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A Method of Guaranteeing Image-Quality for Quantization-Based Watermarking Using a Nonorthogonal Transformation

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SUMMARY This paper proposes a quantization-based *image-quality guaranteed* watermarking (IQGW) method using a nonorthogonal discrete wavelet transformation. An IQGW method generates watermarked images of a desired image quality for any image, neither with trial and error nor with image-dependent parameters. To guarantee the image-quality, the proposed method adjusts the energy of the watermark sequence to be embedded based on the relationship between a nonorthogonally transformed domain and the spatial domain for the signal energy. This proposed method extracts the embedded watermark by quantization of watermarked coefficients, no reference image, thus, is required. In addition, it is capable of controlling the objective and subjective image-quality of a watermarked image independently. With features mentioned above, the proposed method is suitable for real-time embedding of Motion JPEG 2000 videos. Moreover, it is able to fuse quantization- and correlation-based watermarking.

key words: *data hiding, information embedding, image-quality, quality guaranteed, watermarking*

1. Introduction

Through the last decennium, digital watermarking technology has been diligently studied, for not only security-related problems [1], [2], in particular, intellectual property rights protection of digital contents [3], but also nonsecurity-oriented fields [1], [4] such as broadcast monitoring [5]–[7]. An image watermarking method embeds data, referred to as a *watermark*, into a target image directly and imperceptibly. It then generates a slightly degraded image that is referred to as a *watermarked image*.

To improve the imperceptibility of embedded watermark, methods that are referred to as *image adaptive* watermarking [8] or *informed embedding* [9] have been developed [8]–[12]. These methods watermark images dependently on the target image, and computation of several content-dependent parameters is required for each individual image. These methods, thus, not fit real-time watermarking of a video sequence in which the required image-quality is regulated by the objective image-quality.

On the other hand, methods that generate watermarked images of a desired image-quality,

- using no image-dependent parameters,
- automatically, i.e., without trial and error,

have been proposed [6], [7], [13]. These methods are referred to as *image-quality guaranteed* watermarking (IQGW) methods in this paper. Since IQGW methods guarantee a desired image-quality using common and fixed parameters for all images, they are suitable for real-time video watermarking. This paper focuses on IQGW and discusses an IQGW method for *quantization-based* watermarking.

Quantization-based watermarking methods quantize watermarked coefficients/pixels to extract the embedded watermark without any reference image, i.e., *oblivisously* [1]. The other, *correlation-based* [1] methods, require a mapping from binary watermark to a real-number spread spectrum (SS)-based watermark and correlation to extract and verify the embedded watermark. In particular, correlators corresponding to possible SS-based watermarks need huge computation. Whereas quantization-based methods do not need mapping and correlation, they, thus, are suitable for real-time video watermarking.

Conventional IQGW methods watermark images in a discrete cosine transformed (DCT) domain, and the image-quality of a watermarked image that is given by the peak signal-to-noise ratio (PSNR) is guaranteed in the DCT domain as well [6], [7], [13], though the PSNR is defined in the spatial domain. The principle of these methods, however, is dedicated to orthogonal transformations. For joint compression and watermarking, both processes, in general, are desired to use the identical transformation. Thus, an IQGW method using a nonorthogonal transformation is expected for nonorthogonal transformation-based compression.

In this paper, a quantization-based IQGW method that embeds watermarks into target images in nonorthogonal DWT domains is proposed [14], [15]. The proposed method automatically controls the energy of a watermark sequence in the nonorthogonally transformed domain to guarantee a desired image-quality, and this control takes account of the signal energy relationship between the spatial domain and the transformed domain. This method, thus, guarantees the image-quality under the conditions that a watermark is embedded over several subbands.

The remainder of this paper is organized as follows. Section 2 discusses the relationship between the signal energy in the transformed domain and the energy in the spatial domain, that is utilized to guarantee the image-quality of watermarked images. In Sect. 3, a novel IQGW method using DWT is proposed and fundamental features of the proposed method are surveyed. Section 4 further describes features of the proposed method. Section 5 gives the experi-

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mental results, and some concluding remarks are made in Sect. 6.

2. Signal Energy in Transformed Domains

2.1 Guaranteeing Image-Quality in a Transformed Domain

Guaranteeing image-quality is producing watermarked images of a desired image-quality, independently of the characteristics of the target images. In this paper, a desired image-quality is given by the PSNR that is defined in the spatial domain as

$$\mathrm{PSNR} = 10\log_{10}\frac{XYA^2}{\displaystyle\sum_{x=1}^{X}\sum_{y=1}^{Y}\left\{\hat{f}(x,y)-f(x,y)\right\}^2}\ \text{[dB]}, \quad (1)$$

where $f(x,y)$ and $\hat{f}(x,y)$ are the luminance of pixel located (x,y) in the target image and that in a watermarked image, respectively. Both images consist of $X \times Y$ pixels, where each pixel has A levels from zero to $A-1$.

If the denominator of Eq. (1) is represented by using the signal energy in transformed domains, we will know the watermarked image's PSNR without any inverse transformation to the spatial domain. To guarantee an image-quality in a transformed domain, an IQGW method

- utilizes the signal energy relationship between the transformed domain and the spatial domain,
- adapts the energy of the watermark sequence to be embedded to the allowable energy.

In the next section, the former relationship is derived to know the image-quality of a watermarked image in a nonorthogonal transformed domain. The latter energy adaptation is also expanded to nonorthogonal transformations, and is described in Sect. 3.1.

2.2 Signal Energy in a Nonorthogonally Transformed Domain

The relationship between the signal energy in a nonorthogonal transformed domain and that in the spatial domain is able to be derived from the synthesis filter coefficients that are used in multirate filter bank representations of the transformation [16].

For simplicity, one-dimensional DWTs are considered here. Let $e^2_{\mathrm{tr},\lambda}$ and $e^2_{\mathrm{tp},\lambda}$ represent the energy of a signal in subband λ of a DWT domain, and that in the temporal domain, respectively, where tr and tp indicate *transformed* and *temporal*, respectively. Under the condition that a synthesis filter bank is as shown in Fig. 1, the relationship between $e^2_{\mathrm{tr},\lambda}$ and $e^2_{\mathrm{tp},\lambda}$ is given by

$$e^2_{\mathrm{tp},\lambda} = f_\lambda e^2_{\mathrm{tr},\lambda}, \quad (2)$$

where f_λ is referred to as the *scaling factor* for subband λ in

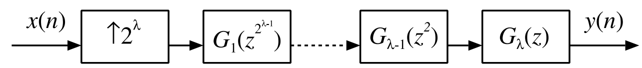


Fig. 1 A one-dimensional DWT synthesis filter bank. Signal $x(n)$ in subband λ is inversely transformed to signal $y(n)$ in the temporal domain.

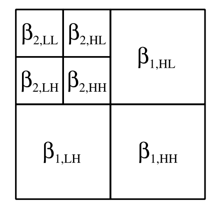


Fig. 2 Subband $\beta_{\lambda,\theta}$ in a two-dimensional DWT. (Decomposition level $\Lambda = 2$. Parameters λ and θ represent the resolution level and the direction, where $\theta \in \{\mathrm{LL}, \mathrm{LH}, \mathrm{HL}, \mathrm{HH}\}$).

Table 1 Scaling factor $f_{\lambda,\theta}$ for two-dimensional DWT with the same 5/3 filter used in JPEG 2000 [17].

λ	θ		
	LL	LH (HL)	HH
5	455.5557	128.5211	36.2583
4	114.2227	32.5217	9.2597
3	28.8906	8.5244	2.5152
2	7.5625	2.5352	0.8499
1	2.2500	1.0781	0.5166

this paper. This scaling factor f_λ is defined by the following equations [16],

$$f_\lambda = \frac{1}{2^\lambda}\sum_{n=-\infty}^{\infty}\left|\xi_1(n) * \xi_2(n) * \cdots * \xi_{\lambda-1}(n) * g_\lambda(n)\right|^2, \quad (3)$$

$$\xi_p = \begin{cases} g_q\left(\frac{n}{2^{\lambda-q}}\right), & n = 2^{\lambda-2}p \\ 0, & \text{otherwise} \end{cases}, p = 0, \pm1, \pm2, \ldots, \quad (4)$$

where $g_q(n)$ and $A * B$ are the inverse z transformation of $G_q(z)$ and the convolution of A and B, respectively. This result holds in two-dimensional DWT and also in other nonorthogonal transformations.

An example of two-dimensional DWT is shown in Fig. 2, in which the decomposition level $\Lambda = 2$. Subband $\beta_{\lambda,\theta}$ is defined by resolution level λ and direction θ, where $\theta \in \{\mathrm{LL}, \mathrm{LH}, \mathrm{HL}, \mathrm{HH}\}$. A two-dimensional scaling factor $f_{\lambda,\theta}$ that satisfies

$$e^2_{\mathrm{sp},\lambda,\theta} = f_{\lambda,\theta} e^2_{\mathrm{tr},\lambda,\theta} \quad \text{for} \quad \beta_{\lambda,\theta}, \quad (5)$$

where sp indicates *spatial*, is introduced as the one-dimensional DWT described above. For example, scaling factors for subbands in a DWT domain, which is two-dimensionally transformed by the 5/3 filter used in JPEG 2000 [17] are shown in Table 1.

On the other hand, for the DCT domain that is used in conventional IQGW methods [6], [7], [13], Parseval's equation is realized, i.e., the signal energy in the spatial domain and in a transformed domain are identical to each other.

Conventional IQGW methods, thus, utilize Parseval's equation to guarantee an image-quality of a watermarked image, and are dedicated to orthogonal transformations.

In the next section, a nonorthogonal DWT-based IQGW method that adapts the energy of a watermark sequence to the allowable energy based on the scaling factors described in this section is proposed. The proposed method watermarks images and automatically guarantees the image-quality in the same nonorthogonal transformed domain without using any image-dependent parameters, though a desired image-quality is given in terms of the PSNR that is defined in the spatial domain.

3. **Proposed IQGW Method** [14], [15]

In this section, it is assumed that the proposed IQGW embeds an L-length binary watermark sequence $\mathbf{w}_g$ into a target grayscale image by a quantization-based embedding algorithm in a DWT domain. $\mathbf{w}_g \in \mathbf{W}$, where $\mathbf{W}$ is the space of L-length binary sequences, and $\mathbf{w}_g$'s element, represented by $w_{g,l}$, where $l = 1, 2, \ldots, L$, is equiprobable $\{0, 1\}$, i.e., $w_{g,l}$ has a uniform distribution, whose mean value $E[\mathbf{W}]$ is 0.5 and variance σ_w^2 is 0.25. In addition, to fuse quantization- and correlation-based watermarking that is described in Sect. 4.1, it is assumed that

$$\max \left| w_{g,l} - E[\mathbf{W}] \right| \leq N_\sigma \sigma_w \quad (6)$$

is satisfied, where $N_\sigma > 0$. An image consists of $X \times Y$ pixels, and each pixel has A levels from zero to $A - 1$.

3.1 Embedding Algorithm

Figure 3 shows the embedding diagram of the proposed IQGW method.

1. Set r [dB] to the desired image-quality in terms of the PSNR.
2. Choose one watermark sequence, $\mathbf{w}_g$, from the available watermark sequences.
3. Apply a two-dimensional DWT, whose decomposition level is Λ, to the target image to obtain $(3\Lambda + 1)$ subbands, represented by $\mathbf{s} = \{s_i | i = 1, \ldots, 3\Lambda + 1\}$, and then choose S subbands for embedding from $\mathbf{s}$. The chosen subbands are represented by $\mathbf{o} = \{o_m | m = 1, \ldots, S\}$. Set $m := 1$.
4. Using desired image-quality r and scaling factor φ_m that corresponds to subband o_m, positive rounding step Q_m is derived to round off the coefficients in o_m. The details are described in Sect. 3.4. Then, using the Q_m, energy adapting factor h_m that corresponds to subband o_m is given by
$$h_m = \frac{M_\sigma Q_m}{2 N_\sigma \sigma_w}, \quad (7)$$
where $M_\sigma (0 < M_\sigma < 1)$ and N_σ, parameters for fusion of quantization- and correlation-based watermarking that is described in Sect. 4.1, are set to 0.5 and one, respectively, in this paper.
5. Divide subband o_m into B_m blocks, where each block consists of $X_m \times Y_m$ DWT coefficients. The blocks are represented by $\mathbf{b}_m = \left\{ b_{m,j} \middle| j = 1, \ldots, B_m \right\}$, and then a_m blocks for embedding, $\mathbf{p}_m = \{p_{m,n} | n = 1, \ldots, a_m\}$, are chosen from $\mathbf{b}_m$. Set $n := 1$.
6. Choose $C_{m,n}$ coefficients from block $p_{m,n}$, where the chosen coefficients are represented by $\mathbf{q}_{m,n} = \{q_{m,n,d} | d = 1, \ldots, C_{m,n}\}$. Set $d := 1$.
7. Round $q_{m,n,d}$ by
$$\bar{q}_{m,n,d} = \mathrm{round}\left(\frac{q_{m,n,d}}{Q_m} \right) Q_m, \quad (8)$$
to obtain rounded coefficient $\bar{q}_{m,n,d}$. The round(u) function returns an integer, rounded off by u. Now, choose unembedded element $w_{g,l}$ from watermark sequence $\mathbf{w}_g$, and add $w_{g,l}$ to $\bar{q}_{m,n,d}$ as
$$\hat{q}_{m,n,d} = \bar{q}_{m,n,d} + \hat{w}_{g,l}, \quad (9)$$
$$\hat{w}_{g,l} = h_m \left(w_{g,l} - E[\mathbf{W}] \right). \quad (10)$$
The expected value and variance of $\hat{w}_{g,l}$ are zero and $h_m^2 \sigma_w^2$, respectively.
8. Set $d := d + 1$, and repeat step 7 until $d = C_{m,n}$.
9. Set $n := n + 1$, and repeat steps 6 to 8 until $n = a_m$.
10. Set $m := m + 1$, and repeat steps 4 to 9 until $m = S$.
11. Apply the two-dimensional inverse DWT to $(3\Lambda + 1)$ subbands to obtain a watermarked image.

It is noteworthy that this propoesd method does not embed $\mathbf{w}$ directly into an image, even $\mathbf{w}_g$ is a binary sequence. $\mathbf{w}_g$ is processed through Eq. (10) to be real-number sequence $\hat{\mathbf{w}}_g$ so that desired image-quality r is guaranteed. Moreover, this energy adaptation process is expanded to nonorthogonal transformations, because this process uses rounding step Q_m, that is decided according to scaling factor φ_m corresponding to subband o_m in Step. 4.

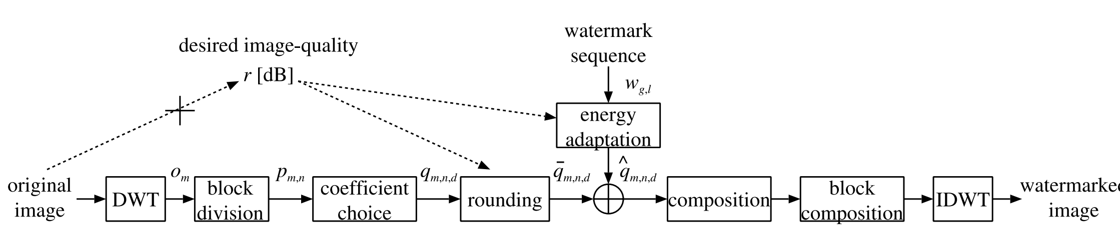


Fig. 3 Embedding diagram of the proposed IQGW method.

In addition, this proposed method allows you to freely choose parameters Λ, $\mathbf{o}$, X_m, Y_m, $\mathbf{p}_m$, and $\mathbf{q}_{m,n}$, according to the applications. The proposed method guarantees a desired image-quality for any combination of these parameters.

3.2 Extracting Algorithm

To extract an embedded watermark from a watermarked image, the following parameters that are pre-negotiated by an embedder and an extractor, are required; desired image-quality r [dB], decomposition level Λ, subbands for embedding $\mathbf{o}$, block size $X_m \times Y_m$ for subband o_m, blocks for embedding $\mathbf{p}_m$ in subband o_m, and coefficients for embedding $\mathbf{q}_{m,n}$ in block $p_{m,n}$. Note, for practical use, parameters $\mathbf{o}$, $\mathbf{p}_m$, and $\mathbf{q}_{m,n}$ will not be required when you use a pseudo-random number generator to choose subbands, blocks, and coefficients, instead of freely selecting them.

1. Set r [dB] to the desired image-quality in terms of the PSNR.
2. Apply a two-dimensional DWT to a watermarked image to obtain subbands, and choose S subbands, corresponding to step 3 in the embedding algorithm. Set $m := 1$.
3. Using desired image-quality r and scaling factor φ_m, obtain rounding step Q_m for o_m. Then, determine energy adapting factor h_m for o_m by Eq. (7).
4. Divide subband o_m into B_m blocks, where each block consists of $X_m \times Y_m$ DWT coefficients. Then, choose a_m blocks that correspond to step 5 in the embedding algorithm. Set $n := 1$.
5. Choose $C_{m,n}$ coefficients corresponding to step 6 in the embedding algorithm. Set $d := 1$.
6. Round target DWT coefficient $\hat{q}_{m,n,d}$, from which watermark element $w_{g,l}$ has not yet been extracted, by
$$\bar{q}_{m,n,d} = \text{round}\left(\frac{\hat{q}_{m,n,d}}{Q_m}\right) Q_m, \tag{11}$$
to obtain rounded coefficient $\bar{q}_{m,n,d}$. Now, subtract $\bar{q}_{m,n,d}$ from $\hat{q}_{m,n,d}$ to extract embedded watermark element $w_{g,l}$ by
$$w_{g,l} = \frac{\hat{w}_{g,l}}{h_m} + E[\mathbf{W}], \tag{12}$$
$$\hat{w}_{g,l} = \left(\hat{q}_{m,n,d} - \bar{q}_{m,n,d}\right). \tag{13}$$
7. Set $d := d + 1$, and repeat step 6 until $d = C_{m,n}$.
8. Set $n := n + 1$, and repeat steps 5 to 7 until $n = a_m$.
9. Set $m := m + 1$, and repeat steps 3 to 8 until $m = S$.

3.3 Features of the Proposed IQGW Method

The proposed method guarantees an image-quality in non-orthogonally transformed domains. It embeds a watermark sequence by a quantization-based algorithm, so that it is able to extract the embedded watermark from a watermarked image without referring to any original images. In addition, it is versatile when determining rounding step Q_m.

In the next section, Image-quality guarantee feature of the proposed IQGW method is focused, and then the oblivious extraction feature is surveyed in the consecutive section.

3.3.1 Guaranteeing Image-Quality

In this section, it is described how the proposed IQGW method guarantees a desired image-quality in watermarked images.

The difference in energy between watermarked coefficient $\hat{q}_{m,n,d}$ and its corresponding original coefficient $q_{m,n,d}$ is defined as
$$e^2_{\text{tr},q_{m,n,d}} = \left(\hat{q}_{m,n,d} - q_{m,n,d}\right)^2, \tag{14}$$
where $e^2_{\text{tr},q_{m,n,d}}$ represents the differential energy between $q_{m,n,d}$ and $\hat{q}_{m,n,d}$ in a transformed domain. Substituting Eq. (9) into Eq. (14) gives
$$\begin{aligned} e^2_{\text{tr},q_{m,n,d}} &= \left\{\bar{q}_{m,n,d} + \hat{w}_{g,l} - q_{m,n,d}\right\}^2 \\ &= \left(\bar{q}_{m,n,d} - q_{m,n,d}\right)^2 + \hat{w}^2_{g,l} \\ &\quad + 2\hat{w}_{g,l}\left(\bar{q}_{m,n,d} - q_{m,n,d}\right). \end{aligned} \tag{15}$$

Let us consider the expected value of Eq. (15), i.e.,
$$\begin{aligned} E\left[e^2_{\text{tr},q_{m,n,d}}\right] &= E\left[\left(\bar{q}_{m,n,d} - q_{m,n,d}\right)^2\right] + E\left[\hat{w}^2_{g,l}\right] \\ &\quad + 2E\left[\hat{w}_{g,l}\left(\bar{q}_{m,n,d} - q_{m,n,d}\right)\right]. \end{aligned} \tag{16}$$

The first term of Eq. (16) is a quantization error of DWT coefficient $q_{m,n,d}$, and is assumed to distribute uniformly. Thus,
$$E\left[\left(\bar{q}_{m,n,d} - q_{m,n,d}\right)^2\right] = \frac{Q^2_m}{12}. \tag{17}$$

Since the expected value and the variance of $\hat{w}_{g,l}$ are zero and $h^2_m \sigma^2_w$, respectively, the second term of Eq. (16) is
$$E\left[\hat{w}^2_{g,l}\right] = h^2_m \sigma^2_w. \tag{18}$$

Under the assumption that a quantization error and a watermark element are statistically independent, the third term is
$$2E\left[\hat{w}_{g,l}\left(\bar{q}_{m,n,d} - q_{m,n,d}\right)\right] = 0. \tag{19}$$

Consequently, substituting Eqs. (7), (17), (18), and (19) into Eq. (16) introduces
$$E\left[e^2_{\text{tr},q_{m,n,d}}\right] = \frac{Q^2_m}{12} + h^2_m \sigma^2_w = \frac{Q^2_m}{D}, \tag{20}$$
$$D = \frac{12N^2_\sigma}{N^2_\sigma + 3M^2_\sigma}. \tag{21}$$

By using scaling factor φ_m and the relation given by Eq. (5), the energy in the spatial domain that corresponds to Eq. (20) is derived as
$$E\left[e^2_{\text{sp},q_{m,n,d}}\right] = \varphi_m E\left[e^2_{\text{tr},q_{m,n,d}}\right] = \frac{\varphi_m Q^2_m}{D}. \tag{22}$$

Consequently, it is concluded that the expected value of the signal energy in the spatial domain, caused by embedding $\mathbf{w}_g$ into a target image, is defined as

$$E\left[e_{\mathrm{sp}}^2\right] = \sum_{m=1}^{S}\sum_{n=1}^{a_m}\sum_{d=1}^{C_{m,n}} E\left[e_{\mathrm{sp},q_{m,n,d}}^2\right] = \sum_{m=1}^{S}\sum_{n=1}^{a_m}\sum_{d=1}^{C_{m,n}} \frac{\varphi_m Q_m^2}{D} = \frac{1}{D}\sum_{m=1}^{S}\varphi_m Q_m^2 \sum_{n=1}^{a_m} C_{m,n}. \quad (23)$$

The PSNR between the original image and a watermarked image is thus given by

$$\mathrm{PSNR} = 10\log_{10}\frac{XYA^2}{E\left[e_{\mathrm{sp}}^2\right]} = 10\log_{10}\frac{XYA^2 D}{\sum_{m=1}^{S}\varphi_m Q_m^2 \sum_{n=1}^{a_m} C_{m,n}}\ [\mathrm{dB}]. \quad (24)$$

In Eq. (24), X, Y, A, D, S, φ_m, a_m, $C_{m,n}$ are constant and independent of the target images in the proposed method. Thus, Eq. (24) is a function of Q_m's. If Q_m's are independent of the target images, Eq. (24) is independent of the target images. Note that any Q_m's are allowed, so long as Eq. (24) is equal to a desired image-quality. Using a simple example for determining Q_m's, it is shown that Q_m's are independent of the target images in Sect. 3.4.

Once watermark is embedded into an image with fixed parameters, the PSNR of a watermarked image is derived as Eq. (24). To guarantee a desired image-quality, the proposed method decided parameters accroding to Eq. (24) without any trial and error, and adapts the energy of $\mathbf{w}_g$ to the allowable energy by Eq. (10). This energy adaptation is important as well as the signal energy relationship, mentioned in Sect. 2.2, to guarantee a desired image-quality.

3.3.2 Oblivious Watermark Extraction

In this section, it is described how the proposed IQGW method extracts embedded watermarks without any reference images, i.e., obliviously.

From Eqs. (8) and (9), extracted element $\hat{w}_{g,l}$ is given as

$$\hat{w}_{g,l} = \hat{q}_{m,n,d} - \mathrm{round}\left(\frac{q_{m,n,d}}{Q_m}\right) Q_m, \quad (25)$$

and Eq. (25) implies that original coefficient $q_{m,n,d}$ is required to extract $\hat{w}_{g,l}$. Under the condition that

$$\max_l \left|\hat{w}_{g,l}\right| < \frac{Q_m}{2}, \quad (26)$$

the following equation, however, holds.

$$\bar{q}_{m,n,d} = \mathrm{round}\left(\frac{q_{m,n,d}}{Q_m}\right) Q_m = \mathrm{round}\left(\frac{\hat{q}_{m,n,d}}{Q_m}\right) Q_m. \quad (27)$$

Thus, if Eq. (26) holds, substituting Eq. (27) into Eq. (25) gives

$$\hat{w}_{g,l} = \hat{q}_{m,n,d} - \mathrm{round}\left(\frac{\hat{q}_{m,n,d}}{Q_m}\right) Q_m, \quad (28)$$

and Eq. (28) shows that no original coefficient $q_{m,n,d}$ is required to extract $\hat{w}_{g,l}$, i.e, the extraction of $\hat{w}_{g,l}$ is oblivious.

Here, it is shown that Eq. (26) holds. From Eqs. (7) and (10), and M_σ, Q_m, N_σ, and σ_w are greater than or equal to zero,

$$\max_l \left|\hat{w}_{g,l}\right| = \frac{M_\sigma Q_m}{2N_\sigma \sigma_w} \max_l \left|w_{g,l} - E[\mathbf{W}]\right|. \quad (29)$$

Substituging Eq. (6) into (29),

$$\max_l \left|\hat{w}_{g,l}\right| \le \frac{M_\sigma Q_m}{2}. \quad (30)$$

Since $0 < M_\sigma < 1$, Eq. (26) is held as follows.

$$\max_l \left|\hat{w}_{g,l}\right| \le \frac{M_\sigma Q_m}{2} < \frac{Q_m}{2}, \quad (31)$$

and is shown in Fig. 4. Parameter M_σ limits the distribution of $\hat{w}_{g,l}$ as shown by Eq. (30) and in Fig. 4.

In the proposed IQGW method, it is concluded that $\hat{w}_{g,l}$ is extracted obliviously using Eq. (28), i.e. by using Eqs. (11) and (13). Then, applying Eq. (12) to $\hat{w}_{g,l}$ gives extracted watermark element $w_{g,l}$.

3.4 Determining Rounding Step Q_m

According to parameters S, $\mathbf{o}$, a_m, and $C_{m,n}$, rounding step Q_m's are determined under the condition that Eq. (24) is equal to desired image-quality r, i.e.,

$$10\log_{10}\frac{XYA^2 D}{\sum_{m=1}^{S}\varphi_m Q_m^2 \sum_{n=1}^{a_m} C_{m,n}} = r. \quad (32)$$

Many sets of Q_m's that satisfy Eq. (32) exist, and we are allowed to determine Q_m's, according to the applications, as

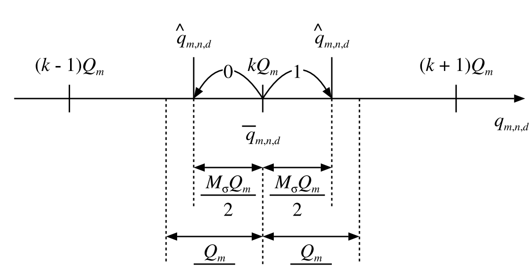


Fig. 4 Chosen coefficient $q_{m,n,d}$, its rounded value $\bar{q}_{m,n,d}$, and watermarked coefficient $\hat{q}_{m,n,d}$ in embedding binary watermark sequence $\mathbf{w}_g$. k is an integer. Embedding '0' and '1' result in $\hat{q}_{m,n,d} = \bar{q}_{m,n,d} - M_\sigma Q_m/2$ and $\hat{q}_{m,n,d} = \bar{q}_{m,n,d} + M_\sigma Q_m/2$, respectively. Rounding both $\hat{q}_{m,n,d}$'s off results in $\bar{q}_{m,n,d}$. M_σ controls $\max_l \left|\hat{w}_{g,l}\right|$.

long as Eq. (32) holds. However, one simple strategy to determine rounding step Q_m is briefly described in this section.

The strategy described here is that the energy of the error signal observed in the spatial domain corresponding to DWT coefficient $q_{m,n,d}$, that is already given by Eq. (22), are identical to each other, i.e.,

$$\frac{\varphi_1 Q_1^2}{D} = \frac{\varphi_2 Q_2^2}{D} = \cdots = \frac{\varphi_S Q_S^2}{D} = e_0. \tag{33}$$

Since watermark sequence $\mathbf{w}_g$ is embedded among the L coefficients,

$$E\left[e_{\mathrm{sp}}^2\right] = Le_0. \tag{34}$$

From Eqs. (24), (32), and (34),

$$r = 10 \log_{10} \frac{XYA^2}{Le_0}, \tag{35}$$

thus,

$$e_0 = \frac{XYA^2}{L10^{0.1r}}. \tag{36}$$

By substituting Eq. (36) into Eq. (33),

$$\frac{\varphi_1 Q_1^2}{D} = \frac{\varphi_2 Q_2^2}{D} = \cdots = \frac{\varphi_S Q_S^2}{D} = \frac{XYA^2}{L10^{0.1r}}, \tag{37}$$

and Q_m is finally derived as

$$Q_m = \frac{A}{10^{0.05r}} \sqrt{\frac{XYD}{\varphi_m L}} \tag{38}$$

to guarantee the PSNR of r [dB]. In Eq. (38), parameters A, r, X, Y, D, φ_m, and L are independent of the characteristics of the target image, so Q_m is also independent of the image. Consequently, it is concluded that the proposed method is an IQGW method.

3.5 Effectiveness of Expansion to Nonorthogonal Transformations

With the proposed method, IQGW is expanded from orthogonal transformations [6], [7], [13] to nonorthogonal transformations. This expansion is meaningful for

- comparison between orthogonal and nonorthogonal transformation on fitting for watermarking,
- joint- or successive-watermarking and compression

Both orthogonal and nonorthogonal transformation-based watermarking methods have been proposed [1], however, comparison between these transformations for watermarking has not been done enough. This lack is due to that conventional methods have difficulties in making conditions even each other; such conditions are the image-quality of watermarked images, the amount of embedded data, and probabilistic or statistical characteristics of watermarks. Orthogonal and nonorthogonal-based IQGW methods make the PSNR of watermarked images even in any transformed domains as well as an orthogonal DCT and a nonorthogonal DWT. This image-quality controllability, being independent of other conditions, accelarates investigations on transformed domain being suit for watermarking and optimization of other parameters.

On the other hand, most images, including watermarked images, are often compressed in the contemporary image transmission and storage. As watermarking methods, both orthogonal [18] and nonorthogonal [19] transformation-based compression techniques are used. It is desired that a common transformed domain is used for watermarking and compression to insert a watermarking method into an encoder effectively or to avoid quantization's effect on embedded watermark. The expansion to nonorthogonal transformation makes IQGW capable to combine with compression techniques using both transformations. Moreover, IQGW's this expansion and the expansion to quantization-based watermarking make real-time watermarking for Motion JPEG 2000 [19] images easy.

4. Extra Features

The proposed IQGW method has extra features; capability of fusing quantization- and correlation-based watermarking, and independently controlling the objective and the subjective image-quality of watermarked images. These two features are briefly described in the following sections.

4.1 Fusion of Quantization-Based and Correlation-Based

The proposed IQGW method is capable to embed a real-number spread spectrum-based watermark sequence. In this scenario, extracted watermark sequence $\mathbf{w}_g$ is verified by correlators for possible sequences in space $\mathbf{W}$ consisting of L-length real number sequences.

Watermark sequence $\mathbf{w}_g$ that consists of L-length real numbers is mapped from the binary data to be embedded by employing a spread spectrum modulation mechanism, e.g., direct sequence/SS (DS/SS) or M-ary DS/SS. Element $w_{g,l}$ is an independent identically distributed sample drawn from a standard normal distribution, i.e., a zero-mean and unit-variance Gaussian distribution. Thus, $E[\mathbf{W}] = 0$ and $\sigma_w^2 = 1$.

Though $\mathbf{w}_g$ consists of Gaussian random real numbers, the algorithms for a binary watermark sequence described in Sects. 3.1 and 3.2 are able to be used without any modification excepting N_σ and M_σ; N_σ and M_σ are set to three and slightly less than one, respectively. This fusion and the expansion to quantization-based method in the proposed method are achieved by introducing these two parameters. Figure 5, corresponding to Fig. 4 in binary watermarking, shows that the relations among original coefficient $q_{m,n,d}$, rounded coefficient $\bar{q}_{m,n,d}$, and watermarked coefficient $\hat{q}_{m,n,d}$.

This fusion of quantization-based watermarking and correlation-based watermarking, in the proposed IQGW method, allows us to effectively use the advantages of both

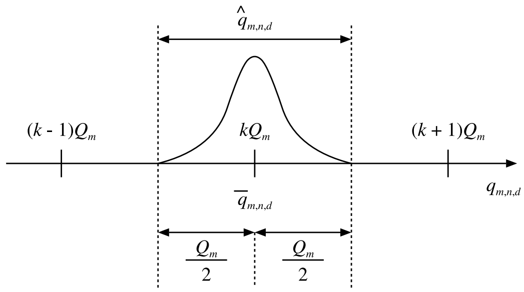


Fig. 5 Chosen coefficient $q_{m,n,d}$, its rounded value $\bar{q}_{m,n,d}$, and watermarked coefficient $\hat{q}_{m,n,d}$ in embedding spread spectrum-based watermark sequence $\mathbf{w}_g$. k is an integer. Rounding $\hat{q}_{m,n,d}$'s off results in $\bar{q}_{m,n,d}$.

watermarking techniques.

4.2 Objective Image-Quality and Subjective Image-Quality

Both subjective and objective image-quality of watermarked images are important. The latter quality measurement is required for, in particular, real-time video watermarking, in which delay by a computation of parameters from each image to improve the subjective quality of watermarked image is inevitable. IQGW methods that guarantee a desired objective image-quality without image-dependent parameters are suitable for such application.

On the other hand, the subjective image-quality has to be taken into account in applications in which offline watermarking is required and/or the maximizing resilience against attaks is the most important matter. Since deriving a strategy for improving the subjective image-quality is a consideration in all watermarking methods, the general and optimized solution for all methods has not been found yet. To improve the subjective image-quality in the proposed IQGW method, effective utilization of the versatility in choosing subbands, blocks, and coefficients for watermarking is important.

The proposed IQGW method is capable of generating watermarked images those each image are different from each other in the subjective image-quality and are identical to each other in the objective image-quality, by varying choise of coefficients for watermarking. It, thus, is capable of controlling the subjective and the objective image-quality independently, whereas the most conventional methods are not. Using this feature, coefficients improving the subjective image-quality are able to be investigated.

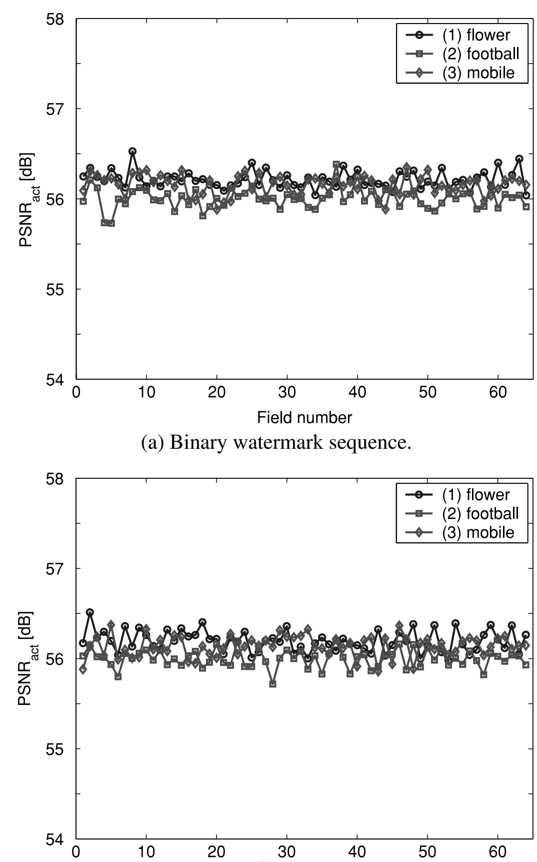
5. Experimental Results

Under the conditions shown in Table 2, the actual PSNR's of the 192 watermarked images generated by the proposed method are investigated. Desired image-quality $r = 56$ [dB] in the PSNR, and $L = 1980$ watermark elements are embedded over three subbands. The results are shown in Fig. 6.

Figure 6(a) that is for binary watermark sequence shows that the proposed IQGW method guarantees a desired

Table 2 Simulation conditions.

Grayscale sequences	"flower garden," "football," and "mobile & calendar"
No. of fields	64 fields/sequence
Field size	$X = 704$, $Y = 240$ [pixels]
Dynamic range	$A = 255$
Sequence length	$L = 1980$
Desired quality	$r = 56$ [dB]
Decomposition level	$\Lambda = 3$
No. of subbands	$S = 3$
Chosen subbands $\mathbf{o}$	$\{\beta_{1,\text{HL}}, \beta_{2,\text{LH}}, \beta_{3,\text{HH}}\}$
Block size	$X_m = Y_m = 16/2^m$
No. of chosen blocks	$a_m = 660 (= B_m)$
No. of chosen coefficients	$C_{m,n} = 1$
Rounding step	Q_m is given as Eq. (38)
DWT filters	5/3 filter



(a) Binary watermark sequence.

(b) Real number Gaussian watermark sequence.

Fig. 6 Actual PSNR's, PSNR_{act}, for 192 images (desired image-quality $r = 56$ [dB], chosen subbands: $\beta_{1,\text{HL}}$, $\beta_{2,\text{LH}}$, and $\beta_{3,\text{HH}}$, watermark sequence length $L = 1980$).

image-quality, similar to conventional IQGW methods [6], [7], [13]. Figure 6(b) is for the fusion of the quantization- and correlation-based watermarking in the proposed method using spread-spectrum modulated real number Gaussian watermark sequence, and it shows that the proposed IQGW

Table 3 Compression resilience of the fusion of the quantization- and correlation-based watermarking in the proposed IQGW method ("flower garden," 30 fields/sec, the number of possible watermark sequences is 1980).

(a) Motion JPEG 2000 [19].

Bit Rate [Mbps]	Avg. PSNR [dB]	Error Rate
25	49.5356	0
20	48.4526	0
15	45.7277	0

(b) MPEG-2 [18].

Bit Rate [Mbps]	Avg. PSNR [dB]	Error Rate
20	46.3194	0
15	43.6816	0

method guarantees a desired image-quality, though $\mathbf{w}_g$ is a real number Gaussian random sequence.

On the fusion of the quantization- and correlation-based watermarking, compression resilience are shown in Table 3. Each video sequence is watermarked under the conditions that $\Lambda = 4$, $S = 3$, $o_m = \{\beta_{4,\mathrm{LH}}, \beta_{4,\mathrm{HL}}, \beta_{4,\mathrm{HH}}\}$, $X_m = Y_m = 1$, $a_m = B_m = 660$, and, then, is compressed by Motion JPEG 2000 [19] codec (kakadu v.4.2.1) or MPEG-2 [18] codec (PVRG MPEG v.1.2.1). For the inside material monitoring and management, the target bit rate's are set over 15 Mbps under the condition that the field rate is 30 fields/sec. With employed codec, the achievable highest bit rate's are 25 Mbps and 20 Mbps for JPEG 2000 and MPEG-2. Error rate represents the number of frames in which the embedded watermark sequence is misidentified.

From Table 3 that is for sequence "flower garden," the embedded watermarks are correctly identified among 1980 possible sequences over all fields, independently of the compression technique. On other two sequence, error rate is zero.

Three watermarked images generated by the proposed method are shown in Fig. 7 to briefly illustrate the description given in Sect. 4.2. All images in Fig. 7 are identical to each other in desired PSNR, $r = 35$ [dB]. The difference among them is coefficients for watermarking. Figures 7(a) and (b) have a 4096-length binary sequence in subband $\beta_{3,\mathrm{LL}}$ and $\beta_{3,\mathrm{HH}}$, respectively. It is clear that the latter is superior in the subjective image-quality than the former.

On the other hand, the border of subbands $\mathbf{o} = \{\beta_{2,\mathrm{LH}}, \beta_{2,\mathrm{HL}}, \beta_{1,\mathrm{LH}}, \beta_{1,\mathrm{HL}}, \beta_{1,\mathrm{HH}}\}$ are used for watermarking a 4076-length binary sequence in Fig. 7(c). The border of Fig. 7(c) is distorted by watermarking and the rest are not degraded at all. A combination of this strategy and the IQGW's expansion to nonorthogonal transformations is suitable for watermarking non Region of Interest (ROI) area of JPEG 2000 coded images in which a non ROI area accepts distortion to preserve an ROI area from distortion.

As this brief example, it is possible for the proposed method to investigate coefficients being suitable for watermarking.

(a) Chosen subband $\mathbf{o} = \{\beta_{3,\mathrm{LL}}\}$, sequence length $L = 4096$, block size $X_m = Y_m = 1$, No. of chosen blocks $a_m = 4096$, No. of chosen coefficients $C_{m,n} = 1$.

(b) Chosen subband $\mathbf{o} = \{\beta_{3,\mathrm{HH}}\}$, sequence length $L = 4096$, block size $X_m = Y_m = 1$, No. of chosen blocks $a_m = 4096$, No. of chosen coefficients $C_{m,n} = 1$.

(c) Watermarking the border of a image like Region of Interest (ROI) in JPEG 2000 [17] (Chosen subbands $\mathbf{o} = \{\beta_{2,\mathrm{LH}}, \beta_{2,\mathrm{HL}}, \beta_{1,\mathrm{LH}}, \beta_{1,\mathrm{HL}}, \beta_{1,\mathrm{HH}}\}$, sequence length $L = 4076$, watermark is embedded into the border of chosen subbands).

Fig. 7 Three different watermarked images that each image has the identical image-quality by the proposed IQGW method (desired image-quality $r = 35$ [dB], watermark sequence $\mathbf{w}_g$ is a binary sequence).

6. Conclusions

This paper has proposed a quantization-based IQGW method using a nonorthogonal DWT. It employs an expanded energy adaptation manner for watermark sequeces to automatically guarantee the PSNR of a watermarked image in nonorthogonally transformed domains. The proposed method extracts the embedded watermark obliviously by the quantization manner. Comparisons among orthogonal and nonorthogonal transformations for watermarking are expected to be accelarated using the proposed and conventional IQGW methods. The proposed method is suitable for real-time video watermarking because of quantization-based and IQGW, in particular, it is suitable for real-time watermarking Motion JPEG 2000 coded videos because of expansion to nonorthogonal transformations. More definitive investigation of coefficients improving the subjective image-quality is a further work.

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