Error Resilience and Error Concealment for Embedded Wavelet Coders

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Abstract

This paper presents an error-resilient coding technique combined with error concealment for embedded wavelet coders. The coded images are partitioned into packets and protected by multiple descriptions. Each packet contains an independent spatial-orientation tree and duplicated copies of other root wavelet coefficients. At decoding, the coefficients that cannot be recovered are predicted through linear interpolation based on inter-subband correlation. Experimental results show that the proposed method achieves good and stable error performance with minimal additional redundancy.

1. Introduction

Shannon's information theory lays the foundation of multimedia transmission. Source coding squeezes the multimedia contents to meet the bandwidth/storage requirement and channel coding protects the compressed bit streams against channel impairment. To date, the most successful image compression algorithms are wavelet based. In particular, the set partitioning in hierarchical trees (SPIHT) coding [1] is the most prestigious owing to its high compression efficiency and progressive nature. The success of SPIHT attributes to the use of the zerotree concept and variable-length codes. However, the resulting SPIHT bit streams are vulnerable to channel errors. Therefore, error control is a necessity for transmitting SPIHT-coded images over error-prone networks. Man *et al*. [2] modified the SPIHT's encoding procedure to generate fixed-length data segments in conjunction with RCPC codes for unequal error protection. Creusere [3] divided the wavelet coefficients into disjoint trees for error isolation and interleaved the generated bit stream to produce scalable data. Yang and Cheng [4] proposed an error-resilient scheme by attaching appropriate side information to partitioned data sequence. Kim *et al*. [5] proposed separating the low-frequency and high-frequency subbands and applied adaptive packetization for better error resilience. Multiple description coding (MDC) schemes for SPIHT were proposed in [6] and [7].

The network congestion may frequently cause packet loss under an IP/UDP/RTP real-time transmission structure. In this paper, we consider a new error-control framework for SPIHT-coded images sent across a bit-error-free but packet-lossy link. The overall system is depicted in Fig. 1, where we highlight the new functions added to original SPIHT codec, namely MDC and packetization at the encoder and error concealment at the decoder. Important wavelet coefficients are duplicated, and packetization is achieved by independent coding each of the directional wavelet branches. When a data packet is lost, the essential information of the packet may be recovered from correctly received packets. The other distinguished feature of the proposed scheme is the incorporation of error concealment into the system. Inter-subband correlation is exploited to predict the coefficients in the largest-scale detail subband. Simulation results are given and the analyses are presented with the factors relevant to the system's performance.

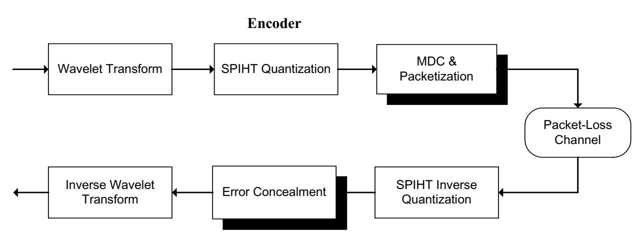
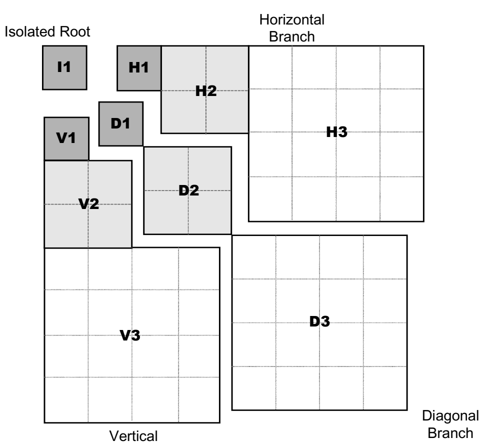


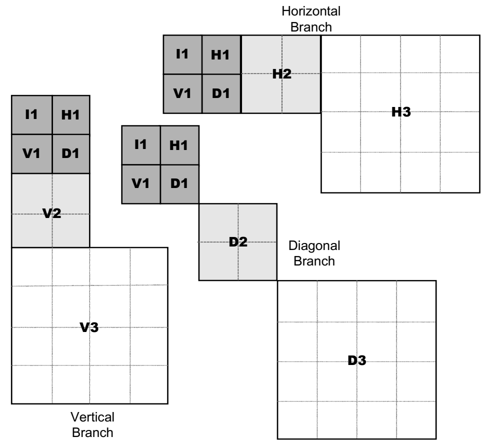
Fig. 1. Framework of the proposed method.

2. Packetization and MDC for error-resilient SPIHT

In SPIHT, the wavelet coefficients that bear the information associated with the same location and orientation are treated as a spatial-orientation tree. The spatial-orientation trees can be naturally classified into three directional categories, horizontal, vertical, and diagonal. Instead of treating the three spatial-orientation trees corresponding to the same isolated root as a whole [8], we instead independently encode each of them (shown in Fig. 2(a)) for better error isolation. As a consequence, a 5-level wavelet decomposition will produce 192 independent variable-size data packets. With the proposed data partitioning scheme, a single packet loss will result in only partial (1/3) damage of a region, whose area is roughly 1/64 of the total image. Among all the SPIHT's coded data, the root (level 1, DC) information is by far the most important. Occupying only $(1/4)^5 < 0.1\%$ in the total number of wavelet coefficients, this subband contains most of the image's energy (typically more than 95%). Moreover, the rest of a spatial-orientation tree cannot be decoded without these root coefficients. We propose strong protection with MDC for these coefficients, as depicted in Fig. 2(b). The root coefficients including the isolated nodes are duplicated and attached to the other two sibling spatial-orientation trees. As a consequence, three copies of the level-1 information are individually transmitted across the channel. To facilitate later error concealment, the sign bits of level-2 coefficients are also duplicated in the another spatial-orientation tree. Without being otherwise specified, all the tests in this paper are performed on the Lena image with the 9/7 filter.



(a)



(b)

Fig. 2. (a) Packetization (b) MDC of the proposed method.

The goal of MDC is to provide good distortion-loss performance with reasonable redundancy. The amount of redundancy of the proposed MDC scheme is listed in Table 1. For typical SPIHT coding rates (1/4–1/2 bpp), the total added redundancy relative to the total generated bits is less than 10%, and the fixed-size level-2 redundancy (sign bits) is even smaller. In contrast, the MD-SPIHT method proposed in [6] introduces 20% redundancy at 0.5 bpp. The MDC redundancy translates into the lossless degradation as shown in Table 2. The PSNR gap at 0.25 bpp is only 0.32 dB, and it shrinks upon increasing the bit rates. In contrast, the PSNR loss at 0.5 bpp for MD-SPIHT is 0.60 dB.

Table 1. Redundancy (in bits and %) of MDC

bpp	1/8	1/4	1/2	1
Level 1	4097, 12.5%	4609, 7.03%	5121, 3.90%	5633, 2.14%
Level 2	768 (2.34%, 1.17%, 0.58%, 0.29%)			

Table 2. Lossless performance in PSNR w/o and w/ MDC

bpp	1/8	1/4	1/2	1
w/o MDC	30.52	33.57	36.73	39.92
with MDC	29.91	33.25	36.57	39.81

3. Reconstruction of lost wavelets coefficients

Error concealment relieves the visual degradation by interpolating the erroneous or lost data at the decoder. Reconstruction can be built from spatially or spectrally correlated samples. In this paper, we develop a spectral-domain error-concealment scheme under the designed error-resilient coding framework. While the MDC protects level-1 and signs of level-2 coefficients, the proposed error-concealment method restores the magnitude of level-2 coefficients (H2, V2, and D2). Although the wavelet transform aims to generate uncorrelated coefficients, it is well acknowledged that there exists a nontrivial dependence among wavelet coefficients. Compared to previous error-concealment efforts [9], [10], [11], the proposed scheme is more general in the sense that the interpolation is made with least restrictions on the coding framework.

Suppose that the estimate $\hat{Y}_n$ of a lost coefficient Y_n is a linear combination of N observations $X_{n-N}, X_{n-N+1}, \cdots, X_{n-1}$,

$$\hat{Y}_n = \sum_{k=1}^{N} a_k X_{n-k} \tag{1}$$

where a_k is the weighting associated with X_{n-k}. To minimize the mean square error (MSE) of $\hat{Y}_n$, the optimal weighting vector $\mathbf{a} = [a_1, a_2, \cdots a_N]$ is the solution to the Yule-Walker equation [12]

$$\mathbf{R}_{\mathbf{XX}}\mathbf{a} = \mathbf{r}_{Y\mathbf{X}} \tag{2}$$

where

$$\mathbf{R}_{\mathbf{XX}} = \begin{bmatrix} E[X_{n-1}^2] & E[X_{n-1}X_{n-2}] & \cdots & E[X_{n-1}X_{n-N}] \\ E[X_{n-2}X_{n-1}] & E[X_{n-2}^2] & \cdots & E[X_{n-2}X_{n-N}] \\ \vdots & \vdots & \ddots & \vdots \\ E[X_{n-N}X_{n-1}] & E[X_{n-N}X_{n-2}] & \cdots & E[X_{n-N}^2] \end{bmatrix} \tag{3}$$

and

$$\mathbf{r}_{Y\mathbf{X}} = \left[E[Y_n X_{n-1}] \quad E[Y_n X_{n-2}] \quad \cdots \quad E[Y_n X_{n-N}] \right] \tag{4}$$

For practical implementation, the correlation matrix $\mathbf{R}_{\mathbf{XX}}$ and correlation vector $\mathbf{r}_{Y\mathbf{X}}$ can be computed from the empirical data. Suppose that the random sequence is stationary, an M^{th}-order approximation of $\mathbf{R}_{\mathbf{XX}}$ and $\mathbf{r}_{Y\mathbf{X}}$ can be found by

$$\tilde{\mathbf{R}}_{\mathbf{XX}} = \frac{1}{M}\mathbf{H}^T\mathbf{H}, \quad \tilde{\mathbf{r}}_{Y\mathbf{X}} = \frac{1}{M}\mathbf{H}^T\mathbf{u} \tag{5}$$

where $\mathbf{H} = \begin{bmatrix} X_{n-2} & X_{n-3} & \cdots & X_{n-1-N} \\ X_{n-3} & X_{n-4} & \cdots & X_{n-2-N} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n-M-1} & X_{n-M-2} & \cdots & X_{n-M-N} \end{bmatrix}_{M\times N}$ and

$$\mathbf{u} = \begin{bmatrix} Y_{n-1} \\ Y_{n-2} \\ \vdots \\ Y_{n-M} \end{bmatrix}_{M\times 1} \tag{6}$$

In (5) and (6), Y_{n-1}, Y_{n-2}, … , Y_{n-M} are M available samples and the i^{th} row of $\mathbf{H}$ represent the observations that are correlated to Y_{n-i} in a similar manner as $\{X_{n-1}, X_{n-2}, \ldots, X_{n-N}\}$ and Y_n.

The inter-subband estimation for the magnitude of level-2 coefficients is exemplified in Fig. 3. Suppose that the four H2 wavelet coefficients {(4,22), (4,23), (5,22), (5,23)} are missing. The missing coefficient Y_n = (4,23) can be predicted from its parent node (4,7) (N = 1) as

$$|\hat{Y}_n| = a_1 |X_{n-1}| \text{ (parent), i.e., } (4,23) = a_1(4,7) \tag{8}$$

In our experiment, we take 4 surrounding samples $\mathbf{u} = \begin{bmatrix} (2,21) \\ (2,23) \\ (2,25) \\ (4,21) \end{bmatrix}_{4\times 1}$ and $\mathbf{H} = \begin{bmatrix} (2,5) \\ (2,7) \\ (2,9) \\ (4,5) \end{bmatrix}_{4\times 2}$. Note that the other lost coefficients such as (4,22) have the same $\mathbf{H}$ but a different $\mathbf{u}$, and thus have different estimations.

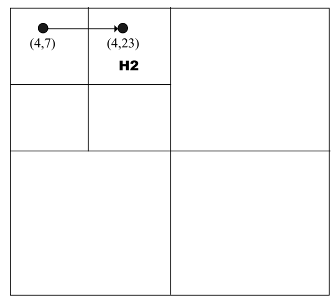


Fig. 3. Inter-subband estimation.

4. Experimental Results

To evaluate the proposed error-resilience and error-concealment methods, five scenarios are considered:

Scenario 1: lossless.
Scenario 2: unprotected (all lost coefficients are filled with 0). This scenario corresponds to the worst case.
Scenario 3: No MDC, and the lost coefficients are concealed by the 4-neighbor average. This scenario corresponds to typical concealment results without MDC.
Scenario 4: MDC + level-2 4-neighbor average.
Scenario 5: MDC + level-2 inter-subband interpolation.

In the following, we analyze two factors relevant to the system's performance, the packet loss rate and bit rate. The lost packets are randomly selected with equal loss rate. The indicated PSNR values are obtained by averaging over 500 experiments to achieve statistical reliability (with variation < 0.1%).

A. Effects of Packet Loss Rates

Three packet loss rates, 5%, 10%, and 20%, are examined, and the simulation results are given in Table

3. It is observed that the gain increases with the packet loss rate. For the Lena image, MDC (level-1 recovery) provides 1-2.5 dB gain and further interpolation (level-2 recovery) provides additional 0.5-1 dB gain.

Table 3. PSNR performance under various packet loss rates (coded at 0.25 bpp)

Scenario	5%	10%	20%
1	33.58	33.58	33.58
2	18.12	15.13	12.23
3	27.82	24.99	21.16
4	29.79	27.52	23.67
5	30.59	28.49	24.54

B. Effects of Bit Rates

Four bit rates, 0.125, 0.25, 0.5, and 1 bpp, are examined. Larger MDC and interpolation margins are observed for higher bit rates, as shown in Table 4. Two sources, the quantization noise and the transmission loss, account for the overall degradation of the SPIHT-coded images transmitted over lossy networks. The channel loss will dominate the total error when no proper error protection is employed (Scenario 2). It can be deduced from the results that MDC is essential for guaranteed quality and the benefit from further interpolation becomes significant at higher packet loss rates and coding bit rates.

Table 4. PSNR performance under various bit rates (10% packet loss)

Scenario	0.125	0.25	0.5	1.0
1	30.52	33.58	36.73	39.92
2	15.08	15.13	15.16	15.17
3	24.48	24.99	25.28	25.43
4	26.51	27.52	28.10	28.42
5	27.24	28.49	29.26	29.68

5. Conclusion

We have presented a hybrid error-protection scheme for SPIHT-coded images transmitted over the packet-loss networks. The proposed method combines the techniques of structured packetization, MDC, and interpolation of lost wavelet coefficients. Design parameters such as the packet loss rate and coding rate have been investigated. Experimental results show that the proposed method achieves good error performance with minimal modification to the SPIHT coding structure.

5. Acknowledgement

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