

Robust multirate lattice quantization index modulation watermarking resilient to multiple description transmission channel

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Abstract. Multiple-description (MD) transmission results in nonlinear value-metric (value-scaling) distortion in the case when some of the sent descriptions are not received. An acceptable image can still be received in the above situation due to the characteristic of MD. However, it is quite damaging to the traditional quantization-based watermarking technique for payload detection. To overcome the problem, a straightforward approach would be to increase the quantization step size in watermark embedding so as to keep the distortion within the tolerant range. However, as a larger quantization step size in watermark embedding would result in a worsened watermarked image, it is not feasible to adopt it without further consideration. The proposed multirate lattice quantization index modulation (MRL-QIM) encodes two watermark bits into each of the four co-set points of a lattice (so-called multirate). Compared to traditional vector-based quantization encoding or combined spread spectrum-quantization encoding, it significantly increases the payload (capacity) and enhances the robustness of watermark detection while preserving the fidelity of the watermarked image. Comprehensive experiments have confirmed that the overall performance and the effectiveness of the proposed scheme are superior to previous approaches.
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1 Introduction

Watermarking is a well-known technique used to hide data or information imperceptibly within image, audio, or video so that valuable contents can be protected. The research that developed robust watermarking techniques that can survive intentional attacks has been extensively explored in the past decade. However, few researchers have put their emphasis on dealing with incidental attacks, such as an attack caused by packet network or error-prone wireless transmission over an unreliable network. In Ref. 1 Hartung and Ramme point out that as the technology of second-generation and third-generation (3G) mobile networks keeps advancing, digital media distribution for mobile E-commerce will eventually evolve into a huge business. Under these circumstances, watermarking applications such as media identification and copy control are getting more and more feasible for mobile E-commerce with the virtue that the identity of a user is known. Aiming at the error-prone nature of wireless communications, Checcacci et al.² propose a robust MPEG-4 watermarking technique for video sequences corrupted with errors. Chandramouli et al.³ propose a multiple-description framework for oblivious watermarking, which uses one description to embed watermark information and another for referential original image

to assist detection. However, it is not a completely blind technique, in the sense that a relationship (defined by the watermark key) between the watermarked coefficients in one description and the corresponding coefficients in the referential one will be needed during the watermark detection process. And since the embedded watermark cannot be extracted without receiving both descriptions, it is not suitable for error-prone packet transmission network applications.

Multiple-description coding (MDC)⁵⁻⁹ is different from either layered coding or simulcast coding or even error-resilient tools described in MPEG-4.⁴ On a wireless multi-hop network or a packet-switched network, there are several parallel channels between the source and the destination and each channel may be temporarily down or suffering from long burst errors. The MDC scheme is designed such that the quality of the decoded signal is acceptable with receiving any individual description and can be further improved as more descriptions are received.

Contrasted to the limited capacity inherent in spread spectrum-based watermarking techniques,¹⁰⁻¹² the quantization-based watermarking techniques^{13,14} normally have a relatively high capacity. Chen and Wornell¹³ presented a quantization index modulation (QIM) scheme based on the concept of dither modulation, which uses the watermark information as an index to select a dither signal. The dither signal is then added to the host signal, and a

least distorted quantizer is selected from a set of possible quantizers. The dithered host signal is quantized using this selected quantizer, and finally the dither signal is subtracted from the quantized signal to form a watermarked value:

$$s(\mathbf{x}; m) = Q[(\mathbf{x} + \mathbf{d}(m)) - \mathbf{d}(m)], \quad (1)$$

where $\mathbf{x} \in \mathbf{X}$ is the host signal, $\mathbf{d}(m)$ is the dither signal representing watermark message bit $m \in \mathbf{W}$, $Q(\cdot)$ denotes the selected quantizer, and $s(\mathbf{x}; m)$ corresponds to the host signal embedded with watermark message m . In the detection process, different dither signals representing the watermark message are added to the received signal using Eq. (1), and the index ($m=0$ or 1) of the dither signal is the extracted watermark information. The detected index m^* is chosen so that it gives the minimum distance between the received signal (\mathbf{x}') and its closest quantized signal:

$$m^* = \arg \min_m \|\mathbf{x}' - s(\mathbf{x}'; m)\|. \quad (2)$$

We argue that the distortion introduced by losing some of the transmitted descriptions of MD transmission can be viewed as a nonlinear value-metric attack (described in Section 2.1). While in this situation an acceptable image can still be received due to the characteristic of MD, it is quite damaging to the traditional quantization-based watermarking technique (QIM) for payload detection. Some other works address the problem of QIM detection in the presence of value-metric distortion,¹⁴⁻¹⁹ yet few papers focus on QIM-related watermarking scheme under MD attack.

In Ref. 20 the authors integrate oblivious watermarking techniques [quantization index modulus modulation (QIMM) and QIM with the multiple-description coding (MDC)] to get a multiple-description watermarking (MDW) framework. In this framework, the watermark embedding is computed in either description and could be extracted with the reception of either one or two descriptions. The main drawback of Ref. 20 is that both the watermark embedding and detection are performed on side description rather than on central description. The other problem is that both QIMM and QIM are quite limited under value-metric attack.

Stimulated by the above-mentioned issues, in this paper we attempt to find an improvement by studying the problem of watermarking under multiple-description diversity transmission from a different perspective; namely, watermark embedding is done in the central description while watermark detection can be done in either central or side description. The merit of watermark embedding done in the central description is that the embedding and detection do not interfere with the MD mechanism. Therefore, this approach is more flexible than the one done in the side description. Furthermore, we propose a blind multirate lattice quantization index modulation (MRL-QIM) watermarking technique to boost the effectiveness. As the proposed MRL-QIM encodes two watermark bits into each of the four co-set points of a lattice (multirate), with the above design, the payload (capacity) and robustness of watermark detection will be significantly upgraded. In the meantime, the fidelity of the watermarked image is also preserved. In next section, the MD attack channel and the hexagonal lattice quan-

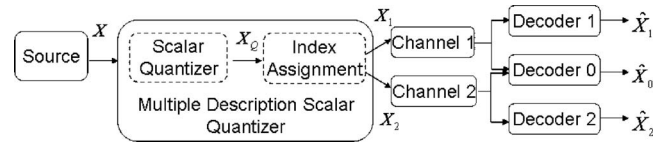


Fig. 1 The flowchart of multiple description coding scheme.^{6,7}

tization (HLQ) algorithm will be introduced. We will elaborate on the proposed MRL-QIM watermarking technique in Section 3. In Section 4, experimental results are presented. The concluding remarks together with future work are addressed in Section 5.

2 Multiple-Description Coding (MDC) and Hexagonal Lattice Quantization (HLQ)

In this section we begin by describing the multiple-description coding (MDC),^{6,7} which introduces possible nonlinear value-metric attack for watermark detection through transmission. Then, we shall introduce a hexagonal lattice quantization (HLQ) algorithm, which will be adopted in our proposed MRL-QIM watermarking technique.

2.1 The MDC Approach^{6,7}

The practical MDC approach for wavelet-based coding was proposed by Survetto et al.⁶ The basic two-description architecture of MDC^{6,7} is illustrated in Fig. 1. The major contribution of the MDC scheme is its capability on receiving satisfactory data quality even if part of the channel is broken. As shown in Fig. 1, the quality of a decoded signal will be acceptable if either receiver 1 or receiver 2 receives the correct signal. In addition, the quality of a received signal can be better if both receivers function well. The most crucial component of the MDC scheme is its multiple description scalar quantizer. It consists of a scalar quantizer component, which quantizes the continuous sample values to smaller countable integer values, and an index assignment component. The source input signal $x \in \mathbf{X}$ is first scalar-quantized to $x_Q \in \mathbf{X}_Q$. The function of the index assignment component $f: x_Q \rightarrow (x_1, x_2)$ is then to split a quantized coefficient x_Q into two complementary and possibly redundant smaller coefficients $x_1 \in \mathbf{X}_1$ and $x_2 \in \mathbf{X}_2$, so that each of these two small coefficients only needs a lower bit rate to describe and both could be recombined later to recover the original quantized coefficient. That is, with the reception of two description values, a perfect reconstructed value $\hat{x} = \hat{x}_0 = x_Q$ can be achieved by using $\hat{x}_0 = f^{-1}(x_1, x_2)$. When only one of the description values is received, an acceptable estimated value $\hat{x} = \hat{x}_d (|\hat{x}_d| < |x_Q|)$ can be obtained through $\hat{x}_d = f^{-1}(x_d)$, where $d=1, 2$.

To better explain the concept, we use an example to discuss the approach. A quantized coefficient x_Q valued at 392 is split into the ordered pair $(x_1, x_2) = (130, 131)$, where 130 and 131 are the values assigned to descriptions 1 and 2, respectively. Similarly, a quantized coefficient x_Q valued at 813 is split into the ordered pair $(x_1, x_2) = (271, 270)$, where 271 and 270 are the values assigned to descriptions 1 and 2, respectively. On receiving only description 1 for the transmitted value 392, the estimated $\hat{x} = \hat{x}_1$ using $x_1 = 130$ will be

391; while receiving only description 2, the estimated $\hat{x} = \hat{x}_2$ using $x_2=131$ will be 394. Similarly, on receiving only description 1 for the transmitted value 813, the estimated $\hat{x} = \hat{x}_1$ using $x_1=271$ will be 814; while receiving only description 2, the estimated $\hat{x} = \hat{x}_2$ using $x_2=270$ will be 811. As can be seen from this example, this leads to nonlinear value-metric distortion. The detailed algorithm for index assignment can be found in Refs. 6 and 7.

2.2 HLQ (Hexagonal Lattice Quantization)

It is well known that quantization error includes overload error and granular error.²¹ The overload error can be reduced by vector quantization, and the granular error is affected by the size and shape of a quantization region. Since the best shape for a quantization region in two dimensions is a hexagon,²² we adopt an efficient lattice quantization algorithm²³ for hexagonal lattice quantizer. In order to make this algorithm better fit our watermarking scheme, we employ the concept from nested lattice²⁴ to implement the software.

2.2.1 Lattice quantization

An N -dimensional lattice is a set of points $\Lambda = \{\mathbf{x}\} = \{u_1 a_1 + \dots + u_N a_N\}$, where \mathbf{x} is an N -dimensional row vector (point) in R^N , $\{a_1, \dots, a_N\}$ is a set of basis vectors in R^N , and u_1, \dots, u_N range through all integers. That is,

$$\mathbf{x} = \mathbf{u}\mathbf{A}; \text{ where } \mathbf{x} = [x_1, x_2, \dots, x_N],$$

$$\mathbf{u} = [u_1, u_2, \dots, u_N], \text{ and } \mathbf{A} = \begin{bmatrix} a_1 \\ a_2 \\ \cdot \\ \cdot \\ \cdot \\ a_N \end{bmatrix}.$$

The Voronoi region, or the nearest-neighbor region for the lattice Λ with respect to \mathbf{x}' , is defined as

$$V(\mathbf{x}') = \{\mathbf{x} \in R^N : \|\mathbf{x}' - \mathbf{x}\| \leq \|\mathbf{y} - \mathbf{x}\|, \text{ for all } \mathbf{y} \in \Lambda\}.$$

Let Q be the quantization function mapping $\mathbf{x} \in R^n$ to the nearest point \mathbf{x}' in Λ . To quantize \mathbf{x} to \mathbf{x}' , we need to find nearest lattice points \mathbf{x}' to \mathbf{x} , that is, $Q(\mathbf{x}) = \mathbf{x}'$. Some of the fast algorithms for lattice quantizer have been proposed in the literature.²³⁻²⁵ We adopt the method proposed in Ref. 23 for its simplicity and then make some minor modifications on its format. This minor change makes the lattice quantization feasible for watermark embedding and detection. Our modified quantizer algorithm for two-dimensional hexagonal lattice A_2 in R^2 can be implemented as follows:

- Step 1: $\mathbf{x} = \mathbf{u}\mathbf{A}$.
- Step 2: $\mathbf{u}^* = \mathbf{u}\mathbf{A}^{-1}$ (as \mathbf{u}^* might not be integers, $\mathbf{x}^* = \mathbf{u}^*\mathbf{A}$ might not be a lattice point, but a close point to a lattice point \mathbf{x}' defined below).
- Step 3: $\mathbf{u}^* = (u_1, u_2)$.
- Step 4: Round \mathbf{u}^* to integer point $(u_1, u_2) = [\text{round}(u_1), \text{round}(u_2)]$.
- Step 5: Find seven neighbor integer pairs for \mathbf{u}^* .

- $\mathbf{u}(1) = (u_1, u_2)$,
- $\mathbf{u}(2) = (u_1 + 1, u_2)$,
- $\mathbf{u}(3) = (u_1, u_2 + 1)$,
- $\mathbf{u}(4) = (u_1 + 1, u_2 + 1)$,
- $\mathbf{u}(5) = (u_1 - 1, u_2)$,
- $\mathbf{u}(6) = (u_1, u_2 - 1)$,
- $\mathbf{u}(7) = (u_1 - 1, u_2 - 1)$.

Step 6: Choose i^* , where i^* is the index i that gives the minimum $\mathbf{u}(i)\mathbf{A} - \mathbf{x}'$;

$$i^* = \arg \min_i \|\mathbf{u}(i)\mathbf{A} - \mathbf{x}'\|.$$

Step 7: Get the closest lattice point \mathbf{x}' to \mathbf{x} :

$$\mathbf{x}' = \mathbf{u}(i^*)\mathbf{A}.$$

After the process of lattice quantization, the next step is to further partition the constructed lattice into co-sets. With the nested lattice structure, one is able to correctly deal with the payload issue.

2.2.2 Nested lattice

For the purpose of watermarking, the constructed lattice should be further partitioned into several co-sets, where points belonging to a different co-set represents a different watermark payload. Figures 2(a) and 2(b) depict the concept of nested lattice pair (Λ_f, Λ_c) ,²⁶ where Λ_f is a fine lattice and Λ_c is a coarse lattice. The generating matrix \mathbf{A}_f of Λ_f and \mathbf{A}_c of Λ_c are related by

$$\mathbf{A}_c = \mathbf{J}\mathbf{A}_f.$$

Lattice Λ_f may be decomposed into $|\det \mathbf{J}|$ co-sets, and Λ_f is the union of co-sets. Λ_f and Λ_c are related by

$$\Lambda_f = \bigcup_{k=0}^{|\det \mathbf{J}|-1} \Lambda_k.$$

For example, let

$$\mathbf{A}_f = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \end{bmatrix}, \quad \mathbf{J} = 2\mathbf{I}_2 = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}.$$

By mapping $(\xi_1, \xi_2) \in Z^2$ to $(\xi_1 - \frac{1}{2}\xi_2, \frac{\sqrt{3}}{2}\xi_2) \in A_2$, we can therefore use $(\xi_1, \xi_2) \in \{(0, 0), (0, 1), (1, 0), (1, 1)\}$ to generate 4 co-set leaders:

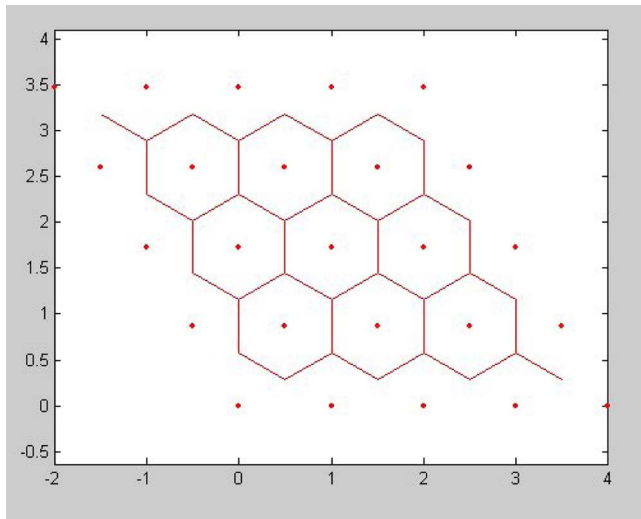
$$C = \{\mathbf{d}_0, \mathbf{d}_1, \mathbf{d}_2, \mathbf{d}_3\} = \left\{ \left(\xi_1 - \frac{1}{2}\xi_2, \frac{\sqrt{3}}{2}\xi_2 \right) \right\}$$

$$= \left\{ (0, 0), \left(-\frac{1}{2}, \frac{\sqrt{3}}{2} \right), (1, 0), \left(\frac{1}{2}, \frac{\sqrt{3}}{2} \right) \right\}.$$

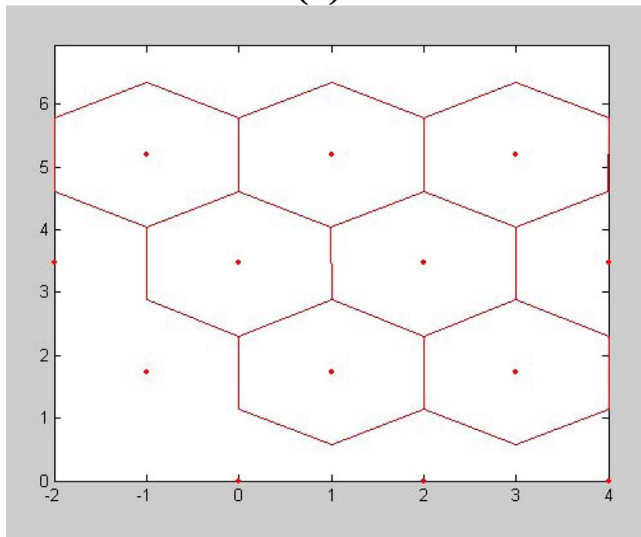
The four co-sets are then defined as follows:

$$\Lambda_0 = \Lambda_c + \mathbf{d}_0,$$

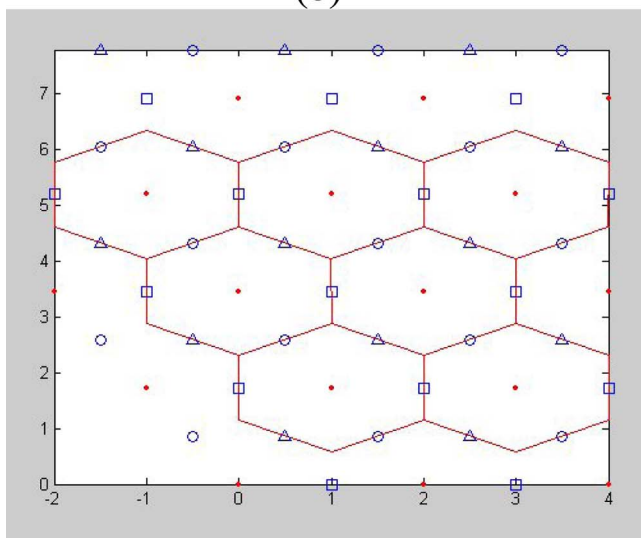
$$\Lambda_1 = \Lambda_c + \mathbf{d}_1,$$



(a)



(b)



(c)

Fig. 2 Nested lattice. (a) Fine lattice Λ_f (b) coarse lattice $\Lambda_c=2\Lambda_f$ (c) union of coarse lattices Λ_k ($k=0, \dots, 3$), where $\Lambda_0=\Lambda_c$.

$$\Lambda_2 = \Lambda_c + \mathbf{d}_2,$$

$$\Lambda_3 = \Lambda_c + \mathbf{d}_3,$$

where Λ_1 (marked with “o”), Λ_2 (marked with “□”) and Λ_3 (marked with “△”) are the translated versions of Λ_0 (marked with “.”) shifted by \mathbf{d}_1 , \mathbf{d}_2 , and \mathbf{d}_3 , respectively [see Fig. 2(c)]. Note that the generating matrix \mathbf{A}_f of Λ_f and \mathbf{A}_c of Λ_c (Λ_0) are related by $\mathbf{A}_c=2\mathbf{A}_f$, where the lattice points of Λ_f are shown in Fig. 2(a), the lattice points of Λ_c are shown in Fig. 2(b), and the lattice points of Λ_k ($k=0, \dots, 3$) are shown in Fig. 2(c).

3 The Proposed Multirate Lattice Quantization Index Modulation (MRL-QIM) Watermarking

In this section, a multirate lattice quantization index modulation (MRL-QIM) watermarking scheme is described. The design goal of the MRL-QIM scheme is to use multirate watermark encoding to increase payload hiding and, at the same time, to increase the robustness of watermark detection. The advantage of the proposed scheme is two-fold: First, it can increase the detection robustness for error-prone transmission over unreliable networks. Second, it is able to increase the watermark capacity while preserving the perceiving transparency. This is achieved by modulating the selected coefficients pair appropriately so that two bits of information can be embedded.

Figure 4(a) shows the flow of MRL-QIM, which is composed of a watermark embedding process and a transmission process. The original image is first transformed into the discrete cosine domain. The transformed coefficients are then grouped into 64 feature bands $\mathbf{X}(i, j) = (x_1, x_2, \dots, x_c)$, where $i=1, \dots, 8$; $j=1, \dots, 8$, and c is the total coefficient count of each feature band. Next, each of two bits (\mathbf{m}) of the watermark message \mathbf{W} is embedded in the selected two-coefficient pair (where the selection depends on key \mathbf{K}) using MRL-QIM quantizer as described in Section 3.1. The perturbed coefficients \mathbf{Y} are then processed by multiple description scalar quantizer (MDSQ) to generate two independent descriptions, \mathbf{Y}_1 and \mathbf{Y}_2 , and sent through two independent channels. The watermarked images (\mathbf{I}'_{w1} from side decoder 1, \mathbf{I}'_{w2} from side decoder 2, or \mathbf{I}'_{w0} from central decoder) could then be obtained by receiving either one description [decoder 1 ($\hat{\mathbf{Y}}_1$) or decoder 2 ($\hat{\mathbf{Y}}_2$)] or two descriptions [decoder 0 ($\hat{\mathbf{Y}}_0$)] and inverting the discrete cosine transforms. In the detection process [Fig. 4(b)], the received image \mathbf{I}'_{wr} ($r=0, 1$ or 2) first goes through a discrete cosine transform. The DCT coefficients are then grouped into 64 feature bands, $\hat{\mathbf{Y}}_r(i, j) = (x_1, x_2, \dots, x_c)$, where $i=1, \dots, 8$; $j=1, \dots, 8$ and c is the total number of coefficients of each feature band. Finally, apply the detection process of MRL-QIM on $\hat{\mathbf{Y}}_r$ depending on key \mathbf{K} to extract the embedded watermark message \mathbf{W}^* .

3.1 MRL-QIM quantizer

The proposed MRL-QIM quantizer takes two DCT coefficients each time to encode two watermark bits into each of the four co-set points of a lattice (so called multirate). For the host signal \mathbf{X} , watermark message \mathbf{W} , and key \mathbf{K} , the

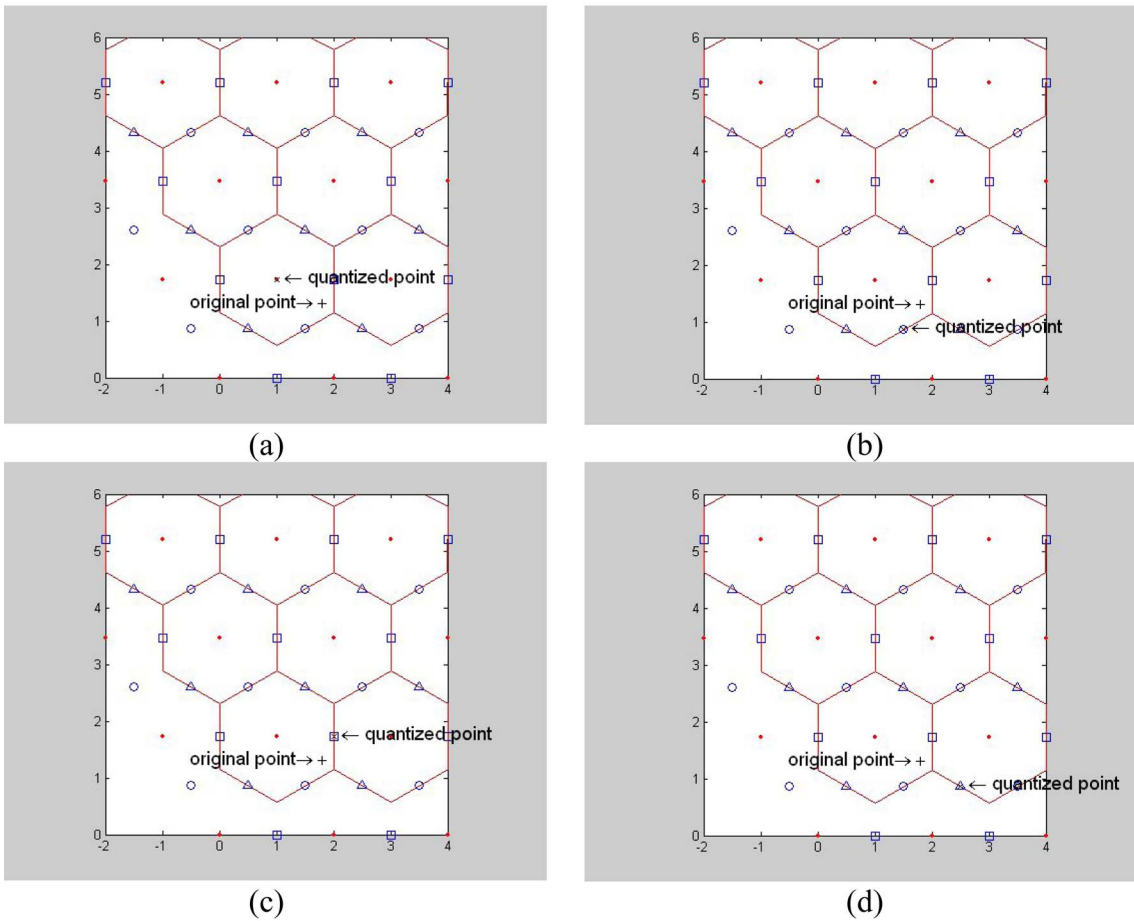


Fig. 3 Examples of multirate lattice watermark embedding. (a) For embedding watermark bits 00, the original point marked with “+” is quantized to the point marked with “.”, with “x” superimposed on the latter; (b) for embedding watermark bits 01, the original point marked with “+” is quantized to the point marked with “o”, with “x” superimposed on the latter; (c) for embedding watermark bits 10, the original point marked with “+” is quantized to the point marked with “□”, with “x” superimposed on the latter; (d) for embedding watermark bits 11, the original point marked with “+” is quantized to the point marked with “△”, with “x” superimposed on the latter.

embedding function is defined as $\mathbf{Y}=f(\mathbf{X},\mathbf{W},\mathbf{K})$. For a chosen DCT coefficient pair $\mathbf{x}=(x_1,x_2)\in\mathbf{X}$ depending on key \mathbf{K} , if $Q(\mathbf{x})$ is used for finding the nearest point of a lattice Λ , then $Q(\mathbf{x}-\mathbf{d}_m)+\mathbf{d}_m$ can be used for finding the nearest point of a co-set $\Lambda+\mathbf{d}_m$. To embed message $\mathbf{m}=00$ or 01 or 10 or 11 $\in\mathbf{W}$ into the host signal \mathbf{x} , we calculate $\mathbf{y}=Q_0(\mathbf{x}-\mathbf{d}_m)+\mathbf{d}_m$ to replace \mathbf{x} with the watermarked coefficient pair $\mathbf{y}=(y_1,y_2)\in\mathbf{Y}$. For a received signal $\hat{\mathbf{Y}}_r(r\in\{0,1,2\})$ and key \mathbf{K} , the detection function is defined as $\hat{\mathbf{W}}=f(\hat{\mathbf{Y}}_r,\mathbf{K})$. To detect watermark message from watermarked signal $\mathbf{y}\in\hat{\mathbf{Y}}_r$, we calculate $\mathbf{m}^*=\arg\min\|\mathbf{y}-Q_0(\mathbf{y}-\mathbf{d}_m)-\mathbf{d}_m\|$ to get the watermark message \mathbf{m}^* .

For example, as depicted in Fig. 3(a), if one wants to embed watermark bits $\mathbf{m}=00$, the original point marked with “+” is quantized to the point marked with “.”, with “x” superimposed on the latter. And similarly, as depicted in Fig. 3(b), if one wants to embed watermark bits $\mathbf{m}=01$, the original point marked with “+” is quantized to the point

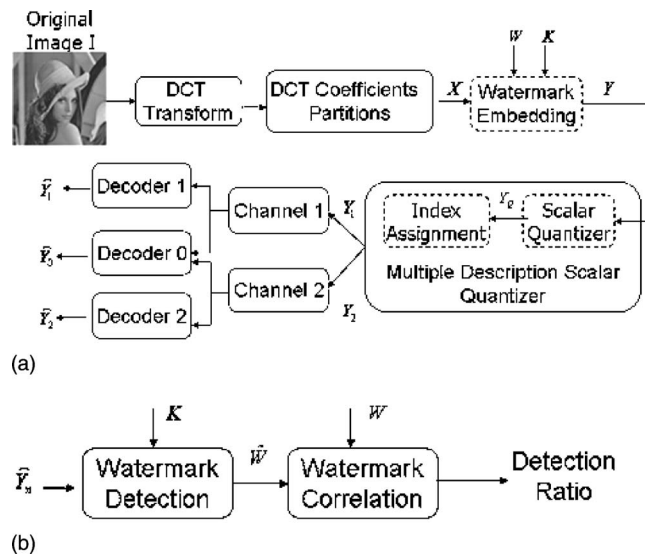


Fig. 4 (a) Flow of proposed MRL-QIM watermark embedding scheme for error-prone transmission over unreliable network. (b) Flow of proposed MRL-QIM watermark detection scheme.

marked with “o”, with “x” superimposed on the latter. Figure 3(c) illustrates the case of embedding bits 10, the original point marked with “+” is quantized to that marked with “□”, with “x” superimposed on the latter. The case of embedding bits 11 is illustrated in Fig. 3(d).

3.2 The Embedding and Transmission Process

To embed n bits of watermark message \mathbf{W} , the algorithm is described as follows:

1. The original image \mathbf{I} is transformed using an 8-by-8-block DCT transform.
2. The DCT coefficients are then grouped into 64 feature bands $\mathbf{X}(i,j)=(x_1,x_2,\dots,x_c)$, where $i=1,\dots,8$, $j=1,\dots,8$, and c is the total number of coefficients of each feature band.
3. Apply embedding process of MRL-QIM on \mathbf{X} depending on key \mathbf{K} to embed watermark message \mathbf{W} to obtain perturbed coefficients \mathbf{Y} .
4. Each of the perturbed coefficients \mathbf{Y} is quantized by a uniform scalar quantizer.
5. Two descriptions ($\mathbf{Y}_1, \mathbf{Y}_2$) of the quantized coefficient are created by mapping each quantized coefficient of \mathbf{Y}_Q to a pair of numbers by the index assignment component.
6. Transmit these two watermarked descriptions over network via two different channels.
7. Apply an inverse transform to obtain a watermarked image \mathbf{I}'_{wr} ($r=0,1$, or 2) depending on received descriptions $\hat{\mathbf{Y}}_r$ ($r=0,1$, or 2).

3.3 The Detection Process

To extract n bits of watermark message \mathbf{W}^* , the algorithm is described as follows:

1. The received image \mathbf{I}'_{wr} is transformed using an 8-by-8, block DCT transform.
2. The DCT coefficients are then grouped into 64 feature bands $\hat{\mathbf{Y}}_r(i,j)=(x_1,x_2,\dots,x_c)$, $r=0,1$, or 2, $i=1,\dots,8$; $j=1,\dots,8$, and c is the total number of coefficients of each feature band.
3. Apply detection process of MRL-QIM on $\hat{\mathbf{Y}}_r$ ($r=0,1$, or 2) depending on key \mathbf{K} to get the extracted watermark message \mathbf{W}^* .

4 Experimental Results

To evaluate the effectiveness of the proposed method, experimental simulations on both of the Monte Carlo simulated Gaussian images and several real images (Lena, Barbara, House, and boat) were performed. To save space, only “Lena” [Fig. 5(a)] and “Barbara” [Fig. 5(b)] as well as the average of detection ratios of Gaussian images are given here. For each run of Monte Carlo simulation, host signals X drawn from 256×256 samples of a Gaussian zero-mean random variable were generated, each having standard deviation σ_X ranging from 10 to 100 with step size 10. All these Gaussian simulated data were then normalized to the range of $0 \sim 255$ to simulate Gaussian gray-level images. We performed 100 times on each of the above simulations

using different seeds, so that 1000 (10×100) Gaussian images were employed to obtain the average detection ratios. In order to further demonstrate the effectiveness of our proposed MRL-QIM, the state-of-the-art watermark technique QIM¹³ and a combined spread spectrum and QIM (SS-QIM)^{18,27} were simulated for comparison. The SS-QIM scheme utilizes spread spectrum approach, in which a watermark strength weighting parameter α is needed, to obtain a correlation value. This correlation value will then be quantized based on specified embedding quantization step size δ and watermark bit (0 or 1) to produce a watermark value.

For the MRL-QIM scheme, two DCT transformed coefficients were simultaneously used to embed two bits of watermark information, and 1024 coefficients in total were used to embed 1024 bits of watermark information. For the traditional vector QIM scheme, two DCT transformed coefficients were formed as a vector to embed one bit of watermark information, and 2048 coefficients in total were used to embed 1024 bits of watermark information. As for SS-QIM, an algorithm adopted from Ref. 27 was implemented, and the trellis error correction coding module was removed to make fair comparisons. Note that the detection rate can be further enhanced by employing an error correction coding module for all these three schemes.

From our experiments, the degree of PSNR dropped depending on the embedding quantization step size. A larger quantization step size brought more robustness, but it also introduced more distortion. We follow the common practice by fixing two requirements, namely watermark capacity and the transparency (distortion) of watermarked image, and then comparing the robustness. To make the comparison fair, the parameters that defined the embedding quantization step size or watermark strength weighting parameter were adjusted so that similar PSNR values (about 41 dB) for these three schemes could be obtained. In our setting, the embedding quantization step size was set to 28, 44, and 7 for MRL-QIM, vector-QIM and SS-QIM, respectively. And for SS-QIM, the other watermark strength weighting parameter α was set to 0.9. The original and watermarked images for MRL-QIM were shown in Figs. 5(a) and 5(b) (one sample of Gaussian images), Figs. 5(c) and 5(d) (Lena) and Figs. 5(e) and 5(f) (Barbara), respectively.

To evaluate the reliability of watermark detection, the detection ratio was defined as

$$\rho = \frac{\text{total number of correctly detected bits}}{\text{total number of embedded bits}}. \quad (3)$$

A higher value of ρ indicated a more reliable detection. The perfect recognition rate could be achieved when the value of $\rho=1$.

In addition to the degree of robustness against packet loss, a desirable and fundamental property for a watermarking algorithm is to survive compression attack. In real-world applications, compression is frequently used to facilitate efficient storage and transmission. Here, we used images compressed by JPEG (low-quality factor ranging from 60 to 80) as test images.

The performance of the detection on receiving only description 1 (similar results can be obtained via description 2) against the MD attack over various transmission rates is

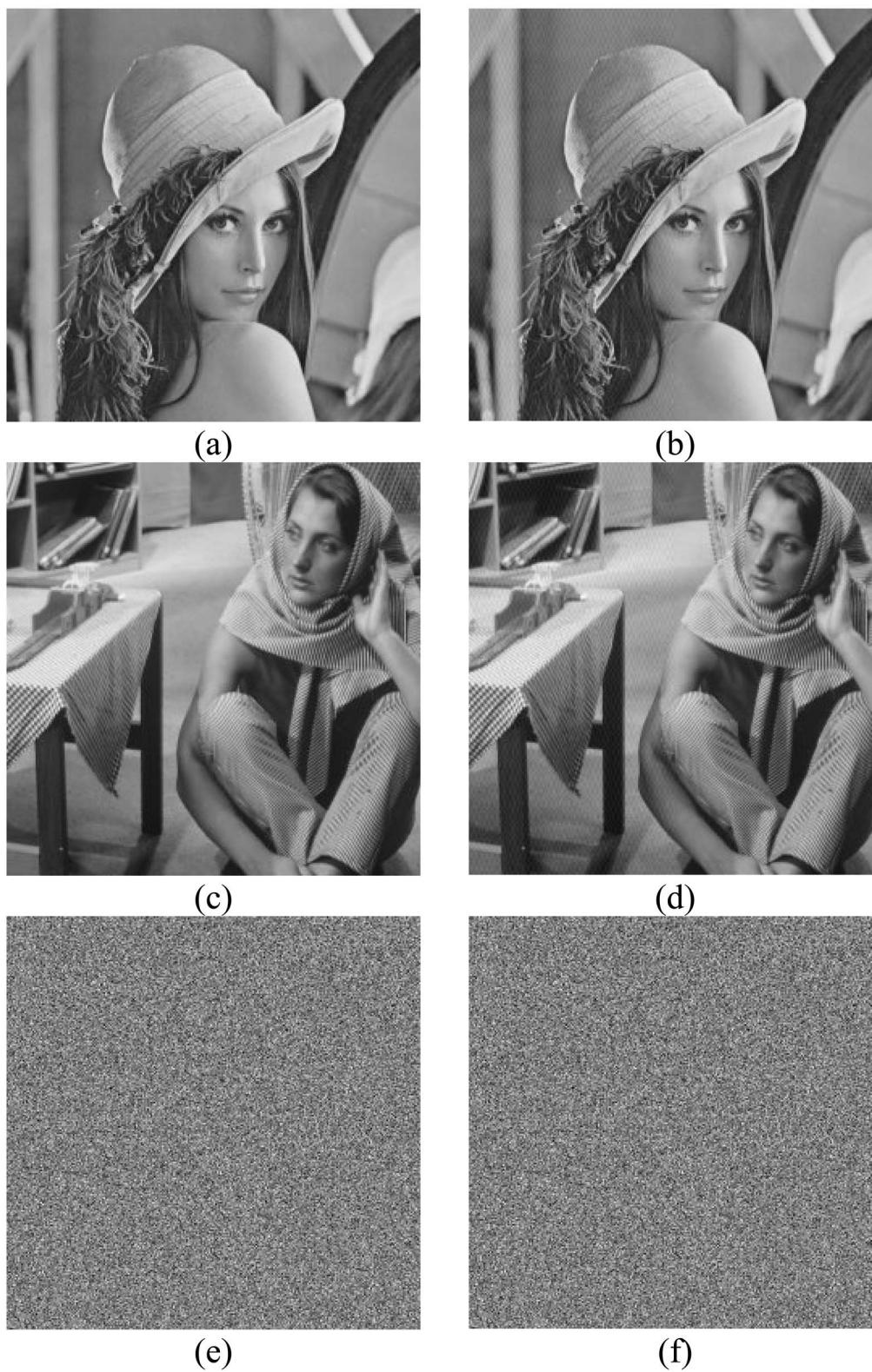


Fig. 5 (a) Original Lena (256×256 with a gray-scaled level). (b) Watermarked Lena (PSNR 41.10). (c) Original Barbara (256×256 with a gray-scaled level). (d) Watermarked Barbara (PSNR 41.11). (e) One sample of original Gaussian images (256×256 with a gray-scaled level). (f) Watermarked Gaussian image (PSNR 41.68).

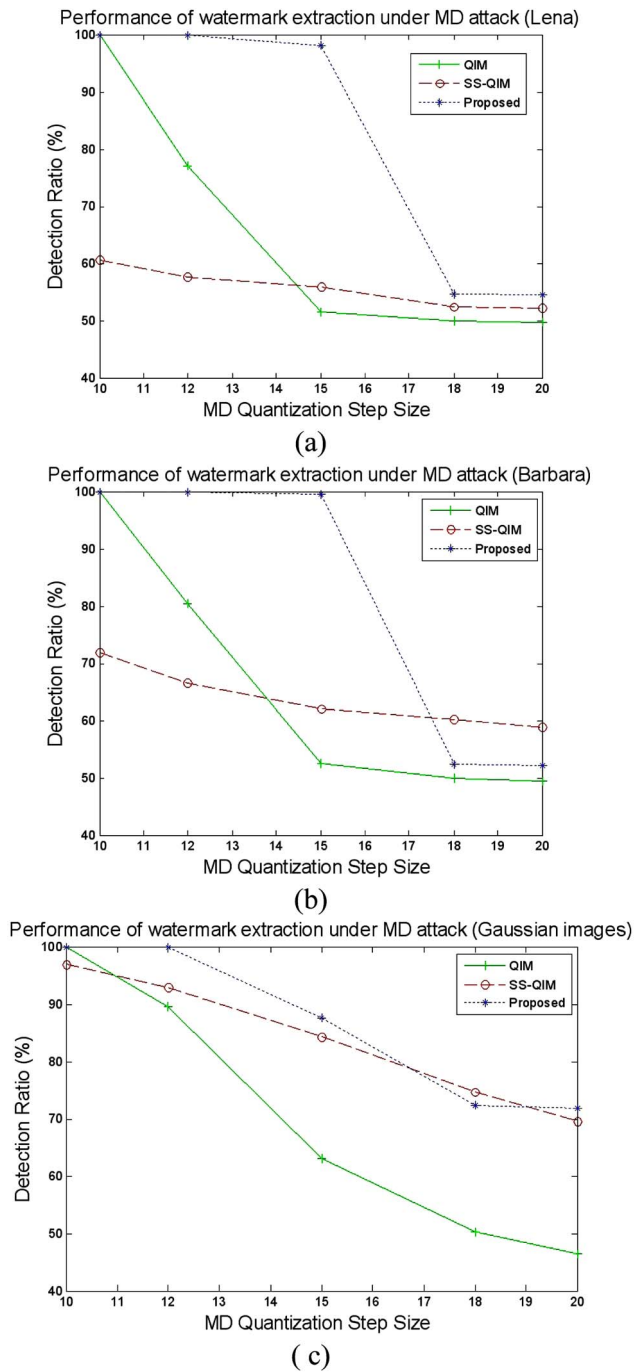


Fig. 6 The comparison in terms of detection ratios among QIM, SS-QIM, and proposed MRL-QIM against various MD transmission rates. (a) “Lena”; (b) “Barbara”; (c) the average of 1000 Gaussian images.

evaluated first. The detection ratios of “Lena,” “Barbara,” and 1000 Gaussian images are depicted in Figs. 6(a)–6(c), respectively. It is clear that the proposed MRL-QIM outperformed traditional vector QIM for all testing images over all transmission rates, and MRAL-QIM performed better than SS-QIM except in the case of high-rate transmission (MD quantization step size=18) for the Gaussian and “Barbara” images.

As for JPEG compression attack, the detection ratios of

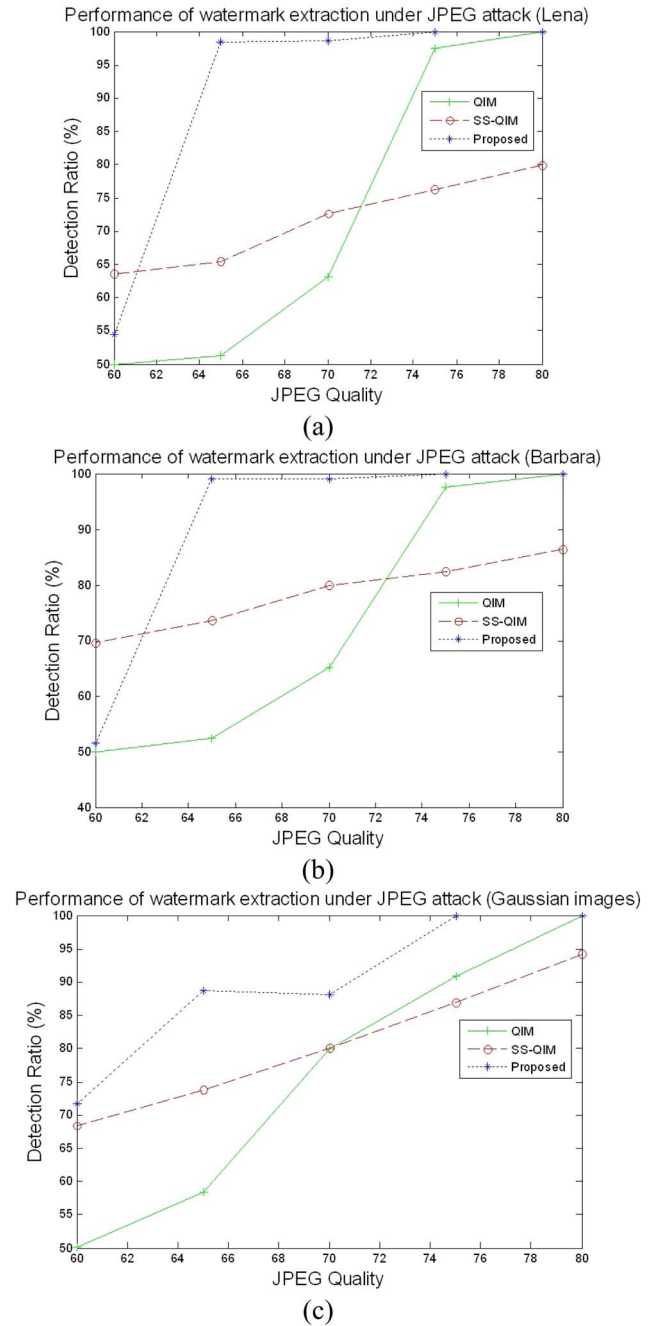


Fig. 7 The comparison in terms of detection ratios among QIM, SS-QIM, and proposed MRL-QIM against JPEG compression. (a) “Lena”; (b) “Barbara”; (c) the average of 1000 Gaussian images.

“Lena,” “Barbara,” and 1000 Gaussian images are shown in Figs. 7(a)–7(c), respectively. The performance of proposed MRL-QIM is still better than traditional vector QIM and superior to SS-QIM for most of the compression rates, except at JPEG quality=60 for “Lena” and “Barbara.”

Note that, even though the detection capability of SS-QIM approach is not as good as the other two schemes when under weaker attacks, it has a smoother decay in detection ratios than pure quantization-based (vector QIM and MRL-QIM) ones when the attacks become stronger.

Based on the experimental result, we speculate that the possible combination SS-MRL-QIM would be a very interesting topic worth further investigation.

5 Conclusion

We have presented in this paper an MRL-QIM watermarking scheme that is robust to nonlinear value-metric distortion introduced by MD transmission. For a traditional balanced two-description case in a packet transmission network, the embedded watermark can be extracted with the reception of either one or two descriptions. The experimental result shows that the proposed MRL-QIM outperforms traditional vector QIM overall and performs better than SS-QIM in the case of high-rate transmission. Furthermore, in the case of compression attack, the performance of proposed MRL-QIM still performs better than traditional vector QIM and superior to SS-QIM for most of the compression rates. In the future, we expect to seek other transforms and statistic models to further enhance the robustness and increase the watermark payload while preserving the visual quality of the transmitted image. Furthermore, the steganography security against statistical steganalysis should also be addressed to enhance the security for reliable transmission.

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