7-2004

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Journal of Electronic Imaging 13(3), 646–653 (July 2004).

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Abstract. *A scheme with three key components including wavelet tree coding, error resilient entropy coding (EREC), and error concealment is proposed for robust image coding and transmission over noisy channels. First, we individually encode the spatial-orientation trees in the wavelet domain using the algorithm of set partitioning in hierarchical trees (SPIHT). Error propagation is thus limited because multiple independent bit streams are generated. Meanwhile, a high source coding efficiency is also preserved because the self-similarity property in each wavelet tree remains intact. Next, we use EREC to reorganize these variable-length bit streams into fixed-length data slots before multiplexing and transmission. Therefore, the synchronization of the start of each bit stream can be automatically obtained at the receiver. Finally, to alleviate the possible catastrophic image degradation that may result from errors in the beginning of the bit streams, we propose an error concealment technique to constrain the EREC decoding as well as to postprocess the decoded wavelet coefficients. As a result of the error concealment, the EREC decoding complexity is reduced and the reconstructed image quality is significantly improved. Experimental results demonstrate an excellent error resilient performance of the proposed scheme.* © *2004 SPIE and IS&T.*

[DOI: 10.1117/1.1762891]

1 Introduction

Forward error correction (FEC) and automatic repeat request (ARQ) retransmission are two common technologies to combat transmission errors. However, they introduce either a large redundancy or a large delay that makes them inappropriate for applications where limited bandwidth and/or real-time processing are concerned. Moreover, an error-free transmission is hard to secure in wireless communications. This is because wireless channels are always time varying and hence the channel errors may not be completely removed even though a low channel code rate is provided. One good feature in image transmission is that even when a certain number of bits are in error, the quality of the reconstructed image at the receiver may still be acceptable, although with some degradation. Therefore, one key technique in image coding and transmission is the enhancement of the error resilience capability of the coded data so that the image degradation can be reduced to the least when residual channel errors exist. In addition, because an image generally has strong correlation in both the spatial domain and the frequency domain (especially in the lowest frequency subband), error concealment is also an important technique that can reduce the impact of the residual errors.

To achieve the highest possible compression efficiency, the variable-length coding (VLC) based on entropy reduction and structure dependency is widely adopted in all successful image coding algorithms, such as the embedded zerotree coding[1] (EZW) and the set partitioning in hierarchical trees[2] (SPIHT). While being able to achieve much higher coding efficiency compared with schemes based on fixed-length coding (FLC), VLC-based schemes are very sensitive to channel errors. Furthermore, this kind of sensitivity in bit level cannot be precisely formulated in a rate-distortion function. When the channel coding fails to perform to the expectation, which is often encountered in time-varying wireless channels, the strong sequential dependency in a VLC-coded bit stream may cause the decoder to discard all the subsequent bits once a single bit error occurs.[3]

Therefore, the localization of error propagation is a key issue to improve the error resilience. Splitting a long single VLC-coded bit stream into multiple independent bit streams is often used so that the decoding dependency and thus the error propagation can be limited within each bit

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Paper 03079 received Jun. 2, 2003; revised manuscript received Oct. 24, 2004; accepted for publication Jan. 27, 2004.
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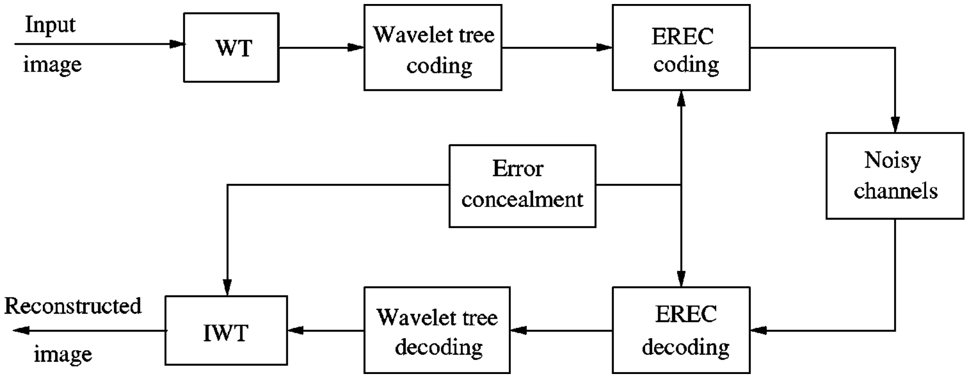

Fig. 1 System diagram.

stream. Multiple description coding[4,5] (MDC) is a potential candidate with the idea that reconstructed image with any one description (bit stream) is acceptable, and an incremental improvement will be achieved while more descriptions are received. However, to guarantee an acceptable quality with a single description, a large redundancy is required among those descriptions, which significantly reduces the source coding efficiency. In Ref. 6, Creusere proposed two methods (offset zerotree and zerotree preserving) to partition the wavelet coefficients and encode them separately using EZW[1] with and without overlapping redundancy among bit streams, respectively. The source coding efficiency is hence improved. In addition, more bits at the receiver can be used for the final image reconstruction in a noisy environment. It was shown[7] that using four bit streams, approximately double number of bits can be obtained for image decoding compared with using only one bit stream.

The approach in Ref. 6, however, does not consider the transmission realization. If all those variable-length bit streams are multiplexed and transmitted sequentially over a channel, channel errors may cause error propagation across multiple bit streams even though certain stop symbols are used for each bit stream.[8] Roger and Cosman[9] proposed to packet a number of wavelet trees into a single packet for transmission over a packet erasure environment. The completely lost trees will be compensated by a postprocessing method. This scheme, however, is not applicable for channels with random errors, because one single error in a packet may destroy a number of wavelet trees as well. To enhance the error resilience capability in discreet cosine transform (DCT) block-based image coding and sequential transmission, Redmill and Kingsbury[8] proposed an elegant scheme known as error resilient entropy coding (EREC). The idea of EREC is to regroup the variable-length data blocks into fixed-length slots so that resynchronization can be obtained naturally at the receiver. Both Huffman coding and arithmetic coding of the DCT coefficients have been examined[10] and yielded comparable results. A method combining EREC and zerotree coding has also been proposed in Ref. 11.

In this paper, we propose a scheme that integrates the wavelet tree-based image coding, EREC, and a new error concealment technique together to improve the robustness for image coding and transmission. The work of wavelet tree coding and EREC is similar to that in Ref. 11, but with more discussions in the relationship between wavelet trees and their spatial representation, SPIHT bit stream reorganization, and the benefit of bit-layer-based SPIHT in EREC, etc. Furthermore, we integrate this scheme with a new error concealment technique that considers the important role of the first a few bytes in each bit stream. With this error concealment, not only is the EREC decoding complexity reduced in the error environment, but the quality of reconstructed images is also significantly improved.

The rest of the paper is organized as follows. Section 2 discusses the proposed scheme in detail, which includes wavelet tree coding, EREC, and error concealment. Section 3 reports the experimental results. Finally, Sec. 4 concludes the paper.

2 System Description

The whole system is described in Fig. 1. First, input image is hierarchically decomposed by wavelet transform (WT). The spatial orientation tree structure[2] is adopted to achieve a better source coding efficiency compared with using the tree structure in Ref. 6. The SPIHT algorithm is employed to code each wavelet tree so that independent multiple bit streams are generated. Since the self-similarity in the coefficients across subbands is preserved, a high source coding efficiency is also obtained. Before the encoded images are transmitted over noisy channels, EREC is employed to reorganize these encoded variable-length bit streams into fixed-length slots so that the beginning of each block can be automatically determined at the receiver. Because the error propagation in EREC decoding impacts bits at the end of bit streams more than those in the beginning, the fact that SPIHT coded bit streams have the most important bits in the beginning results in less distortion in an error environment. To enable an error concealment process at the receiver, a small number of parity bits are added after the EREC encoding. From the parity detection results, the EREC decoding will be constrained to reduce both error impact and complexity. In addition, the ‘‘badly’’ decoded wavelet coefficients can be compensated from their ‘‘good’’ neighbors. Finally the reconstructed image is obtained through the inverse wavelet transformation (IWT).

2.1 *Multiple Wavelet Tree Coding*

After the hierarchical wavelet decomposition, there is a direct relationship between the wavelet coefficients and what

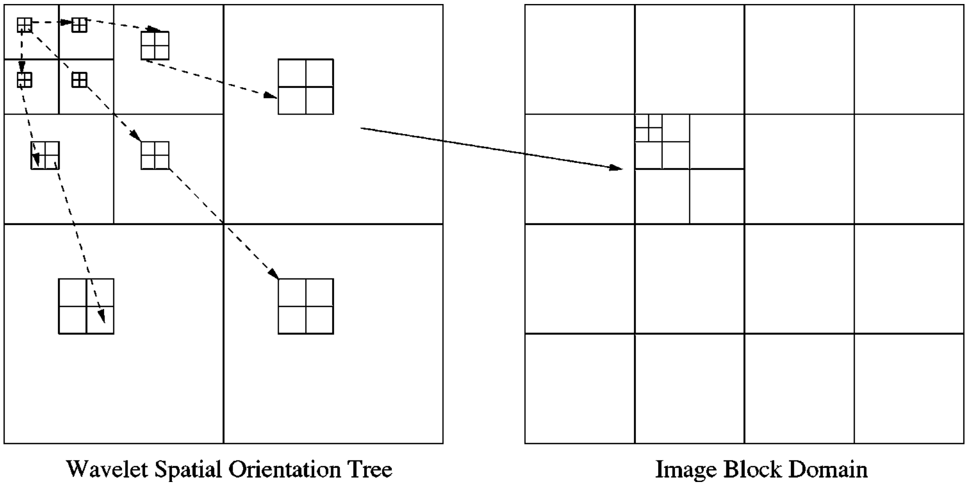

Fig. 2 Wavelet tree corresponds to an image block in the image domain.

they represent in the image content.[12] Figure 2, left, is the spatial orientation tree structure proposed by Said and Pearlman.[2] This wavelet tree is rooted at the lowest frequency subband. Each node in the tree has either no descendants or four offspring grouped in 2×2 adjacent coefficients. If all coefficients in the tree are grouped together, they constitute a square block of data, as shown on the right of Fig. 2. These data are the frequency components for a specific image area with the same block size at the corresponding position. As a result, one tree corresponds solely to one image block. Furthermore, in each tree, if one node is insignificant (i.e., less than) with respect to a given threshold, all of its offspring will be insignificant with respect to the same threshold with a very high probability. This is the well-known property of self-similarity in insignificance across different wavelet frequency subbands.

The SPIHT algorithm[2] is employed to encode each wavelet tree independently. This algorithm processes the coefficients by magnitude, and has the same subset partitioning algorithm in both encoder and decoder. Specifically, the coding is conducted for each bitlayer, from the highest to the lowest. It can achieve a completely embedded bit stream in which the more important bits in terms of mean square error (MSE) reduction occur earlier. Since the self-similarity property in each wavelet tree is intact, a very high source coding efficiency can be achieved. For SPIHT without arithmetic coding, this self-similarity is the only resource that can be exploited by the algorithm. As a result, coding wavelet trees independently will not suffer any loss in bit budget or peak SNR (PSNR) compared with coding the whole image using a single SPIHT without arithmetic coding. Therefore, the multiple wavelet tree coding discussed here can be regarded as a reorganization process that transfers the single bit stream, coded using SPIHT over the whole image, into multiple segments without the loss of coding efficiency. As shown in Fig. 4 in Sec. 2.2 each segment may have different length and corresponds to a single wavelet tree and thus a single spatial block in the original image. Accordingly, this scheme can also be regarded as a block-based coding scheme.

2.2 *EREC and Characteristics*

After the preceding block-based wavelet tree coding, we apply EREC to obtain an error-resilient transmission. EREC was originally proposed by Redmill and Kingsbury[8] to handle the sequential transmission of DCT coded data blocks over noisy channels. For DCT-based block image coding schemes such as JPEG, H.263, etc., the number of the coded binary bits in one block is generally different from those of other blocks. If these variable-length data blocks are multiplexed sequentially for transmission, channel errors may corrupt the boundary information between blocks and hence cause a catastrophic decoding of the image. The key idea of the EREC is to reorganize the variable-length data blocks into fixed-length slots with negligibly increased data size.[8] Data in the blocks are allocated to the corresponding slots, starting from the beginning of each block. Blocks with sizes larger than the slot size are chopped and the remaining data are appended onto other slots that still have available space according to a predefined offset sequence. Figure 3 shows the process of

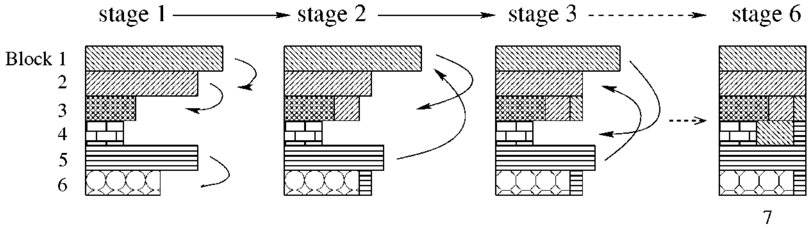

Fig. 3 EREC reorganization process.

EREC reorganization according to an offset sequence {1,2,3,4,5,6}. A number of steps up to the total number of blocks (six in Fig. 3) may be required to complete the reorganization. Therefore, EREC for a larger number of blocks may have a higher complexity in coding and decoding. With EREC, the start of each block can be automatically determined at the receiver as the start of each fixed-length slot. Without channel errors, the decoder can follow the same algorithm to recover all the variable-length blocks using the same offset sequence. It is further shown in Ref. 11 that when slots are divided into two consecutive groups and each slot in the second group has one more bit than each slot in the first group, no additional data are required to implement EREC coding and decoding. A fast EREC method has also been proposed[13] by setting a specific value for the first element in the offset sequence followed with a bidirectional searching method for mapping between slots and blocks. Efficiency of this method, however, generally varies with the specific source data. Therefore, we adopt the pseudorandom offset sequence in our research.

It has been shown[8] that when channel error occurs, the error propagation in EREC decoding impacts data close to the end of each block more likely than data close to the beginning of each block. This characteristic of EREC decoding suggests the advantage to encode more important information earlier in each block. For DCT-based and zigzag scan image coding schemes where coefficients are encoded from the lowest frequency to the highest frequency, the error effect generally impacts the high-frequency information. Our proposed scheme, however, unlike the DCT-based schemes, has even stronger sequential importance in terms of signal energy because the SPIHT encodes the wavelet coefficients from the highest bit layer to the lowest bit layer. When the uniform threshold quantization is applied to a range of $[-Q/2,Q/2]$ with n bits, the MSE of the quantization is

$$\mathrm{MSE}=\frac{1}{12}\left(\frac{Q}{2^n}\right)^2. \tag{1}$$

As expressed by Ruf and Modestino,[14] the magnitude sensitivity for the j'th bit layer is

$$\epsilon_j=\left(2^j\frac{Q}{2^n}\right)^2,\quad j=1,\ldots,n-1. \tag{2}$$

Therefore, except for the sign bits, bits in the j'th bit layer contribute twice in terms of magnitude as bits in the $(j-1)$'th bit layer. Hence the distortion energy caused by the j'th bit-layer is four times that of $(j-1)$'th bit layer. An error in the n'th bit layer, i.e., the sign bit, causes even higher distortion energy that is the summation of the energy resulting from bits in all the lower bit layers. Apparently, such decreasing of bit importance along the bit stream fits very well with the characteristic of EREC. In the case of noisy channels, the error propagation will be more likely to damage the lower bit layers, which generally contribute less to the distortion energy.

We can summarize the basic idea of using wavelet tree coding and EREC in the proposed scheme from the point of view of data reorganization shown in Fig. 4. A long and single bit stream originally coded by SPIHT without arithmetic coding is very sensitive to channel errors. Therefore, we first use wavelet tree coding to reorganize the data into multiple independent short bit streams, but with the same total size and coding efficiency. We then apply EREC to further reorganize the bit streams into fixed-length slots so that synchronization of the beginning of each bit stream can be automatically obtained at the receiver.

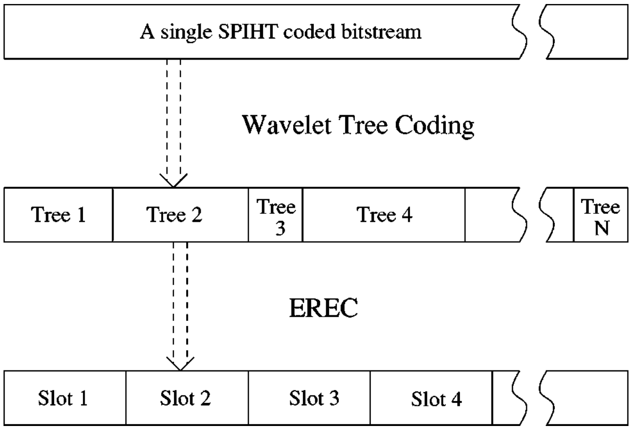

Fig. 4 Same content in different representation (without arithmetic coding). The results are fixed-length slots for error-resilient transmission.

2.3 *Error Concealment*

The SPIHT algorithm generates progressive data. As a result, an error at the beginning of each bit stream may cause a catastrophic decoding because of its high distortion for pixel amplitude, as well as its potential to deviate the following decoding path based on the set partitioning rules. Thus, SPIHT decoding of each bit stream in an error environment may stop much earlier or later than it should. This fact also corrupts EREC decoding because EREC decoding requires the SPIHT decoding to stop at a predefined position. This position, for example, can be a stop symbol or a certain bit layer. To alleviate the strong impact of errors in the first a few bytes in each bit stream, we propose an error-concealment technique that can both constrain the EREC decoding and compensate the ‘‘bad’’ wavelet coefficients with their ‘‘good’’ neighbors in the lowest frequency subband.

First, after EREC encoding, we add one parity bit for the first several L bytes ($L=4$ is used in the simulation) in each data slot, i.e., the first $8L$ bits will have one more bit for the detection of the odd number of errors. As such, the total extra load due to the parity detection will be N bits, where N denotes the total number of blocks. This load is very small in terms of bit per pixel. Note that channel errors assumed in the research are sparse and random. This is because we assume that forward error correction (FEC) codes have been applied in severe channel conditions. Error-resilient techniques are appropriate only to handle the impact of a small number of residual errors that have not been removed by FEC codes. It is also assumed that burst errors have been handled by techniques such as interleaving. The detection results of these parity bits will be exploited in both EREC decoding and postprocessing of wavelet coefficients.

EREC decoding actually depends on the SPIHT decoding to determine the stop position of each bit stream. For example, if the SPIHT decoding of one slot of data has not met the stop point (such as a stop symbol or the bit layer used in simulation), this slot is deemed to be a part of the bit stream. Otherwise, the slot consists of a complete bit stream and data from some other bit streams. When errors in one bit stream cause the SPIHT decoding to stop in a wrong position, EREC decoding from fixed-length slots to variable-length blocks (an inverse procedure in Fig. 3) are impaired by losing the correct mapping between slots and blocks. Consequently, data from several different bit streams might be misregarded as data of one bit stream. Therefore, in our error concealment, when one slot is detected to have bit errors at the beginning, this slot will not be used again after the first step of EREC decoding. Moreover, all its corresponding blocks (bit streams) determined by the offset sequence will not accept data from other slots after the first step of EREC decoding. With this approach, the bad decoding of EREC that may result in unreasonably long or short bit streams will be avoided. In addition, a fast EREC decoding is also achieved because a smaller number of reorganization steps from slots to blocks are carried out with this constrained process.

After the EREC decoding stops, the final SPIHT decoding of each bit stream will be conducted. An inherent property of the SPIHT algorithm is that it knows at which bit layer the decoding stops. Suppose all the wavelet coefficients are in the range of $[-2^{n-1},2^{n-1}]$, where the n'th bit represents the sign of the magnitude. If decoding of one bit stream stops at bit layer $k\leqslant(n-1)$, we know the decoded value, $\hat{x}$, of any wavelet coefficient within the wavelet tree contains all the information between bit layers $n-1$ and $k+1$, and some information at bit layer k, but no information at all of the bit layers less than k. Therefore, the actual value x of any coefficient from this bit stream can be represented by

$$x=\hat{x}+\varepsilon,\quad \hat{x}\in[2^{k-1}+u,\ 2^{n-1}]\ \text{or}$$

$$[-2^{n-1},\ -2^{k-1}-u],\ \ \varepsilon\in(-2^{k-1}-u,\ 2^{k-1}+u), \tag{3}$$

where u is determined by the exact position in bit layer k where SPIHT decoding stops, and $\hat{x}$ and ε are the known and unknown parts of the coefficient x. We denote the range of ε as the uncertainty range. Because each bit stream actually corresponds to a specific block in the image, the idea of error concealment here is that we can use the surrounding blocks whose coefficients have smaller uncertainty ranges to compensate the block whose coefficients have a larger uncertainty range. The concealment process is carried out in the wavelet domain. Tanabe and Farvardin[15] have shown that wavelet coefficients in the lowest frequency subband have similar spatial correlation with that of the original image, but little gain can be expected by exploiting the interpixel redundancy in the high-frequency subbands. Therefore, our error concealment for wavelet coefficients is only conducted in the lowest frequency subband. One wavelet tree in SPIHT has four coefficients in the lowest frequency subband. For a data block with error detected in the first L bytes, each coefficient of the four will be replaced by the average of its neighboring coefficients whose bit streams have not been detected errors in the first L bytes. In addition, to conceal the error propagation to the high-frequency subbands, we set the high-frequency coefficients equal to zero for those bit streams that have been corrupted in the beginning.

Table 1 Source efficiency of five- scale SPIHT and three-scale wavelet tree coding.

	Stop Layer=4	Stop Layer=3	Stop Layer=2
Bits/pixel	0.271	0.465	0.864
Original SPIHT	34.040	36.521	39.296
Wavelet tree	32.58	35.67	38.86

3 Experiments

The SPIHT without arithmetic coding is applied in the experiment. As indicated in Ref. 2, images reconstructed using SPIHT with arithmetic coding have only marginal improvement in PSNR over images coded without arithmetic coding. A random offset sequence is adopted for the EREC operation. In the decoding of EREC, it is required that the EREC can find the end of each block in the absence of channel errors. In our experiment, we obtain this self-termination by specifying the same stop bit layer for the source encoding and decoding of each wavelet tree. It is also possible to add a stop symbol together with the arithmetic coding to terminate the encoding and decoding process, which will result in a small PSNR improvement but with more complicated arithmetic coding. In the experiment, we use 2, 3, and 4 as the values of the stop layer, to test the performance with different bit rates. WT with three scales was applied to the ''Lena'' 512×512 image with 8 bits/pixel (bpp). Therefore, 1024 wavelet trees were constructed. Then 1024 parity bits were added for the error concealment, which resulted in 0.004 bpp extra load. The total bit rates are 0.271, 0.465, and 0.864 bpp, respectively, for each stop layer. The source coding efficiency is still very high due to the intact of the self-similarity property in each wavelet tree. However, compared with the original SPIHT for the entire image with five-scale WT, the coding efficiency was decreased to generate multiple bitstreams to increase the error resilience capability. Table 1 shows the comparison in PSNR between the original SPIHT algorithm and the wavelet tree coding. Nevertheless, the performance of the wavelet tree coding is still higher than JPEG. For example, the baseline JPEG algorithm obtains 34.75 dB for the same ''Lena'' image at 0.5 bpp, while the wavelet tree coding here provides 35.66 dB at 0.465 bpp.

Figure 5 shows the error-resilient performance of the proposed scheme for the ''Lena'' 512×512 image over the binary symmetric channels (BSCs). Thirty trials were carried out for each channel error condition. The solid lines denote the results without error concealment, while the dotted lines represent results with error concealment. Some features can be observed from the figure. First, without error concealment, when the bit error rate (BER) goes up to

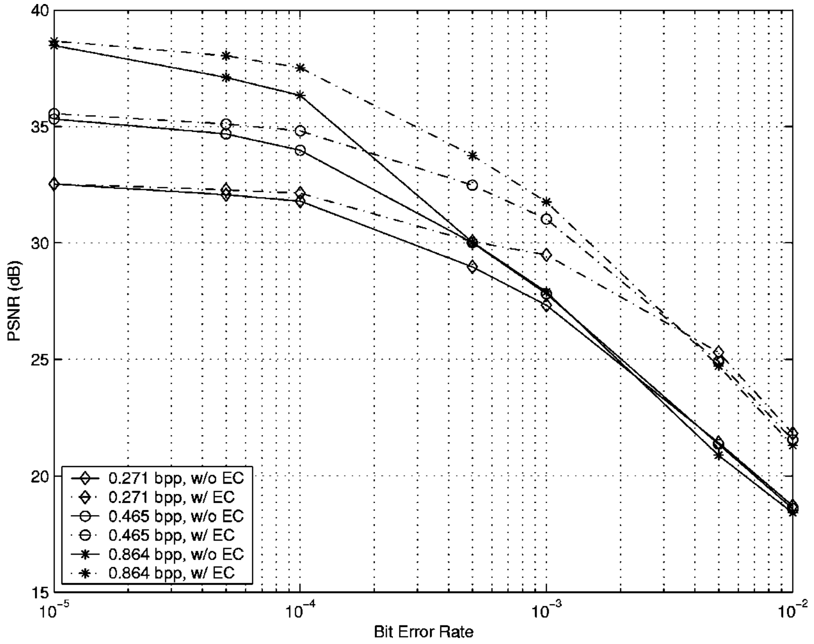

Fig. 5 Image PSNR versus BER with and without error concealment.

10^{-3}, the PSNR performance of the three bit rates converges. When the BER increases beyond this point, the performance decreases dramatically and quickly falls below 20 dB, which presents unacceptable image quality. This is primarily because with more and more bit streams experiencing bit errors in the beginning of bit streams, the quality of reconstructed images will be significantly reduced no matter whether or not the following bits in bit streams are corrupted. As a result, we can consider the point where PSNR performance converges as the transition point from which forward error control codes must be applied to remove most of the channel errors. Error resilience without or with a little redundancy performs well only when a small number of residual errors exist. Second, the improvement of the proposed error concealment technique is significant. The performance with error concealment outperforms the scheme without error concealment in all three bit rates and in all BER conditions, with the highest improvement of 3 to 4 dB. This error concealment technique expedites the EREC decoding as well. In Table 2 "De/En" shows the ratio of the number of EREC decoding steps (with error concealment) to the number of EREC encoding steps. We can find that when the number of errors increases, the error concealment will terminate the EREC decoding with a smaller number of steps.

Table 2 Error concealment for EREC decoding with a total of 1024 blocks.

	0.465 bpp		0.864 bpp	
BER	Average errors	De/En	Average errors	De/En
10^{-5}	1.48	98.2%	2.34	94.4%
5×10^{-5}	6.5	90.9%	11.64	88.2%
10^{-4}	12.64	80.1%	22.88	81.4%
5×10^{-4}	61.94	37.0%	118.44	47.2%
10^{-3}	119.56	29.5%	229.2	38.0%
5×10^{-3}	605.74	11.7%	1156.2	14.2%
10^{-2}	1231.3	8.5%	2287.4	11.2%

We also tested a scheme in which EREC decoding is constrained but the wavelet coefficients are not postprocessed. The PSNR performance was found to be similar to the scheme having no error concealment at all. This is because the difference in the final multiple bit streams generated with and without constraining EREC decoding is at the end of bit streams, which contributes only marginal distortion in image reconstruction. Therefore, the PSNR improvement in image restoration is basically due to the postprocess of wavelet coefficients. However, constraining EREC decoding does speed up the decoding process as shown in Table 2.

The proposed scheme without error concealment is actually same with the "Plain EREC" scheme presented in Ref. 11, except that 1024 trees instead of 256 trees were used in this research. The SPIHT with four scales can be applied for 256 trees, which can slightly improve the source coding efficiency in the error-free condition. However, with a smaller number of independent trees, the error resilience capability is reduced. In Ref. 11, another scheme called "H-EREC (hierarchical EREC)" was also proposed with the goal to localize errors and postprocess the data. However, the usefulness of this method is not clearly justified in terms of their simulation results. In Ref. 11, the H-EREC presents consistently inferior performance to the plain EREC when BER is less than 5×10^{-3}. All improvements of the H-EREC, however, with all final PSNRs below 20 dB, occur under conditions with higher BERs, where FEC should actually be applied.

Results using EREC with DCT-based block coding, Huffman or arithmetic coding, as well as one error concealment technique were reported by Redmill and Bull.[10] A

Fig. 6 Left, the ''Lena'' 512 image, and right, the reconstructed image based on original SPIHT when a single error occurs at the 10,000'th bit. PSNR=22.22 dB.

qualitative comparison with this scheme shows that our scheme outperforms when BER is small (less than around 5×10^{-4}). As BER increases higher, the degradation of our scheme is slightly faster. This is basically attributed to the high error sensitivity of the SPIHT-coded data that considers set partitioning. However, the performance of both schemes drops rapidly to very low PSNRs (<25 dB) so that no acceptable image quality can be provided with either scheme in high-BER cases. Actually, when BER is high, the error-resilient technique alone would not be enough and the FEC codes are generally desired.

Fig. 7 Samples of reconstructed images over BSCs with BERs of 10^{-4},5×10^{-4}, and 10^{-3}, respectively. The stop bit layer is 3. Left column shows images without error concealment and PSNRs of 33.92, 29.57, and 27.81 dB. Right column shows images with error concealment and PSNRs of 34.83, 32.69, and 31.37 dB.

Figure 6 shows the impact of a single bit error on the bit stream coded by the original SPIHT algorithm. On the left is the original ''Lena'' image, and on the right a reconstructed image using the single SPIHT for the whole image at 0.5 bpp is shown. Only one bit error occurred at the 10,000'th bit in the bit stream, and the PSNR of the reconstructed image was 22.22 dB. This corrupted bit is a significant decision bit located in bit layer 3 in the SPIHT algorithm. Since the significant bits generated by the ''sorting pass'' in the SPIHT are the majority of bits compared with the sign and refinement bits, and the highest bit layer is 11 for the ''Lena'' image, an error in a bit layer higher than 3 may result in even worse image quality. Figure 7 shows some samples of the images reconstructed under various error conditions using our proposed scheme at 0.465 bpp. Results without and with the error concealment technique are shown in the left and right columns, respectively. These results show clearly that the blocks with high error impact are eventually smoothed by their neighboring blocks.

4 Conclusion

We proposed a technique integrating the wavelet tree coding, EREC, and an error concealment for robust image transmission. After hierarchical wavelet decomposition, wavelet trees were encoded independently to obtain high source coding efficiency and to localize the error propagation. EREC was then applied to reorganize these variable-length-coded bit streams into fixed-length slots so that synchronization of the start of each block could be automatically obtained. An error-concealment technique was proposed to constrain the EREC decoding and improve image reconstruction using parity detection. Promising error-resilient performance of the proposed scheme was demonstrated by simulations.

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