A Hidden Markov Model-based Blind Detector for Multiplicative Watermarking

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***Abstract*—Nowadays, transmission of data via Internet has made illegal data distribution a major problem in digital world. Watermarking is known as a possible solution to protect digital data. In this work, we propose a blind detector for multiplicative watermarking of images in the wavelet domain. To this end, the vector-based hidden Markov model (HMM) is employed as a prior model for the wavelet coefficients of the host image. This model is known to provide an accurate fit to the distribution of the wavelet coefficients by capturing both their heavy-tailed marginal statistics and their inter-subbands and cross-orientations dependencies. Analytical expressions for the proposed watermark detector such as the mean and variance of the log-likelihood ratio test are derived and used to evaluate its performance. The performance of the proposed detector is shown to outperform that of the other detectors by providing higher detection rate and better imperceptibility of the embedded watermark. It is also shown that the proposed vector-based HMM detector under various attacks such as compression, rotation, filtering and noise, is more robust than other existing detectors.**

***Index Terms*—Hidden Markov model, optimum detector, maximum likelihood, watermarking.**

I. INTRODUCTION

Watermarking ensures copyright protection and digital data security. It is realized by embedding a piece of information into the host media which can be detected only by the rightful owner of the intellectual property. Embedding the watermark can be performed in spatial [1] or frequency domain [2]-[10]. The latter has shown to be more suited domain for watermarking. For instance, wavelet domain watermarking techniques have commonly been used in past few years [4], [6]-[10]. In some applications of watermarking, it may only be necessary to check the existence of a watermark in the received signal [2]-[6], whereas in the others, the watermark needs to be accurately extracted [9]-[10]. In a blind watermark detection, the host unwatermarked image need not be refereed at the detector and thus, statistical properties of the image coefficients are taken into account. So far, many works have focused on the statistical properties of these coefficients to design a blind watermark detector [2]-[10]. In [2], a watermark detection scheme has been proposed by assuming a generalized Gaussian (GG) distribution for the discrete cosine transform coefficients of images. An additive watermarking scheme in the wavelet domain and its corresponding detector have been proposed in [4] using the GG distribution. In [5], the Weibull distribution has been used for modeling the image Fourier coefficients in an image watermarking context. In [6], the Bessel K-form (BKF) distribution has been employed as a prior model for the wavelet coefficients to design a watermark detector.

The wavelet subband coefficients have been considered to be independent and modeled by marginal statistics such as GG, Cauchy or BKF. However, in [7], [9] and [12], it has been shown that the wavelet image coefficients have considerable dependencies across scales and inter-orientations. It has also been shown that joint statistical models such as vector-based hidden Markov models (HMM) [7]-[9], provide a very close fit to the empirical distribution of the wavelet coefficients. In view of this, additive and multiplicative watermark decoders have been proposed in [9] and [10], respectively. In case of a watermark detector, the vector-based HMM has been used to design a detector for additive watermarking [7],[8].

In this paper, we propose a blind multiplicative watermarking scheme and its corresponding detector based on the vector-based HMM as a prior for the wavelet image coefficients, which is an alternative to its additive counterpart. The proposed detector is designed using the maximum likelihood ratio criterion as a decision rule. The performance of the proposed detector, in terms of the receiver operating characteristics (ROC) curve, is investigated through several experiments and compared with that of the other existing detectors with or without presence of attacks.

The paper is organized as follows. Section II introduces the vector-based hidden Markov model. Section III presents the proposed watermarking scheme, both the multiplicative embedding and blind detection parts. Section IV includes the experimental results and finally Section V concludes the paper.

II. VECTOR-BASED HIDDEN MARKOV MODEL

Wavelet coefficients have been first modeled using vector-based hidden Markov model (HMM) in [11]. This modeling has been realized by considering the non-Gaussianity of the

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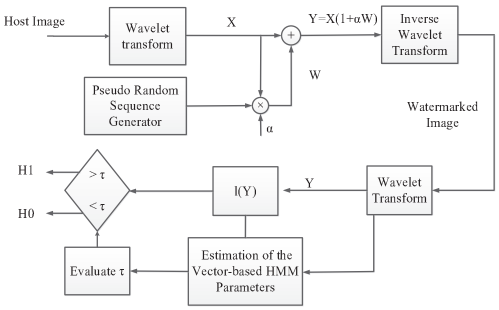


Fig. 1. Proposed watermarking scheme; embedding and detection parts.

wavelet image coefficients as well as the dependencies between the orientations. The probability density function of the M-state vector-based HMM for a wavelet coefficient is expressed as [7]

$$f_X(x_i) = \sum_{m=1}^{M} \frac{p_j^m \exp\left\{\frac{-1}{2}\left(x_i-\mu_j^m\right)^T \left(C_j^m\right)^{-1}\left(x_i-\mu_j^m\right)\right\}}{\sqrt{(2\pi)^3\left|C_j^m\right|}}, \tag{1}$$

where i represents the node on jth scale, μ_j^m and p_j^m are respectively the mean and probability of a coefficient in state m, and C_j^m is the covariance of the wavelet coefficients in different orientations $d:\{HL, LHorHH\}$.

III. WATERMARKING SCHEME

In this section, we introduce our proposed watermarking scheme. The proposed scheme is comprised of two stages; embedding and detection. In the former, the watermark is hidden in the host image, whereas in the latter, the presence of the watermark is examined. Fig. 1 illustrates the schematic of both the embedding and detection parts of the proposed scheme.

A. Multiplicative Watermark Embedding

In order to hide some piece of information in the host image, we employ a multiplicative watermarking approach. The grayscale image I of size $N_I \times N_I$ is decomposed using two-level wavelet transform. The subband X with the maximum variance in the second level is selected for hiding the watermark. Utilizing a pseudo random sequence generator, the watermark W is generated taking equiprobable values $\{+1,-1\}$. The coefficients in subband X are then modified according to the following multiplicative embedding approach as given by

$$Y = (1+\alpha W)X, \tag{2}$$

where α is controlling the strength of the watermark. In other words, α controls the invisibility of the watermark while ensuring the robustness of the watermarking scheme. By applying the inverse transform to the modified coefficients Y, the watermarked image is obtained.

B. Multiplicative Watermark Detection

In order to realize a blind watermark detection, we take advantage of the statistical properties of the image wavelet coefficients by employing the vector-based HMM for modeling the wavelet coefficients. To design the watermark detector, hypothesis testing is performed to check whether the watermark exists or not. This test can be formulated as follows

$$\begin{aligned} &H_1 : Y = (1+\alpha W)X, \\ &H_0 : Y = X \end{aligned} \tag{3}$$

where $X = (x_1, x_2, ..., x_N)$ and $Y = (y_1, y_2, ..., y_N)$ are respectively the selected subband coefficients of the original and watermarked images, $W = (w_1, w_2, ..., w_N)$ is the watermark sequence and N is the number of considered coefficients. The proposed detector is then developed using the log-likelihood ratio criterion as given by

$$l(\mathbf{y}) = \ln\frac{f_Y(\mathbf{y}|H_1)}{f_Y(\mathbf{y}|H_0)} = \ln\prod_{i=1}^{N}\frac{f_Y(y_i|H_1)}{f_Y(y_i|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \tau, \tag{4}$$

where τ is the threshold which is obtained using NeymanPearson criterion [2], and

$$f_Y(y_i|H_1) = \frac{1}{1+\alpha w_i} f_X\left(\frac{y_i}{1+\alpha w_i}\right). \tag{5}$$

Using (5), (4) can be simplified to

$$l(Y) = \sum_{i=1}^{N}\ln\left(\frac{1}{1+\alpha w_i}\frac{f_X\left(\frac{y_i}{1+\alpha w_i}\right)}{f_X(y_i)}\right) \underset{H_0}{\overset{H_1}{\gtrless}} \tau. \tag{6}$$

After inserting the M-state vector-based HMM distribution in (6), the log-likelihood becomes

$$l(Y) = \sum_{i=1}^{N}\ln\frac{\frac{1}{1+\alpha w_i}\sum_{m=1}^{M}\frac{p_j^m \exp\left\{\frac{-1}{2}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)^T\left(C_j^m\right)^{-1}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)\right\}}{\sqrt{(2\pi)^3\left|C_j^m\right|}}}{\sum_{m=1}^{M}\frac{p_j^m \exp\left\{\frac{-1}{2}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)^T\left(C_j^m\right)^{-1}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)\right\}}{\sqrt{(2\pi)^3\left|C_j^m\right|}}}. \tag{7}$$

At this stage, in order to evaluate the performance of the proposed detector, the probabilities of false alarm P_{Fa} and detection P_{Det} are related and the corresponding ROC curves are obtained. To this end, the mean and variance of $l(Y)$ need to be estimated under each hypothesis which in case of H_0 are obtained as

$$m_0 = E\left[l(Y|H_0)\right] = \sum_{i=1}^{N}\ln\frac{\sqrt{a_i b_i}}{c_i}, \tag{8}$$

where

$$
\begin{aligned}
a_i &= \sum_{m=1}^{M} \frac{p_j^m \exp\left\{\frac{-1}{2}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)^T \left(C_j^m\right)^{-1}\left(\frac{y_i}{1+\alpha w_i}-\mu_j^m\right)\right\}}{(1+\alpha)\sqrt{(2\pi)^3\left|C_j^m\right|}}\\
b_i &= \sum_{m=1}^{M} \frac{p_j^m \exp\left\{\frac{-1}{2}\left(\frac{y_i}{1-\alpha w_i}-\mu_j^m\right)^T \left(C_j^m\right)^{-1}\left(\frac{y_i}{1-\alpha w_i}-\mu_j^m\right)\right\}}{(1-\alpha)\sqrt{(2\pi)^3\left|C_j^m\right|}}\\
c_i &= \sum_{m=1}^{M} \frac{p_j^m \exp\left\{\frac{-1}{2}\left(y_i-\mu_j^m\right)^T \left(C_j^m\right)^{-1}\left(y_i-\mu_j^m\right)\right\}}{\sqrt{(2\pi)^3\left|C_j^m\right|}}.
\end{aligned}
\tag{9}
$$

and

$$\sigma_0^2 = E\left[\left(l(Y|H_0)-m_0\right)^2\right] = 0.25\left(\sum_{i=1}^{N} ln\frac{a_i}{b_i}\right)^2. \tag{10}$$

Similarly, the mean and variance under H_1 can be derived. The resulting ROC curve is then obtained as

$$P_{Det} = Q\left(\frac{\sigma_0}{\sigma_1}Q^{-1}\left(P_{Fa}-\frac{m_1-m_0}{\sigma_1}\right)\right), \tag{11}$$

where $Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(\frac{-t^2}{2}\right)dt$.

IV. SIMULATION RESULTS

To assess the performance of the proposed vector-based HMM watermark detector, experiments are carried out on a set of test images. The strength of the embedded watermark can be controlled by the watermark-to-signal ratio (WDR), given by

$$WDR = 10\log_{10}\frac{\sum_{i=1}^{N}\left(\alpha_i w_i\right)^2}{\sum_{i=1}^{N} x_i^2}, \tag{12}$$

where the numerator being the energy of the weighted pseudo-watermark bits and the denominator being the energy of the host wavelet coefficients. The peak signal-to-noise-ratio (PSNR) between the original and watermarked images is computed to examine the invisibility of the embedded watermark. The original and watermarked *Barbara* and *Peppers* images are shown in Fig. 2. From this figure, it is seen that the proposed watermarking algorithm provides high PSNR values for watermarked images, indicating the imperceptibility of the watermarking scheme.

Next, in order to validate the theoretical expression derived for the detector, we compare it against the experimental results obtained from the Monte-Carlo simulations. Fig. 3 depicts the theoretical ROC curves and corresponding experimental ones, obtained using the proposed detector for different WDR values. From this figure, it is seen that the ROC curves obtained theoretically are very close to the experimental ones; validating the expressions in (9) and (10).

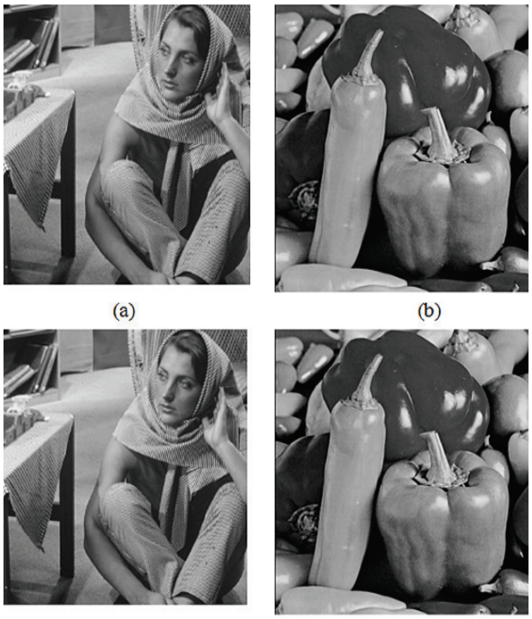

(a) (b)
(c) PSNR= 54.09 dB (d) PSNR= 53.43 dB

Fig. 2. Original (a)-(b) and the watermarked (c)-(d) images for WDR= -50 dB.

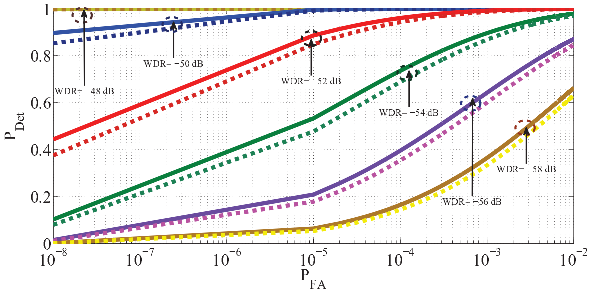
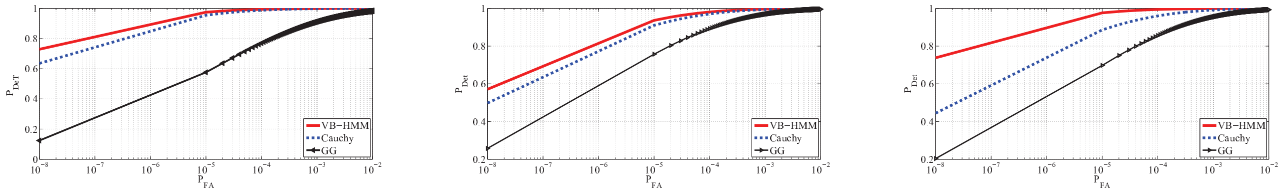


Fig. 3. Theoretical (solid) and experimental (dashed) ROC curves averaged over 96 test images for the multiplicative vector-based HMM detector for different values of WDR.

We now study the robustness of the proposed detector against various attacks. To this end, we obtain the ROC curves obtained from the proposed multiplicative watermark detector when images are contaminated by JPEG compression, median filtering and additive Gaussian noise. Fig. 4 depicts ROC curves obtained using the proposed watermark detector as well as those obtained using the Cauchy [3], and GG-based detectors [4], when the watermarked images with WDR = -50 dB are JPEG compressed with QF = 30, median filtered with a window of size 3 × 3, and corrupted by the Gaussian noise (SNR = 25 dB), respectively. From these figures, it can be seen that the robustness of the proposed multiplicative watermark detector is higher than that of the other detectors against any of the attacks considered.

Finally, we compare the performance of the proposed multiplicative detector with its additive counterpart [7], in terms of both PSNR values and the area under ROC curves. Table



(a) (b) (c)

Fig. 4. ROC curves averaged over a number of test images obtained using various detectors for WDR = -50 dB when image is (a) JPEG-compressed with QF = 30, (b) median filtered with a window size of 3 × 3, (c) contaminated by the Gaussian noise with SNR=25 dB.

I gives the area under ROC curve values for the proposed multiplicative detector and its additive version for a given P_{Fa} in $[0, 1]$, when the watermarked image is subjected to different kinds of attacks. From this table, it is observed that the proposed multiplicative vector-based HMM detector provides higher area under ROC curves values, indicating its superior robustness against the various attacks. It is also seen from this table that PSNR value provided by the multiplicative watermark detector is lower than that of the additive one. This can be attributed to the data-dependent nature of the multiplicative watermarking, which results in watermarked images having less imperceptibility than those resulted from the additive watermarking.

TABLE I

PSNR AND AREA UNDER ROC (AUROC) CURVES VALUES FOR THE REGION $[0, 1]$, AVERAGED OVER 96 TEST IMAGES FOR VARIOUS DETECTORS UNDER DIFFERENT ATTACKS WITH WDR = -40 dB.

	[7]	Proposed
PSNR (dB)	72.25	44.09
No attack	0.9405	1
JPEG QF = 20	0.9009	0.9820
Median filter 3 × 3	0.9370	0.9996
Gaussian noise SNR = 10	0.5909	0.9102
Rotation 2°	0.9115	0.9721
Gaussian filter 3 × 3	0.9386	0.9982

V. CONCLUSION

A blind multiplicative watermark detector based on the vector-based HMM has been proposed. The watermark has been embedded in the wavelet image coefficients using a multiplicative embedding approach. The detector has been formulated by employing a binary hypothesis test for the cases when there exists a watermark in the received image or not. This test has been reduced to a log-likelihood ratio test exploiting the statistical properties of the image coefficients. Closed-form expressions for the test statistic leading to the receiver operating characteristics curves has been derived. The performance of the proposed watermark detector has been investigated by carrying out several experiments and comparing the results with that of the other existing methods. The theoretical ROCs have been validated experimentally. Due to the data-dependent nature of the multiplicative watermarking, the resulting watermarked images have been shown to be less imperceptible than those resulting from the additive watermarking. However, proposed scheme employing the multiplicative embedding approach has been shown to provide improved watermark detection performance against various attacks as compared to other existing detectors, including its additive counterpart, by providing higher watermark detection rates with or without imposing any distortions.

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