Robustness of Watermarking: Is Error Correcting Coding Effective?1)

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Abstract Robustness is one of the most important requirements of digital watermarking for many applications. Spread-spectrum based methods are not effective enough to ensure their robustness. By modeling digital watermarking as digital communications, several researchers proposed using error correcting coding (ECC) to improve robustness. However, an important fact that has long been neglected is that due to the imperceptibility requirement, the redundancy introduced by ECC will lead to a decrease of the magnitude of watermark signal. Therefore, a problem arises naturally: Could the usage of ECC effectively improve the robustness of watermarking? This paper addresses this problem from the perspectives of both theoretical analysis and experimental investigation. Our investigation shows that ECC cannot effectively improve the robustness of watermarking against a great majority of various attacks except for cropping and jitter attacks. Hence, ECC should not be considered as a universal measure that can be employed to enhance robustness of watermarking.

Key words Digital watermarking, error correcting coding (ECC), robustness, binary symmetric channel (BSC)

1 Introduction

Digital watermarking technology has aroused great concerns in recent years[1]. Imperceptibility and robustness that are in conflict with each other are two basic requirements of watermarking in many applications. Hence, one the important goal of watermarking is to improve robustness while keeping the watermark imperceptive. This presents a great challenge.

To improve the robustness of watermarking, much effort has been made. The reported approaches include spread-spectrum-based methods[2,3], side information[4], DC[5] and low frequency[4] component embedding strategies, and adaptive watermarking based on HVS/HAS (human vision system/human auditory system) models[6,7], and algorithms using error correcting coding (ECC)[8~11].

Due to similarities between digital watermarking and digital communications, some papers in the literature viewed watermarking as a digital communication problem[4,8,12] and hence applied the theories and methods of digital communications to watermarking. It was reported that some watermarking algorithms applied ECC to lower BER (bit error rate) of watermarks and thus improved robustness. For example, BCH code, convolutional code[9], R-S code[10], and Turbo code[11] have been adopted.

The above idea seems straightforward since ECC is effectively used in noisy channel in digital communications. It should be, however, noted that there are some differences between watermarking and digital communication. That is, watermark signal is embedded in a media under the constraint of imperceptivity of watermark. In fact, this difference has been overlooked in the literature.

When applying ECC to enhance robustness of watermarking, the following problems will arise:

1) Is ECC effective in the improvement of watermark robustness? And to what extent could ECC improve the robustness?

2) Which error correcting code performs best for watermarking?

3) How to choose the coding ratio in using ECC?

Some efforts to address the above issues have been reported. Huang *et al.*[13] compared the performance of repetition coding and BCH coding, hard-decision decoding and soft-decision decoding. Zinger *et al.*[14] investigated the performance of BCH coding, repetition coding, and their concatenations over watermarking channel modeled as binary symmetric channel (BSC). Baudry *et al.*[15] addressed ECC strategies in watermarking. They analyzed the performance of BCH coding, repetition coding,

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and their concatenations. Balado *et al.*[16] pointed out that Turbo coding schemes has lower error rate than hybrid coding for the same amount of hidden information. Viewing watermark channels as very noisy channels (BER from 0.1 to 0.5), Desset *et. al.*[17] analyzed the BER performance of BCH coding and repetition coding, and obtained the BER interval where repetition coding performs better.

In the above efforts, an important fact is neglected when applying ECC to watermarking. That is, due to the requirement on watermarking imperceptibility, the redundancy introduced by ECC leads to a decrease of the magnitude of watermark, and consequently, may result in an increase of bit error rate in watermark signal detection. Therefore, the difference between watermarking channel and common communications channel raises the question: Is ECC effective for the improvement of the robustness of watermark? In this paper, we address the issue of to what extent ECC could improve the robustness of watermark.

2 Communication model for watermarking channel

The watermarking procedure can be viewed as a digital communication problem[8], as shown in Fig. 1. The source encoder is employed to compress the watermark information bits if a watermark has a high bit rate. The channel encoder is applied to lower watermark detection error rate with respect to various attacks, such as JPEG compression, RST (rotation, scaling, translation) transforms, and noise corruption. The feature extraction is adopted to generate the carrier from the original signal for watermarking. Commonly, mathematical transforms such as DFT (discrete fourier transform), DCT (discrete cosine transform), and DWT (discrete wavelet transform) are often exploited. The fidelity monitor is used to ensure the imperceptibility of watermark. The watermark embedding procedure is modeled as modulation, while the detection procedure is modeled as demodulation. Note that the fidelity monitor is normally not included in commonly used communication systems. This reflects the peculiar feature of watermarking, which motivates this paper.

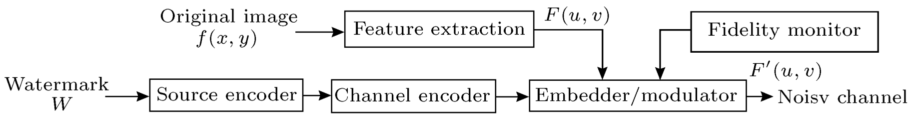


Fig. 1 General model for watermarking procedure

In watermark embedding, LSB-based model[18] is frequently used. In this paper, we use a similar method. Let matrix A, $A = \{a_{ij}\} \in I^{M\times N}$, $i = 1, 2, \cdots, M$, $j = 1, 2, \cdots, N$, denote the original image and matrix B, $B = \{b_{ij}\} \in I^{M\times N}$, the transform domain matrix of A. Vector Y, $Y = \{y_k\} \in I^K$, $k = 1, 2, \cdots, K$, is a subset of B, specifically, vector Y consists of low-frequency or mid-frequency coefficients in matrix B. The watermark embedding is fulfilled when the watermark W, $W = \{w_k\}$, $k = 1, 2, \cdots, K$, is embedded in vector Y. The following formula is used for watermark embedding[19]:

$$\begin{cases} y_k' = y_k - (y_k \bmod S) + \frac{3}{4}S, & \text{if } w_k = 1 \\ y_k' = y_k - (y_k \bmod S) + \frac{1}{4}S, & \text{if } w_k = 0 \end{cases} \tag{1}$$

where S controls the watermark embedding strength and should be as large as possible under the constraint of imperceptivity. In what follows, we call S the embedding strength. The operator calculates the modulo of y_k with respect to S. If $y_k < 0$, its absolute value is used in (1).

In the watermark extraction, the maximum likelihood method is first employed to retrieve each hidden bit, and then the extracted bits are were decoded to obtain an estimated version, W', of the original watermark W. The watermark error rate can be obtained by comparing W' with W. Generally, when the embedded bits are demodulated to produce a binary codeword, the watermarking channel can be modeled as a BSC channel[15]. In this paper, hard-decision decoding is exploited, and hence, the watermarking channel is modeled as BSC channel.

3 Relationship between watermark coding length and embedding strength

3.1 Watermark coding length and embedding strength

Due to the constraint of imperceptibility, watermark embedding strength and coding length, if ECC is applied, are conflicting with each other. Given a PSNR (peak signal-to-noise ratio), there is a trade-off between these two factors. According to [20], for the unitary transform domain embedding algorithms using the following popular additive embedding equation:

$$y_k' = y_k + S^* w_k, \quad k = 1, 2, \cdots, K \tag{2}$$

we can derive the following inequality for the lower bound of PSNR of a marked image, T_{PSNR}.

$$T_{PSNR} \leqslant 20 \log_{10} \frac{N^* b_m}{\sqrt{\sum_k (S^* w_k)^2}} \tag{3}$$

where the size of image is $N \times N$ and the maximum grayscale level in the image is b_m, S is the embedding strength, w_k 's are watermark signals. The derivation is contained in Appendix. Therefore, it is clear that, given a lower bound of PSNR, T_{PSNR}, there exists a upper bound of embedding strength S to ensure watermark imperceptibility.

For the data embedding using (1), the change of transform coefficient due to the embedding is:

$$\begin{cases} \Delta y_k = y_k \bmod S - \frac{3}{4} S, \text{if } w_k = 1 \\ \delta y_k = y_k \bmod S - \frac{1}{4} S, \text{ if } w_k = 0 \end{cases} \tag{4}$$

Let X, Y and Z be random variables and defined as $X \in \left\{\frac{1}{4}, \frac{3}{4}\right\}$, $Y \in [0, 1)$ and $Z \in \{\Delta y_k\}$, $k = 1, 2, \cdots, K$. Then (4) can be rewritten as

$$Z = (Y - X)^* S \tag{5}$$

X and Y can be considered as independent. Then, with (1), we have (3) expressed as

$$T_{PSNR} \leqslant 20 \log_{10} \frac{N^* b_m}{\sqrt{K^* E(Z^2)}} = 20 \log_{10} \frac{N^* b_m}{\sqrt{K^* S^{2*} [E(X^2) + E(Y^2) - 2E(X)E(Y)]}} \tag{6}$$

where K and S denote the length and strength of the watermark signal, respectively, $E(\cdot)$ indicates the expectation operation.

If keeping the original image, hidden watermark signal, the type of channel code, and embedding model unchanged, for different length of hidden bits K and embedding strength S, we have

$$\sqrt{K_1} S_1 = \sqrt{K_2} S_2 \tag{7}$$

where K_1, S_1, K_2, and S_2 denote the length of hidden bits and embedding strength in the two different schemes, respectively.

From the viewpoint of digital communications theory, for a repetition code, an increase of repetition times R leads to a decrease of error rate. However, in digital watermarking, the increase of R will result in a longer coding length. Under the constraint of imperceptivity, say, maintaining the same PSNR of watermarked image versus original image, we have to lower the embedding strength, as shown in (7). In Fig. 2, S-R curves were obtained with Lena image, and data were embedded in the mid-frequency coefficients of $8 * 8$ block DCT with a 64 bit watermark.

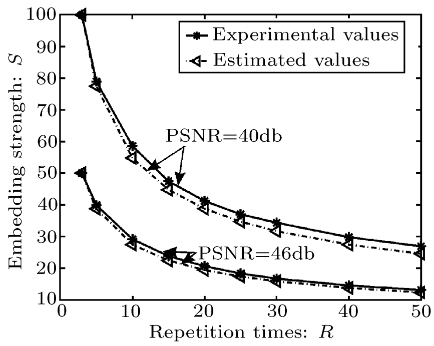


Fig. 2 The relationship between reperition times R and embedding strength S (data were embedded in the mid-frequency coefficients of $8 * 8$ DCT coefficients of “Lena” image)

Similar results have been obtained for BCH codes as shown in Table 1, where PSNR=50.72db, also with "Lena" image, a 64-bit watermark signal is embedded in the mid-frequency coefficients of 8*8 block DCT. Table 1 illustrates the impact of different BCH coding length on embedding strength for a given PSNR. When encoding the 64-bit watermark, BCH code (31, 6) has a longer coding length, and hence brings embedding strength down dramatically.

Table 1 BCH coding length K vs. embedding strength S (64 bits in watermark)

BCH codes	Coding length K	Estimated strength S	Experimental strength S'
BCH (31,6)	341	21.8	21.8
BCH (63,18)	252	25.4	25.8
BCH (63,30)	189	29.3	30.2
BCH (127,64)	127	35.7	34.4

It is clear that when watermark error bits occur in extraction, ECC can correct some error bits by introducing redundancy. Nevertheless, the redundancy leads to a decrease of embedding strength and thus an increase of error rate. It is known that large embedding strength itself can decrease error bits in watermark detection. Therefore, there is a trade-off between the coding length and the embedding strength.

3.2 Lowering BER by increasing embedding strength

The BER varies with different codes and channel properties. Here, we discuss the problem under the assumption of BSC channel corrupted by additive white Gaussian noise (AWGN). The detected watermark signal can be modeled as follows:

$$r = q + \tau, \quad v = r \bmod S \tag{8}$$

where q is a random variable representing embedded watermark signal, *i.e.*, $q \in \{S/4, 3S/4\}$; τ is the AWGN component, $\tau \sim N(0, \sigma^2)$; S is the embedding strength, r is the received signal, and v is a decision variable. Then, the watermark bit is derived by comparing v with $S/2$.

When binary "0" is transmitted, the received signal is $r = q_0 + \tau = \frac{S}{4} + \tau$. Similarly, when binary "1" is transmitted, the received signal is $r = q_1 + \tau = \frac{3S}{4} + \tau$. Hence, the two conditional probability density functions (pdf) of r are

$$p(r|q_0) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(r - S/4)^2}{2\sigma^2}\right\} \tag{9}$$

$$p(r|q_1) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left\{-\frac{(r - 3S/4)^2}{2\sigma^2}\right\} \tag{10}$$

It is the modulo S in (8) that makes error probability of watermarking different from that of common communications. Owing to the property of modulo S, the interval of $(-\infty, +\infty)$ is mapped onto the interval of $[0, S)$. The received signal r can be expressed as $r = kS + v$, where $k \in Z$. In fact, whenever r is in the intervals of $[(k + 1/2)S, (k + 1)S)$, the decision variable v will be greater than $S/2$, and consequently the decision is made in favor of $q = 3S/4$. If $q = S/4$ was transmitted and the decision variable v was greater than or equal to $S/2$, false decision in watermark detection would occur (as shown in Fig. 3 by the shadowed parts). If $q = 3S/4$ was transmitted and the decision variable v was less than $S/2$, false decision in watermark detection would also occur. Since the channel discussed in this paper is BSC channel, we have

$$P(v \geqslant S/2|q = S/4) = P(v < S/2|q = 3S/4) \tag{11}$$

So, the channel bit error rate is as follows.

$$\begin{aligned} P_b = & P(v \geqslant S/2|q = S/4)P(q = S/4) + P(v < S/2|q = 3S/4)P(q = 3S/4) = \\ & P(v \geqslant S/2|q = S/4) = \frac{1}{\sqrt{2\pi}\sigma} \sum_{k=-\infty}^{\infty} \left[\int_{(k+\frac{1}{2})S}^{(k+1)S} \exp\left\{-\frac{(x - S/4)^2}{2 * \sigma^2}\right\} \mathrm{d}x\right] = \\ & 2 * \sum_{k=0}^{\infty} \left[Q\left(\frac{(4k+1)S}{4\sigma}\right) - Q\left(\frac{(4k+3)S}{4\sigma}\right)\right] \end{aligned} \tag{12}$$

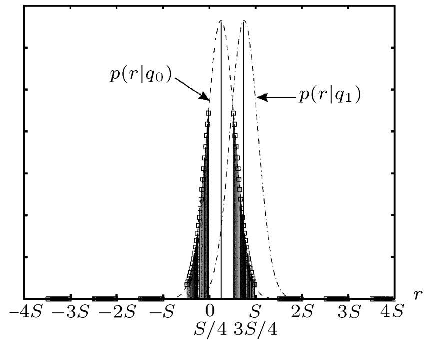


Fig. 3 The Gaussian pdf of random variable r, and the false negative regions of case $q = S/4$

Obviously, the distribution of error regions here are different from that of general binary signals in AWGN, due to modulo S operation in (8). Note that the Gaussian pdf has dropped closely to zero at three times standard deviation from the mean value. Hence, the above equation can be written as

$$P_b = 2 * \sum_{k=0}^{M} \left[Q\left(\frac{(4k+1)S}{4\sigma}\right) - Q\left(\frac{(4k+3)S}{4\sigma}\right) \right] \tag{13}$$

where M is a finite integer number.

Owing to the power constraint in digital watermarking, the energy per symbol E_c after using ECC with code ratio k/n satisfies the following equation[21]:

$$\frac{E_c}{N_0} = \left(\frac{k}{n}\right) \frac{E_b}{N_0} \tag{14}$$

where N_0 is the variance of AWGN; E_b is the energy per bit before applying ECC. Thus, we use the below equation to calculate the channel BER for ECC with coding ratio k/n:

$$p_b = 2 * \sum_{k=0}^{M} \left[Q\left(\frac{(4k+1)S}{4\sigma}\sqrt{\frac{k}{n}}\right) - Q\left(\frac{(4k+3)S}{4\sigma}\sqrt{\frac{k}{n}}\right) \right] \tag{15}$$

Since the channel BER, P_b, is available, we can investigate the final BER of ECC after decoding. Table 2[15,17] shows the expressions used in this paper to calculate the BER of various repetition and BCH codes, using the channel BER derived in (13).

Table 2 Bit error probability expressions

	Repetition $(r, 1)$	BCH (n, k, t)
Symbol bit error	$p_{rep} = \sum_{i=r/2+1}^{r} \binom{r}{i} p_b^i (1-p_b)^{r-i}$	$p_{BCH} = \frac{1}{n} \sum_{i=t+1}^{n} i \binom{n}{i} p_b^i (1-p_b)^{n-i}$

Thus, it is feasible to compare the performance of schemes using ECC with that of uncoded scheme. Fig. 4 illustrates the performance of several codes in term of BER, with a 64-bit binary sequence as watermark under the corruption of AWGN noise. The watermark channels are usually very noisy (BER from 0.1 to 0.5)[17]. In this range of BER, the value of S/σ is about $0 \sim 8$dB. The uncoded scheme obviously outperforms repetition code and BCH code. Only when the value of S/σ is bigger than 10dB, which is uncommon in watermarking channels, some BCH codes perform better than the uncoded scheme. Since our watermark is a 64-bit sequence, schemes using BCH (127,22,23) and BCH (127,8,31) introduce too much redundancy and thus have lower embedding strengths. So they are outperformed by the schemes of BCH (127,64,10) and BCH (127,106,3). Curves in Fig. 4 show that it is more important to increase embedding strength in order to improve the robustness of watermarking against Gaussian noise.

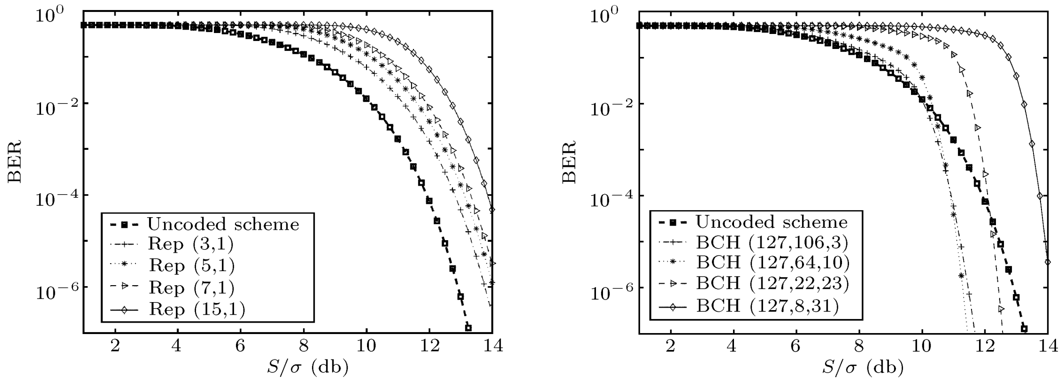


Fig. 4 Performance of repetition codes and BCH codes

In practice, however, the noise introduced by many testing functions in StirMark 3.1 cannot be modeled as AWGN. So, we further investigate the performance of ECC by numerous experiments.

4 Coding schemes and robustness of watermarking

To answer the questions listed in Section I, we conducted extensive experiments to investigate the relationship between coding scheme and robustness of watermarking.

It is known that different coding schemes with similar coding length have similar embedding strength. Hence, the more powerful correcting ability a coding scheme has, the better robustness of watermarking the scheme achieves. For different coding schemes with different coding lengths and correcting abilities, our investigation on watermarking robustness takes this factor into account.

To address the relationship between the coding types and watermarking robustness (in terms of BER), we compare the following four coding schemes.

1) Scheme without using ECC (uncoded scheme). In this case, the length of information bits is the shortest in the four schemes. Hence, we can use the highest embedding strength. This scheme is used to investigate to what extent an increase of embedding strength could improve the robustness of watermarking.

2) BCH coding. Considering the contending relationship between error correcting capability and redundancy introduced by using ECC, we choose BCH (63,36) in case of 32-bit informative watermark, while BCH (127,64) is employed in case of 64-bit and 128-bit informative watermarks. Here, no interleaving[22] is employed.

3) Convolutional coding. Similarly, with regard to the trade-off between correcting ability and coding length, we use convolutional code with coding ratio 1/2, maximum free distance 10, constraint length 8.

4) Repetition coding. To have similar length of information bits with BCH and convolutional coding schemes, we choose repetition code (3,1). In detection, we first use hard-decision to extract each hidden bit, then determine the watermark bit to be "1" or "0" by means of majority decision. At the end, we compare the detected watermark with the original watermark, thus obtaining the error rate in watermark detection.

In experiments, data are embedded in the DCT mid-frequency coefficients of $8*8$ blocks and the mid-frequency as well as the low-frequency DWT coefficients. The informative watermarks composed of 32 bits, 64 bits, and 128 bits are all tested.

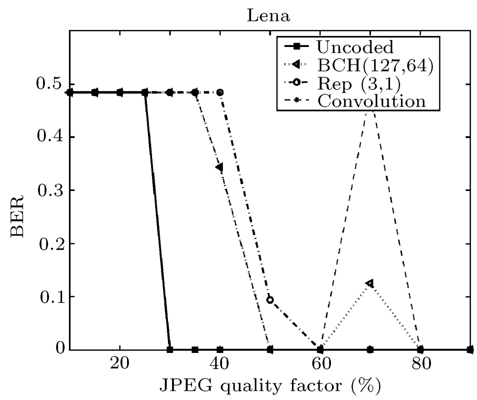
In the investigation, we test the above four schemes with the same amount of informative watermark bits. By adjusting the embedding strength S, the watermarked images with the four schemes have approximately the same PSNR. That is, we decrease the embedding strength S for a long to-be-embedded information bit sequence, and increase the embedding strength for a short to-be-embedded information bit sequence. Thus, the schemes meet the objective criteria of image quality. The requirement of invisibility is maintained. Then, we can expect to compare the robustness performance of watermark with the four schemes fairly.

The experiments were carried out on the images with different texture complexity, including "Lena", "Pepper", "Boats", and "Baboon". For the sake of brevity, we only report in this paper the results on "Lena" and "Baboon" images. The similar results can be obtained on "Pepper" and "Boats".

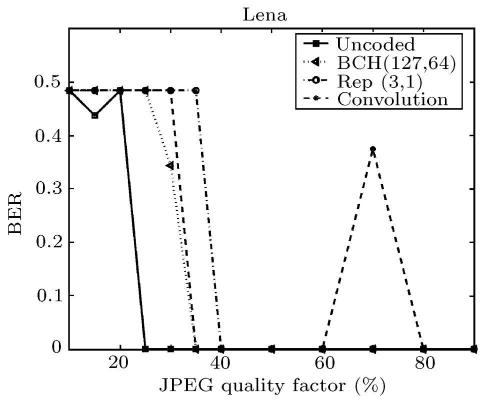
In Fig. 5, (a), (b), and (c) show the performance comparison between different coding schemes in term of BER for different JPEG compression quality levels, as a 64-bit watermark is embedded in the mid-frequency DCT coefficients of 8∗8 blocks. Note that for JPEG compression, there is little difference between the performance of BCH coding and convolutional coding with similar coding length, while repetition coding scheme is outperformed by both BCH and convolutional coding schemes. Note that the uncoded scheme has the lowest error rate for all different JPEG compression quality levels. The experiments with a 64-bit watermark embedded in the low-frequency DCT coefficients of $8 * 8$ blocks also achieve similar results. Furthermore, experiments with a 32-bit watermark or a 128-bit watermark, embedded in the low-and mid-frequency DCT coefficients of 8∗8 blocks and DWT, demonstrate similar trend too. This indicates that ECC cannot improve the robustness of watermarking against JPEG compression.

In Fig. 5, (d), (e), and (f) show the robustness of watermark with different coding schemes under Gaussian noise attack (measured by PSNR of the attacked watermarked image versus the original watermarked image), as a 64-bit watermark signal is embedded in the mid-frequency DCT coefficients of $8 * 8$ blocks. Obviously, all the schemes have high BERs when strong noise is added. However, we can see that the uncoded scheme has the lowest error rate than other schemes for the most of time, meaning that ECC cannot improve the robustness of watermarking against additive Gaussian noise attack. Schemes with different sizes of watermark, embedded in both low-and mid-frequencies of DWT and mid-frequency of $8 * 8$ DCT, exhibited the same trend too.

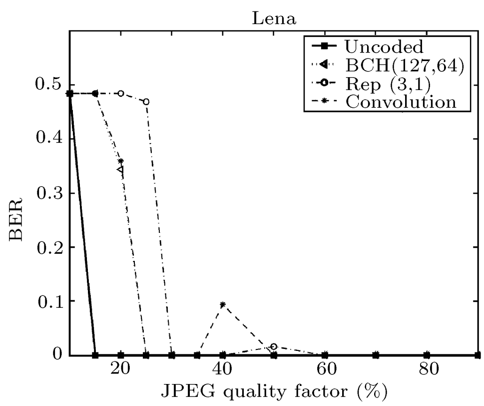
Note that experimental results are shown for three different PSNR values, *i.e.*, 44.2db, 42.0db and 38.1db, in Fig. 5. Thus, the experimental work is sufficient to support the observations made above.



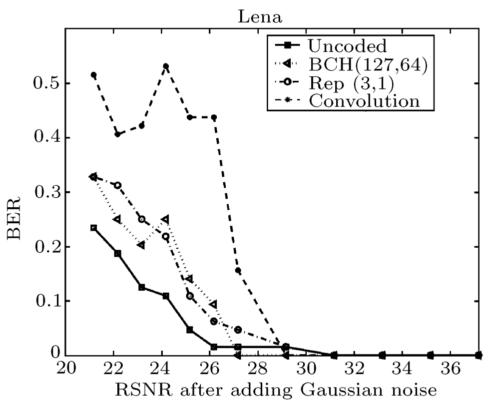
(a)



(b)



(c)



(d)

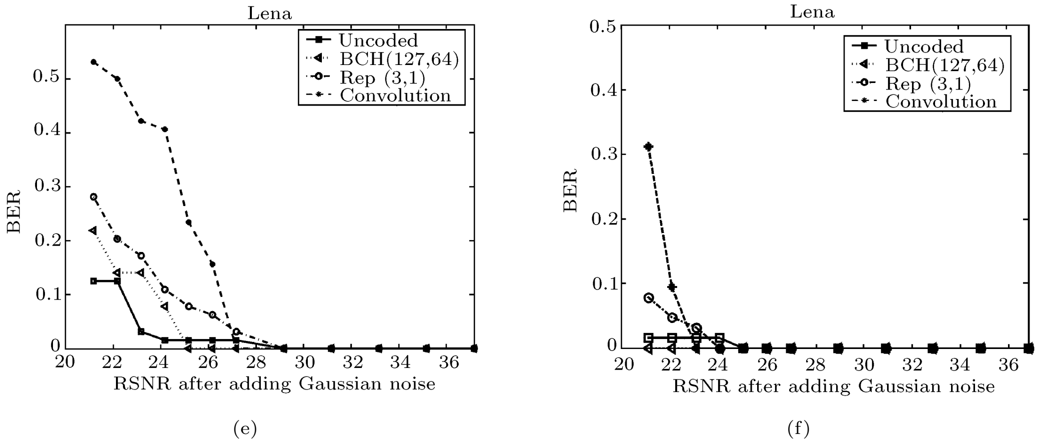


Fig. 5 Robustness achieved by different codes against JPEG compression or Gaussian noise corruption as watermark embedded in the mid-frequency of 8×8 DCT. PSNR of watermarked images are: (a), (d) 44.2 db; (b), (e) 42.0 db; (c), (f) 38.1 db

Tables 3 lists the robustness performance of the uncoded and BCH coding schemes when StirMark 3.1 testing functions were applied, as a 64-bit watermark was embedded into the mid-frequency DCT coefficients of $8*8$ blocks. In the table, there are only $7\sim8$ out of 45 testing functions, where BCH scheme outperforms the uncoded scheme. Note that, here, we only count the testing functions, conducted on both test images, where the BER of the BCH scheme is lower than that of the uncoded scheme. It is observed that the uncoded scheme performs better than BCH scheme for the most of testing functions in StirMark 3.1, except for cropping and jitter attacks. For jitter attacks, the uncoded scheme outperforms BCH scheme in some cases while being outperformed in other cases. Note that all the cropping testing functions in StirMark 3.1 are not listed in Table 3. For cropping, the situation is different because enhanced embedding strength does not play a role. Instead, ECC can resist these two types of attacks to a certain extent. Furthermore, since DCT and DWT cannot preserve geometrical invariant property, all schemes have high error rates under geometrical attacks. Even so, we can see that BER corresponding to the uncoded scheme is lower, compared with the BCH scheme. We also conducted experiments with the PSNR of 38.1 db, and had similar conclusions.

Under the constraint of imperceptivity, embedding strength and length of embedded bits are conflicting each other. ECC can correct some error bits in watermark extraction by means of introducing redundancy. At the same time, however, redundancy introduced by using ECC will lower the embedding strength, hence increasing BER in decoding. Although having no error correcting capability possessed by ECC, the uncoded scheme does lower error rate by means of increasing watermark strength. The above experiments show that it is more important to increase embedding strength in the improvement of watermark robustness against most of attacks except cropping and jitter attacks.

It is noted that error bits caused by some attacks, such as cropping in image/audio watermarking, losing frame in video watermarking are independent of embedding strength. In such cases, the higher embedding strength in the uncoded scheme does not make sense, whereas ECC can improve the robustness of watermarking. This observation has been supported by our experiments. In the case of burst errors, it has been reported[22] that better performance can be achieved through combining ECC and interleaving coding.

Another special case is discussed below. In the LSB-based watermarking algorithms, embedding strength is fixed and has no impact on imperceptivity. Even hiding fewer watermark bits, the embedding strength cannot be increased. In such case, ECC may improve the robustness of watermark to some extent. Because the LSB-based algorithms belong to early watermarking methods and have low robustness in general, we have not paid much attention on them in this paper.

Table 3 Performance of two different coding schemes on "Lena" and "Baboon" as watermark is embedded in the mid-frequency coefficients of 8 ∗ 8 DCT blocks and PSNR of watermarked image is 44.2db

StirMark functions	Lena		Baboon	
	Uncoded	BCH	Uncoded	BCH
5_row_17_col_removed	0.250	0.234	0.219	0.313
3x3_median_filter	0.453	0.484	0.344	0.406
2x2_median_filter	0.484	0.484	0.438	0.484
Gaussian_filtering_3_3	0.484	0.484	0.484	0.484
linear_1.010_0.013_0.009_1.011	0.438	0.484	0.469	0.484
ratio_x_1.20_y_1.00	0.078	0	0.078	0.156
ratio_x_1.10_y_1.00	0	0	0.016	0
ratio_x_1.00_y_1.20	0.141	0.141	0.109	0.156
ratio_x_1.00_y_0.90	0.156	0.188	0.141	0.188
ratio_x_1.00_y_0.80	0.016	0.156	0.016	0.172
ratio_x_0.80_y_1.00	0.016	0.125	0.063	0.141
rotation_−0.50	0.375	0.484	0.375	0.375
rotation_0.50	0.391	0.484	0.375	0.484
rotation_scale_−0.25	0.328	0.359	0.313	0.297
rotation_scale_0.25	0.359	0.359	0.375	0.344
scale_0.90	0.406	0.484	0.438	0.484
scale_1.10	0.266	0.375	0.297	0.344
sharpening_3_3	0.297	0.375	0.453	0.391
Shearing_x_0.00_y_1.00	0.266	0.266	0.281	0.297
Shearing_x_0.00_y_5.00	0.422	0.484	0.422	0.406
Shearing_x_1.00_y_0.00	0.297	0.281	0.234	0.328
Shearing_x_1.00_y_1.00	0.422	0.422	0.406	0.406
Shearing_x_5.00_y_0.00	0.422	0.453	0.391	0.453
Shearing_x_5.00_y_5.00	0.469	0.484	0.469	0.484
JPEG_50	0	0	0	0
JPEG_40	0	0.344	0	0.344
JPEG_35	0	0.484	0	0.484
JPEG_30	0	0.484	0	0.484
JPEG_25	0.484	0.484	0.484	0.484
FMLR	0.266	0.484	0.016	0.297
Random_bending	0.484	0.484	0.484	0.484

5 Conclusions

In this paper, we have addressed an interesting issue, *i.e.*, whether applying ECC can always lead to the robustness enhancement of watermark signal. The main contributions and conclusions are listed below.

1) Having emphasized the differences between watermarking channel and common communication channel. That is, the imperceptibility of original media signal is a peculiar constraint in digital watermarking, which does not exist in common communication systems.

2) Having analyzed the contending relationship between watermark embedding strength and total amount of embedded bits (length of embedded sequence) both theoretically and experimentally, from the perspective of the imperceptibility constraint.

3) Having conducted extensive experiments. In experiments, both StirMark 3.1 testing functions and additive Gaussian noise are applied. Data are embedded in the mid-frequency 8∗8 DCT coefficients, and the mid-frequency DWT coefficients as well as the low-frequency DWT coefficients. The informative watermarks composed of 32 bits, 64 bits, and 128 bits are all tested. The performance of four coding schemes, *i.e.*, uncoded scheme, BCH scheme, repetition scheme and convolutional codes scheme, are compared.

4) Having pointed out that it is more important to increase embedding strength in the improvement of watermark robustness against most of attacks except for cropping and jitter attacks. The experimental results support our analysis and conclusions.

Hence, using ECC to achieve robust watermarking is not straightforward.

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