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Error Concealment Based on Multiple Representation for Wireless Transmission of JPEG2000 Image

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ABSTRACT

The transmission of multimedia information over error-prone channels such as wireless networks has become an important area of research. In this paper, we propose two Error Concealment (EC) schemes for wireless transmission of JPEG2000 image. The Multiple Representation (MR) is employed as the preprocessing in our schemes, whereas the main error concealing operation is applied in wavelet domain at receiver side. The compressed code-stream of several subsampled versions of original image is transmitted over a single channel with random bit errors. In the decoder side, the correctly reconstructed wavelet coefficients are utilized to recover the corrupted coefficients in other sub-images. The recovery is carried out by proposed basic (MREC-BS) or enhanced (MREC-ES) methods, both of which can be simply implemented. Moreover, there is no iterative processing during error concealing, which results a big time saving. Also, the simulation results confirm the effectiveness and efficiency of our proposed schemes.

Key Word : Error Concealment, Multiple Image Representation, Horizontal/Vertical Correlation, Random Bit Error

Ⅰ. Introduction

In multimedia applications, the transmission of multimedia information over error-prone channels such as wireless networks has become an important area of research. Since the bandwidth of the wireless channel is narrow and expensive, when errors occur, it is not economical and adequate to retransmit the corrected data through this narrow bandwidth. And also, unreliable wireless channel may inject errors into the transmitted bit-stream. When compressed images are transmitted over such channel, the compressed code-streams received at the decoder may include errors. It is highly desirable that the errors can be handled with some preprocessing in encoder side and recovering in decoder side, so that the reconstructed image can be achieved the highest quality from these noisy code-streams. The new standard JPEG2000[1] is a growing image coding standard which is suitable to be applied to wireless image transmission, since JPEG2000 delivers image with lower bit rate and takes more accounts of error resilience than other image standards.

JPEG2000 standard is based on Discrete Wavelet Transform (DWT) and adaptive binary arithmetic coder – MQ coder, which is error

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sensitive during compression. The error resilient tools defined in JPEG2000 baseline aim at reducing the error propagating depending on some forward processing, such like data partitioning, inserting segmentation resynchronization and markers[2]. These methods provide the decoder with error detection capabilities and allow one to skip the decoding of erroneous sections of the code-stream, thus preventing the propagation of the transmission errors. It is worth noting that, since the decoder simply conceals the errors, the obtained image quality can be heavily impaired even for Bit Error Rate (BER) in the range $10^{-5} \sim 10^{-4}$. In such a scenario, the Part-11 of JPEG2000 standard[3], JPEG2000 for Wireless Applications (JPWL), targets on transmission of JPEG200 code-stream over an error-prone network. In particular, JPWL supports a set of tools and methods for error protection and correction such as Forward Error Correcting (FEC) codes[4], Unequal Error Protection (UEP)[5], and data partitioning and interleaving[6]. However, the FEC methods adds much more redundant bits to the original bit-stream in order to provide higher error protection for important data, which induces a large overhead on data transmission.

There are also several techniques presented for error resilience and concealment of JPEG2000 image besides JPWL. Data embedding and genetic algorithm are employed to conceal errors in [7], in which the embedded data is inserted into a bit-mask in the highest resolution subband. P. Chung et al.[8] proposed an uneven block-sized information included marker used in JPEG2000 for error resilient coding. However, in both techniques the data embedded during encoding may be lost if the code-stream is truncated in progressive applications, inducing an impossible recovery.

Due to the redundancy adding at encoder and the instability of embedded data during transmission, recovery of lost data in the decoder by means of post-processing methods is very attractive. A code-block-based error concealment scheme for JPEG2000 image is proposed in [9] to deal with packet loss in transmission. In this scheme, the original image is represented by two sub-images before encoding and transmission; in decoder side, if some code-blocks in one sub-image is corrupted, the code-blocks from the other sub-image in the same position can be employed to replace the corrupted ones. However, if both sub-images lose the code-block in the same position, the recovered image can not achieve an expectative performance.

In order not to increase the overhead of transmission, as well as enlarging the available data which can be utilized in decoder, in this paper, we propose two efficient error concealment schemes which are also based on image subsampling. In both proposed schemes, the original image is subsampled into several sub-images which are compressed into one code-stream, then transmitted over a single channel with random bit errors. The decoder simply utilizes the correctly reconstructed wavelet coefficients to recover the corrupted coefficients in other sub-images. The proposed schemes avoid searching and iteration procedures, therefore the error concealing is very efficient.

The rest of the paper is organized as follows. Section II provides the background, including an overview of JPEG2000 compression and its error resilience tools. In Section III, two error concealment schemes are proposed in detail. Simulation Results are presented and analyzed in Section VI. Finally, conclusions are discussed in Section V.

Ⅱ. Preliminary

2.1 JPEG2000 Image Compression Standard

The JPEG2000 image compression is a wavelet transform-based coding scheme[1]. In JPEG2000, the input image is first decomposed into one (for gray scale images) or several (for color images) components and each component is optionally partitioned into smaller independent rectangular blocks called tiles. The tile component is the basic unit of the original or decoded image, and it can be independently compressed. Then the DWT is applied to each tile to decompose it into different resolution levels. The sub-bands in each resolution level are partitioned into smaller non-

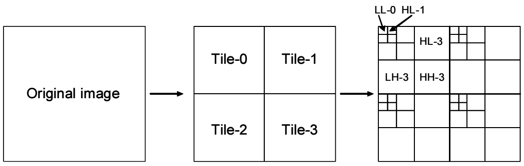


Fig. 1 Tiling and DWT in JPEG2000 encoder

overlapping rectangular blocks called code-blocks. The wavelet coefficients inside a code-block are processed from the most significant bit-plane (MSB) towards to the least significant bit-plane (LSB). Further more, in each bit-plane the bits are scanned in a maximum of three passes called coding passes. Finally, during each coding pass, the scanned bits with their context value are sent to a context-based adaptive arithmetic encoder that generates the code-block's bit-stream.

In practice, in order to ease decoding, coding passes from different bit-planes of different code-blocks are typically grouped into so-called packets. Each packet has its own header, which contains information about the sub-bands, code-blocks, bit-planes, and coding passes that contribute to the data in the packet body. Conceptually, the code-stream is organized as a succession of layers, each layer containing the additional contributions from each code-block. The block truncation points associated with each layer are optimal in the rate distortion sense.

2.2 Error resilience in JPEG2000

In order to improve the transmission performance of compressed images over channels prone to bit errors and packets losses, error resilient code-stream syntax and tools have been included in JPEG2000[2] standard, using the following approaches:

2.2.1 Data partitioning and resynchronization;

The resynchronization approach adopted by JPEG2000 is a packet approach. A packet that is a level in default or a specific region of a particular tile, component, and resolution is a part of a layer or a whole layer. Each packet will be added with a unique marker, if necessary, at the beginning along with header information. As bit error occurs, when the unique marker in a packet is encountered indicating the start of a new packet, the decoding is reset. As such, following packet would not be damaged by the errors and the bit error effect could be limited locally. When bit errors are detected, the decoder uses packet approach for resynchronization to the next packet, discard the damaged data and then replace erroneous block by zeros.

2.2.2 Error detection and concealment;

A segmentation marker is a special segmentation symbol "1010" inserted at the end of each bit plane, i.e. after clean up coding pass. At the decoder side, a segmentation marker should be decoded correctly at the end of each decoding pass. If the segmentation marker is not decoded correctly, then an error is flagged in the preceding pass. An alternative way is to create a separate predictably terminated codeword segment for each coding pass. Any error in the bit-stream is likely to leave the coder in a state which is inconsistent with the predictable termination policy. An error resilient decoder may detect this condition at the end of the coding pass in which the error occurred and discard only the coding pass in which this error occurs and all the following passes.

2.3 Multiple Image Representation

An image can be multiple represented by several available techniques[7,10-12]. In this paper, we adopt the spatial domain subsampling for multiple image representing as introduced in [7], since it is simple and quick to be implemented.

Subsampling is a process to decompose an original image into k subimages in the spatial domain. Given the image V[m, n] with the size of M * N, where m = 0, ..., M-1, and n = 0, ... , N-1, that image can be decomposed into four subimages using the following equations:

$$\begin{aligned} V_0[m,n] &= V[2m,2n], \\ V_1[m,n] &= V[2m,2n+1], \\ V_2[m,n] &= V[2m+1,2n], \\ V_3[m,n] &= V[2m+1,2n+1], \end{aligned}$$

$$\text{for } m=0,\ldots,\frac{M}{2}-1,\ n=0,\ldots,\frac{N}{2}-1 \qquad (1)$$

When M and/or N are odd numbers, one extra column and/or row can be added and filled with the pixels taken from the image boundary. This four-sub-image decomposition is focused in our work, whereas the more details of subsampling of other types are described in [7].

Ⅲ. Proposed Multiple Representation Error Concealment Scheme

Our proposed scheme is based on JPEG2000 image compression, which combines with preprocessing of image multiple representation, and the error control is operated in wavelet domain. The overview of coding flow with JPEG2000 is described in Fig. 2, in which the gray blocks are extending processing besides JPEG2000 normal coding procedure.

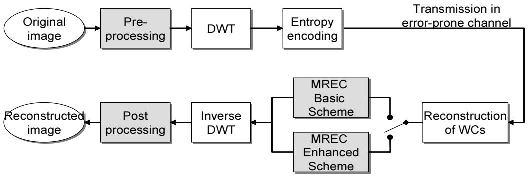


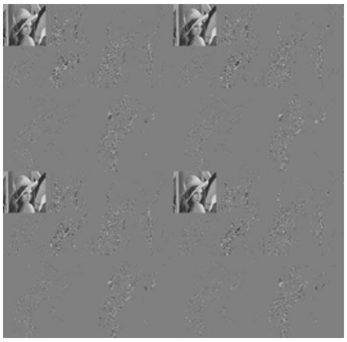
Fig. 2 Block diagram of coding flow

3.1 Preprocessing

The preprocessing procedure of our scheme is applied on spatial domain, where the original image is firstly decomposed into several sub-images with same size. The spatial subsampling introduced in section 2.3 is operated pixel by pixel to decompose the input image. Since the correctly received data in sub-images are used to recover the error-occurred data in other sub-images, in order to reduce the probability of error occurrence in the same position in all sub-images, more sub-images are expected to be used to represent the input image. However, the compression efficiency can be reduced due to image subsampling. Thus, to compromise the error occurring probability and compression efficiency, we consider that a new image is represented by four same size sub-images, shown in Fig.

(a) Original image

(b) Subsampled image



(c) DWT on subsampled image

Fig. 3 Subsampling and DWT in Encoder side of Lena image

3 In case, the probability of error concurrence in all sub-images is about 2^{-8} ($\approx$ 0.39%).

3.2 JPEG2000 Encoding

The reorganized image which includes four same sub-images is input into JPEG2000 encoder with tiling. The tiling is an optional coding step in JPEG2000 which is generally used on large images to reduce computer memory requirements. Each tile is compressed and reconstructed independently as they are entirely distinct images.

In our scheme, tiling is compulsorily used, also the tile border is set at the sub-image boundary, i.e. each sub-image is encoded as a tile, whereas the same encoding parameters are applied to each tile, such as the wavelet decomposition level, code-block size, etc. Therefore, whether the wavelet coefficients or the code-stream structure of each tile, are exactly similar and these information can be employed to conceal errors occurring in other tiles. In the following, we use tile and sub-image alternatively.

The segmentation marker defined in JPEG2000 compression baseline is exploited in our error concealing scheme. As mentioned in section 2.2, a symbol string ″1010″ is encoded at the end of each bit-plane. Specifically, the string must be delivered to the MQ coder using the unique non-adaptive context. These symbols complete the third coding pass, i.e. cleanup coding pass, in each bit-plane. Following, the decoder carefully decodes these four symbols before proceeding to the next bit-plane.

3.3 Error Concealing in Decoder Side

At the decoder side, the JPEG2000 compressed code-stream transmitted in error-prone channel is received. The code-blocks in each tile are checked for whether errors occur, and then decoded independently until the wavelet coefficients in all tiles are reconstructed (successfully or not). Since most of the meaningful images have the horizontal/vertical correlations between neighboring pixels or regions, this correlation can be directly employed for error concealment. Two Multiple Representation Error Concealment (MREC) schemes are presented in this section.

The following notations are used in our schemes:

- $T_0 \sim T_3$:four tiles (four sub-images), 0~3 are tiles indices;
- CB_i^t: the code-block in t th tile;
- $WC_j^{CB_i^t}$: the wavelet coefficient value in code block CB_i^t;
- $D_{tt'}^{CB_i^t}$: the difference between two wavelet coefficients in tile t and t';

In each tile, the code-blocks with the same index, i.e. the same position, are identified in one code-block group (BG), e.g. $CB_0^0, CB_0^1, CB_0^2, CB_0^3$ are the first code-blocks in four tiles, respectively; and then they are detected for whether error occurs or not. If error occurs in one or more code-blocks, the error concealing is applied, where each losing wavelet coefficient is the basic unit to be recovered. In our proposed schemes, four possible error occurring cases are considered:

- **Case-1**: Only one code-block is corrupted in the BG.
- **Case-2**: Two code-blocks are corrupted in the BG.
- **Case-3**: Three code-blocks are corrupted in the BG.
- **Case-4**: All the code-blocks are corrupted in the BG.

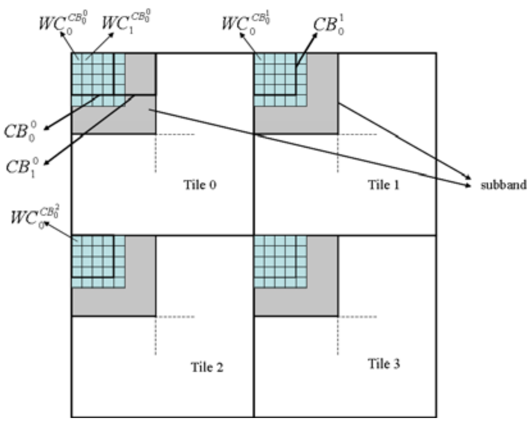


Fig. 4 The presentation of processing units in our scheme

3.3.1 Multiple Representation Error Concealment Basic Scheme (MREC-BS)

The basic scheme is very simple and efficient to be implemented. The main approach is to use the average value of the correctly received coefficients to replace the corrupted coefficients in one BG. The coding steps are followed as:

▸ Step 1: In each BG, collecting the four wavelet coefficients $WC_j^{CB_i^0}, WC_j^{CB_i^1}, WC_j^{CB_i^2}, WC_j^{CB_i^3}$ with the same index in these four code-blocks as one wavelet coefficient group (WG). Since the corrupted block is known advanced, the uncorrected wavelet coefficient can be also confirmed.

▸ Step 2: For case-1 to case-3, the average value of correct coefficients are calculated, which is used to replace the corrupted wavelet coefficients in this WG.

▸ Step 3: For case-4 which is hardly happened, if the corrupted code-blocks are in level 0 to level 3, we use the average value of four coefficients to replace themselves; if the corruption occurs in higher resolution level, such as level 4 or 5, we just set the coefficients to zero.

3.3.2 Multiple Representation Error Concealment Enhanced Scheme (MREC-ES)

The horizontal/vertical correlation in image spatial domain is utilized in our enhanced scheme. The main procedure of MREC-ES for a corrupted BG is presented in the following.

- **Case-1**: Only one code-block is corrupted in the BG.

▸ Step 1: Grouping four coefficients into a WG;

▸ Step 2: In each WG, calculating $D_{tt'}^{WC_i}$ between any two correctly reconstructed wavelet coefficients, where

$$D_{tt'}^{WC_i} = \left| WC_j^{CB_i^t} - WC_j^{CB_i^{t'}} \right| \tag{2}$$

There are at least three correct coefficients, thus after calculation we get three values of $D_{tt'}^{WC_i}$.

▸ Step 3: Finding

$$\min\left\{ D_{tt'}^{WC_i} \right\} \tag{3}$$

then using the most similar wavelet coefficient to replace the corrupted one.

There is an example to explain the detailed coding procedures in case 1.

Example-1:

Supposing the first code-block in tile-0, denoted as CB_0^0 is corrupted:

- First, collecting the coefficients group as $\left\{ WC_j^{CB_0^0}, WC_j^{CB_0^1}, WC_j^{CB_0^2}, WC_j^{CB_0^3} \right\}$.

- Second, calculating $D_{tt'}^{WC_j}$ as:

$$D_{12}^{WC_j} = \left| WC_j^{CB_0^1} - WC_j^{CB_0^2} \right|,$$
$$D_{13}^{WC_j} = \left| WC_j^{CB_0^1} - WC_j^{CB_0^3} \right|,$$
$$D_{23}^{WC_j} = \left| WC_j^{CB_0^2} - WC_j^{CB_0^3} \right|;$$

$WC_j^{CB_0^2}$ to replace $WC_j^{CB_0^0}$;

If $\min\left\{ D_{12}^{WC_j}, D_{13}^{WC_j}, D_{23}^{WC_j} \right\} = D_{23}^{WC_j}$, higher similarity in horizontal direction, using $WC_j^{CB_0^1}$ to replace $WC_j^{CB_0^0}$;

If $\min\left\{ D_{12}^{WC_j}, D_{13}^{WC_j}, D_{23}^{WC_j} \right\} = D_{12}^{WC_j}$, using $(WC_j^{CB_0^1} + WC_j^{CB_0^2} + WC_j^{CB_0^3})/3$ to replace $WC_j^{CB_0^0}$;

- **Case-2**: Two code-blocks are corrupted in the BG.

▸ Step 1: Grouping four coefficients into a WG;

▸ Step 2: Considering three different error occurring positions:

- If both two corrupted wavelet coefficients are in horizontal or vertical direction, we use the other two coefficients to replace them horizontally or vertically, respectively;

- If two diagonal coefficients are corrupted, they are discretionarily replaced by the other two correct coefficients.

Example-2:

If errors occur on $WC_j^{CB_0^0}, WC_j^{CB_0^1}$, we use $WC_j^{CB_0^2}, WC_j^{CB_0^3}$ to replace them respectively;

If errors occur on $WC_j^{CB_0^0}, WC_j^{CB_0^2}$, we use $WC_j^{CB_0^1}, WC_j^{CB_0^3}$ to replace them respectively;

If errors occur on $WC_j^{CB_0^0}, WC_j^{CB_0^3}$, we arbitrarily use $WC_j^{CB_0^1}, WC_j^{CB_0^2}$ to replace them.

- **Case-3** and **Case-4**:

The error handling approaches are the same as MREC-BS.

3.4 Post-processing

After the error concealing of wavelet coefficients, the following normal decoding steps in JPEG2000 are carried out to reconstruct the multiple represented sub-images. Subsequently, an inverse subsampling operation is applied to obtain the whole recovered image.

Ⅳ. Evaluations

4.1 Experimental Environment

The proposed schemes have been implemented based on the publicly available JPEG2000 implementation OpenJPEG (Version v1.1)[13]. Error concealing is simulated on following five monochrome images: Lena, Graves, Peppers, Sailsboat, Plane. All of them are 512*512 pixels, and in gray level with 8 bit per pixel (bpp). The images are compressed lossily at 1.0 and 0.5 bpp. In our experiments, the JPEG2000 compression parameters are set as: four tiles division, three-level DWT decomposition, 16*16 code-block size, 20 layers, and layer progressive bit-stream.

The simulated transmission channel model is the Binary Symmetric Channel (BSC) with random bit errors, where the channel bit error rate (BER) is kept in the range $(10^{-4}, 10^{-5})$. Note that, the main headers and tile headers in the code-stream are protected using Reed Solomon (RS) code as described in [4]. The Peak Signal to Noise Ratio (PSNR) was used for objective measure of the image distortion. PSNR for an image with bit depth of n bits/pixel is defined as

$$PSNR = 10\log_{10}\frac{(2^n-1)^2}{MSE}$$

In our simulation, the PSNR is computed as the linear average value over 50 trails, obtained by simulating 50 independent transmissions of the same image in BSC.

4.2 Performance of Concealment

In this section ,the performance obtained with MREC-BS and MREC-ES decoding is analyzed. We also simulate the zero-replace method which just simply replaces all the corrupted coefficients to zero.

In Fig. 5 and Fig. 6, the PSNR for 50 trails

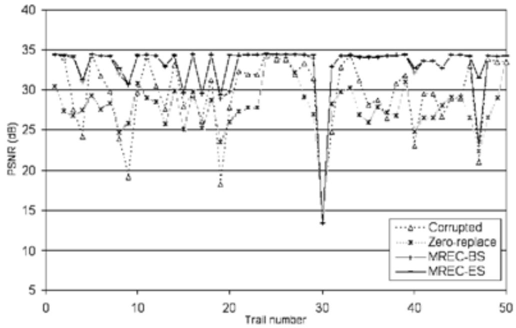


Fig. 5 PSNR performance of 50 trails of peppers at 1bpp, BER=10^{-5}

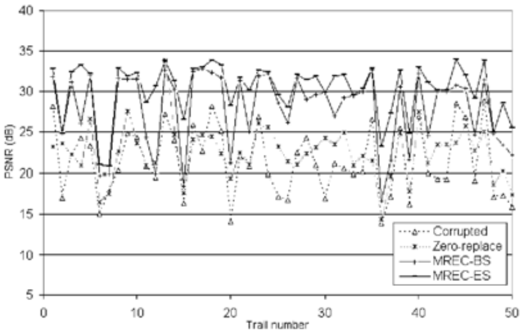


Fig. 6 PSNR performance of 50 trails of peppers at 1bpp, BER=10^{-4}

of the peppers image is reported for the BSC with BER=10^{-5} and 10^{-4}, respectively. The PSNR is yielded by the corrupted (triangle), zero-replace (asterisk), MREC-BS (cross) and MREC-ES (horizontal line). The original pepper image is encoded with the target bit-rate at 1 bpp, obtaining the PSNR at 34.56 dB at error free channel. Since all coefficients in the corrupted code-block should be replaced due to the error propagation of arithmetic coding, we can observe that zero-replace error concealment does not always generate better performance than corrupted one, particularly in lower BER. It can be seen that both of our proposed error concealment schemes are very effective in most trails in Fig. 5. Especially, from trails 20 to 30 and 32 to 40, the concealing performance is almost the same as error free value. At the same time, it should be mentioned that there is an obvious crack at trail 30, since the random bit errors may occur at any

Table 1. Average PSNR (dB) over 50 trails of peppers image with different BER

BER	Corrupted	Zero-replace	MREC-BS	MREC-ES	Gains by MREC-ES
10^{-5}	29.46	27.90	32.93	33.26	3.8
10^{-4}	21.37	22.54	27.88	30.27	8.9
5×10^{-4}	21.58	22.47	28.34	30.68	9.1

Table 2. PSNR Performance (dB) of five test image using four decoding ways with BER=10^{-4}, at 0.5 bpp

	Lena	Graves	Peppers	Sailboat	Plane
Corrupted	25.24	21.73	21.07	24.34	19.94
Zero-replace	26.98	23.46	22.70	24.88	20.43
MREC-BS	27.98	24.82	27.23	25.31	24.45
MREC-ES	30.29	24.86	28.95	25.30	26.89
Error free	30.54	26.94	30.65	25.86	29.29
Recovered Loss	0.25	2.08	1.70	0.56	2.40

Table 3. PSNR Performance (dB) of five test image using four decoding ways with BER=10^{-4}, at 1 bpp

	Lena	Graves	Peppers	Sailboat	Plane
Corrupted	25.58	20.45	24.45	20.54	23.56
Zero-replace	28.98	20.93	24.87	23.65	24.55
MREC-BS	33.82	29.99	32.39	26.43	31.39
MREC_ES	34.56	30.08	33.58	27.23	31.52
Error free	34.97	31.90	34.56	29.48	34.09
Recovered Loss	0.41	1.82	0.98	2.25	2.97

Table 4. Independent processing time (seconds) of both proposed schemes

BER	Method	Lena	Graves	Peppers	Sailboat	Plane
10^{-4}	MREC-BS	0.00912	0.00924	0.00927	0.00906	0.00912
	MREC-ES	0.00959	0.00975	0.00961	0.00949	0.00939
	Increased ratio	5.15%	5.52%	3.67%	4.75%	2.96%
5×10^{-4}	MREC-BS	0.00965	0.00984	0.00932	0.00930	0.00915
	MREC-ES	0.01277	0.01111	0.01173	0.01170	0.00980
	Increased ratio	32.33%	12.91%	25.86%	25.80%	7.10%

positions in code-stream, in which the receiver side could not get any information except headers to reconstruct image. The curves in Fig. 6 seems less stable than Fig. 5 due to the increased BER. However, most PSNR values of error concealed images are above 30 dB and the average gained PSNR is about 8 dB.

Table-1 shows the linear average PSNR over 50 trails of peppers image with different BER, in four decoding ways. Obviously, even though the proposed basic scheme has some better results showed in Fig. 5 and Fig. 6, from a general view, the enhanced scheme averagely gets about 1.5 dB higher than basic scheme. Moreover, the zero-replacement method does not work better at 10^{-5} error rate. The last column shows the gains of MREC-SC contrasted to corrupted image. At BER=5×10^{-4} the average gain is reached at 9.1 dB, which achieves a similar, even higher value compared with other error recovering schemes based on data embedding and iterations or big searchings[7,8]. Note that in [7], data should be carefully extracted and embedded at encoder side and extracted again at decoder to recover the

Fig. 7 Lena image decoded with different ways. (a) Corrupted subsampled image; (b) Corrupted represented image; (c) Zero-replacement; (d) MREC-BS; (e) MREC-ES

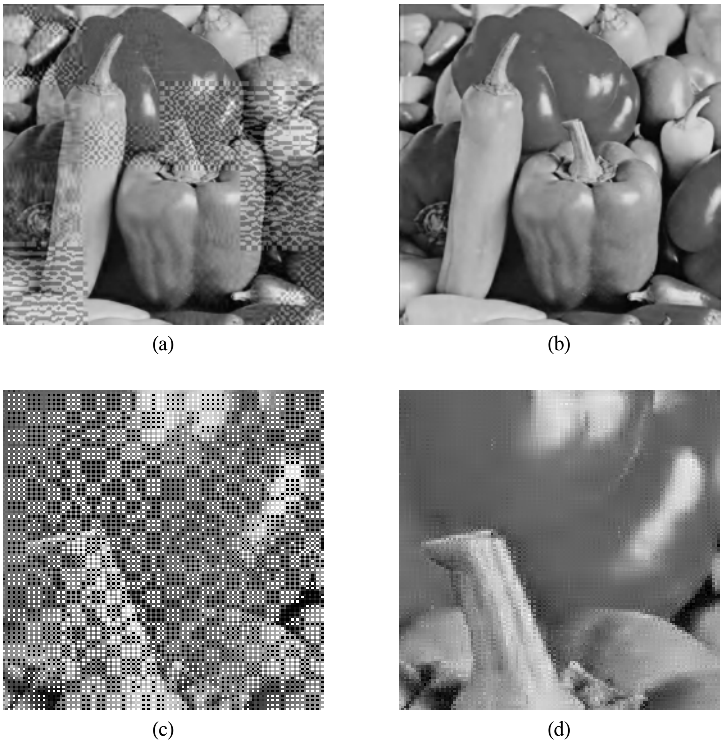


Fig. 8 Pepper image, with BER=5×10^{-4}, 1bpp (a) Corrupted represented image; (b) MREC-ES reconstruction; (c) A corrupted some region of the image; (d) Recovered region with MREC-ES

corrupted image, which costs more extended processes and coding time.

Table-2 and Table-3 present the PSNR performance of several test images with BER= 10^{-4}, at 0.5 bpp and 1 bpp, respectively. The PSNR losses after recovering are given in the last row in each table, which is the difference between error free and MREC-ES decoding. It is observed that the biggest loss is only less than 3 dB, which can be obtained by increasing the target bit-rate slightly. Fig. 7 (b)~(e) shows different decoding ways of lena image, which is encoded at 1 bpp with BER=10^{-4}. Clearly, the basic scheme still leaves some flaws unrecovered, whereas the enhanced scheme reconstructs the image very nicely. Moreover, Fig. 8 depicts the reconstructed pepper image, using enhanced scheme, at BER=5×10^{-4}, 1 bpp. Comparing Fig. 8 (a) and (b), (c) and (d), the visual quality is increased much obviously.

4.3 Processing Time

In this section, we shortly discuss the time consuming by our proposed two schemes, comparing with the standard JPEG2000 decoding. Table 4 illustrates the independent processing time of our proposed schemes. It can be notified that with the increasement of BER, MREC-ES costs more time contrasted to MREC-BS. Therefore, there is a tradeoff between time consuming and error concealment performance. However, even though MREC-ES takes more time than MREC-BS, it still reduces about 40 times compared with the basic scheme in [7].

Ⅴ. Conclusions

In this paper, we proposed two error concealment schemes based on multiple image representation. The proposed schemes only need a simple subsampling preprocessing before transmission. Then the error recovery is easily carried out in wavelet domain at decoder side, where the horizontal/ vertical correlation in spatial domain of image is employed to conceal the corrupted wavelet coefficients. The processing time is much saved in our schemes. Simulation results justify that our proposed schemes is effective and available to be used in error-prone wireless channel.

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