ROBUST SIGNIFICANCE-LINKED CONNECTED COMPONENT ANALYSIS FOR LOW COMPLEXITY PROGRESSIVE IMAGE TRANSMISSION OVER NOISY CHANNELS

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ABSTRACT

A highly robust channel coding scheme to be seamlessly integrated into our previously developed high performance wavelet-based significance-linked connected component analysis (SLCCA) image coding technique is proposed. The SLCCA source coding algorithm is slightly modified to enable synchronization after each bit-plane. Thus even after uncorrectable errors, the decoding can be continued at the next refinement level. An unequal error protection scheme is also developed by using Reed-Solomon codes. The proposed scheme outperforms Sherwood and Zeger's technique by 0.66 dB on average for the "Lena" image in peak signal-to-noise ratio. Furthermore, the proposed codec has very low computational complexity well applicable for the power constrained mobile scenario.

1. INTRODUCTION

The recent success of wavelet image coding is attributed to innovative data organization and representation strategies. There have been several such high performance image codecs developed. Shapiro's embedded zerotree wavelet (EZW) [1] and Said and Pearlman's set partitioning in hierarchical trees (SPIHT) [2] use the regular tree structure and the set-partitioned tree structure to approximate *insignificant* wavelet coefficients across subbands, respectively. Servetto *et al.*'s morphological representation of wavelet data (MRWD) [3] finds irregular-shaped clusters of *significant* coefficients within subbands. Chai *et al.*'s significance-linked connected component analysis (SLCCA) [4, 5, 6, 7] exploits both the within-subband clustering of significant coefficients and cross-scale dependency in significant fields rendering the best performance among the above mentioned high performance wavelet image codecs.

Image codecs utilizing advanced data organization and representation strategies face severe error resilience problem when the source bitstream is transmitted over noisy channels. First, they all use variable length coding, which may result in the loss of synchronization between the encoder and decoder even in the case of a single bit error in the bitstream. Second, to reach high coding efficiency, the pixel dependency (across scales and/or neighboring pixels) must be maximally exploited, i.e., in all the codecs, the location of significant coefficients is recursively specified by the so-called *significance map*. Thus even a single error in the significance map may render the rest of the bitstream unusable.

The rest of the paper is organized as follows. Section 2 overviews related work in robust image coding for noisy channels. The proposed error correction scheme is presented in Section 3. Performance evaluation is given in Section 4 and the last section concludes the paper.

2. RELATED WORK

To maintain high coding performance, in the meantime to reduce the error sensitivity of wavelet codecs, which utilize advanced data organization and representation strategies, several algorithms have been developed providing robustness against transmission errors.

The first class of techniques is built on the source-channel coding theorem, i.e., optimal system design is accomplished by separately optimizing the source and channel coding algorithms. Sherwood and Zeger [8] divide the SPIHT source bitstream into fixed-sized packets and each packet is protected with the same rate-

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compatible punctured convolution code/cyclic redundancy code (RCPC/CRC) irrespective of importance. Later, cross-packet Reed-Solomon (RS) code was also added to combat the effect of fading channels [9]. In the above two techniques, the decoding is terminated after the first *uncorrectable* error is encountered. Thus to obtain high coding performance, the RCPC/CRC (and RS) channel code must be selected for a *given* bit error rate (BER) so that the probability of incomplete decoding due to transmission errors is kept very small (below 0.01 in [8]).

In the second class of algorithms, robustness against transmission errors is obtained by both making the source coding algorithm more error resilient and applying channel coding as well. In addition to modifying the SPIHT source coder, Man *et al.* [10] uses fixed length coding for certain parts of the bitstream. Unequal error protection is implemented by applying RCPC channel code for the dominant pass (significance map) and the subordinate pass (refinement of magnitudes) is not protected at all. For the noiseless case, their proposed algorithm results in 1–2 dB drop in peak-signal-to-noise ratio (PSNR) when compared to the original SPIHT algorithm. Creusere [11] proposes to divide the wavelet coefficients into S groups and each group is independently encoded by the EZW algorithm producing S embedded bitstreams. The disadvantage is clear that the correlation among neighboring pixels cannot be effectively exploited resulting in 3–4 dB loss in PSNR.

As seen from above, modifying the source coding algorithm may result in significant performance loss that cannot be compensated later. The best coding performance is provided by that of Sherwood and Zeger [8], where the source and channel coding algorithms are separately optimized.

3. ROBUST SIGNIFICANCE-LINKED CONNECTED COMPONENT ANALYSIS

This section is divided into two parts. First, we briefly review the SLCCA data organization and representation strategy. More details can be found in [6]. Second, the proposed error protection scheme, which incorporates synchronization and unequal forward error correction, is described.

3.1. SLCCA Data Organization and Representation Strategy

The main components of the SLCCA data organization and representation strategy include

- wavelet decomposition and uniform quantization;
- within-subband clustering of significant wavelet coefficients by using conditioned dilation operation;
- cross-scale significance-link registration;
- adaptive arithmetic coding with scale-space variant high order Markov source modeling.

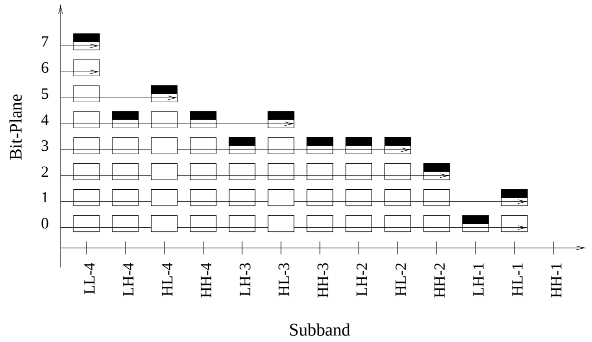

Figure 1: Global bit-plane order transmission. The significance map (represented by black boxes) is transmitted along with the most significant bit-plane in each subband.

After dyadic wavelet decomposition, all the coefficients are quantized with a uniform scalar quantizer. Wavelet coefficients quantized to nonzero are termed *significant* coefficients and zero coefficients are referred as *insignificant* coefficients.

The within-subband clustering property of significant wavelet coefficients [3, 6] is exploited by using conditioned dilation operation. In SLCCA, the conditioned dilation operation is used to recursively construct the *significance map*. The significance map is of the same size as the original image and denotes the significant status of each wavelet coefficient. Starting at a seed position, the conditioned dilation operation recursively segments the wavelet field into clusters of significant coefficients.

Both EZW and SPIHT exploit the cross-scale dependency of wavelet coefficients. However, as opposed to EZW and SPIHT, in SLCCA, the relationship between *significant* wavelet coefficients is exploited. Due to the magnitude decay property of wavelet coefficients [6], the parent coefficient of a significant coefficient is likely to be significant. This can be used to mark the parent coefficient as having a significance-linkage and thus explicit seed information of the child cluster can be avoided, which results in significant bit savings.

After the significance map is transmitted to the decoder, the magnitude of each significant coefficients is to be specified. Magnitudes of significant coefficients are transmitted in *global bit-plane* order as shown in

Fig. 1. For each subband, the significance map is transmitted along with the most significant bit-plane.

3.2. Proposed Error Protection Strategies

In the proposed technique, we only slightly modify the original SLCCA image coding technique by transmitting the size of the source file of each bit-plane and initializing the adaptive arithmetic coder model before the encoding of each bit-plane. This two modifications enable synchronization after uncorrectable transmission errors and result in less than 0.1 dB drop in PSNR.

Although all the four above described channel coding techniques [8, 9, 10, 11] target wavelet codecs utilizing advanced data organization and representation strategies, only Man *et al.*'s makes use of the fact that the bitstream is not of equal importance. The importance of each bit-plane for the "Lena" image coded at 0.5 bits-per-pixel (bpp) is demonstrated in Fig. 2. Along with the size of the source file, the contribution of each bit-plane to the root mean-squared error (RMSE) reduction is also shown. As clearly seen, despite the smaller size, more significant bit-planes carry most information.

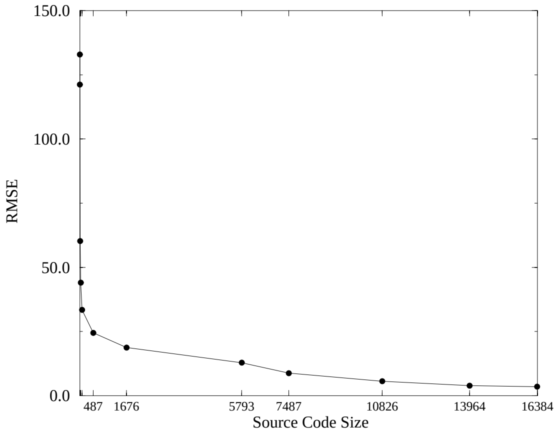

Figure 2: RMSE reduction for the the "Lena" image coded at 0.5 bpp. The "null" image (all pixel values are set to 0) has RMSE = 132.98. The size of the source file of the first five bit-planes are 4 bytes, 6 bytes, 27 bytes, 50 bytes, and 400 bytes. The size of the source file of the rest of the bit-planes are shown in the figure.

In the proposed algorithm, each bit-plane is protected with a different Reed-Solomon code. More significant bit-planes are allocated more parity bits than less significant bit-planes. In the developed system, the total number of parity bits is allocated among bit-planes based on the importance. The importance of the ith bit-plane ($0 \leq i < N$) is defined by

$$\alpha \exp\left(\frac{i-N-1}{\beta}\right),$$

where N is the number of bit-planes and α and β are the code parameters. While the two different sets of parameters used in the experiments are shown in Table 1, the resulting RS codes are given in Table 2. Codec 0 uses equal error protection and serves as our baseline algorithm. In Codec 0, the number of parity bits is decided for a given BER so that all the transmission errors are corrected.

Codec	α	β
Codec I	0.5	2
Codec II	2	3

Table 1: Code parameters used in the experiments.

Bit-Plane	Codec 0	Codec I	Codec II
First Packet	(207,255)	(187,255)	(159,255)
6	(207,255)	(197,255)	(178,255)
5	(207,255)	(202,255)	(191,255)
4	(207,255)	(205,255)	(200,255)
3	(207,255)	(207,255)	(207,255)
2	(207,255)	(208,255)	(211,255)
1	(207,255)	(209,255)	(215,255)
0	(207,255)	(210,255)	(217,255)

Table 2: Applied RS codes for the three codecs designed for BER = 0.005.

The actual transmitted bitstream is divided into packets as shown in Fig. 3. Since we use RS codes over GF(256), the maximal packet size is chosen to be

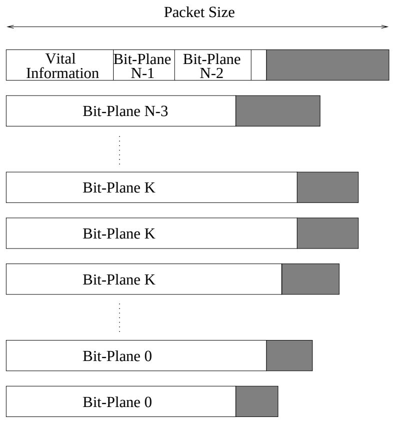

Figure 3: Bitstream packetization with error protection.

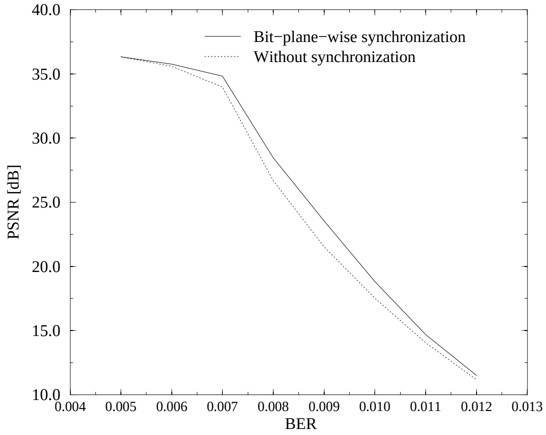

Figure 4: Effectiveness of synchronization for "Lena" image coded at 0.5 bpp.

Algorithm/Rate [bpp]	0.25	0.5	1.0
Noiseless SLCCA	34.28	37.35	40.47
Proposed scheme	33.83	36.94	39.93
Sherwood & Zeger [8]	33.16	36.25	39.34
Man *et al.* [10]	32.59	35.77	–
Tanabe & Farvardin [12]	30.94	33.90	36.71

Table 3: Coding results (PSNR, [dB]) for "Lena" image over BSC with BER = 0.001.

255 bytes. The first packet of each image contains *vital* information, which is necessary for decoding. Vital information includes the image size, number of wavelet scales, and quantizer step size. In addition, it also contains synchronization information, i.e., the number of bit-planes and the size of the source file of each bit-plane. The first few most significant bit-planes are also placed in the first packet as shown in Fig. 3. The rest of the source bitstream is packetized so that each packet only contains information pertaining to a given bit-plane, which is necessary for synchronization.

4. PERFORMANCE EVALUATION

The performance of the proposed error protection scheme is evaluated on the 512 × 512 grayscale test image "Lena" coded at the total bit rate of 0.25 bpp, 0.5 bpp, and 1 bpp. In the performance evaluation, we exclusively use binary symmetric channel (BSC). The reported results are the average of PSNR values over 100 simulations.

First, the effectiveness of synchronization is evaluated applying equal error protection. As seen in Fig. 4, the advantage of synchronization is less significant in relatively low BER and relatively high BER. However, it shows as much as 2 dB improvement in PSNR with an average increase of 1.01 dB.

Algorithm/Rate [bpp]	0.25	0.5	1.0
Noiseless SLCCA	34.28	37.35	40.47
Proposed scheme	32.59	35.60	38.70
Sherwood & Zeger [8]	31.91	34.96	38.03
Man *et al.* [10]	31.52	34.14	–
Tanabe & Farvardin [12]	29.96	32.38	35.44

Table 4: Coding results (PSNR, [dB]) for "Lena" image over BSC with BER = 0.01.

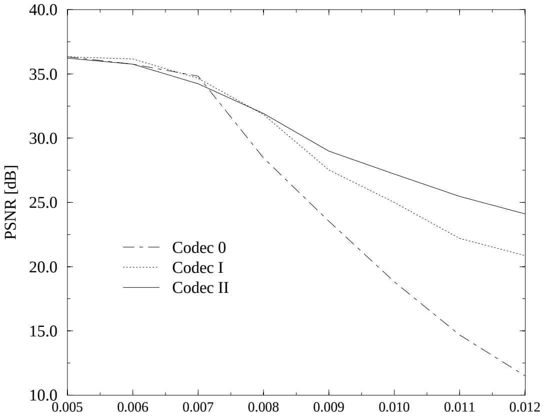

Figure 5: Performance comparison (PSNR, [dB]) of the proposed codecs for the "Lena" image at 0.5 bpp. All the codecs are designed for BER = 0.005.

Average PSNR results for BER = 0.001 and BER = 0.01 are shown in Tables 3 and 4, respectively. When the BER used to design the codecs is equal to the applied BER, all the three codecs show approximately equivalent performance. As seen, the proposed scheme exceeds Sherwood and Zeger's technique by 0.66 dB on average. When compared to the noiseless SLCCA, the proposed scheme results in only 0.47 dB and 1.74 dB drop in PSNR at BER = 0.001 and BER = 0.01, respectively.

The problem with equal error protection lies in that the codec only gives good performance when the BER used in the design is equal to the applied BER. However, this requires accurate knowledge of the channel characteristics, which is rarely the case in a real communication system especially in highly dynamic wireless environments with time-varying channel conditions. The result of applying the codec designed for BER = 0.005 to higher BER is shown in Fig. 5. As seen, Codec

I and II results in 9.36 dB and 12.61 dB PSNR improvement over Codec 0 (equal error protection), when the bit error rate is about two and a half times higher than that is used for the design.

The probability of packets loss (uncorrectable packet error) for Codec II (designed for BER = 0.005) at BER = 0.01 is given in Fig. 6. The received bitstream is never fully decoded. However, as clearly seen in the figure, the first packet containing vital information is always correctly received and the majority of lost packets occurs at less significant bit-planes.

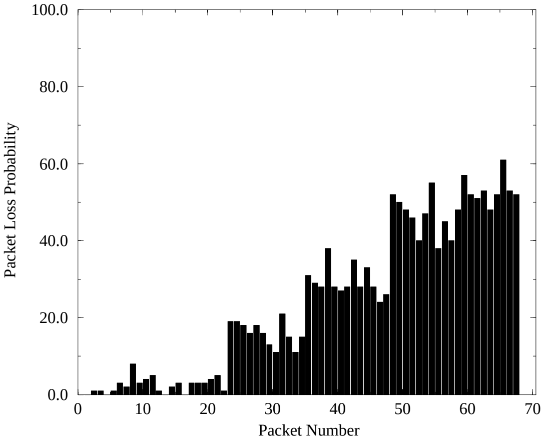

Figure 6: Packet loss probability for the "Lena" image at 0.5 bpp for Codec II with BER = 0.01. Codec II is designed for BER = 0.005.

Finally, the computational complexity of the proposed scheme is compared with Sherwood and Zeger's RCPC/CRC technique at BER = 0.01 running on a 195 MHz R10000 CPU of an SGI Octane workstation. While RCPC/CRC spends 6.02 seconds for decoding, the proposed scheme requires only 0.14 seconds. This low complexity is inevitable in mobile computers in order to achieve low power consumption or for real-time implementation.

5. CONCLUSIONS

In the paper, a highly efficient and low complexity codec utilizing unequal error protection and bit-plane-wise synchronization is proposed for robust image transmission over noisy channels. On average, the proposed scheme outperforms the best known results in the literature by 0.66 dB in PSNR. Further research directions include more efficient parity bit allocation and modification of the proposed scheme to adapt to time-varying wireless channel characteristics.

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