel case.

For blind watermarking, i.e. when detection is performed without reference to the unwatermarked host signal, the host energy interferes with the watermark signal. Modeling of the host signal $\mathbf{x}$ is crucial for watermarking detection performance. The GGD given by

$$p(\mathbf{x}) = A \exp(-|\beta \mathbf{x}|^c), \quad -\infty < x < \infty \tag{1}$$

where $\beta = \frac{1}{\sigma_x}\sqrt{\frac{\Gamma(3/c)}{\Gamma(1/c)}}$ and $A = \frac{\beta c}{2\Gamma(1/c)}$ has been successfully used in image coding to model subband and DCT coefficients of natural images [19]. The shape parameter c is typically in the range of 0.5 to 0.8 for DCT and DWT coefficients, see Figure 2. The watermark detection problem on a received signal $\mathbf{y}$ can be formulated as a hypothesis test

$$\begin{aligned} H_0 :\ & y[k] = x[k] \\ H_1 :\ & y[k] = x[k] + \alpha w[k] \end{aligned} \tag{2}$$

where $\mathbf{x}$ represents the original signal, α denotes the watermark embedding strength and $\mathbf{w}$ is the pseudo-random bipolar watermark sequence generated from a secret key identifying the copyright owner. The optimal decision rule is

$$l(\mathbf{y}) = \frac{p(\mathbf{y}|H_1)}{p(\mathbf{y}|H_0)} = \frac{\prod_{k=1}^{N} \exp\left(-|\beta(y[k] - \alpha w[k])|^c\right)}{\prod_{k=1}^{N} \exp\left(-|\beta y[k]|^c\right)} \underset{H_0}{\overset{H_1}{\gtrless}} T, \tag{3}$$

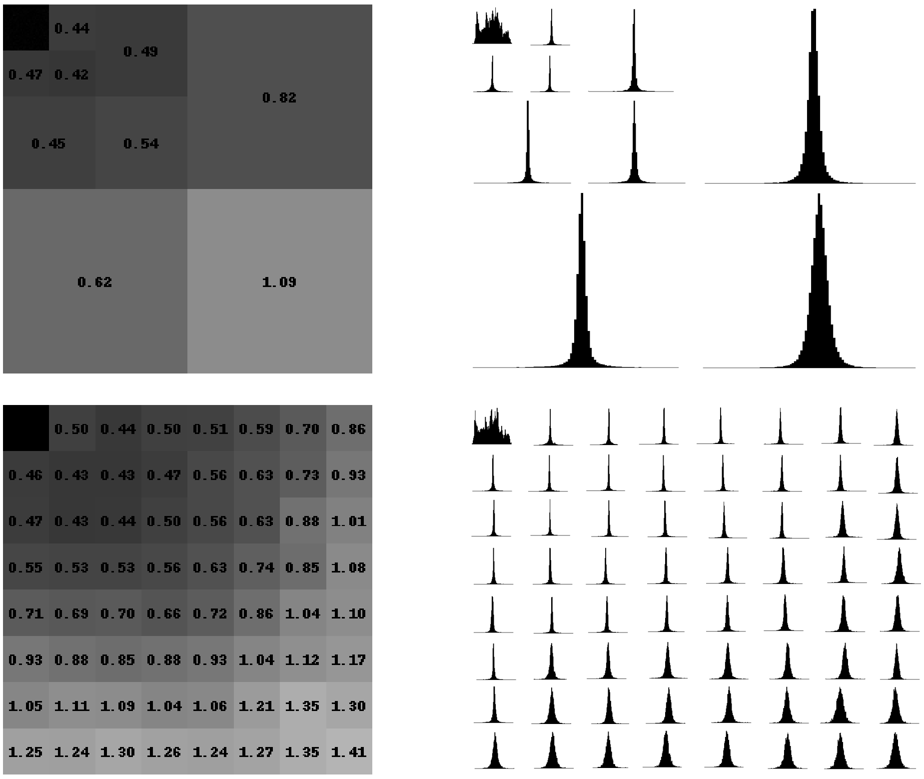


Fig. 2. GGD shape parameter per DWT subband (top) and DCT frequency subband (bottom); histograms of the subband coefficients are shown right (Lena image).

where $l(\mathbf{y})$ is the likelihood function with $\mathbf{x}$ modeled by a GGD and T is a decision threshold, usually set according to the Neyman-Pearson criterion. The detection statistic is then given by the log-likelihood ratio

$$L(\mathbf{y}) = \sum_{k=1}^{N} \beta^c (|y[k]|^c - |y[k] - \alpha w[k]|^c) \tag{4}$$

for which the PDFs under hypothesis H_1 and H_0 are approximately Gaussian with the same variance

$$\sigma^2_{L(\mathbf{y})|H_1} = \sigma^2_{L(\mathbf{y})|H_0} = \frac{1}{4} \sum_{k=1}^{N} \beta^{2c} (|y[k] + \alpha|^c - |y[k] - \alpha|^c)^2 \tag{5}$$

and mean

$$\mu_{L(\mathbf{y})|H_0} = \sum_{k=1}^{N} \beta^c (|y[k]|^c - \frac{1}{2} \sum_{k=1}^{N} \beta^c (|y[k] + \alpha|^c + |y[k] - \alpha|^c), \tag{6}$$

where $\mu_{L(\mathbf{y})|H_1} = -\mu_{L(\mathbf{y})|H_0}$ (see [18] for details). The probability of missing the watermark, P_m, is then given by

$$P_m = \frac{1}{2} \operatorname{erfc}\left(\frac{\mu_{L(\mathbf{y})|H_1} - T}{\sqrt{2\sigma^2_{L(\mathbf{y})}}} \right) \tag{7}$$

for a detection threshold T which is set to achieve a desired false-alarm rate denoted by P_{fa},

$$T = \sqrt{2\sigma^2_{L(\mathbf{y})}} \operatorname{erfc}^{-1}(2P_{fa}) - \mu_{L(\mathbf{y})|H_0}, \tag{8}$$

where erfc$(\cdot)$ is the complement of the error function [20].

3.1 Multi-channel detection

So far, we have only addressed the detection problem for one channel. However, in case we mark more than one channel, we have to discuss how to combine the detector responses and how to determine a suitable global detection threshold. We will consider the straightforward approach of simply summing up the detector responses of each channel (i.e. subband and/or frequency band), normalized to unit variance. In order to derive a model for the global detection statistic, we assume that the detector responses $L(\mathbf{y}_i)$, $1 \leq i \leq K$ for each of the K channels are independent. Further, the watermark sequences are independent as well. This assumption allows to exploit the reproductivity property of the Normal distribution, namely that the sum of Normal random variables is again normally distributed.

Formally, if we have K random variables $L(\mathbf{y}_1), ..., L(\mathbf{y}_K)$ which all follow Normal distributions with standard deviation σ_1,...,σ_K and mean $\mu_1, ..., \mu_K$ (under H_0), we obtain a global detection statistic

$$L_{global}(\mathbf{y}) = \sum_{i=1}^{K} \frac{L(\mathbf{y}_i) - \mu_i}{\sigma_i} \tag{9}$$

which again follows a Normal distribution with variance K. We can then determine a threshold $T_{global} = \sqrt{2} \operatorname{erfc}^{-1}(2P_{fa})$ for the global detector response in order to decide on the presence or absence of the watermark.

4 Two Watermarking schemes

Based on the multi-channel detection strategy outlined in the previous section, we now formulate a DCT-domain as well as a DWT-domain watermarking scheme. Our DCT-domain scheme is very similar to the method discussed in [18] and serves as a reference. Wavelet-domain watermarking algorithms can exploit the inherently hierarchical structure of the transform [21]. Especially, when watermark detection is integrated with image decoding from an embedded bitstream (such as JPEG2000), progressive watermarking detection can be easily achieved [22, 23].

The embedding strength α is determined for each channel such that a fixed document-to-watermark ratio (DWR) is maintained for each channel. More sophisticated watermark energy allocation strategies have been proposed [24], but are not adopted here to keep the scheme simple. Furthermore, perceptual shaping of the watermark is not used.

4.1 DCT-domain reference scheme

For the DCT-domain watermarking method, a 8×8-block DCT is computed on the host image. From each transform-domain block, the frequency bands 3 to 20 in zig-zag order are extracted and concatenated to construct the marking space. These bands correspond to the low- and mid-frequency range commonly used as marking space [18]. An independent, bipolar watermark $\mathbf{w}$ is added to the coefficients of each frequency band (denoted by $\mathbf{x}$), $y[k] = x[k] + \alpha w[k]$, where $1 \leq k \leq N$ with $N = \frac{W \cdot H}{64}$ and W,H correspond to the width and height of the image. Thus we have 18 channels with N coefficients each.

4.2 DWT-domain scheme

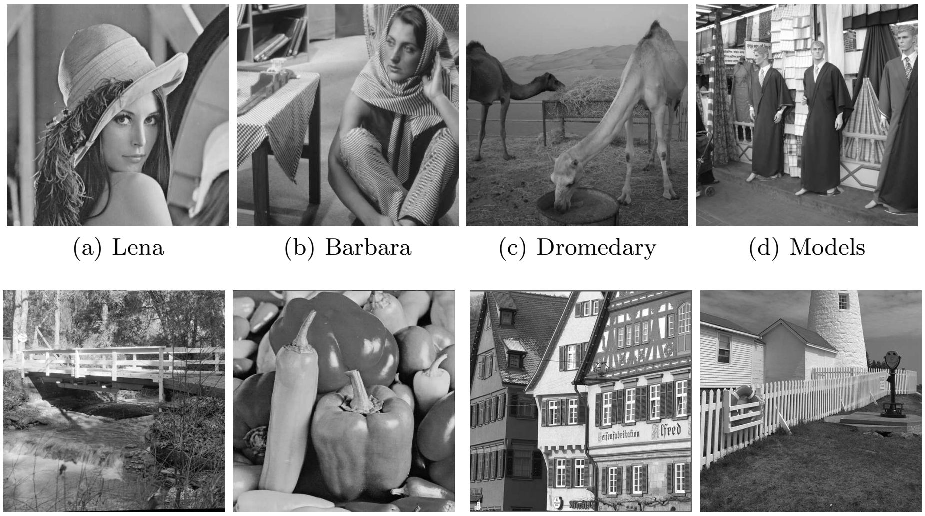
The DWT-domain scheme decomposes the host image using a $J-$level pyramidal DWT to obtain $3 \cdot J$ detail subbands and the approximation subband. The approximation subband is further decorrelated with a $8 \times 8-$block DCT. As above, an independent, bipolar watermark $\mathbf{w}$ is embedded in each of the separate signal components obtained by the transformations: we have $3 \cdot J$ channels relating to the detail subbands with $N = \frac{W \cdot H}{2^{2j}}$ coefficients, where $1 \leq j \leq J$ is the decomposition level of the subband, and 18 channels with $N = \frac{W \cdot H}{2^{2J+6}}$ coefficients, each relating to one concatenated DCT frequency band derived from the approximation subband.

4.3 Watermark detection

For watermark detection, first the GGD parameters β and c (the shape parameter) are computed for each channel using Maximum Likelihood Estimation (MLE), e.g. with the Newton-Raphson algorithm given in [25]. Next, the variance and mean of the detection statistic are determined per channel invoking Eq. 5 and 6, respectively. Eq. 9 permits to combine the individual per-channel detection results to obtain the global detector response and fix the global detection threshold. Note that the channels are independent and no order is imposed by the watermark detector, thus it can be applied bottom-up (i.e. integrated in a scalable decoder) or top-down (i.e. detector decomposes received image). The experimental results presented in the next section relate to the bottom-up case: base layer image data is incrementally augmented with resolution as well as quality enhancement data and we observe the combined watermark detection performance.

5 Experimental Results

Experimental results are reported on eight 512×512 gray-scale images, including six common test images and two images taken with a popular digital camera, see Figure 3.



(a) Lena (b) Barbara (c) Dromedary (d) Models

(e) Bridge (f) Peppers (g) Houses (h) Lighthouse

Fig. 3. Test images

We employ our DCT- and DWT-domain watermarking schemes presented in section 4. The document-to-watermark ratio (DWR) for each channel is fixed to 15 dB and 20 dB, for the DCT- and DWT-scheme, respectively, see Table 1 for the resulting PSNR. A two-level wavelet decomposition with biorthogonal 9/7 filters is used by the DWT algorithm. In the interest of reproducible research, the source code and image data is available at `http://www.wavelab.at/sources`.

We evaluate the performance of our watermarking schemes in the context of the application scenario depicted in Figure 1. We rely on the Kakadu 6.0 JPEG2000 implementation for constructing scalable bitstreams with quality layers ranging from 0.1 to 2.0 bits per pixel (bpp) from the watermarked test images. In the case of JPEG, we choose to simulate scalable bitstream formation for comparison: the watermarked image is downsampled with a bilinear filter and then compressed with a specific JPEG quality factor Q. Note that the methods described in JPEG Annex F, G, J are not used.

Watermark detection performance is evaluated in terms of the probability of missing the watermark (P_m), see Eq. 7, given a false-alarm rate (P_{fa}) of 10^{-6}. For each test image, we have generated 1000 copies with unique watermark seeds which have been subjected to JPEG and JPEG2000 coding. Watermark detec-

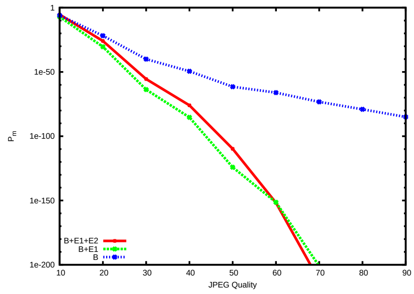
Image	Embedding		JPEG $Q = 90$		JPEG $Q = 30$		JPEG2000 2.0 bpp		JPEG2000 0.3 bpp	
	DWT	DCT	DWT	DCT	DWT	DCT	DWT	DCT	DWT	DCT
Lena	42.34	42.81	38.54	38.67	33.72	33.87	40.35	40.68	34.17	34.49
Barbara	39.98	40.61	37.24	37.39	29.82	29.91	38.40	38.68	28.82	28.88
Dromedary	46.25	46.09	40.30	40.16	33.85	33.89	43.94	43.81	33.88	33.95
Models	39.88	39.89	38.05	37.95	32.60	32.69	39.27	39.30	31.10	31.36
Bridge	39.79	38.60	35.61	35.08	27.83	27.74	34.91	34.54	25.24	25.26
Peppers	41.19	42.40	36.89	37.24	32.94	33.17	39.02	39.78	33.32	33.75
Houses	36.86	35.22	34.63	33.52	28.87	27.81	34.63	33.57	23.95	23.96
Lighthouse	40.00	37.44	36.41	35.04	29.84	29.53	37.29	35.70	28.27	28.28

Table 1. Average PSNR in dB after embedding as well as JPEG and JPEG2000 compression for the DWT and DCT scheme

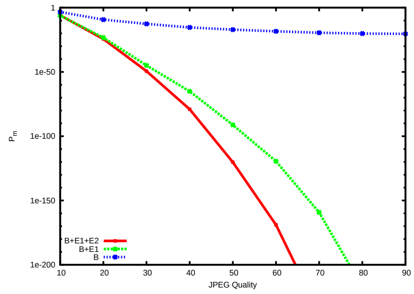
tion is performed after decoding the quality- and resolution adapted bitstream. A base layer (denoted B), one sixteenth the size of the full resolution image, and two resolution enhancement layers (denoted $E1$ and $E2$), each doubling the resolution, are examined at different quality layers. In case of the DCT watermark detector, the received image is upsampled to its original size before detection. For each setting, the 1000 detection results are used to estimate the mean and variance of the global detection statistic, in order to compute P_m.

In Figures 4 and 5, we observe the detection performance of our DWT watermarking scheme. The probability of missing the watermark (P_m) is plotted against a varying JPEG quality factor ($Q = 10, ..., 90$) and JPEG2000 bit rates ranging from 0.1 to 2.0 bits per pixel (bpp). Combining the detection response of the base layer with the first resolution layer result significantly boosts the detection performance, unless the decoded image has very poor quality ($Q \leq 20$ for JPEG, bit rate $\leq$ 1.0 bpp for JPEG2000). Only for the Barbara, Bridge, Houses and Lighthouse images, the second resolution layer contributes to an improvement of the detection result at high bit rates. As expected, the detection reliability increases also with improved quality; the effect is more pronounced for higher resolutions.

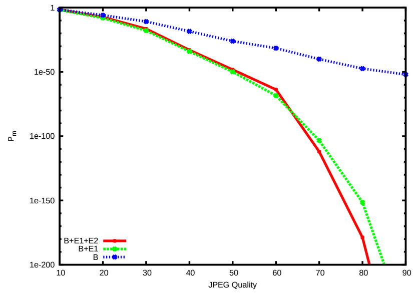
The DCT scheme fails to detect the watermark solely from the base resolution layer when using JPEG coding, see Figure 6. The first resolution aids in detection only for high quality images ($Q \geq 70$). However, with the second enhancement layer, reliable detection is achieved in all cases. Note that the DCT scheme outperforms the DWT detector for full-resolution images. In Figure 7 we observe that the DCT scheme's base-layer detection fares better with JPEG2000 coding. Both resolution layers improve the detection results. Note that the upsampling operation before detection must carefully match the downsampling due to JPEG2000's wavelet decomposition.



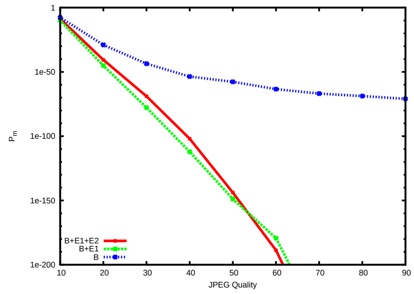
(a) Lena



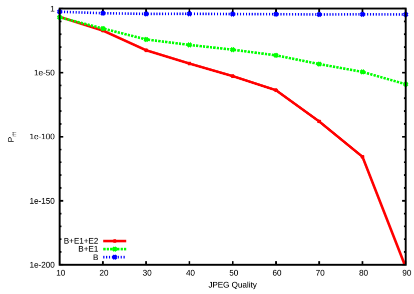
(b) Barbara



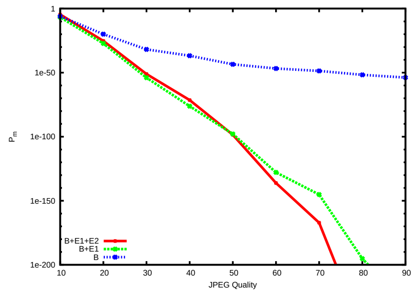
(c) Dromedary



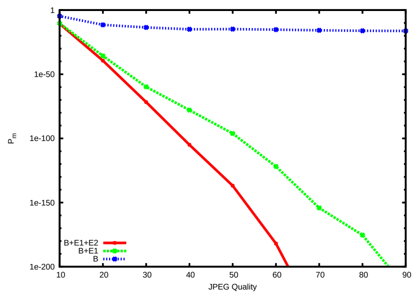
(d) Models



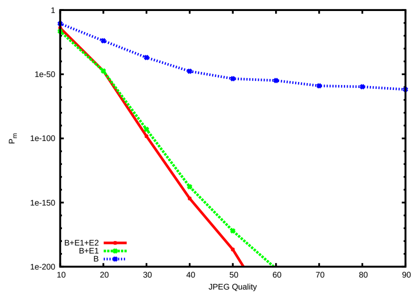
(e) Bridge



(f) Peppers

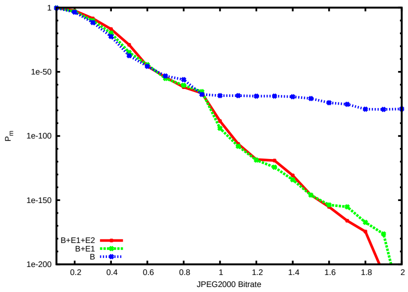


(g) Houses

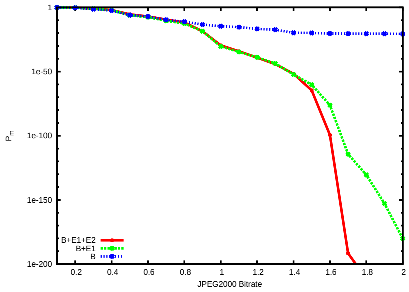


(h) Lighthouse

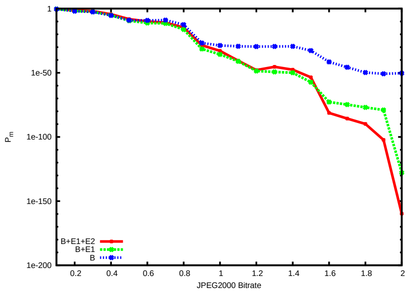
Fig. 4. Probability of miss (P_m) for the DWT scheme under resolution adaption and JPEG compression



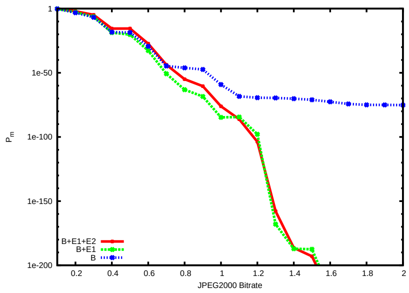
(a) Lena



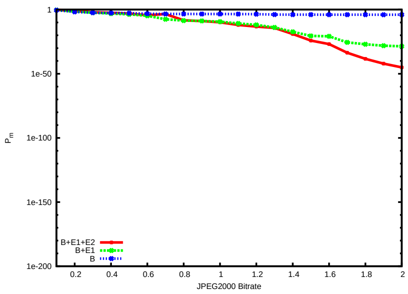
(b) Barbara



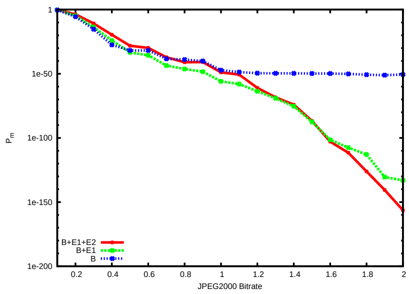
(c) Dromedary



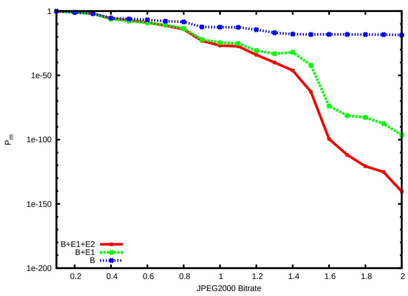
(d) Models



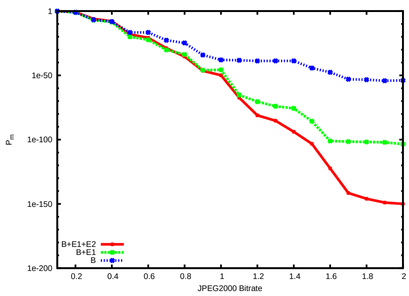
(e) Bridge



(f) Peppers

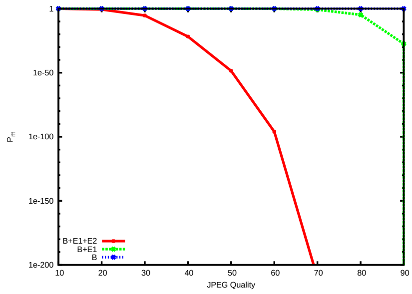


(g) Houses

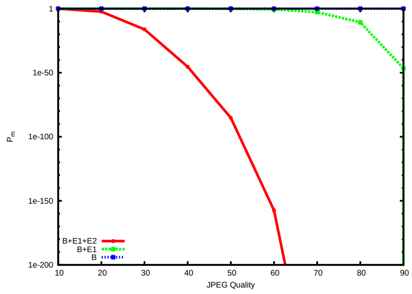


(h) Lighthouse

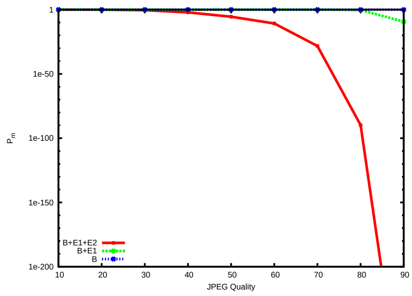
Fig. 5. Probability of miss (P_m) for the DWT scheme under resolution adaption and JPEG2000 compression



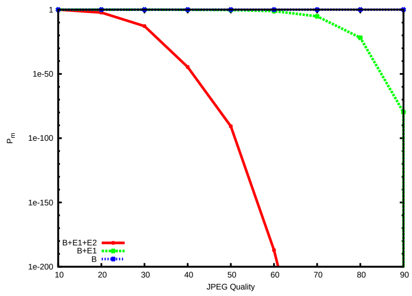
(a) Lena



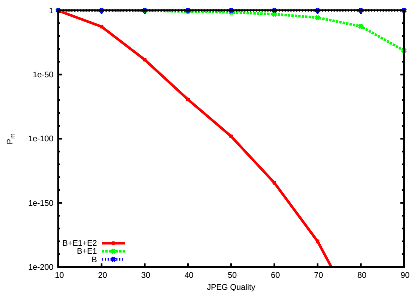
(b) Barbara



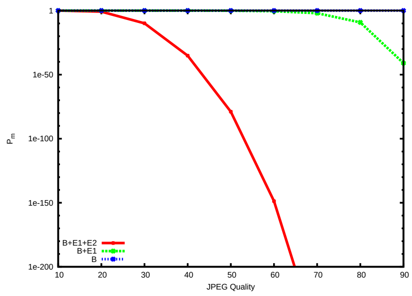
(c) Dromedary



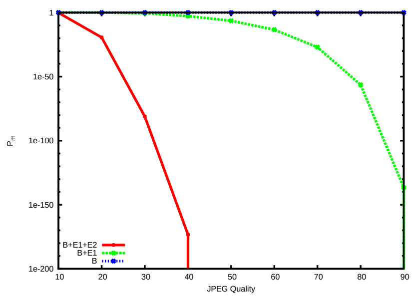
(d) Models



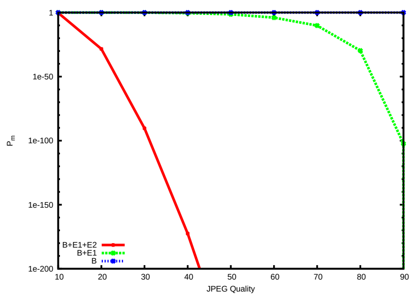
(e) Bridge



(f) Peppers

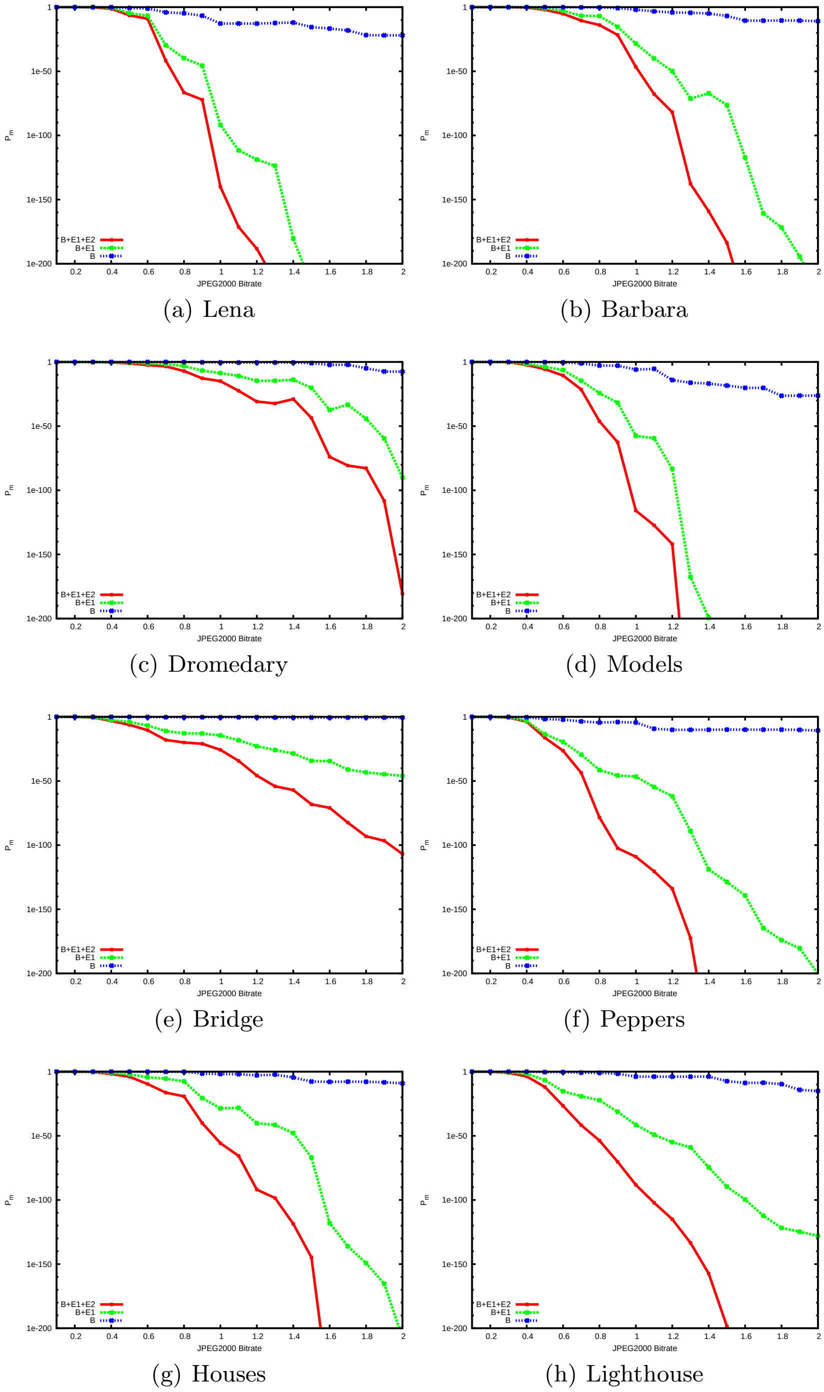


(g) Houses



(h) Lighthouse

Fig. 6. Probability of miss (P_m) for the DCT watermark under resolution adaption and JPEG compression



(a) Lena (b) Barbara (c) Dromedary (d) Models (e) Bridge (f) Peppers (g) Houses (h) Lighthouse

Fig. 7. Probability of miss (P_m) for the DCT watermark under resolution adaption and JPEG2000 compression

6 Conclusions

We have proposed two additive spread-spectrum watermarking schemes with blind, scalable detection and evaluated their detection performance in the context of scalable JPEG2000 and JPEG coding. Both schemes fulfill the properties of a scalable watermark set out by Piper et al., i.e protection of the base layer and graceful improvement as more image data is transmitted, to some extent. However, the DCT scheme fails to protect the base layer in the JPEG coding experiment and the DWT scheme does not benefit from the second resolution layer except for high bit rates. A more sophisticated watermark energy allocation strategy together with perceptual shaping might improve the detection performance and lift these deficiencies; we have not studied the impact of the selection of frequency bands on detection performance [26, 15].

The proposed multi-channel modeling and detection approach enables investigation of blind, scalable watermark detection which we believe will become increasingly important as scalable codec gain widespread use. Further work will incorporate temporal scalability for video watermarking applications and assess protection of scalable video.

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