Robust Watermarking Procedure based on JPEG-DCT Image Compression

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Abstract— **A new procedure for watermarking in the 8x8 block-based DCT domain (used for JPEG compression) is proposed. The influence of JPEG quantization on watermarked coefficients and on watermark is considered. The criterion for coefficients selection is derived, providing robustness for an arbitrary quantization degree. The modified form of coefficients pdf leads to the class of modified optimal detectors. Theoretical results are illustrated on various examples. Efficiency of the proposed procedure is shown in the presence of different quantization degrees, and some other common attacks.**

I. INTRODUCTION

During the last decade various techniques for digital image protection have been proposed [1-3]. One of them that has been intensively developed is digital watermarking. Generally, it consists of two procedures: watermark embedding and watermark detection. Watermark embedding is usually based on an additive or multiplicative rule, while watermark detection can be blind or non-blind. Non-blind detection assumes presence of the original image. Since the original image is not always available, blind watermark detection is desirable. Watermark embedding and detection can be performed in the spatial domain or in the transform domains [4-6]. The DCT domain is one of the frequently used transform domains for image watermarking, particularly the 8x8 block-based DCT domain [6-10]. The block-based DCT provides lower computational costs compared to full-image DCT, and it is also suitable for the statistical modeling of coefficients [10]. The optimal (under certain assumptions) detector forms, based on different statistical models of coefficients, have been proposed in [7] and [8], where the generalized Gaussian function (GGF) has been used. The DCT coefficients from the 8x8 blocks are considered, and the detector form has been obtained by using the maximum likelihood test. Nonlinear detectors based on the Cauchy model have been proposed in [9] and [10] (the 8x8 block-based DCT coefficients are used as well). Note that the JPEG compression is based on these DCT coefficients. Quantization used in the JPEG compression algorithm influences the DCT coefficients. Thus, it can affect the efficiency of detection in watermarking. Quantization effects in watermark detection procedure have been intensively studied [11-13]. Briassouli and Strintzis in [13] provided a brief analysis of the quantization effects on nearly optimal Cauchy detector, showing that detector performance depends on watermark strength and quantization degree (step size). Also, the empirical measure of detector performance in the presence of quantization has been provided.

This paper represents an extension of the concepts introduced in [14]. A certain number of middle frequency coefficients from full frame DCT were selected for watermarking. However, the number and position of watermarked coefficients significantly varied from image to image, and were chosen experimentally. Thus, it required significant efforts to set up the values of these parameters and to obtain satisfying results. The goal of this paper is to provide an image independent procedure that enables robustness to an arbitrary quantization degree. The analysis of quantization effects leads to the analytical expression for selection of suitable DCT coefficients within 8x8 blocks. An appropriate approximation of coefficients probability density function (pdf) is introduced (a simplified form was used in [14], but without any theoretical justifica-

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tion). Based on the pdf model, the new class of optimal detectors is proposed. The detectors from the proposed class have shown very good performance in the presence of JPEG quantization, as well as in the presence of some other common signal processing techniques (attacks).

The paper is organized as follows. In Section II, the analysis of quantization effects on watermarked coefficients and watermark itself are provided. The criterion for watermarked coefficients selection is derived. The watermark embedding procedure is given in Section III. A modified class of coefficients pdfs is introduced, as well as a modified class of optimal watermark detectors based on the pdf approximations (Section III B. and C.). The criterion that provides robustness to any JPEG quantization degree, chosen in advance, is derived in Section IV. The efficiency of the proposed class of detectors is illustrated through the examples in Section V. The proposed detector forms are also tested on Gaussian and impulse noise, median filtering and image darkening. The concluding remarks are given in Section VI.

II. SELECTION OF THE COEFFICIENTS FOR WATERMARKING

A number of the existing watermarking approaches use middle or middle to low frequency bands for watermark embedding. The high frequency components are usually omitted, since they will be discarded by the JPEG compression [6]. However, some of the middle frequency coefficients could also be discarded, depending on the nature of the particular 8x8 block. Thus, in this work, we will not use a priori selection of the middle frequency coefficients. The idea is to determine a single parameter that defines a criterion for selection of coefficients suitable for watermarking. The same parameter will be used to control the robustness to an arbitrary JPEG compression degree by anticipating and avoiding coefficients that will be discarded [15].

In the presence of quantization, watermarked coefficients can be quantized to the same value as the original (non-watermarked) coefficients. This case is useless for detection. Namely, a watermark can be considered as detectable only if the values of quantized watermarked coefficient and quantized non-watermarked coefficient are different.

Therefore, the quantization effects are analyzed with respect to the following requirements:

1. Avoiding coefficients that will be eliminated by compression (quantization), i.e. quantized to zero;
2. Avoiding the possibility that a watermarked coefficient is quantized to the same value as the corresponding original coefficient.

Quantization of the JPEG compression is done by using the 8x8 matrix Q. Quantization degree is defined by the quality factor QF (higher QF means lower quantization step, i.e. compression degree). After the quantization, the coefficient on (i,j) position will be $K(i,j)Q(i,j)$, where:

$$K(i,j) = round\left(\frac{DCT(i,j)}{Q(i,j)}\right) , \qquad (1)$$

and $round(\cdot)$ stands for rounding to the nearest integer. To avoid the influence of quantization error, let us consider the case when the DCT coefficients are quantized before watermark embedding. In the following analysis the additive spread-spectrum watermark embedding procedure is considered.

The watermarked coefficient will not be discarded under quantization and will be considered as robust if $|K(i,j)Q(i,j)+w| \geq Q(i,j)/2$ holds, where w is the watermark value. We will consider the most critical case when coefficient and watermark are of opposite signs: $|(|K(i,j)Q(i,j)| - |\mathrm{w}|)| \leq |K(i,j)Q(i,j)+w|$. Thus, the more rigorous condition is:

$$|(|K(i,j)Q(i,j)| - |\mathrm{w}|)| \geq \frac{\mathrm{Q(i,j)}}{2}. \qquad (2)$$

It is reasonable to assume that the watermark strength should not exceed the strength of the coefficient. Therefore, the case $|\mathrm{w}| - |\mathrm{K(i,j)Q(i,j)}| \geq \frac{\mathrm{Q(i,j)}}{2}$ is not considered. Otherwise, the perceptual distortion is unavoidable. Now, the above relation can be written as:

$$|K(i,j)Q(i,j)| \ - \ |\mathrm{w}| \geq \frac{\mathrm{Q(i,j)}}{2} \qquad (3)$$

The watermarked coefficient will not be quantized to the same value as the original one if the following conditions are satisfied:

$$K(i,j)Q(i,j)+w < K(i,j)Q(i,j) \ - \frac{\mathrm{Q(i,j)}}{2} \ \text{or}$$
$$K(i,j)Q(i,j)+w \geq K(i,j)Q(i,j) \ + \frac{\mathrm{Q(i,j)}}{2}. \qquad (4)$$

Therefore, in order to be detectable, the watermark w should satisfy:

$$|w| \ > \frac{\mathrm{Q(i,j)}}{2}. \qquad (5)$$

According to (3) and (5), we have:

$$w \subset \left(-\left(|K(i,j)|-\frac{1}{2}\right)Q(i,j), -\frac{Q(i,j)}{2}\right) \cup$$
$$\cup \left(\frac{Q(i,j)}{2}, \left(|K(i,j)|-\frac{1}{2}\right)Q(i,j)\right). \qquad (6)$$

In order to satisfy (6), $|K(i,j)| \geq 2$ should be provided. Thus, the minimum value of K (floor value) used for coefficients selection is $K_f = 2$ ($|K(i,j)| \geq K_f$). As long as watermark values are within the interval defined by (6) and $|K(i,j)| \geq 2$ holds, the conditions of watermark detectability and coefficients robustness are satisfied. The magnitude of watermark can be significantly lower than the upper limit $(K_f - \frac{1}{2})Q(i,j)$, but it should not exceed it.

Note that the watermark strength is controlled by the values of quantization matrix. The watermark imperceptibility is obtained by using Q with the high quality factor QF that introduces negligible image distortion (having in mind that the matrix is created in accordance with the human visual system) [16].

III. PROPOSAL OF WATERMARKING PROCEDURE

A. Watermark embedding procedure

Based on the previous analysis, a watermark embedding procedure is defined here.

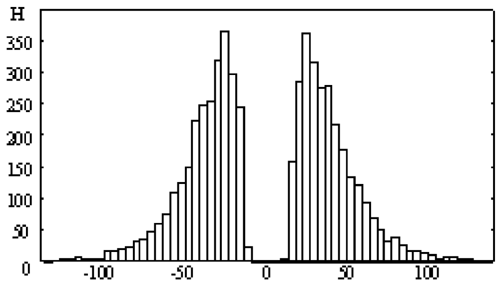

Fig. 1. The histogram of the watermarked coefficients

As stated before, the watermark is added to the already quantized coefficients in order to avoid the influence of quantization error. The quantization is defined by the high quality factor to prevent perceptual image degradation. Note that the quantization is done only on the coefficients used for watermarking, producing smaller distortion than in the case of high quality JPEG applied on the whole image.

The watermark will be embedded according to:

$$I_w = round\left(\frac{I}{Q}\right) \cdot Q + Qw. \qquad (7)$$

where I_w represents the watermarked coefficient, while Qw is the watermark created as a pseudo-random sequence, whose values satisfy (6). Indexes are omitted to simplify notation. The histogram of the watermarked coefficients is illustrated in Fig. 1.

It is important to note that the histogram of watermarked coefficients is not of the continuous form. Namely, there is a gap in the histogram on the positions of low amplitude coefficients. Thus, in the sequel the novel form of coefficients distribution function will be introduced.

B. Modified class of pdfs

Watermarked coefficients from the block-based DCT domain have usually been modeled by using GGF or Cauchy function [7-9] that can, in a simplified form, be written as:

$$G(I_w) = \begin{cases} A \cdot \exp\left(-\left|\frac{I_w}{\beta}\right|^{2c}\right) & \text{for GGF} \\ \frac{\gamma}{\pi(\gamma^2+(I_w-\delta)^2)} & \text{for Cauchy} \end{cases}, \quad (8)$$

where I_w represents the watermarked coefficients, $2c$ represents the shape parameter of GGF, $\beta = \sigma(\Gamma(1/2c)/\Gamma(3/2c))$ for standard deviation σ, while $A = \beta \cdot c/\Gamma(1/2c)$. In the case of Cauchy function, γ and δ are dispersion parameter and location parameter, respectively.

However, the coefficients with $|K(i,j)|<K_f$ are omitted in the proposed procedure. Thus, the histogram of coefficients used for watermarking does not have continuous form, Fig. 2. The decaying tails of the histogram correspond to the tails of function G (doted line in Fig. 2). Based on the numerous experiments, a flexible function F (thick line in Fig. 2) has been introduced to model the central part of the histogram:

$$F\left(\frac{I_w}{a}\right) = \left(\frac{I_w}{a}\right)^{2n} / \left(1 + \left(\frac{I_w}{a}\right)^{2n}\right), \quad (9)$$

where a defines the position of the pdf maximum, while n controls the decay of F between the maximum and the origin. Thus, the pdf of coefficients considered for watermarking can be approximated by:

$$p(I_w) \simeq F\left(\frac{I_w}{a}\right) \cdot G\left(\frac{I_w}{a}\right). \quad (10)$$

A simple procedure is used to estimate a value of parameter n in the function F. If the histogram of coefficients is denoted by H, then $H(a)$ represents its maximum value. The position of the first non-zero histogram value is b, while the corresponding value of the histogram is $H(b)$ (Fig. 2). Thus, having in mind the function F defined by (9) and the illustration in Fig. 2, the following relation holds:

$$\frac{H(b)}{H(a)} = \frac{F(b/a)}{1/2} \quad (11)$$

From (9) and (11), an approximate estimation of parameter n is obtained as:

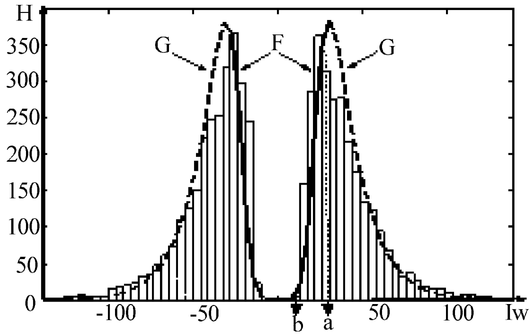

Fig. 2. Histogram and modeled pdf $p(I_w)$ of watermarked coefficients satisfying $|K(i,j)|>K_f$

$$n = round(\frac{1}{2}\log_{b/a}\frac{\frac{1}{2}\frac{H(b)}{H(a)}}{1-\frac{1}{2}\frac{H(b)}{H(a)}}). \quad (12)$$

Thus, the value of parameter n can be estimated by determining a, b, $H(a)$ and $H(b)$, for the considered image coefficients. The procedure for pdf modeling is tested for coefficients satisfying K_f=2 (QF=50 is used to provide better illustrations with wider gap) for different images. The histograms and pdf approximations for some of them are shown in Fig. 3. The estimated values of parameter n for all tested images are either 3 or 4.

C. Class of Modified Optimal Detectors

A number of watermark detectors based on continuous pdf form have been proposed in the literature. The optimal detectors based on continuous GGF and Cauchy functions have been designed for additive watermarking schemes in the DCT domain [6-9]. However, the central part of the pdf is significantly altered if the selected coefficients satisfy $|K(i,j)| > K_f$. Thus, the modified detector form should be provided.

The optimal detector form can be obtained according to [17]:

$$D = \sum_{i=1}^{L} w_i g_{lo}(I_{w_i}), \quad (13)$$

where L is the length of watermark w.

The function g_{lo} is defined as [9], [17]:

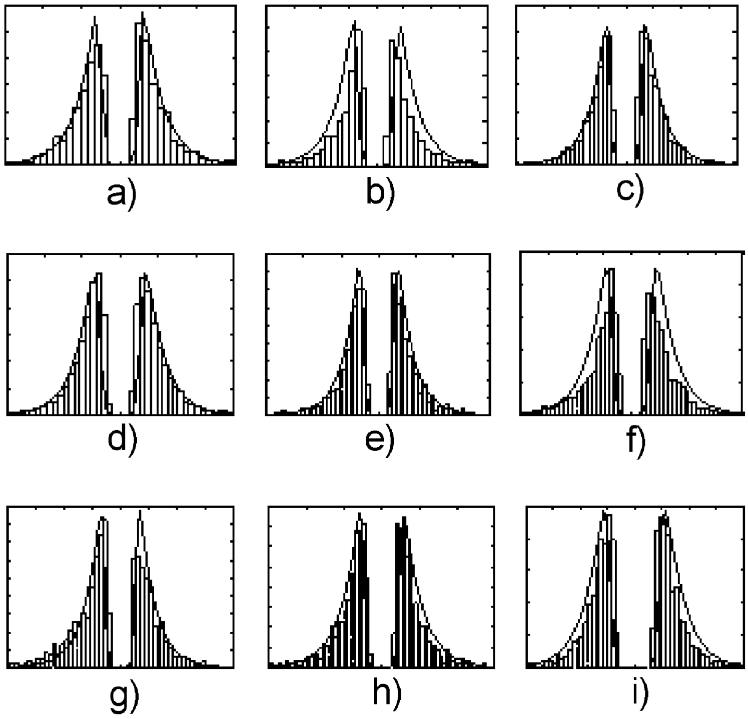

Fig. 3. Histogram and modeled pdf $p(I_w)$ of watermarked coefficients for: a) Lena n=3, b) Barbara n=4, c) Boat n=4, d) Bridge n=3, e) Elaine n=3, f) F16 n=3, g) Pepper n=4, h) Cameraman n=3, i) Lily n=3

$$g_{lo}(I_w) = -\frac{p^{'}(I_w)}{p(I_w)}, \qquad (14)$$

where $p(I_w)$ and $p'(I_w)$ represent the pdf of watermarked coefficients and its first derivative, respectively. The detector form defined by (13) and (14) corresponds to the well-known Locally Optimal (LO) Detector, which is well suited to watermark detection. For the proposed class of pdf approximations given by (10), the optimal detector forms can be defined as:

$$D_{opt}^{GGF} = \sum_{i=1}^{L} w_i\Big(\frac{c}{(\beta a)^{2c}} I_{w_i}^{2c-1} sgn\big(\frac{I_{\omega_i}}{\beta a}\big)^{2c} - \frac{n}{I_{w_i}(1+(\frac{I_{w_i}}{a})^{2n})}\Big),$$
$$D_{opt}^{C} = \sum_{i=1}^{L} w_i\Big(\frac{I_w}{a^2\gamma^2+I_w^2} - \frac{n}{I_{w_i}(1+(\frac{I_{w_i}}{a})^{2n})}\Big), \qquad (15)$$

for $G(I_w)$ modeled with GGF (D_{opt}^{GGF}) and Cauchy function (D_{opt}^{C}).

IV. ROBUSTNESS TO AN ARBITRARY JPEG QUANTIZATION DEGREE

In this Section, robustness of the proposed procedure to an arbitrary quantization degree will be considered. Assume that *QF*' is a JPEG quality factor that is chosen in advance by the ordering party of the watermarking procedure. To provide robustness for the chosen quantization *Q*' defined by *QF*', the criterion for coefficients selection should be modified. Here, it is supposed that *QF*' $\leq$ *QF* holds, where *QF* is used in the embedding procedure. This criterion allows us to preserve the form of watermarked coefficients histogram even after attack. As long as the pdf given by (10) is preserved, the proposed detectors provide reliable detection results.

In analogy with (3), the watermarked coefficients will be robust even after the quantization *Q*' (with quality factor *QF*') if the following relation is satisfied:

$$|K|\,Q - WQ \geq \frac{Q'}{2} \tag{16}$$

where W is the absolute value of the watermark, while matrix Q is used in the embedding procedure. The modified floor value $K_f{}'$ is:

$$K_f^{'} \geq W + \frac{Q'}{2Q}. \tag{17}$$

Thus, if Q (with an arbitrary high QF) is used in the embedding procedure, the robustness is provided for any Q' (with QF' $\leq QF$), as long as (17) is satisfied. This is one of the main advantages of the proposed procedure, since the full control over the robustness to any JPEG quantization level, required by the ordering party, can be assured in advance.

In the case of QF'$\leq$ QF, a certain percentage of embedded watermark will be detectable. The error e under quantization Q' could influence watermark detectability [13]. Namely, watermark can be considered as non-detectable if $Qw \in (-\frac{Q'}{2} - e, \frac{Q'}{2} - e)$, for positive e (analogy holds for negative e). Note that, according to the embedding procedure, Qw will not be in the interval $(\frac{-Q}{2}, \frac{Q}{2})$. The probability that Gaussian sequence is in the range $(-Q/2 \mp e, Q/2 \mp e)$ and $e \in (0, \pm Q/2)$, is estimated from the Gaussian pdf as: $P(e) = \frac{1}{Q}\int_0^{\frac{Q}{2}} \left(\mathrm{erf}\left(\frac{\frac{Q}{2}-\mathrm{e}}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{-\frac{Q}{2}-\mathrm{e}}{\sqrt{2}\sigma}\right)\right) de$.Thus, the probability of detectable watermark existence can be approximately calculated as:

$$P = \lambda(1 - P(e)), \tag{18}$$

where,

$$P(e) = \frac{1}{Q'-Q} \int_0^{\frac{Q'}{2}-\frac{Q}{2}} \left(\mathrm{erf}\left(\frac{\frac{Q'}{2}-\mathrm{e}}{\sqrt{2}\sigma}\right) - \right.$$
$$\left. -\mathrm{erf}\left(\frac{-\frac{Q'}{2}-\mathrm{e}}{\sqrt{2}\sigma}\right)\right) de. \tag{19}$$

Parameter σ represents the standard deviation of Qw: σ=$Q\sigma_w$, where $\sigma_w$is the standard deviation of watermark w. Since the watermark is part of the Gaussian sequence satisfying min(W) $\geq 1/2$, the scaling factor λ is:

$$\lambda = \frac{1}{1 - \mathrm{erf}\left(\frac{\mathrm{Q}/2}{\sqrt{2}\sigma}\right)}. \tag{20}$$

This scaling factor represents the reciprocal term of the probability that Gaussian random sequence is outside the range $[-1/2, 1/2]$, and it provides only an approximate calculation of (18).

Note that the proposed procedure, also, provides a completely detectable watermark for any quantization degree defined by QF' $\leq QF$.

V. EXAMPLES

In this section, the main advantages of the proposed procedure will be highlighted through various examples. It is shown that the robustness to any predefined JPEG quantization degree is assured by the introduced coefficients selection criteria. At the same time, the robustness is achieved under other common attacks. Furthermore, the introduced detectors class that follows from the novel form of coefficients pdf significantly outperforms some existing and commonly used detectors. Finally, we show that, compared with standard (commonly used) procedure in the 8x8 DCT domain, the proposed approach provides higher robustness, especially in the case of JPEG compressions.

Example 1: The watermark is embedded according to the procedure defined by (7). The DCT coefficients (except the DC), that satisfy K_f=2 and quantization matrix Q with the quality factor QF=80, are used. The watermark w (where $Q{\cdot}w$ satisfies (6)) is created as a part of the Gaussian sequence. In order to provide its imperceptibility, the watermark takes values within the range $(-3/2, -1/2) \cup (1/2, 3/2)$. The original and watermarked images (Lena and Pepper) are shown in Fig. 4. The peak signal to noise ratio (PSNR) is around 48 dB (it is the average value for 100 trials). In order to ensure the same number of coefficients for all test images, only 1000 coefficients satisfying K_f=2 are considered. Detectors from the proposed class produce reliable results even in this case. Similar performance is obtained if only the low or middle frequency coefficients satisfying K_f=2 are considered.

Performance of the proposed detectors' class is tested by using the following measure of detection quality [18]:

$$R = \frac{\overline{D}_{w_r} - \overline{D}_{w_w}}{\sqrt{\sigma^2_{w_r} + \sigma^2_{w_w}}}, \quad (21)$$

where $\overline{D}$ and σ^2 represent the mean value and the standard deviation of the detector responses, respectively, while notations w_r and w_w indicate the right and wrong keys (trials), respectively. The measure R corresponds to the detectability index used in the signal detection theory to evaluate decoding performance [19-20]. The watermarking procedure has been done for 100 different right keys (watermarks). For each of the right keys, R is calculated for 100 wrong trials. The probability of detection error P_{err} can be easily calculated by using measure R, as follows:

$$P_{err} = \frac{1}{2} erfc(\frac{R}{\sqrt{2}}), \quad (22)$$

where the normal distribution of detector's responses is assumed.

By increasing the value of R the probability of error decreases. For example, $P_{err}(R{=}3){=}0.0013$, $P_{err}(R{=}4){=}3{\cdot}10^{-5}$, while $P_{err}(R{=}5){=}2.6{\cdot}10^{-7}$.

The detectors from the proposed class are compared with some existing detectors forms (used in the literature): standard correlation detector, $D_1 = \sum_{i=1}^{L} sign(I_{wi}) \left|I_{wi}\right|^{c-1} w_i$ (for c=0.5) given in [8] and $D_2 = \sum_{i=1}^{L} \frac{2(I_{wi}-\delta)}{(I_{wi}-\delta)^2+\gamma^2} w_i$ given in [9]. Note that the standard correlation detector and detectors denoted as D_1 and D_2 could be considered as counterparts of the detectors from the proposed class. This comparison is made only to show that the existing detectors are not optimal for the proposed approach. The measures of detection quality are shown in Table I. Detectors that belong to the proposed class show better performances compared to their counterparts. Also, the proposed detectors have similar value of measure R for different images (Table I), which is an additional advantage. It is important to note that slight variations of parameters values of individual function G or F do not significantly influence detector performance as long as the resulting form $F{\cdot}G$ is preserved (we have also performed various experiments by using n=3 and n=4 in function F).

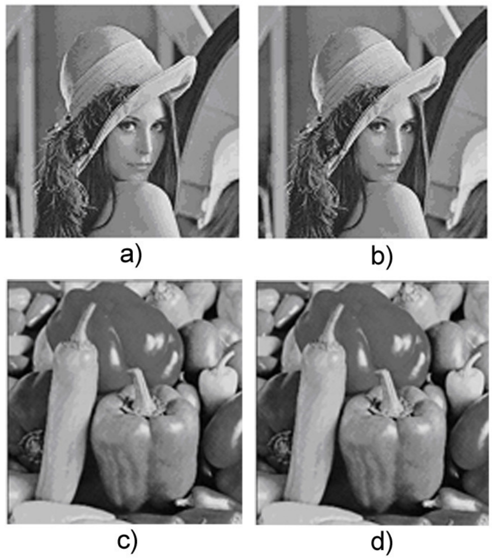

Fig. 4. Original (left) and watermarked images (right): a) Lena, b) Pepper

Example 2: Robustness of the proposed detectors to an arbitrary quantization degree is illustrated in this example. The watermark is embedded by using quantization matrix Q with QF=80 (as in the previous example). In order to provide robustness for each quantization degree defined by QF'>10, the coefficients are selected according to (17). Namely, since $\max_{i,j}(Q'(i,j)/2Q(i,j)) \leq 6.25$ for $\forall QF'$>10, the coefficients with floor value K_f=8 are used. Again, the watermarking procedure is tested using 100 right keys, while measure R (test statistic) is computed using 100 wrong trials (for each right key). The measures of detection performances for quantization degree QF=80 used in the embedding process, as well as for quantization degrees QF'=50, QF'=30 and QF'=15 are shown in Table II. Additionally, the proposed class of detectors is tested against the following attacks: median filtering, Gaussian noise with variance 0.003, impulse noise with variance

TABLE I
MEASURES OF DETECTION PERFORMANCES

Image	R for D_{opt}^{GGF}			R for D_{opt}^{C}	R for Standard Correlator	R forD_1	R forD_2
	c=0.25	c=0.5	c=1				
Lena	11.85	12.1	12.1	12.2	2.6	4	3.5
Pepper	11.1	11.3	11.4	11.3	2.9	3.6	3.25
Lake	11.4	11.6	12	11.5	4.4	4.2	3.7
Barbara	10.4	10.5	10.3	10.5	2.8	3.7	3.2
Elaine	14.2	14.5	14.9	14.5	4.3	4.5	4
Boat	12.2	12.5	12.9	12.5	3.7	4.6	4.2
F16	10	10.2	9.4	10.2	2.6	3.9	3.6
Baboon	11.2	11.4	12.3	11.3	4.8	4.9	3.9

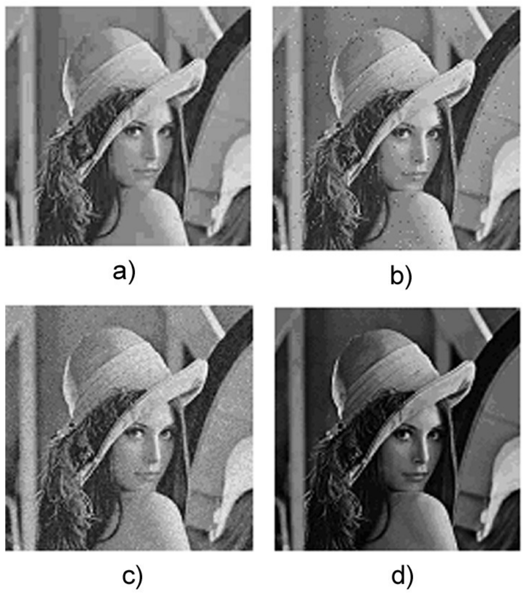

Fig. 5. Lena, sample image from large set of tested images a) quantization with QF'=15, b) impulse noise with variance 0.007, c) Gaussian noise with variance 0.003, d) darkening with factor 0.4

0.007 and image darkening with factor 0.4 (Fig. 5). In all cases the proposed detectors have produced satisfactory results (Table II).

Note that the detectors denoted as D_1, D_2 and standard correlation detector are useless in the case of the considered coefficients' pdf. Namely, they can not produce the reliable performance like in the case of continuous pdf.

Example 3: In the previous examples it has been shown that for the proposed selection of coefficients, the class of modified detectors outperforms their counterparts based on the continuous pdf. These results are expected, since the pdf of watermarked coefficients is not of the continuous form. However, to provide a fairer comparison, we have considered the following procedures:

1. Proposed procedure - The coefficients satisfying K_f=4 (except the DC) from the 8x8 blocks are used (approximately between 4000 and 6000 coefficients). The obtained SNR is around 47 dB. The watermark detection is performed by using the detectors from the proposed class ($D_{opt}^{GGF}$and D_{opt}^{C}).
2. Standard procedure (commonly used additive procedure in the 8x8 DCT domain) - All middle frequency coefficients from 8x8 DCT blocks are used for watermarking (22050 coefficients for images of size 256x256). A standard additive watermark embedding procedure is performed, with the same SNR (47 dB) as in the previous case. The detection is tested by using existing detectors denoted as D_1 and D_2, since in this case the pdf of watermarked coefficients is a continuous function.

Both procedures are tested on different JPEG quantization degrees, Gaussian noise, impulse noise and median filtering. The comparison of the procedures is made in terms of their ability to provide reliable detection performances. As a parameter for comparison, measures of detection performance R are given

TABLE II
MEASURES OF DETECTION PERFORMANCES

Lena	R forD_{opt}^{GGF}			R for D_{opt}^{C}	R for Standard Correlator	R for D_1	R forD_2
	c=0.25	c=0.5	c=1				
QF=80	8.1	8.6	8.5	8.5	1.9	1.7	1.9
QF'=50	7.8	8.4	8.4	8.3	1.8	1.5	1.8
QF'=30	5.6	6	6.4	6	1.7	1.4	1.6
QF'=15	3.8	4	4	3.9	1.5	1.2	1.4
Median 3x3	3.14	3.19	3.53	3.18	1.6	1.6	1.6
Impulse noise	3.7	3.8	4.11	3.8	1.7	1.6	1.8
Gaussian noise	3.1	3.1	3.3	3.1	1.6	1.6	1.8
Darkening	2.9	2.9	3.2	3	1.7	1.6	1.8
Pepper	R forD_{opt}^{GGF}			R for D_{opt}^{C}	R for Standard Correlator	R for D_1	R forD_2
	c=0.25	c=0.5	c=1				
QF=80	7.8	8.2	8.3	8.2	1.9	1.8	1.9
QF'=50	7.4	7.9	8	7.8	1.9	1.6	1.7
QF'=30	6	6.3	5	6.2	1.8	1.5	1.6
QF'=15	3.5	3.6	3.2	3.7	1.5	1.4	1.5
Median 3x3	2.9	3.1	3.3	3.1	1.6	1.5	1.5
Impulse noise	4	4.1	4.4	4.1	1.8	1.6	1.7
Gaussian noise	3.1	3.2	3.5	3.2	1.8	1.7	1.7
Darkening	4.3	4.5	4.8	4.5	1.8	1.6	1.7
Lake	R forD_{opt}^{GGF}			R for D_{opt}^{C}	R for Standard Correlator	R for D_1	R forD_2
	c=0.25	c=0.5	c=1				
QF=80	9.9	10.4	10.8	10.4	2.7	2.7	2.8
QF'=50	9.2	10	10	9.9	2.5	2.6	2.6
QF'=30	7.2	7.6	8	7.5	2.1	2.2	2.3
QF'=15	4.5	4.6	3.5	4.6	1.8	1.8	1.9
Median 3x3	3.82	4	4.3	4.1	1.9	1.8	1.9
Impulse noise	4.2	4.25	4.5	4.3	2.5	2.5	2.7
Gaussian noise	2.9	3	3.2	3.1	2.5	2.4	2.5
Darkening	4.6	4.9	5.1	4.9	2.3	2.2	2.3

in Table III (higher R means lower probability of error).

As it is expected, in the presence of different JPEG compression degrees, the proposed class of detectors always provides significantly better detection results. However, even under other tested attacks, the performance of the proposed procedure is slightly better for plenty of cases.

Additionally, the sensitivity of the proposed procedure against attacks is tested experimentally. For different amounts of considered attacks, the probabilities of detection error P_{err} are given in Table IV. Note that the results are reported for image Lena, but they are very similar for other tested images.

TABLE III
MEASURES OF DETECTION PERFORMANCES

Image	**Proposed procedure**		**Standard procedure**	
Pepper	R for D_{opt}^{GGF}	R for D_{opt}^{C}	R for D_1	R for D_2
No attack	13.5	13.4	11.8	12.6
QF'=75	12.9	12.6	10.9	11
QF'=50	11.8	11.8	6.8	7
QF'=40	5.9	5.8	4.8	4.7
Median 3x3	6.8	6.7	4.9	6.1
Impulse noise	6.8	6.6	6.4	5.9
Gaussian noise	3.2	3.3	3.2	2.9
Image	**Proposed procedure**		**Standard procedure**	
Lake	R for D_{opt}^{GGF}	R for D_{opt}^{C}	R for D_1	R for D_2
No attack	11.5	11.4	9.1	9.2
QF'=75	11	11	8.6	8.3
QF'=50	10.2	10.2	6.8	6.5
QF'=40	9	9	5	5.1
Median 3x3	4.6	4.7	3.7	4.5
Impulse noise	5.7	5.8	5.4	5.6
Gaussian noise	5.3	5.2	3.5	3
Image	**Proposed procedure**		**Standard procedure**	
Boat	R for D_{opt}^{GGF}	R for D_{opt}^{C}	R for D_1	R for D_2
No attack	11.5	11.2	10.2	9.3
QF'=75	9.9	10	9.1	8.6
QF'=50	9.6	9.6	6.7	6.4
QF'=40	9.4	9	5.6	5.2
Median 3x3	4.3	4.3	4.4	4.2
Impulse noise	6.7	6.3	5.8	5.2
Gaussian noise	4.3	4.5	3.8	2.8
Image	**Proposed procedure**		**Standard procedure**	
Lena	R for D_{opt}^{GGF}	R for D_{opt}^{C}	R for D_1	R for D_2
No attack	13	13.5	12.9	13.2
QF'=75	12.7	13.1	11.5	12.5
QF'=50	11	11.1	5.6	6
QF'=40	8.1	8.4	4.2	4.3
Median 3x3	5.7	5.9	6.2	6.5
Impulse noise	7.2	7.1	7.7	8
Gaussian noise	3.4	3.5	3.5	2.8
Image	**Proposed procedure**		**Standard procedure**	
Barbara	R for D_{opt}^{GGF}	R for D_{opt}^{C}	R for D_1	R for D_2
No attack	13.9	14.6	11.5	12.5
QF'=75	13.2	13.6	10	10.4
QF'=50	12	12.2	6.6	6.7
QF'=40	7.2	7.3	5.9	6
Median 3x3	5.3	5.4	4.5	5.2
Impulse noise	7.7	7.8	8.3	8
Gaussian noise	3.7	3.8	3.4	2.6

TABLE IV
SENSITIVITY AGAINST ATTACKS ON THE WATERMARKED IMAGE LENA

Attack	**Low strength**	**Middle strength**	**High strength**
JPEG	**QF'=75**	**QF'=50**	**QF'=35**
	$P_{err} \sim 10^{-39}$	$P_{err} \sim 10^{-29}$	$P_{err} \sim 10^{-7}$
Median filter	**3x3**	**5x5**	**7x7**
	$P_{err} \sim 10^{-9}$	$P_{err} \sim 10^{-4}$	$P_{err} \sim 10^{-2}$
Impulse noise	**variance=0.007**	**variance=0.01**	**variance=0.02**
	$P_{err} \sim 10^{-13}$	$P_{err} \sim 10^{-5}$	$P_{err} \sim 10^{-3}$
Gaussian noise	**variance=0.001**	**variance=0.003**	**variance=0.004**
	$P_{err} \sim 10^{-14}$	$P_{err} \sim 10^{-5}$	$P_{err} \sim 10^{-3}$

Note that even for high strength of JPEG compression (*QF'*=35), very low probability of error is obtained ($P_{err}$of order 10^{-7}). Unlike the JPEG, the robustness to other attacks is not controlled by an analytical expression. Therefore, the strength of these attacks that still does not imperil reliability of detection is determined experimentally (Middle strength column in Table IV). For stronger attacks, the watermarked coefficients' pdf becomes significantly modified. In this case the proposed detector form is not optimal any longer, resulting in higher probabilities of error (of order $10^{-2}$and 10^{-3}).

VI. CONCLUSION

Watermark detection in the presence of JPEG quantization is considered. The influence of quantization effects on watermarked coefficients and watermark itself is analyzed. The criterion for selection of the coefficients suitable for watermarking is obtained. An appropriate pdf modeling leads to the new class of optimal detectors. Detectors that belong to the proposed class have their counterparts in the GGF and Cauchy detectors forms. It is shown that the proposed class of detectors provides better results than their counterparts. Also, by modifying the criterion for coefficients selection, the proposed procedure provides robust watermark detection for any JPEG quantization degree, chosen in advance at the embedding side. The theoretical considerations are illustrated through various examples. Apart from the efficiency of detection in the presence of different JPEG quantization degrees, the reliable detection results are obtained also for some other usual signal processing techniques (attacks). However, the robustness to these attacks is not controlled by an analytic expression that could be an interesting topic for future research.

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