Optimizing PSNR for Image Watermarking using Summation Quantization on DWT Coefficients

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***Abstract*—This study presents an optimization-based image watermarking scheme that applies summation quantization technique to multi-coefficients of discrete wavelet transform (DWT). Peak signal-to-noise ratio (PSNR) and bit error ratio (BER) are commonly performance indexes in measuring the quality and robustness of an image watermarking scheme. To optimize the tradeoff between PSNR and BER, we minimize the difference between original and watermarked frequency coefficients. First, PSNR is expressed as a performance index using matrix form. Then, an optimized-quality functional that relates the performance index to the summation quantization technique is obtained. Finally, the Lagrange Principle is utilized to obtain the optimal solution. The optimal solution is applied to watermarking. Experimental results show that the watermarked image can keep high PSNR and achieve better BER even when the number of coefficients for embedding a watermark bit increases.**

Keywords—PSNR; BER; image; watermarking; quantization; wavelet; optimization.

I. INTRODUCTION

With the development of internet, much digital information is widely used. Digital watermarking was developed to hide digital information and protect the copyright of an image. Image watermarking can be divided into special domain methods [1-7] and transform domain methods [8-26] such as discrete cosine transform method [8, 9], discrete Fourier transform method [10, 11], and discrete wavelet transform method [12-26], etc.

In recent years, gray-scale image digital watermarking based on wavelet transformation has become mature. According to theoretical analysis and simulation results, in general, the watermarking in the frequency domain is usually more effective than watermarking in the time domain under the same embedding capacity [21, 24]. In this study, DWT LH3 and HL3 coefficients are used to embed watermark. Peak signal-to-noise ratio (PSNR) and bit error ratio (BER) are commonly performance indexes in measuring the quality and robustness of an image watermarking scheme. We use the proposed optimized-quality quantization watermarking scheme to balance the tradeoff between them. First, the PSNR is rewritten as a performance index. An optimization functional is then proposed to relate this performance index to the quantization technique. Finally, the Lagrange Principle is utilized to obtain the optimal solution. The optimal solution is applied to watermarking. In addition, the watermark is extracted without the original image. The performance of the proposed scheme is evaluated by PSNR and BER. Experimental results show that the watermarked image using the proposed scheme can keep high PSNR and achieve better BER even the number of coefficient for embedding a watermark bit increases.

The rest of this paper is organized as follows. Section 2 reviews some mathematical preliminaries. Section 3 first rewrites PSNR as a performance index. An optimized-quality functional that relates the performance index to the quantization technique is then proposed. Finally, the Lagrange Principle is used to solve the optimization problem and the solution is applied to watermarking. Section 4 does some experiments to test the performance of the proposed scheme. Conclusions are finally drawn in Section 5.

II. PRELIMINARIES

To develop an optimized-quality image watermarking in the wavelet domain, DWT and some mathematical preliminaries are reviewed in this section.

A. Discrete-time wavelet transform (DWT)

The wavelet transform is obtained by a single prototype function which is regulated with a scaling parameter and shift parameter [26]. The discrete normalized scaling and wavelet basis function are defined as

$$\varphi_{j,l}(t) = 2^{j/2}\varphi(2^j t - r) \tag{1}$$

$$\psi_{j,l}(t) = 2^{j/2}\psi(2^j t - r) \quad (2)$$

where j and r are the dilation and translation parameters; From this, one can require that the sequence

$$\{0\} \subset \cdots \subset V_1 \subset V_0 \subset V_{-1} \subset \cdots \subset L^2(\mathbb{R}) \quad (3)$$

form a multiresolution analysis of $L^2(\mathbb{R})$ and that the subspaces $\cdots, W_1, W_0, W_{-1}, \cdots$ are the orthogonal differences of the above sequence, that is, W_j is the orthogonal complement of V_j inside the subspace V_{j-1}. Then, the orthogonality relations follow the existence of sequences $h = \{h_r\}_{r\in\mathbb{Z}}$ and $g = \{g_r\}_{r\in\mathbb{Z}}$ that satisfy the following identities:

$$h_r = \langle \varphi_{0,0}, \varphi_{-1,r} \rangle \text{ and } \varphi(t) = \sqrt{2}\sum_{r\in\mathbb{Z}} h_r \varphi(2t-r) \quad (4)$$

$$g_r = \langle \psi_{0,0}, \varphi_{-1,r} \rangle \text{ and } \psi(t) = \sqrt{2}\sum_{r\in\mathbb{Z}} g_r \varphi(2t-r) \quad (5)$$

where $h = \{h_r\}_{r\in\mathbb{Z}}$ and $g = \{g_r\}_{r\in\mathbb{Z}}$ are respectively the sequence of low-pass and high-pass filters. In this paper, we use Haar scaling function and wavelet to transform the host image into the orthogonal DWT domain by three-level decomposition. A method to implement DWT is a filter bank that provides perfect reconstruction. If DWT is applied to an image, it will produce high-frequency parts, middle-frequency parts, and a lowest-frequency part.

B. Some mathematical definitions and theorems

To find the extreme of the matrix function, some optimization methods are summarized. The operations of the matrix function are first shown as follows.

Theorem 1. *If* $\mathbf{M}$ *is an* $k \times k$ *matrix, and* $\bar{\mathbf{C}}$ *is an* $k \times 1$ *column vector, then* $\frac{\partial \mathbf{M}\bar{\mathbf{C}}}{\partial \bar{\mathbf{C}}} = \mathbf{M}$. (6)

Theorem 2. *If* $\bar{\mathbf{C}}$ *is an* $k \times 1$ *column vector and* $\mathbf{C}$ *is an* $k \times 1$ *constant vector, then* $\frac{\partial (\bar{\mathbf{C}}-\mathbf{C})^T(\bar{\mathbf{C}}-\mathbf{C})}{\partial (\bar{\mathbf{C}}-\mathbf{C})} = 2(\bar{\mathbf{C}}-\mathbf{C})$. (7)

In order to apply the Lagrange Principle, we have to introduce the gradient of a matrix function $f(\bar{\mathbf{C}})$ as follows.

Definition 1. *Suppose that* $\bar{\mathbf{C}} = [\bar{c}_1\ \bar{c}_2\ \cdots\ \bar{c}_k]^T$ *is an* $k \times 1$ *unknown vector and* $f(\bar{\mathbf{C}})$ *is a function of the vector* $\bar{\mathbf{C}}$. *Then the gradient of* $f(\bar{\mathbf{C}})$ *is*

$$\nabla f(\bar{\mathbf{C}}) = \frac{\partial f}{\partial \bar{\mathbf{C}}} = \left[\frac{\partial f}{\partial \bar{c}_1}\ \frac{\partial f}{\partial \bar{c}_2}\ \cdots\ \frac{\partial f}{\partial \bar{c}_k}\right]^T \quad (8)$$

Now we consider the problem of minimizing (or maximizing) the matrix function $f(\bar{\mathbf{C}})$ subject to a constraint $g(\bar{\mathbf{C}}) = 0$. This problem can be described as follows :

$$\text{minimize } f(\bar{\mathbf{C}}) \quad (9a)$$

$$\text{subject to } g(\bar{\mathbf{C}}) = 0 \quad (9b)$$

In order to solve (9), we apply the Lagrange Principle as follows.

Theorem 3. *Suppose that* g *is a continuously differentiable function of* $\bar{\mathbf{C}}$ *on a subset of the domain of a function* f. *Then if* $\bar{\mathbf{C}}_0$ *minimizes (or maximizes)* $f(\bar{\mathbf{C}})$ *subject to the constraint* $g(\bar{\mathbf{C}}) = 0$, $\nabla f(\bar{\mathbf{C}}_0)$ *and* $\nabla g(\bar{\mathbf{C}}_0)$ *are parallel. That is, if* $\nabla f(\bar{\mathbf{C}}_0) \neq 0$, *then there exists a scalar* λ *such that*

$$\nabla f(\bar{\mathbf{C}}_0) = \lambda \nabla g(\bar{\mathbf{C}}_0). \quad (10)$$

Based on Theorem 3, if we let

$$H(\bar{\mathbf{C}}, \lambda) = f(\bar{\mathbf{C}}) + \lambda g(\bar{\mathbf{C}}), \quad (11)$$

then the original problem (9) becomes a function $H(\bar{\mathbf{C}}, \lambda)$ which has no constraint. The necessary conditions for existence of the extreme of $H(\bar{\mathbf{C}}, \lambda)$ are $\frac{\partial H}{\partial \lambda} = 0$ and $\frac{\partial H}{\partial \bar{\mathbf{C}}} = 0$. Since there is a tradeoff relationship between image quality measured by PSNR and robustness measured by BER, in next section we introduce the scalar parameter λ to connect the performance index obtained from PSNR and amplitude quantization equation. Finally, Lagrange Principle in Theorem 3 is applied to find the optimal solution.

III. PROPOSED OPTIMIZATION-BASED EMBEDDING AND EXTRACTION

A. Embedding

First, the watermark is randomly generated using a binary PN sequence. Hence the watermark values belong to the set $\{1,0\}$ and is adopted as the secret key . After the host image is transformed by applying DWT, values of the DWT-coefficient are grouped into a column vector form $\mathbf{C} = [c_1\ c_2\ \cdots\ c_k]^T$. (12)

The proposed embedding technique is given as follows. Let the coefficients in $\mathbf{C}$ (the j^{th} group) are quantized to

$$z_j = \left\lfloor \mathbf{WC}/q + \frac{1}{2} \right\rfloor \quad (13)$$

where $\lfloor\ \rfloor$ indicates the floor function, and $q \in \mathbb{R}^+$ is the quantization size which is adopted as another secret key K_1 ; $\mathbf{W} = [1.0\ \ 1.0\ \ \cdots\ \ 1.0]$ is an $1 \times k$ matrix. The proposed embedding rules are in the following:

- If z_j **mode 2** $= \beta_i$, the coefficients in $\mathbf{C}$ is modified to $y_1 = z_j \times q$. (14)
- If z_j **mode 2** $\neq \beta_i$ and $z_j - \left\lfloor \mathbf{WC}/q \right\rfloor = 0$, the coefficients in $\mathbf{C}$ is modified to $y_2 = (z_j + 1) \times q$ (15)
- If z_j **mode 2** $\neq \beta_i$ and $z_j - \left\lfloor \mathbf{WC}/q \right\rfloor \neq 0$, the coefficients in $\mathbf{C}$ is modified to $y_3 = (z_j - 1) \times q$ (16)

According to Eqs. (14) and (16), the embedding technique can be rewritten as an equation of the form:

$$g(\bar{\mathbf{C}}) = \mathbf{W}\bar{\mathbf{C}} - y_1 = 0, \text{ if "} z_j \text{ mode } 2 = \beta_i \text{".} \quad (17)$$

or $$g(\bar{\mathbf{C}}) = \mathbf{W}\bar{\mathbf{C}} - y_2 = 0, \text{ if "} z_j \text{ mode } 2 \neq \beta_i \text{ and } z_j - \left\lfloor \mathbf{WC}/q \right\rfloor = 0\text{".} \quad (18)$$

or $$g(\bar{\mathbf{C}}) = \mathbf{W}\bar{\mathbf{C}} - y_3 = 0, \text{ if "} z_j \text{ mode } 2 \neq \beta_i \text{ and } z_j - \left\lfloor \mathbf{WC}/q \right\rfloor \neq 0\text{".} \quad (19)$$

where $\bar{\mathbf{C}}$ is the watermarked wavelet-coefficient vector that corresponds to $\mathbf{C}$; $\lfloor \; \rfloor$ indicates the floor function, and q is the quantization size. Generally, the quality of a watermarked image is evaluated by peak signal to noise ratio (PSNR) which is introduced as follows. If $\mathbf{I}(i,j)$ and $\bar{\mathbf{I}}(i,j)$ are the values of original and the corresponding modified pixel in original image $\mathbf{I}$ and watermarked image $\bar{\mathbf{I}}$, then PSNR is defined as

$$PSNR = -10\log_{10}\left(\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\bar{\mathbf{I}}(i,j) - \mathbf{I}(i,j)\right)^2}{255^2 mn} \right), \quad (20)$$

where m and n represent the height and width of the image. Since the DWT is implemented with orthogonal wavelet bases, PSNR is expressed as

$$PSNR = -10\log_{10}\left(\frac{\left\|\bar{\mathbf{C}} - \mathbf{C}\right\|_2^2}{255^2 mn} \right) \quad (21)$$

For the optimization of the watermarked image quality, Eq. (21) is rewritten as a performance index :

$$f(\bar{\mathbf{C}}) = \frac{\left\|\bar{\mathbf{C}} - \mathbf{C}\right\|_2^2}{255^2 mn} \quad (22)$$

or

$$f(\bar{\mathbf{C}}) = \frac{(\bar{\mathbf{C}} - \mathbf{C})^T(\bar{\mathbf{C}} - \mathbf{C})}{255^2 mn} \quad (23)$$

Based on the performance index $f(\bar{\mathbf{C}})$ in Eq. (23) and the constraint $g(\bar{\mathbf{C}})$ in Eq. (17), the optimization-based quantization problem has the following form:

$$\text{minimize } f(\bar{\mathbf{C}}) = \frac{(\bar{\mathbf{C}} - \mathbf{C})^{\mathbf{T}}(\bar{\mathbf{C}} - \mathbf{C})}{255^2 mn} \quad (24a)$$

$$\text{subject to } g(\bar{\mathbf{C}}) = \mathbf{W}\bar{\mathbf{C}} - y_1 = 0 \quad (24b)$$

To embed the watermark B , we need to solve optimization problem (24). By Theorem 3, we set Lagrange multiplier λ to combine (24a) and (24b) into a matrix function:

$$H(\bar{\mathbf{C}},\lambda) = f(\bar{\mathbf{C}}) + \lambda g(\bar{\mathbf{C}}) = \frac{(\bar{\mathbf{C}} - \mathbf{C})^{\mathbf{T}}(\bar{\mathbf{C}} - \mathbf{C})}{255^2 mn} + \lambda\left(\mathbf{W}\bar{\mathbf{C}} - y_1\right) \quad (25)$$

which has no constraint. Since $255^2 mn$ is a constant, we redefine $H(\bar{\mathbf{C}},\lambda)$ as follow:

$$H(\bar{\mathbf{C}},\lambda) = (\bar{\mathbf{C}} - \mathbf{C})^{\mathbf{T}}(\bar{\mathbf{C}} - \mathbf{C}) + 255^2 mn\lambda\left(\mathbf{W}\bar{\mathbf{C}} - y_1\right) \quad (26)$$

The necessary conditions for existence of the minimum of $H(\bar{\mathbf{C}},\lambda)$ are

$$\frac{\partial H}{\partial \bar{\mathbf{C}}} = 2(\bar{\mathbf{C}} - \mathbf{C}) + 255^2 mn\lambda \mathbf{W}^{\mathbf{T}} = 0 \quad (27a)$$

$$\frac{\partial H}{\partial \lambda} = \mathbf{W}\bar{\mathbf{C}} - y_1 = 0 \quad (27b)$$

Multiply (27a) by $\mathbf{W}$, we observe that

$$2(\mathbf{W}\bar{\mathbf{C}} - \mathbf{WC}) + 255^2 mn\lambda \mathbf{WW}^{\mathbf{T}} = 0 \quad (28)$$

Since $\mathbf{W}\bar{\mathbf{C}} = y_1$ from (27b) and $255^2 mn$ is a scalar, we rewritten (28) as

$$(y_1 - \mathbf{WC}) + \frac{255^2 mn}{2}\lambda \mathbf{WW}^{\mathbf{T}} = 0 \quad (29)$$

Some operations yield optimal solution for parameter λ as

$$\lambda^* = \frac{2}{255^2 mn}(\mathbf{WW}^{\mathbf{T}})^{-1}(\mathbf{WC} - y_1) \quad (30)$$

Replacing Eq. (30) with Eq. (27a) yields the optimal solution for the modified coefficients as

$$\bar{\mathbf{C}}^* = \mathbf{C} - \frac{255^2 mn}{2}\lambda^* \mathbf{W}^{\mathbf{T}} = \mathbf{C} - \mathbf{W}^{\mathbf{T}}(\mathbf{WW}^{\mathbf{T}})^{-1}(\mathbf{WC} - y_1) \quad (31)$$

This optimal coefficients $\bar{\mathbf{C}}^*$ can be embedded when "z_j **mode 2=**β_i". Restated, "z_j **mode 2** $\neq \beta_i$ **and** $z_j - \left\lfloor \mathbf{WC}/q \right\rfloor = 0$" can be embedded by using y_2 instead of y_1 as follows :

$$\bar{\mathbf{C}}^* = \mathbf{C} - \mathbf{W}^{\mathbf{T}}(\mathbf{WW}^{\mathbf{T}})^{-1}(\mathbf{WC} - y_2) \quad (32)$$

The same restated "z_j **mode 2** $\neq \beta_i$ **and** $z_j - \left\lfloor \mathbf{WC}/q \right\rfloor \neq 0$" can be embedded by using y_3 instead of y_1 as follows :

$$\bar{\mathbf{C}}^* = \mathbf{C} - \mathbf{W}^{\mathbf{T}}(\mathbf{WW}^{\mathbf{T}})^{-1}(\mathbf{WC} - y_3) \quad (33)$$

Figure 1 shows the proposed embedding process.

B. Extraction

To detect the watermark, every k consecutive DWT LH3 or HL3 coefficients are grouped into $\bar{\mathbf{C}}^* = \{\bar{c}_1^*, \bar{c}_2^*, \cdots, \bar{c}_k^*\}$, where the superscript * denotes the optimal result with respect to the corresponding variable. Then, the embedded binary bits are extracted by using the following rule.

- $$\hat{\beta}_i = \left\lfloor \mathbf{W}\bar{\mathbf{C}}^*/q + \frac{1}{2} \right\rfloor \bmod 2, \quad (34)$$

where $\hat{\beta}_i$ denotes the extracted value.

Finally, the hidden watermark bits (binary bits) are extracted as $B = \{\hat{\beta}_i\}$ without the original image.

IV. Experimental Results

This section presents experiments. The host images, each of size 512×512, are decomposed into three levels by applying DWT, and then the watermark is embedded into the LH3 and HL3 coefficients.

A. Image quality assessment and embedding capacity

To evaluate the quality of the watermarked image, four images, Lena, Jet, Peppers, Cameraman, are adopted as the example images. In addition to PSNR defined in (14), the perceptual quality measurement method quantified by mean opinion score (MOS) has applied to evaluate the quality of watermarked images. MOS uses the five grade impairment scale which is listed in Table I. To score each watermarked image by subjective MOS values, both original and watermarked image were provided to ten viewers. They were requested to give each audio a rating. The MOS values of different image files were obtained by averaging the scores given by the viewers.

Table II shows the results of the image quality evaluation and the embedding capacity under different parameters. Since the multi-coefficients in LH3 and HL3 are optimally quantized by Lagrange Principle, the values of PSNR can exceed 42 dB even the number of coefficient for embedding a watermark bit increases. Figs. 2 shows the watermarked images obtained in case k=8, q=78.

B. Robustness testing

To evaluate the robustness of the proposed method, 100 images including the four images, Lena, Jet, Peppers, Cameraman, are tested. After the embedding process, four attacks are adopted to test the robustness of the embedded watermark in case $k=2$, $\mathrm{q}=26$, $k=4$, $\mathrm{q}=52$, and $k=8$, $\mathrm{q}=78$. The robustness is measured by Bit error ratio (BER) defined by $\mathrm{BER}=(B_{error}/B_{total})\times 100\%$, where B_{error} and B_{total} denote the number of error bits and the number of total bits, respectively. The method proposed herein is compared with single-sample quantization method in the spatial-domain [7] and SVD method in the DWT domain [22]. The test of robustness supports the following conclusions.

(1) JPEG2000 compression is the most popular compression. It is widely used to reduce the sizes of images. Usually, an image is compressed before it is transmitted over the Internet. Table III concerns the compression of the 100 watermarked images by JPEG2000 compression with different quality factors. The average BER of the proposed method is higher than the methods [7] and [22]. As the parameters *k* and *q* increases, average BER decreases rapidly.

(2) Table IV shows the robustness against Gaussian noise with different noise power in dB. By testing the 100 watermarked images, the average BER of the proposed method is higher than the methods [7] and [22]. As the parameters *k* and *q* increases, average BER decreases.

(3) Table V shows the robustness against median filter with different radius in pixels. By testing the 100 watermarked images, the average BER of the proposed method is higher than the methods [7] and [22]. As the parameters *k* and *q* increases, average BER decreases.

(4) Table VI shows the performance against rotation with different degree. By testing the 100 watermarked images, the average BER of the proposed method is similar with that of the method [22] in case $k=8$, $\mathrm{q}=78$, but higher than the method [7] in all cases.

TABLE I. FIVE GRADE IMPAIRMENT SCALE.

Grade	Quality	Impairment
5	Excellent	Imperceptible
4	Good	Perceptible but not annoying
3	Fair	Slightly annoying
2	Poor	Annoying
1	Bad	Very annoying

(a) Lena (b) Jet (c) Peppers (d) Cameraman

Fig. 2 Watermarked images for k=8, q=78.

TABLE II. PSNR AND EMBEDDING CAPACITY.

Method	Image genre	Parameters	PSNR (dB)	MOS	Embedding capacity (bits)
Ref. [7]	Lena	No	42.3	4.2	4096
	Jet	No	42.6	4.1	4096
	Peppers	No	42.1	4.1	4096
	Cameraman	No	41.7	4.0	4096
Ref. [22]	Lena	α=55	43.2	4.4	512
	Jet	α=55	43.1	4.4	512
	Peppers	α=55	42.2	4.4	512
	Cameraman	α=55	42.6	4.2	512
Proposed method	Lena	k=2, q=26	42.5	4.2	4096
		k=4, q=52	42.4	4.4	2048
		k=8, q=78	42.4	4.2	1024
	Jet	k=2, q=26	42.6	4.2	4096
		k=4, q=52	42.3	4.4	2048
		k=8, q=78	42.3	4.6	1024
	Peppers	k=2, q=26	42.1	4.1	4096
		k=4, q=52	42.2	4.2	2048
		k=8, q=78	42.3	4.2	1024
	Cameraman	k=2, q=26	42.1	4.2	4096
		k=4, q=52	42.3	4.4	2048
		k=8, q=78	42.1	4.1	1024

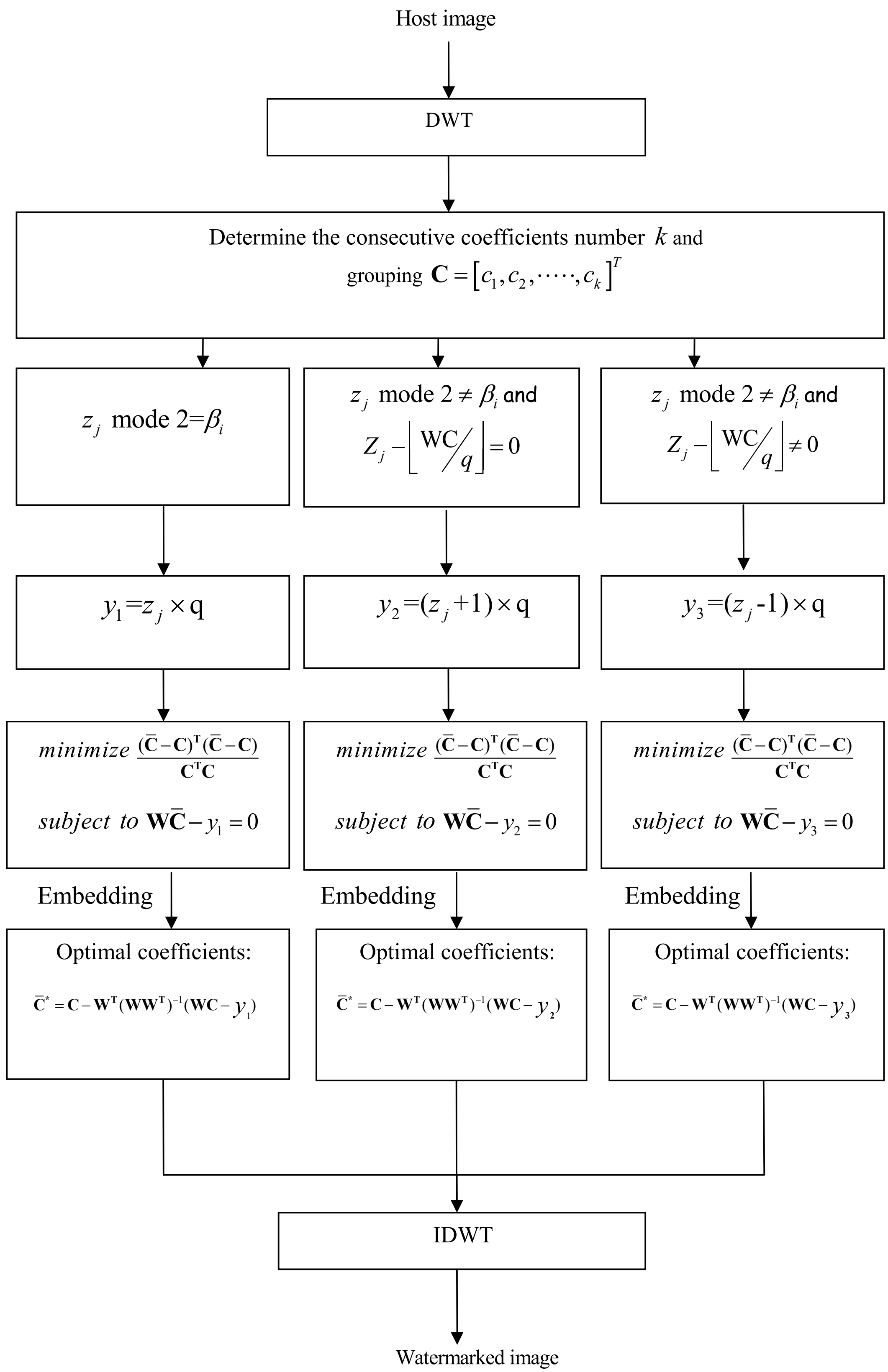

Fig. 1 Watermark embedding.

TABLE III. JPEG2000 COMPRESSION

Quality factor		3	5	7	10	12
Reference [7]		54.83	49.61	48.23	34.92	29.10
Reference [22]		34.22	11.46	6.21	3.39	1.24
Proposed method	k=2, q=26	28.27	7.70	5.31	1.32	0
	k=4, q=52	15.11	3.71	3.02	0.76	0
	k=8, q=78	8.42	2.26	1.92	0.12	0

TABLE IV. GAUSSIAN NOISE

Method & parameter \ dB		35	30	25
Reference [7]		48.52	51.72	50.06
Reference [22]		0.59	19.53	22.66
Proposed method	k=2, q=26	0	0.05	2.93
	k=4, q=52	0	0	0
	k=8, q=78	0	0	0

TABLE V. MEDIAN FILTER

Method & parameter \ Radius(pixels)		3	4
Reference [7]		53.47	54.57
Reference [22]		50	49.61
Proposed method	k=2, q=26	0.63	9.47
	k=4, q=52	0	2.05
	k=8, q=78	0	1.56

TABLE VI. ROTATION

Method & parameter \ Degree		1	2	4
Reference [7]		53.47	54.57	54.57
Reference [22]		5.47	8.98	12.31
Proposed method	k=2, q=26	29.19	31.05	29.10
	k=4, q=52	20.41	20.99	22.75
	k=8, q=78	10.13	10.54	12.69

V. CONCLUSION

Based on an equation that connects PSNR and quantization technique, this study obtained an optimization-based formula for image watermarking. Experimental results show that the watermarked image can keep high PSNR even the number of coefficient for embedding a watermark bit increases. In addition, the proposed scheme also achieves better BER. The future work is the consideration of improving robustness by using a new cost function.

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