A Channel-Dependent Statistical Watermark Detector for Color Images

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***Abstract*—Data security is a main concern in everyday data transmissions over the Internet. A possible solution to guarantee secure and legitimate transaction is via hiding a piece of tractable information into the multimedia signal, that is, watermarking. In this paper, we propose a new color image watermarking scheme and its corresponding detector in the sparse domain. The watermark detector aims at verifying the ownership and circumventing any unauthorized duplication of the digital data. Most of the existing color image watermarking schemes disregard the inter-channel dependencies. In view of this, we take into account the interchannel dependencies between RGB channels and interscale dependencies of the sparse coefficients of color images by employing the hidden Markov model. An efficient detector is designed by establishing a binary hypothesis test through which the existence of the hidden watermark is examined. Experiments are conducted to evaluate the performance of the proposed watermark detector for color images. The results show that the proposed detector provides detection rates higher than those provided by the other detectors, even in the presence of attacks. It is also shown that the proposed detector exhibits better performance in terms of the robustness of the embedded watermark.**

***Index Terms*—Multimedia security, copyright protection, statistical modeling, detection, receiver operating characteristics.**

I. Introduction

SECURE multimedia data transmission across Internet can be achieved by hiding a secret message behind the multimedia signals. At the receiver, the message can either be decrypted by entering the same key used to encrypt or its existence be verified. For instance, image watermarking is performed by embedding a secret message into the original image in order to ensure authentication and verify the ownership of the shared multimedia data. Although a great deal of effort has been made by the researchers for improving grayscale image watermarking techniques, color image watermarking has not received as much attention. In order for a color image watermarking scheme to be realized, a simple approach is to use a known grayscale watermarking technique and hide the watermark message only into the luminance channel. However, it has been shown that the performance of such a method for color images is not satisfactory and may be improved by taking advantage of the correlation between RGB channels.

So far, several watermarking schemes have been proposed for color images. For instance, a watermarking scheme has been developed in [1], where a global correlation has been accounted for RGB channels dependencies. In another work, a non-blind color image watermarking technique has been developed in the quaternion Fourier domain [2]. Using the full components of the quaternion Fourier transform, a watermarking scheme has been proposed in [3], which has been shown to be computationally expensive. A watermarking scheme for color images has been proposed in the wavelet domain in [4], where a visual masking has been applied to the luminance channel by ignoring the chrominance components. A reversible color image watermarking has been proposed in [5] by using the histogram bin shifting technique. A self-embedding watermarking scheme for JPEG-compressed color images has been proposed in [6]. In [7], a color image data hiding technique has been proposed by using color partitioning in which the extra data has been added by color replacement. A dual watermark extractor for color images has been proposed in [8] to achieve copyright protection and image authentication simultaneously. One watermark has been embedded in YCbCr color space in the wavelet domain and extracted blindly and the other one has been embedded into the RGB color space in a fragile manner. In [9], a blind color image watermarking decoder has been proposed using Hessenberg decomposition. In [10], an informed additive decoder in the wavelet domain has been proposed by using the HMM. However, this method is an informed watermarking technique, i.e., the HMM parameters have to be sent as side information to the receiver. In some applications of watermarking, like the proposed watermarking method, it may only be necessary to determine whether a specific watermark is present or not in the received signal, whereas in the others such as [10], the embedded watermark is considered as a hidden unknown message that needs to be decoded accurately. It should be noted that the role of a watermark detector is to verify the existence or absence of a hidden message in the original multimedia signal. In fact, it facilitates verifying the ownership and preventing any unauthorized duplication or distribution of digital data. In view of this, several image watermarking schemes in the sparse domain

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have focused on designing watermark detectors by establishing a valid decision rule. Among them, blind watermark detectors have received greater attentions due to the fact that in a communication system, there is no access to the original signal at the receiver. It has been shown that the performance of a blind watermark detector depends on the statistical model chosen for the image coefficients in the sparse domain [11]–[13]. For instance, a watermark detector has been designed in [11] in which the Weibull distribution has been employed for modeling purpose. A color image watermarking scheme has been proposed in [12], where the multivariate power-exponential distribution has been employed for modeling the wavelet coefficients as well as the dependencies across RGB channels of images. A color image watermarking scheme and the corresponding detector has been developed in [13], where the multivariate Cauchy distribution has been used for modeling the sparse domain coefficients. However, none of the above-mentioned works is highly robust under severe distortions and watermark message may not be detected in the presence of high-level noise or high compression ratio, especially when the watermark energy is low.

In view of this and to improve the watermark detection rate in the presence of severe distortions, in this work, we propose a new multiplicative multichannel watermark detector for color images by using the HMM in the contourlet domain in which, the dependencies of RGB channels are captured and used to design a watermark detector. To this end, a statistical decision rule is established by using a binary hypothesis test. Efficient closed-form expression for the likelihood ratio test is derived. To evaluate the performance of the proposed detector, several experiments are performed. The results of the proposed detector are compared to that of the other existing detectors in terms of the receiver operating characteristics (ROC) curve and the area under ROC (AUROC) curve. The proposed watermarking scheme is also assessed for its robustness by testing the watermarked images which undergo various kinds of distortions such as compression, filtering and noise.

This paper is organized as follows. In Section II, the proposed color image watermarking scheme including a watermark embedding process and a statistical watermark detector are presented. In Section III, simulation results are provided and finally Section IV concludes the paper.

II. Color Image Watermarking Scheme

In this section, we present our proposed multiplicative multichannel watermark detector for color images using the hidden Markov model (HMM) in contourlet domain. We work in the contourlet domain since the contourlet transform is known to provide an efficient representation for images and offer a higher degree of directionality with better sparseness than other transforms like wavelets which fails to recognize the smoothness of the contour. In addition, it offers a higher degree of directionality with better sparseness. Further, due to using iterated filter banks, it is computationally efficient than curvelet transform. In terms of the embedding strategy, we use the multiplicative approach since it has been shown that the multiplicative watermarking algorithms are image content dependent, and thus provide higher robustness as compared to the additive ones [12], [14], [15]. In addition, watermarking schemes employing the multiplicative embedding approach have been shown to provide improved watermark detection performance against various attacks [13].

TABLE I
KSD Values Between the Empirical Data and Various Distributions for the Second Level of Contourlet Transform of the R Color Channel

	D_1	D_2	D_3	D_4
Cauchy [13]	0.0391	0.0758	0.0593	0.0580
GG [15]	0.0419	0.0790	0.0605	0.0616
BKF [17]	0.0401	0.0694	0.0598	0.0567
HMM-Proposed	0.0311	0.0601	0.0574	0.0499

The proposed watermarking scheme comprises two stages; hiding the watermark bits into the original image and detecting the existence of the watermark from the received image. In the former, each individual channel of the original RGB color image is decomposed into several subbands, by using a multi-scale and multi-directional transform such as contourlet transform. In order to insert the watermark bits in each channel, the subband with the highest entropy in the second scale is selected. The corresponding subbands are vectorized in matrix $\mathbf{X} = [X^R, X^G, X^B]^T$ of size 1×3. The watermark embedding is performed as

$$\mathbf{Y} = \mathbf{X} + \theta\mathbf{X} \circ \mathbf{W}, \tag{1}$$

where $\mathbf{Y} = [Y^R, Y^G, Y^B]^T$ is the marked subband coefficients, $\mathbf{W} = [W^R, W^G, W^B]^T$ is the watermark, where we assume $W^R = W^G = W^B = W$, θ is a weighting factor that provides a trade-off between the robustness of the watermarking scheme and the imperceptibility of the embedded watermark and $\circ$ denotes Hadammard product. The weighting factor θ is obtained by taking into account the human visual system properties using the watermark-to-document ratio (WDR) by relating the energy of the weighted watermark bits to the energy of the contourlet coefficients of the selected subband as given by

$$WDR = 20log_{10}\frac{\sum_i \theta W_i}{\sum_i X_i}, \tag{2}$$

It should be mentioned that the weighting factor θ may be increased to a point where the watermark is still invisible, and yet it is still detectable. $\mathbf{W}$ is generated by using a pseudo random sequence generator giving equiprobable $\{-1, +1\}$ values. To obtain the watermarked image, the watermarked coefficients are then inverse transformed.

To design a watermark detector, we take advantage of the statistical properties of the coefficients of the color images. In other words, availability of the original image is not required and a blind watermark detector is realized. To this end, we fit the empirical distribution of the data to various known distributions to see how accurately they can model the distribution of the image subband coefficients. To this end, Table I gives the corresponding Kolmogorov-Smirnov distance (KSD) [14] in the second level of the contourlet transform having four directions $\{D_i\}_{i=1}^4$, for various distributions, namely, Cauchy [13],

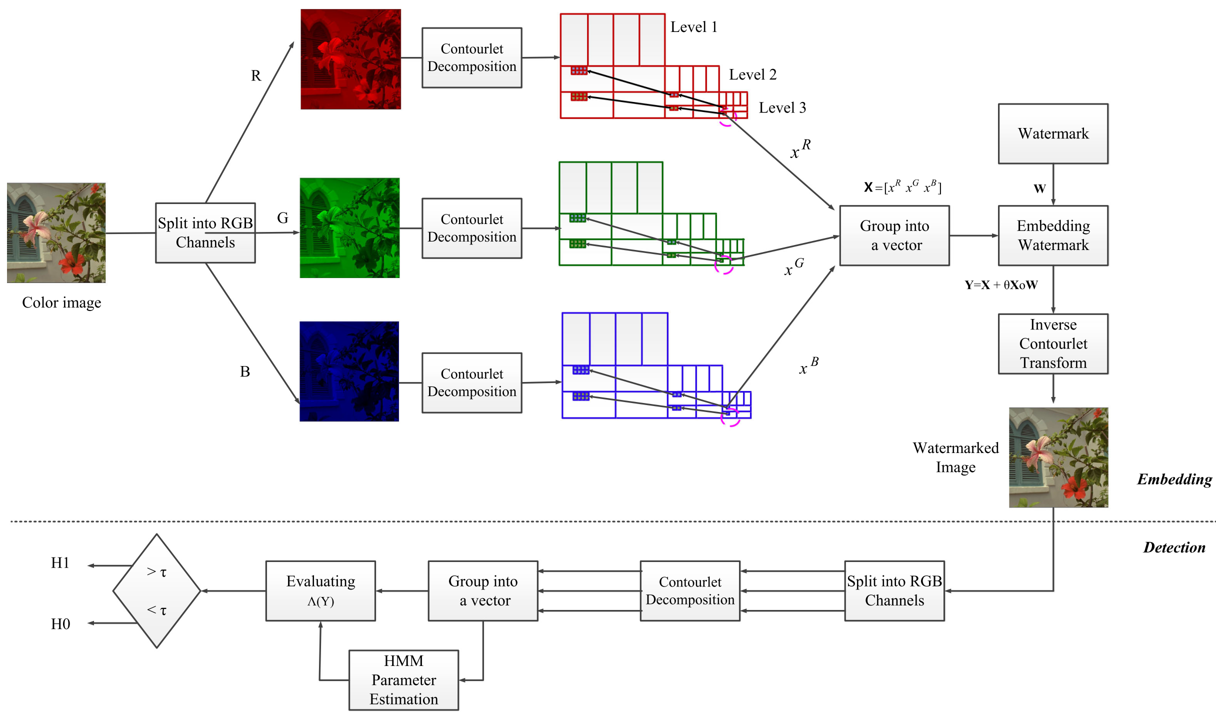

Fig. 1. Proposed color image watermarking scheme; embedding and detection.

generalized Gaussian (GG) [15], BKF [17] and hidden Markov model (HMM) [14]. The KSD metric is defined as

$$\mathrm{KSD} = \max \left| \int \left(P_f(f) - \hat{P}_f(f) \right) df \right|, \tag{3}$$

where $P_f(f)$ and $\hat{P}_f(f)$ denote the PDF of the random variable and empirical PDF of the data, respectively. It is seen from this table that the HMM provides lower values for the KSD metric, indicating that it can fit the coefficients of images more accurately than other distributions do. This can be attributed to the fact that HMM not only captures the peaky and heavy-tailed marginal distribution, but also takes into account the inter-scale dependencies of the image coefficients [14], [18], [19].

The contourlet coefficients of RGB channels are modeled using the HMM distribution [14], [16], [19]. The probability density function of a zero-mean HMM for color image coefficients is given by [14], [16]

$$f(\mathbf{X}_v) = \sum_{i=1}^{M} (2\pi)^{\frac{-3}{2}} \left|\mathbf{Q}_q^i\right|^{\frac{1}{2}} p_q^i \exp\left\{ \frac{-1}{2} \mathbf{X}_v^T \left(\mathbf{Q}_q^i\right) \mathbf{X}_v \right\}, \tag{4}$$

where M is the number of states, v represents the node on qth scale, p_q^i is the probability of a coefficient being in the state i, and $\mathbf{Q}_q^i$ is the precision matrix describing the cross correlation between the coefficients of the RGB channels. In order to estimate the parameters of the model, the expectation maximization algorithm is employed [20].

In the second stage, the watermark detection problem is formulated as a hypothesis test:

$$\begin{aligned} H_1 &: \mathbf{Y} = \mathbf{X} + \theta \mathbf{X} \circ \mathbf{W} \\ H_0 &: \mathbf{Y} = \mathbf{X} \end{aligned} \tag{5}$$

The two hypotheses concern the existence of a watermark, i.e., no watermark H_0 and watermark H_1. In order to maximize the probability of detection for a predefined probability of false-alarm, the detector is designed based on the log-likelihood ratio test given by [21] as

$$\Lambda(Y) = \ln \frac{f_Y(\mathbf{Y}|H_1)}{f_Y(\mathbf{Y}|H_0)} = \ln \prod_{k=1}^{N} \frac{f_Y(Y_j^R, Y_j^G, Y_j^B|H_1)}{f_Y(Y_k^R, Y_k^G, Y_k^B|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \tau, \tag{6}$$

where τ is the threshold and the PDFs under each hypothesis are defined as follows

$$\begin{aligned} f_Y(\mathbf{Y}|H_1) &= \frac{1}{(1+\theta W)^3} f_X(\mathbf{Y} \oslash (\mathbf{1} + \theta \mathbf{W})) \\ f_Y(\mathbf{Y}|H_0) &= f_X(\mathbf{Y}) \end{aligned} \tag{7}$$

where $\mathbf{1}$ and $\oslash$ denote the constant one vector and Hadammard division operation, respectively.

The log-likelihood ratio test can be simplified to (8), shown at the bottom of the next page. It should be noted that the watermark insertion process will not significantly change the statistical characteristics of the original image coefficients. Therefore, we insert the HMM for PDFs under both hypotheses. According to the central limit theorem, sum of a large number of samples, $\Lambda(Y)$, is assumed to follow the normal distribution with parameters (μ_0, σ_0^2) and (μ_1, σ_1^2), corresponding to the hypotheses H_0 and H_1, respectively. The parameters can theoretically be obtained under each hypothesis. For instance, under H_0, μ_0 and σ_0^2 are obtained using (9) and (10), respectively, shown at the bottom of the next page. Similarly, corresponding parameters under H_1 can be obtained, where $\mu_1 = -\mu_0$ and $\sigma_1 = \sigma_0$. Fig. 1

Fig. 2. Kodak test images.

illustrates the schematic of both the embedding and detection parts of the proposed scheme.

III. Simulation Results

In order to evaluate the performance of the proposed watermark detector, we carry out experiments on publicly available Kodak dataset, shown in Fig. 2. The peak signal-to-noise-ratio (PSNR) between the original and watermarked images is computed to assess the invisibility of the watermark. Fig. 3 shows the original and watermarked images when WDR $= -42$ dB. It can be seen from this figure that there is no noticeable difference between the watermarked and original images. The high PSNR values for the watermarked images also reinforce the proposed watermarking technique's imperceptibility.

At the receiver, we do not have access to the parameters of the original image, and thus, we estimate these parameters from the received signal. It is assumed that embedding the watermark bits will not considerably change the statistics of the signal if the watermark weighting factor is small. To validate this assumption, we investigate the influence of using the HMM parameters estimated from the contourlet coefficients of the watermarked image, y, instead of those estimated from the coefficients of the original image, x. To this end, we obtain the state probabilities for 2-state HMM for the original image x and watermarked image y. Tables II and III respectively give the parameters and mean square difference (MSD) between the corresponding elements of the precision matrices of x and y, for some of the test images when WDR is equal to -42 dB. It is seen from these tables that the values of the estimated parameters from watermarked coefficients, y, are very close to that of the non-watermarked coefficients, x. Therefore, in the watermark detection scheme, we use the parameters obtained for the watermarked image y instead of using those of x.

We now compare the theoretical mean $\mu_{0,\text{Theo}}$ and variance $\sigma^2_{0,\text{Theo}}$ of the test statistic under the hypothesis H_0, given by (9) and (10) to the experimental ones estimated from

$$\mu_{0,\text{Exp}} = \frac{1}{n}\sum_{i=1}^{n}\Lambda_i(Y)$$
$$\sigma^2_{0,\text{Exp}} = \frac{1}{n-1}\sum_{i=1}^{n}\left(\Lambda_i(Y)-\mu_{0,\text{Exp}}\right)^2 \tag{11}$$

by evaluating $\Lambda(Y)$ for $n = 1000$ random watermark sequences, i.e., Monte Carlo simulations. Table IV gives these values for the experimental and theoretical cases. It is seen from this table that the theoretical parameters are close to the empirical ones, indicating the accuracy of the closed-form mathematical expressions for the proposed detector.

According to the Neyman-Pearson criterion (NP) [21], the performance of a detector can be measured in terms of the

$$\Lambda(Y) = \sum_k \ln \frac{\frac{1}{(1+\theta W)^3}\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\left(\frac{-1}{2}\left(\mathbf{Y}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{Y}_k\right)\oslash(\mathbf{1}+\theta\mathbf{W})^{\circ 2}\right)\right\}}{\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\frac{-1}{2}\mathbf{Y}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{Y}_k\right\}} \underset{H_0}{\overset{H_1}{\gtrless}} \tau, \tag{8}$$

$$\mu_0 = E[\Lambda(\mathbf{Y})|H_0] = E[\Lambda(\mathbf{X})] = \sum_k \ln \frac{\sqrt{\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\left(\frac{-1}{2}\left(\mathbf{X}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{X}_k\right)\oslash(\mathbf{1}+\theta\mathbf{1})^{\circ 2}\right)\right\}.\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\left(\frac{-1}{2}\left(\mathbf{X}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{X}_k\right)\oslash(\mathbf{1}-\theta\mathbf{1})^{\circ 2}\right)\right\}}}{\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\mathbf{X}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{X}_k\right\}} - \frac{3}{2}\ln(1-\theta^2) \tag{9}$$

$$\sigma_0^2 = \text{var}[\Lambda(\mathbf{Y})|H_0] = E[(\Lambda(\mathbf{X})-\mu_0)^2] = \frac{1}{4}\left(\sum_k \ln \frac{\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\left(\frac{-1}{2}\left(\mathbf{X}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{X}_k\right)\oslash(\mathbf{1}+\theta\mathbf{1})^{\circ 2}\right)\right\}}{\sum_{i=1}^{M} p_q^i\left|\mathbf{Q}_q^i\right|^{\frac{1}{2}}\exp\left\{\left(\frac{-1}{2}\left(\mathbf{X}_k^T\left(\mathbf{Q}_q^i\right)\mathbf{X}_k\right)\oslash(\mathbf{1}-\theta\mathbf{1})^{\circ 2}\right)\right\}} + \ln\left(\frac{1-\theta}{1+\theta}\right)^3\right)^2 \tag{10}$$

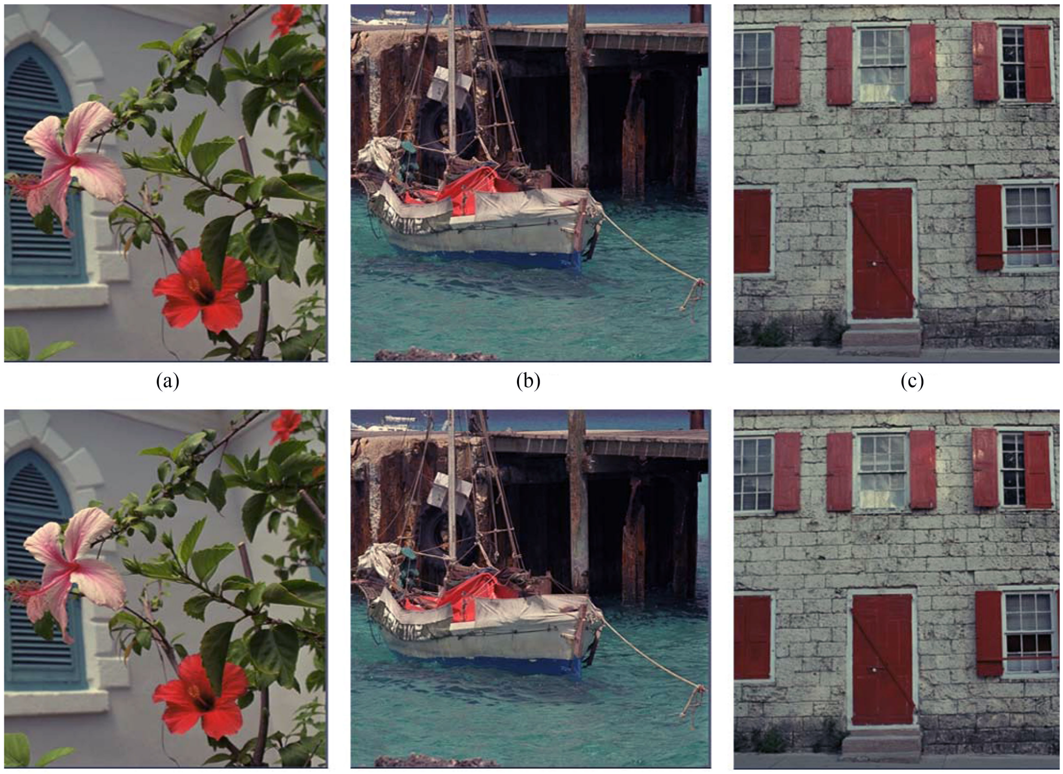

Fig. 3. (a)–(c) Original and (d)–(f) watermarked images.

TABLE II
HMM PARAMETER ESTIMATION FOR THE CONTOURLET COEFFICIENTS OF THE ORIGINAL IMAGE x AND THE CORRESPONDING WATERMARKED IMAGE y

Modeling		State Probability p_q^i	
Image	State i	1	2
Window	$\mathbf{x}$	0.3895	0.6103
	$\mathbf{y}$	0.3903	0.6083
Boat	$\mathbf{x}$	0.9039	0.1008
	$\mathbf{y}$	0.9124	0.0876
Flower	$\mathbf{x}$	0.4977	0.5022
	$\mathbf{y}$	0.4962	0.5037

TABLE III
MSD VALUES BETWEEN THE CORRESPONDING ELEMENTS OF THE PRECISION MATRICES Q_q^i FOR $\mathbf{x}$ AND $\mathbf{y}$

	MSD	
Image	State $m = 1$	State $m = 2$
Window	0.0001	0.0093
Boat	0.0054	0.0017
Flower	0.0000	0.0096

probabilities of false alarm and detection, leading to the ROC curves obtained as

$$P_{Det} = \frac{1}{2}\, erfc\left(2\, erfc^{-1}(P_{FA}) + \frac{\mu_0}{\sqrt{2}\sigma_0}\right) \tag{12}$$

TABLE IV
EXPERIMENTAL AND THEORETICAL VALUES FOR THE MEAN AND VARIANCE OF THE LOG-LIKELIHOOD RATIO

	$\mu_{0,\text{Exp}}$	$\mu_{0,\text{Theo}}$	$\sigma^2_{0,\text{Exp}}$	$\sigma^2_{0,\text{Theo}}$
Window	-2.45	-2.38	23.77	23.87
Boat	12.31	12.18	3.89	3.75
Flower	12.01	12.23	3.54	3.61
Average	4.76	4.93	17.87	17.18

where $erfc(.)$ is the complementary error function. It should be noted that the detection is performed by comparing $\Lambda(Y)$ with a threshold τ, where NP maximizes the probability of detection P_{Det} for a predefined probability of false alarm P_{FA}, which are given by

$$\begin{aligned} P_{Det} &= \frac{1}{2} erfc\left(\frac{\tau - \mu_1}{\sqrt{2\sigma_1^2}}\right) \\ P_{Fa} &= \frac{1}{2} erfc\left(\frac{\tau - \mu_0}{\sqrt{2\sigma_0^2}}\right) \end{aligned} \tag{13}$$

Fig. 4 depicts the theoretical and experimental ROC curves for WDR varying from -42 to -48 dB and P_{Fa} in $[10^{-8}, 10^{-2}]$. It is seen from this figure that the experimental ROC curves coincide with the theoretical ones, thus establishing the validity of the theoretical expressions obtained for the proposed detector.

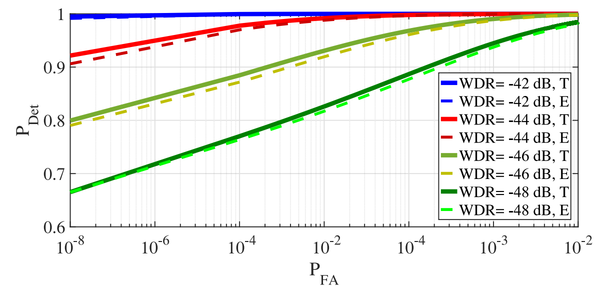

Fig. 4. Theoretical (solid) and experimental (dashed) ROC curves for the proposed detector for different values of θ.

TABLE V
AUROC VALUES ($\times 10^{-4}$) OBTAINED USING VARIOUS WATERMARK DETECTORS FOR THE REGION $[0, 10^{-4}]$

	AUROC
Proposed	0.9934
W-HMM [16]	0.9117
Cauchy [13]	0.8362
GG [15]	0.5637
BKF [17]	0.7286
MPE [12]	0.8043

The performance of the proposed HMM-based watermark detector is compared to that of the detectors using MPE distribution [12], multivariate Cauchy distribution [13], BKF distribution [17] and GG [15], in terms of the ROC curves and the robustness against various attacks. It is noted that the comparison is made within the context of the proposed watermark detection framework in the contourlet domian with a multiplicative embedding approach. The maximum likelihood method is employed to estimate the parameters of GG and multivariate Cauchy distributions, whereas the moments method is used to estimate the parameters of the BKF distribution. The reported results are averaged over all the images in the Kodak dataset. In order to compare the performance of the proposed watermark detector using HMM with that of the other detectors, the values of the AUROC are obtained. Table V gives AUROC values averaged over a number of test images for a given P_{Fa} in $[0, 10^{-4}]$ when WDR is equal to -42 dB. It is seen from this table that the proposed HMM-based detector provides the highest AUROC values, i.e., a detection rate higher than that of the other detectors, indicating its superior performance. The performance improvement of the proposed HMM-based detector can be attributed to the fact that the HMM takes into account both the marginal heavy-tailed property across-scale and inter-channel dependencies of the contourlet coefficients.

The robustness of the proposed detector is then studied against various attacks by obtaining the corresponding ROC curves, when images are contaminated by JPEG compression, additive Gaussian noise, median filtering and salt & pepper noise. Figs. 5–8 show AUROC values obtained using the proposed watermark detector as well as those obtained using the other

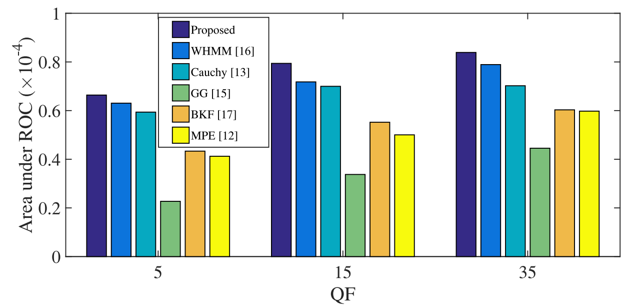

Fig. 5. AUROC values obtained using the proposed HMM-based watermark detector as well as those obtained using other existing detectors in presence of JPEG Compression.

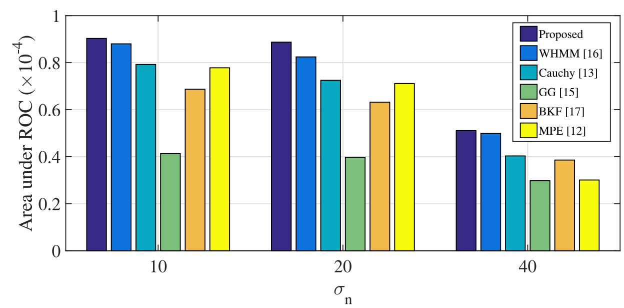

Fig. 6. AUROC values obtained using the proposed HMM-based watermark detector as well as those obtained using other existing detectors in presence of additive Gaussian noise.

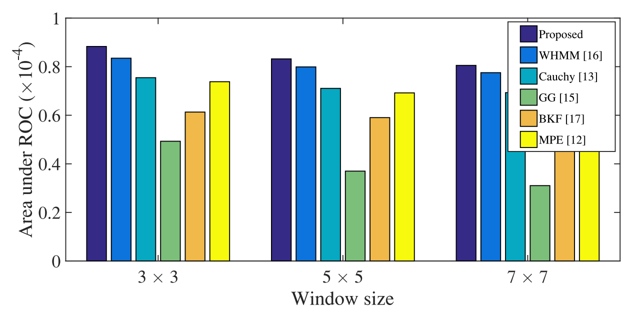

Fig. 7. AUROC values obtained using the proposed HMM-based watermark detector as well as those obtained using other existing detectors in presence of median filtering.

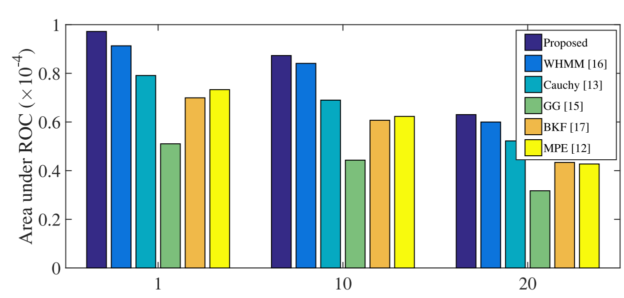

Fig. 8. AUROC values obtained using the proposed HMM-based watermark detector as well as those obtained using other existing detectors in presence of salt & pepper noise.

TABLE VI
AUROC VALUES ($\times 10^{-4}$) OBTAINED USING THE PROPOSED WATERMARK DETECTOR AND THOSE OBTAINED USING THE OTHER METHODS FOR CROPPING,GAUSSIAN FILTERING, GAMMA CORRECTION, ROTATION AND SCALING ATTACKS

	Proposed	WHMM	Cauchy	GG	BKF	MPE
	Cropping					
5%	0.9104	0.8567	0.8310	0.4887	0.69983	0.7846
10%	0.8045	0.7517	0.7369	0.4005	0.6118	0.7263
	Gaussian filtering					
3×3	0.9007	0.8854	0.7893	0.4453	0.7009	0.8032
5×5	0.8865	0.8032	0.7245	0.4202	0.6875	0.7854
7×7	0.8644	0.7769	0.6879	0.3394	0.4765	0.4988
	Gamma correction					
$\gamma = 0.9$	0.9032	0.8876	0.8004	0.5123	0.6998	0.7543
$\gamma = 1.1$	0.9007	0.8132	0.7993	0.4872	0.6435	0.7395
	Rotation					
$\theta = 0.5°$	0.9121	0.8921	0.7832	0.4832	0.8821	0.7832
$\theta = 1°$	0.9003	0.8764	0.7251	0.4263	0.8054	0.7324
$\theta = 2°$	0.8732	0.8021	0.6673	0.3998	0.7994	0.7001
	Scaling					
0.8	0.8548	0.7591	0.6554	0.3542	0.5889	0.6972
1.2	0.8003	0.7254	0.6118	0.3561	0.5982	0.6482

existing detectors, where the watermarked color images undergo JPEG-compression with quality factor (QF) varying from 5 to 35, Gaussian noise with the standard deviation σ_n varying from 10 to 40, median filter with the window sizes of 3×3, 5×5 and 7×7, and salt & pepper noise with the noise level p varying from 1 to 20. It is seen from Fig. 5 that the proposed HMM-based detector is more robust than the other detectors against JPEG compression. In particular, the proposed detector is capable of detecting the presence of the watermark in the challenging case of $QF = 5$ with a gain of 61.02%, 11.80%, 192.33%, 5.29%, and 53.18%, over the methods in [12], [13], [15], [16] and [17], respectively.

From Fig. 6, it is observed that the HMM-based detector exhibits more robustness in the presence of additive Gaussian noise than the other methods do. More specifically, when $\sigma_n = 40$, the proposed method provides an area under the ROC curve, a value of 0.5111, which is higher than the values yielded by the other methods. It should be noted that although all the detectors perform poorly when the noise level is high, the proposed detector still outperforms the other methods.

It is seen from Fig. 7 that compared to the other methods, the proposed watermark detector using HMM is more resilient when the watermarked image undergoes median filtering. It is noted that median filtering is regarded as a common attack in evaluating the performance of any watermarking scheme.

As seen from Fig. 8, the proposed detector is more robust than the other detectors against salt & pepper noise by providing higher values of AUROC. It is noted that the salt & pepper noise is regarded as randomly setting the pixel values in the watermarked images to be either 0 or 1.

The robustness of the proposed scheme is now evaluated against some other attacks including the geometric attacks such as rotation, scaling and cropping as well as Gaussian filtering and Gamma correction when WDR is equal to -42 dB. To this end, the watermarked images are cropped by 5%, 10%, rotated by $0.5°$, $1°$ and $2°$ degrees and scaled by factors of 0.8 and 1.2. In addition, the robustness of the proposed detector against Gaussian filtering with window sizes $3 \times 3, 5 \times 5, 7 \times 7$, and Gamma correction with gamma values 0.9 and 1.1, is examined. Comparison of the area under ROC curves for the region [0, 10^{-4}], averaged over a number of color test images of proposed detector against different kinds of attacks is given in Table VI.

It is noted that the proposed multiplicative detector using HMM is computationally efficient, since it requires only 1.04 sec of CPU time averaged over a set of images on an Intel Core i7 2.93-GHz personal computer with 8-GB RAM.

IV. CONCLUSION

In this work, a new multichannel watermark detector for color images has been proposed by using the HMM to capture inter-channel dependencies of the contourlet coefficients of the color images. The imperceptibility of the watermarking technique has been studied through experiments and shown no visible difference between the original and watermarked images. Theoretical expressions for test statistics have been validated experimentally. The performance of the proposed detector has been studied in terms of the ROC curves and area under ROC curves and compared with that of the other existing detectors. It has been shown that the proposed detector provides a performance superior to that of the methods based on power-exponential, Cauchy and GG distributions. The robustness of the proposed watermarking scheme against compression, filtering, noise, histogram modification and geometric attacks has also been studied and shown to be more robust than the other existing schemes.

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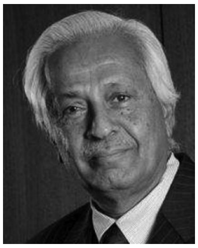

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