Error-Resilient Triple-Watermarking with Multiple Description Coding

Shu-Chuan Chu
Cheng-Shiu University, Kaohsiung, Taiwan
Email: scchu@csu.edu.tw

Lakhmi C. Jain
University of South Australia, Adelaide, Australia
Email: lakhmi.jain@unisa.edu.au

Hsiang-Cheh Huang
National University of Kaohsiung, Kaohsiung, Taiwan
Email: hchuang@nuk.edu.tw

Jeng-Shyang Pan
National Kaohsiung University of Applied Sciences
Email: jspan@cc.kuas.edu.tw

Abstract—Watermarking is one useful solution for digital rights management (DRM) systems, and it is a popular research topic in the last decade. In this paper, besides the inherent behavior to conquer against intentional or unintentional attacks for watermarking, we not only watch the survivability of embedded watermark, but also focus on retaining the watermarked image quality with the aid of multiple description coding (MDC). MDC is a technique for error resilient coding, suitable for transmitting compressed data over multiple channels. In this paper, we propose a new algorithm on vector quantization (VQ) based image watermarking, which is suitable for error-resilient transmission. By incorporating watermarking with MDC, the scheme we proposed for embedding three watermarks can effectively overcome channel impairments while retaining the capability for ownership protection. With the promising simulation results presented, we can demonstrate the utility and practicability of our algorithm.

Index Terms—watermarking, vector quantization, multiple description coding, attack, transmission

I. INTRODUCTION

Digital watermarking is one useful solution for digital rights management (DRM) systems, and it is also a popular research topic in the last decade. It embeds secret information into the digital contents in order to protect intellectual properties or the ownership of the original multimedia sources [1]. There might be little perceptible differences between the original media content and the watermarked one. Typical watermarking schemes embed the watermark by altering coefficients relating to the original source in some specific domains, including spatial-domain methods [2], transform-domain techniques using discrete cosine transform (DCT) [3], discrete wavelet transform (DWT) and discrete Fourier transform (DFT) [4], or VQ domain schemes [5][6]. These schemes have been popular research topics in the last decade.

The main concept of watermarking is to properly adjust the corresponding coefficients in the original multimedia contents. For watermarking in the spatial domain [7], replacing the least significant bitplane (LSB) [8][9] by the watermark to be embedded seems to be the easiest way to accomplish the watermarking process. The watermark can be extracted by simply obtaining the least significant bitplane in the watermarked multimedia content; however, this method is vulnerable to attacks such as JPEG compression. From the research results in literature, due to the ease of removing the watermark, techniques for imperceptible watermarking in the spatial domain are seldom employed for practical applications.

For watermarking in the frequency domain (or the transform domain), similar procedures for altering coefficients will be performed. Properly chosen coefficients in the DCT, DWT, or DFT domains will be adjusted based on the input watermark bit 0 or 1. Taking natural images for instance, most of the energy is normally concentrated on the lower frequency bands [12]. Therefore, embedding the watermark bits into the coefficients in the lower frequency bands may greatly deteriorate the image quality after watermark embedding. On the contrary, if the watermark is embedded into the higher frequency bands where less energy is allocated, the watermarked image quality should be good, while the watermark information tends to be removed easily due to the fact that image compression, such as JPEG, is performed on the watermarked image to reduce the space for storage, and higher frequency bands are generally discarded during the quantization process in embedding. From this perspective, embedding the watermark into the
higher frequency band coefficients in the frequency domain is like embedding the watermark into the least significant bitplane in the spatial domain. To speak heuristically, since embedding into both the lower and higher frequency bands has their own advantages and disadvantages, embedding the watermark information into the middle frequency bands seems a direct consequence for the design of the algorithm.

Another domain for performing watermark embedding is by use of vector quantization (VQ) [13][14]. VQ is a compression technique that employs the codebook, or a combination of pre-determined codewords based on the characteristics of original image, to accomplish the compression procedure. For making watermarking possible, generally by swapping particular codeword pairs or by modifying the representations of codewords, including the quantization index modulation (QIM) scheme, may finish the watermark embedding process.

Here we aim at transmitting the watermarked image over lossy communication networks, including the Internet or the mobile channels. We first design our algorithm for embedding the watermark, and then transmit the output over the lossy channels. After reception of media from the channels, the watermark extraction algorithm, which is likely to be the inverse process of the watermark embedding process, is performed. By doing so, the embedded watermarks can later be extracted or detected from the watermarked multimedia and/or the key secret for authentication or identification. In order to strengthen the capability for copyright protection, we embed three watermarks in the algorithm proposed in this paper.

After completing the embedding process, the watermarked image is produced, and then it is transmitted over the lossy communication networks. During transmission or delivery, the watermarked media may experience some intentional or unintentional processing on the watermarked media, called attacks. Both the quality of watermarked media and the embedded watermarks are expected to get degraded. The goal of our algorithm is to ensure the existence of at least one watermark that can be successfully extracted after experiencing such a scenario. Most watermarking researches in the past concentrated on robust and imperceptible watermarking [8]. After transmission, we expect to have both the reasonable quality in watermarked image, and the acceptable robustness in the watermarks due to the survivability of at least one watermark that can be successfully extracted.

There are other papers for VQ-based watermarking [15][16] published recently. Besides the image-based watermarking, since VQ is widely used for speech compression, authors in [15] proposed the VQ-based watermarking for speech signals. In [16], the authors designed a VQ-based image watermarking algorithm by considering the effective partition of codebook with genetic algorithm (GA). It can be regarded as an improved version over existing algorithms. By use of GA, better results can be obtained. In comparison with closely related topics in literature, we can find that the proposed algorithm in literature is quite different from recently published ones. We aim at integrating watermarking with error resilient coding, which can be considered to be the contribution of this paper.

In spite of the conventional viewpoints to apply intentional attacks on watermarked media, the error induced during the transmission of watermarked contents is another typical issue that needs to be considered [17]. Therefore, we propose a new algorithm concentrating on vector quantization based embedding three watermarks, suitable for error-resilient transmission over noisy channels. By incorporating watermarking algorithm with multiple description coding (MDC), our proposed schemes can efficiently overcome channel impairments while retaining the capability for copyright protection.

This paper is organized as follows. In Section II we describe the fundamentals of multiple description coding and practical applications based on multiple description quantization, namely, multiple description scalar quantization (MDSQ) and multiple description vector quantization (MDVQ). Existing schemes for watermarking with MDVQ are briefly described in this Section. In Section IV, we address the design of MDVQ with watermarking, including watermark embedding, transmission of watermarked image, and watermark extraction schemes. Simulation results are presented in Section V. Finally we summarize and conclude our major findings and contributions in Section VI.

II. FUNDAMENTAL CONCEPTS OF MULTIPLE DESCRIPTION CODING

MDC is an error resilient coding technique that uses diversity to overcome channel impairments such that a decoder, which receives an arbitrary subset of the channels, may re-produce a useful reconstruction. Information-theoretic issues of MDC have been studied extensively since early eighties. In multiple description (MD) coders, the same source material is coded into several chunks of data, called descriptions, such that each description can be decoded independently to obtain a minimum fidelity; while combining with other descriptions to achieve the better quality.

Applications of MDC focus on error concealment and error resilience [18]. For transmission, MDC is suitable for noisy channels with long bursts of errors. Figure 1 depicts the typical scenario for MD source coding with

![Figure 1](source_image.jpg)

Figure 1. Scenario for MD source coding with two channels and three receivers. The general case has $K$ channels and $2^K - 1$ receivers.

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two channels and three decoders, where Decoder 0 is
called the central decoder, and Decoders 1 and 2 are the
side decoders. The central decoder needs to decode all the
received description and reconstruct the received image,
while the side decoders perform the error resilient
reconstruction on the partially received descriptions. It
suggests a situation in which there are three separate
users or three classes of users, which could arise in
broadcasting on two channels. The same abstraction
holds if there is a single user that can be in one of three
states depending on which descriptions are received.

Generally speaking, if we extend the number of
transmission channels in Fig. 1 to \( K \), there will be \( 2^K - 1 \)
receivers that decode with different number of
descriptions received, and obtain different qualities of the
reconstructed image.

Unlike repeatedly transmitting the original images for
several times to the receiver, the design of the multiple
description coding algorithm focuses on how to
effectively separate the original image into different
chunks of data, and how to introduce the correlations
between two different chunks. If the correlations are high
enough, the quality of the reconstructed image is good
even when some chunks are lost, however, by doing so,
the compression efficiency can be degraded. On the other
hand, by taking the lower correlations between the
different chunks, the output bitrate after compression can
be somewhat increased, with the observation that the
quality of reconstructed image can be sacrificed. How to
choose the appropriate correlation that can approach both
the reasonable increase in bitrate and the acceptable
quality in the reconstructed image is the major concern to
make an MDC algorithm applicable.

### III. QUANTIZATION BASED MULTIPLE DESCRIPTION
CODING

In addition to making theoretic researches of MDC in
Fig. 1, it is also important to devise practical designs to
make MDC applicable. Practical applications of MDC
emerged in the nineties. Two major categories for MDC
applications are: (i) quantization based schemes, such as
Multiple Description Scalar Quantization (MDSQ) [19]
and Multiple Description Vector Quantization (MDVQ)
[20], and (ii) transform-domain based schemes, called
Multiple Description Transform Coding (MDTC)
[21][22]. In this paper, we focus on quantization based
MD schemes for watermarking.

Figure 2 is a general structure for quantization based
MD. Taking scalar quantization for example because
MDSQ is the first practical design of MDC, employing
different quantization levels into the MD structure is a
straightforward solution. Also, MDSQ is flexible in that it
allows a designer to choose the relative importance of the
central distortion and each side distortion. In Fig. 2,
encoder produces from each scalar sample \( X \) a pair of
quantization indices \( (i_i, i_\ell) \). In [19], the author described
in detail how to perform quantization with an invertible
function, and to turn the scalar sample into the indices by
carrying out the index assignment process. After
transmission of indices over different channels, the three
decoders produce estimates from received indices, that is,
\( (i_{0i}, i_{0\ell}) \) for Decoder 0, \( i_i \) for Decoder 1, and \( i_\ell \) for
Decoder 2, respectively. By performing the inverse
quantization process, the central decoder outputs the
reconstructed sample \( \hat{X}^{(0)} \) with low central distortion,
while the side decoders output the reconstructions \( \hat{X}^{(1)} \)
and \( \hat{X}^{(2)} \) with somewhat higher side distortions.

It is easy and straightforward to extend MDSQ to
MDVQ. The structure for VQ-based multiple description
coding is depicted in Fig. 3. At the beginning, the
codewords in the codebook is assigned to each of the
block in the original image with the smallest error
produced. Next, the codeword is split into two parts with
the aid of the index assignment procedure. However, the
index assignment of MDVQ becomes more difficult than
MDSQ. The paper in [17] demonstrates the structure with
two descriptions. Here the input \( X_i \) denotes the small
block for VQ operation.

After the generation of two descriptions with the index
assignment process, the two generated descriptions, \( i_i \) and
\( i_\ell \), are transmitted over the mutually independent, lossy
channels with the packet loss probability of \( p_1 \) and \( p_2 \),
respectively. At the receiver side, the received
descriptions are combined by use of the inverse process
of index assignment and the error resilient and
reconstruction capability of multiple description coding.
Again, the reconstruction \( \hat{X}_i^{(0)} \) from the central decoder has
less distortion than that from each of the side decoder,
\( \hat{X}_i^{(1)} \) or \( \hat{X}_i^{(2)} \).

In this paper, we follow the MDSQ in [19] and MDVQ
algorithm in [21] and devise a robust watermarking
algorithm, suitable for both error resilient transmission
and copyright protection.
IV. WATERMARKING WITH MULTIPLE DESCRIPTION VECTOR QUANTIZATION

Here we briefly depict the implementations for watermarking with multiple description coding with Figure 3. At the beginning of the input, the original image is input into a VQ encoder, producing the compressed VQ indices with the aid of the codebook $C$ having the codebook size of $L$. Next, the watermark bit is embedded into the indices just produced. In order to embed the watermark, every two codewords need to be grouped into a pair, making the effective codebook size of $\frac{L}{2}$. After that, multiple description coding is performed, and two descriptions are produced with the index assignment process. Then, the two descriptions are transmitted over two mutually independent channels.

After receiving the received data, both the watermark and the image can be recovered with multiple description coding. By determining the codeword in a specific group, the watermark bit 0 or 1 can be determined. Moreover, by performing the inverse process of index assignment, an estimate of output codeword can be determined whether some descriptions might be lost during transmission.

As we can see from the derivations above, we can see that by combining the concepts of watermarking and multiple description coding, not only the quality of the received image can be preserved, but it also guarantee the copyright of transmitted image by using watermarking.

A. Embedding of the Three Watermarks

A.1. Embedding the first watermark

Let the input image be $X$ with size $M \times N$. We perform the VQ operation first [23] to train the codebook for $X$, and obtain the codebook with length $L$, $C = \{c_0, c_1, \ldots, c_L\}$. Each index in $C$ is represented by a $\lceil \log_2 L \rceil$-bit binary string, where $\lceil \star \rceil$ means a ceiling function.

The input image $X$ is divided into non-overlapping blocks $x_b$ with size $\frac{M}{2} \times \frac{N}{2}$, $0 \leq b < M \cdot N$, then each $x_b$ finds its nearest codeword $c_0$ in the codebook $C$, and the index $i_0$ is assigned to $x_b$.

Let the three watermarks for embedding be $W_1 = [w_{1,1}, w_{1,2}, \ldots, w_{1,n_1-1}], W_2 = [w_{2,1}, w_{2,2}, \ldots, w_{2,n_2-1}]$, and $W_3 = [w_{3,1}, w_{3,2}, \ldots, w_{3,n_3-1}]$, respectively, all having sizes $M_p \times N_p$. Each element in $W_1$, $W_2$, and $W_3$, $w_i \in [0,1]$, $0 \leq b < M_p \cdot N_p$, represents one watermark bit to be embedded into the corresponding index of $x_b$.

At this stage, the codebook $C$ is divided into two groups, Group 0, corresponding to sub-codebook $S_0$, is suitable for embedding bit ‘0’ in the first watermark, and Group 1, corresponding to sub-codebook $S_1$, is suitable for embedding bit ‘1’ in the first watermark. And we can see that $C = S_0 \cup S_1$ and $S_0 \cap S_1 = \emptyset$.

Thus, for embedding bit ‘1’ in one block $x_b$ as an example, we need to search for the codeword in $S_1$ that is nearest to $c_0$ to complete the embedding process. For embedding bit ‘0’, we need to do the same thing by searching for $S_0$. We denote that $i_w$ is the index containing the watermark bit relating to the first watermark. That is, $i_w = \begin{cases} \text{nearest codeword in } S_0, & \text{if } w_{i_w} = 0; \\ \text{nearest codeword in } S_1, & \text{if } w_{i_w} = 1. \end{cases}$ (1)

We can see from Figure 4 about the whole watermark embedding and extraction structure, and see how to perform the embedding of the first watermark. After embedding the first watermark for every block in the original image, it is ready for embedding the second watermark.

A.2. Embedding the second watermark

For watermarking purposes, the new index containing the second watermark, $i_{w_2}$ for representing $x_b$, is generated from two parts: to shift the index containing the first watermark, $i_w$, to the left by one bit, and to tag watermark bit $w_{i_{w_2}}$ to the end of the shifted index. That is, $i_{w_2} = (i_w \ll 1) + w_{i_{w_2}}$ (2) and we can see that $i_{w_2}$ is a $\lceil \log_2 L \rceil + 1$-bit binary string.
By doing so, the watermarked image quality might be somewhat degraded, since half of the indices are valid for VQ compression. On the other hand, more embedded bits imply the goal for copyright protection.

A.3. Embedding the third watermark

Next, we make use of the MDSQ algorithms in [19] for index assignment. The index assignments in [19], \( i_1 = a_1(i_{ip}) \) and \( i_2 = a_2(i_{ip}) \), map the quantizer output index \( i_{ip} \) to two descriptions \( i_1 \) and \( i_2 \). By following this concept, for increasing the watermark robustness, the watermarked indices for embedding bit 0 and bit 1 should be as far as possible. Regarding to the watermarked image quality, by use of MDSQ, after transmission, the received image can be reconstructed based on the error-resilient capability with MDC.

B. Transmission of the Watermarked Image

After the embedding of the three watermarks is completed, the watermarked image is ready to be transmitted over multiple channels, which meets the need for MDC. Referring to the middle part of Figure 4, \( i_1 \) and \( i_2 \) are transmitted over two memoryless and mutually independent channels, or the lossy packet networks, with erasure probabilities \( p_1 \) for Channel 1, and \( p_2 \) for Channel 2, respectively. Under different test conditions, we will see the effectiveness by combining watermarking with MDC in the simulations in Sec. I.

C. Extraction of the Three Watermarks

C.1. Extraction of the third watermark

When receiving the watermarked image, in extracting the first watermark, we carry out the estimation criterion from received indices for determining the value of the watermark bits. With MDC, if both descriptions for one block \( x_r \) are received, then the resulting index decoded by MDSQ can be determined uniquely, and watermark bit is extracted by taking out the last bit. Besides, because of the error concealment capability for index assignment, when only one description is received, the block can be partly reconstructed, and the watermark bit need to be determined from several possible indices assigned in MDSQ row or column matrix [19]. We first use majority vote to determine the watermark bit ‘0’ or ‘1’. However, if there are equal numbers of 0’s and 1’s obtained in MDSQ decoding process, we assign the watermark bit randomly. Thus, we use table-lookup to determine the watermark bits in the third watermark based on the

![Figure 5](image-url)  

Figure 5. The watermarks in this paper, all have sizes 128×128. (a) The first watermark. (b) The second one. (c) The third one.

C.2. Extraction of the second watermark

In extracting the second watermark, we perform the reverse process to (2). We determine whether the reconstructed index for each block is even or odd. If it is even, the second watermark bit for such a block is determined to be 1. If it is even, the watermark bit is determined to be 0.

C.3. Extraction of the First Watermark

At the MD decoder, it first shifts received binary indices \( i' \) and \( i'' \) to the right by one bit to smooth away the effects from watermark embedding, and determines the outcome \( i' \) from received indices with MDSQ decoder. Next, it performs a table look-up process on the determined \( i' \) with codebook \( C \) to obtain \( i'' \) and then obtain the reconstructed block \( x' \). After gathering all the blocks, we obtain the reconstruction image \( x' \).

In extracting the first watermark, we only determine whether the index corresponding to the reconstructed block belongs to Group 0 or Group 1. If such an index belongs to sub-codebook \( S_0 \), it is determined to belong to Group 0, and the extracted bit for the first watermark is 0. Otherwise, the watermark bit is 1.

V. SIMULATION RESULTS

In our simulations, we take the test image, Lena, with size \( 512 \times 512 \), as the original source. We have the three embedded watermarks with size \( 128 \times 128 \) in Figure 5. The original source is divided into \( 4 \times 4 \) blocks for VQ compression, which also meets the number of bits for watermark embedding. The codebook size is \( L = 1024 \), and indices therein are represented by \( \lceil \log_2 1024 \rceil \)-bit, or 10-bit strings. We perform a series of examples under different channel conditions to demonstrate the usefulness and effectiveness of the proposed robust watermarking algorithm with MDVQ.

Two quantities are considered for evaluating the proposed algorithm. One is Peak Signal-to-Noise Ratio (PSNR), for measuring the watermarked image quality and the imperceptibility of the watermark, and the other is Bit Correct Rate (BCR) between the extracted watermark and the embedded one for measuring the robustness of the watermarking algorithm:

\[
\text{BCR} = \left(1 - \frac{1}{M_w \cdot N_w} \sum_{i=1}^{N_w} (w_i \oplus w'_i)\right) \times 100\%  
\]

where \( w_i \) and \( w'_i \) represent the embedded watermark bit and the extracted one, \( M_w \cdot N_w \) denotes the watermark size, and \( \oplus \) indicates the exclusive-or operation. If more bits are correctly extracted, the BCR value becomes larger, leading to the better robustness directly. We can see that larger BCR values correspond to better capability for recognizing the extracted watermarks. On the other hand, the bit error rate (BER), which follows the term from digital communications, is employed in literature.
erroneously extracted bit, which can be expressed in (4). The BER means the percentage for calculating the evaluations. More comparison s for objective evaluations only show the results for the two images for subjective and 31.646 dB, respectively. Due to space limitations, we for Lena and pepper that have the PSNR of 32.638 dB can be found in Table 1. And in Fig. 6(c) and Fig. 6(d), the watermarked image qualities become 31.886 dB and 31.328 dB. From subjective viewpoint, both images look

![Image](image-url)

Figure 6. Comparisons between the VQ-compressed image, and the watermarked image containing the three watermarks for test images Lena and pepper.

![Image](image-url)

Figure 7. When no error occurs in both channels. The three extracted watermarks are all identical to the embedded ones for Lena and pepper. BCR1 = BCR2 = BCR3 = 100%.

The BER means the percentage for calculating the erroneously extracted bit, which can be expressed in (4).

\[
\text{BER} = \left( 1 - \text{BCR} \right) \times 100\% \quad (4)
\]

Thus, lower BER values correspond to better robustness of watermarking algorithm. Generally speaking, the desirable results are twofold.

A. The watermarked image quality should have higher PSNR value objectively, and look similar to its original counterpart subjectively.

B. Extracted watermarks have higher BCR values objectively, and they can be recognizable subjectively.

A. The Watermarked Image Quality

After the embedding process is accomplished, we obtain the watermarked image containing three watermarks. In Fig. 6(a) and Fig. 6(b), with the codebook size of \( L = 1024 \), we obtain the VQ-compressed images for Lena and pepper that have the PSNR of 32.638 dB and 31.646 dB, respectively. Due to space limitations, we only show the results for the two images for subjective evaluations. More comparisons for objective evaluations can be found in Table 1. And in Fig. 6(c) and Fig. 6(d), after embedding the three watermarks shown in Fig. 5, the watermarked image qualities become 31.886 dB and 31.328 dB. From subjective viewpoint, both images look similar, hence the three watermarks are imperceptibly embedded and can hardly be recognized.

B. When Channel Erasure Probabilities = 0

Here we assume that there is no loss in both channels. By following the watermark extraction procedures for the three watermarks in Section VII, we have the three extracted watermarks obtained from the watermarked Lena and pepper images in Fig. 7, and numerical results can be depicted in Tables 2 to 4 for objective evaluations. With (3), we can calculate the BCR values for measuring the robustness of watermarks. And the three BCR values are all 100%, meaning that the extracted watermarks from test images are identical to the embedded ones.

C. When Channel Erasure Probabilities = 0.5

We also simulate the heavily erased conditions for both channels by setting the error probabilities to 0.5. And we can see the results from Fig. 8 and from Tables 2 to 4. Even though the BCR values for the three watermarks are reasonable, only the third watermark is recognizable.

For the first watermark, by classifying indices into Group 0 or Group 1 might not be robust enough. How to efficiently obtain the classified results and consequently the two sub-codebooks needs further research.
For the second watermark, by tagging the watermark bit into the index, even though the implementation is simple, robustness might have spaces for improvements.

Summing up, under the scenario for the heavily erased channels, at least one of the watermarks is recognizable, hence keeping its value for copyright protection.

D. When Channel 1 Is Broken Down

We also simulate the extreme case when one of the channels is totally broken down. We set the channel erasure probability for Channel 1 to be 1.0, and that for Channel 2 to be 0. Results are depicted in Fig. 9 and in Tables 2 to 4.

Even though the BCR values are acceptable, only the third watermark is recognizable, while the first watermark is partially recognizable. BCR values also lead to similar outcome. And we conclude that by combining watermarking with MDC, it offers an effective means for copyright protection after testing under severe conditions.

E. Observations in Watermark Robustness

We performed extensive simulations among the three test images, namely, Lena, pepper, and baboon, with the proposed algorithm. Robustness comparisons among the three embedded watermarks are depicted in Table 2 to Table 4, respectively. BCR values for the three test images presented similar values, meaning that our algorithm work well for the test images. BCR values in Table 4 perform better than those in Tables 2 and 3. In addition to the observations that embedding the third watermark performs better than the other two, from Sec. VIII.C to VIII.D, we may consider to follow the characteristics of images for watermark embedding and to obtain good results for the three watermarks.

F. The Embedding Capacity

In order to make a better coverage of our presentation, we also make comparisons between the results with MDC-based triple-watermarking and those with [17]. In [17], the combination of MDC and watermarking has been presented, under the condition that one watermark having the size of 128×128 is embedded into the Lena image having the size of 512×512. These parameters are identical to those employed in this paper. Simulation results between the two algorithms are depicted in Table 5. We can easily see that with our algorithm, slight degradation in image quality with our algorithm, or 0.644 dB, can be observed. On the other hand, with our algorithm, the triple amount of watermarking bits, or 200% increase, can be obtained. With somewhat sacrifice in image quality, the triple amount of watermarking bits can further protect the copyright of original images.

VI. CONCLUSIONS

In this paper, we propose an innovative scheme by integrating the thought of error resilient coding for accomplishing the goal of watermarking. In our scheme for triple watermark embedding with multiple description coding (MDC), it is suitable for transmission over noisy channels. We modify the MDVQ and MDSQ index assignments for watermark embedding and extraction with the VQ-based image compression techniques. By incorporating this with MDC, we obtain promising results, with the following observations.

- For embedding the first watermark, the VQ codebook is classified into two groups, Group 0 and Group 1 corresponding to watermark bit 0 and watermark bit 1, to embed the first watermark effectively by considering the watermarked image quality. The classification of original codebook into the two groups may influence the robustness of the watermark.

- For embedding the second watermark, the watermark bit is tagged into the VQ indices. Even though this method is easy for implementation, the watermark fails to survive under conditions when channels are severely erased.

- For embedding the third watermark, MDC is taken into consideration to further remind both the watermarked image quality and watermark robustness. With the simulation results presented, by combining watermarking with MDC, the watermark can survive well under lightly-erased to heavily-erased conditions. The copyright can well be preserved.
By comparing between our algorithm and others given in literature, our algorithm has much more watermark capacity (50% to 100% more bits can be embedded) with comparable watermarked image quality, measured by PSNR, and competitive watermark robustness because at least one of the watermarks can be survived under severe conditions, evaluated by BCR. Simulation results present the effectiveness of our watermarking algorithm, and the more resilience to combat with channel noise under both lightly and heavily erased channels. Therefore, our algorithm is not only one of the innovative directions for research, but is also suitable for practical applications.

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Shu-Chuan Chu received the B.S. in Department of Industrial Management from the National Taiwan of Science and Technology, Taiwan, in 1988 and the Ph.D. degree in School of Informatics and Engineering, Flinders University, Australia, in 2004. Dr. Chu joined the editorial board of the International Journal of Knowledge Engineering and Soft Data Paradigms (IJKESEP, INDERSCIENCE Publishers), the Intelligent Decision Technologies (An International Journal, IOS Press) and ICIC Express Letters (An International Journal of Research and Surveys, ICIC International). Up to now, she has published more than seventy journal and conference papers, and was invited to be a reviewer and program committee member in many international conferences. Currently, she is an assistant professor in the Department of Information Management, Cheng Shiu University, Taiwan. Her current research interests include Data Mining, Computational Intelligence, Information Hiding and Signal Processing.

Lakhmi C. Jain is a Director/Founder of the Knowledge-Based Intelligent Engineering Systems (KES) Centre, located in the University of South Australia. He is a fellow of the Institution of Engineers Australia.

His interests focus on the artificial intelligence paradigms and their applications in complex systems, art-science fusion, e-education, e-healthcare, unmanned air vehicles and intelligent agents.

Hsiang-Cheh Huang received his Ph.D. from the Dept. of Electronics Engineering at National Chiao-Tung University in 2001. He is currently with Department of Electrical Engineering, National University of Kaohsiung in Taiwan.

His research interests include digital watermarking, video compression, and error resilient coding. For more details, please refer to the website at http://hchuang.ee.nuk.edu.tw.

Jeng-Shyang Pan received the B. S. degree in Electronic Engineering from the National Taiwan University of Science and Technology, Taiwan in 1986, the M. S. degree in Communication Engineering from the National Chiao Tung University, Taiwan in 1988, and the Ph.D. degree in Electrical Engineering from the University of Edinburgh, U.K. in 1996. Currently, he is a Chair and Professor in the Department of Electronic Engineering, National Kaohsiung University of Applied Sciences, Taiwan. He is the Tainan Chapter Chair of IEEE Signal Processing Society. Professor Pan has published more than 150 journal papers and 200 conference papers. He joins the editorial board for LNCS Transactions on Data Hiding and Multimedia Security, Springer, and International Journal of Hybrid Intelligent System, Advanced Knowledge International. He is the Co-Editors-in-Chief for International Journal of Innovative Computing, Information and Control. His current research interests include image and speech signal processing, digital watermarking and pattern recognition.