A LOSSLESS MULTI-PARTITIONING SUCCESSIVE ZERO CODER FOR WAVELET-BASED PROGRESSIVE IMAGE TRANSMISSION

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ABSTRACT

This paper proposed an embedded image compression algorithm called Lossless Multi-Partitioning Successive Zero Coder (LMP-SZC) using the integer wavelet transform for progressive image transmission (PIT). By dynamically adjusting the partitions based on the space-frequency domain coefficients, our algorithm can achieve lower complexity and superior coding efficiency as compared with other well-known embedded lossless wavelet-based coder even without the zerotree analysis.

Keywords: LMP-SZC, Lossless wavelet coder, PIT.

1. INTRODUCTION

Conventional transform codec like JPEG [6] scans each coefficient bit-wisely from MSB to LSB through the zig-zag scanning manner in each transformed block. This kind of vertical scanning encodes each coefficient completely before proceeding to the next coefficient in both lossy and lossless mode. Apart from context-based entropy coding in spatial domain, we adopted the ideas of the modified run-length bit-plane coding with the partition priority coding (PPC) in the DCT-based domain [1] and embedded zerotree coding (EZW) [2-5]. Our algorithm is designed with the same goal of CREW [4] and S+P [11], but lower complexity by eliminating the zerotree analysis in EZW (even it can lower the bit-rate in the beginning few significant passes, e.g. SPIHT, LZC). In our proposed LMP-SZC, after significant passes, we adopts a special bit-plane scanning order in the space-frequency domain with successive approximation quantization (SAQ) and multi-partitioning algorithm in refinement passes. With different context models, the resulting size of compressed bitstream can be different even if either the same transform or the scanning order is used.

In the following sections, we will introduce the reversible integer wavelet transform, the multi-partitioning algorithm in the successive approximation quantization, as well as the proper adaptation of context in modeling the first-order entropy of the transformed coefficients. In conjunction with the space-frequency domain, our proposed low-complexity LMP-SZC shows superior results, even without the zerotree analysis, over other state-of-the-art lossless coders [10] with or without embedded property.

2. REVERSIBLE INTEGER WAVELET TRANSFORM

Wavelet transforms have been successfully adopted in the field of image coding with the unprecedented performance in both lossy and lossless image coding, for progressive image transmission. However, the common wavelet transforms often result in floating point coefficients. Lossless coding cannot be achieved from the non-integral transformed coefficients. Thus, integer transform is required in lossless coding.

We denote the original intensity of image as $s_{0,k}$, the lowpass and highpass coefficients as $s_{1,k}$ and $d_{1,k}$ respectively after wavelet decomposition. For the transform being reversible, it must recover the original $s_{0,k}$ from $s_{1,k}$ and $d_{1,k}$. The modified Haar transform or the S transform is formulated as shown in (1). Most of the reversible integer wavelet transform may be obtained from these 2 equations using lifting scheme [7-9].

$$\begin{aligned} d_{1,k} &= s_{0,2k+1} - s_{0,2k} \\ s_{1,k} &= s_{0,2k} + \left\lfloor d_{1,k}/2 \right\rfloor. \end{aligned} \quad (1)$$

In this paper, the S+P transform with (2, 2) vanishing moment shown in equation (2) are used throughout the coder.

$$\begin{aligned} d_{1,k}^{(1)} &= s_{0,2k+1} - s_{0,2k} \\ s_{1,k} &= s_{0,2k} + \left\lfloor d_{1,k}^{(1)}/2 \right\rfloor \\ d_{1,k} &= d_{1,k}^{(1)} - \left\lfloor \sum_{i=-1}^{1} \alpha_i \Delta s_{1,k+i} - \beta_1 d_{1,k+1}^{(1)} \right\rfloor, \end{aligned} \quad (2)$$

where $\Delta s_{j,k+i} = s_{j,k+i-1} - s_{j,k+i}$, $\alpha_{-1} = 0$, $\alpha_0 = 2/8$, $\alpha_1 = 3/8$ and $\beta_1 = -2/8$; $\lfloor \bullet \rfloor$ is download truncation operation.

2-D wavelet transform is achieved by applying the above 1-D transform sequentially to the rows and columns. Perfect reconstruction is simply the backward running of the forward transform.

3. MULTI-PARTITIONING FOR SAQ

Applying the 2-D integer wavelet transform to a 2-D image, a space-frequency plane as shown in Figure 2 can be obtained. Lossless Multi-Partitioning Successive Zero Coder (LMP-SZC) algorithm scans the subbands from coarsest to finest subband in a Z-scan manner. We use the lower bound of each partition as the flow-control parameter to handle the order-by-magnitude behavior during scanning the coefficients in both bit-by-bit and coefficient-by-coefficient manners. The successive approximation quantization (SAQ) will then be applied to the coefficients which are classified as significant with respect to the current threshold.

However, as the binary representation of the transformed coefficients is randomly distributed, the number of symbols increase with the region of bits of interest. Thus, we introduce a novel multi-partitioning (MP) algorithm for the SAQ process during the refinement subordinate pass. This multi-partitioning algorithm is dynamically adjusted based on the trunks of 1's and 0's during refinement.

Figure 3 shows one of the subband coefficients with their 9-bit magnitudes in descending order. At threshold = 256, coefficient with magnitude greater than this threshold will give out a significant symbol as well as its corresponding sign. Instead of vertically scanning the whole residue in the binary representation of the integral coefficients, we firstly send out the consecutive trunk of 1's, if any. Then the consecutive trunk of 0's follows, if any. Finally an escape symbol of next '1' follows, if any. Otherwise, it may be no bit left for the second multi-partitioning refinement passes. At threshold = 2, we can see that all coefficients are almost refined. Such kind of dynamic multi-partitioning algorithm gains lower bit rate than that obtained by directly coding the whole residue bits since it maintains the larger possibility of preserving the order-by-magnitude feature. The consecutive occurrence of the same symbols achieves higher coding efficiency, dynamically depending on the distribution of imagery, especially for natural images. In addition, our multi-partitioning algorithm can be initiated by either trunk of 1's (1s-0s-1) or trunk of 0's (0s-1s-0) once significant coefficients detected. As the ultimate probability distribution is almost the same in lossless coding, LMP-SZC may have superior performance in embedded bit-stream if 0s-1s-0 is applied, depending on the binary pattern of the transformed coefficients.

The basic idea of the multi-partitioning successive zero coder is to generalize both the MTWC from Wang *et al.* [13] and PPC from Huang *et al.* [1]. PPC divides the coefficient magnitude into several variable-sized partitions successively. Each partition may be restricted from 2^{N-1} to 2^N in the P_N partition such that $\{P_0, P_1, P_2, P_3, \dots, P_N\}$ represents the possible range of coefficients. As shown in Figure 3, with $N = 8$, $\{P_0=\{511, \dots, 256\}, P_1=\{255, \dots, 128\}, P_2=\{127, \dots, 64\}, \dots, P_8=\{1,0\}\}$ forms a disjoint and nonempty space varied halved from one partition to the next.

For each significant pass, i.e. $C_{i,j} \in P_c$, $C_{i,j}$ is coded as significant in current pass, its sign bit is encoded and its residue is refined immediately until block of 1s-0s-1, i.e. $r_{i,j} = [Ci_j - \text{LowerBound}(P_c)]$ and $r_{i,j} \in \cup_{i=c-1}^{c-k} P_i \notin \cup_{i=c-k-1}^{c-m} P_i \in P_{c-m-1}$. The coefficient $C_{i,j}$ encoded in current pass by partition P_c will be diminished as multi-partitioning refinement proceeds and never be encoded again.

The LMP-SZC algorithm is summarized as follows:

1. *Initialization:* Find out the maximum absolute value C_{max} for the set of coefficients $C_{i,j}$, Set $Layer = \log_2(C_{max})$, $bit\_left_{i,j} = 0$ and lower partition bound as the threshold $T_k=2^{Layer}=0x01<<Layer$, where $Layer+1$ bits are used to represent the largest possible range of magnitude of the coefficients.

2. *Signified Refinement:*
   If $bit\_left_{i,j} = \log_2(T_k<<1)$ and $C_{i,j} \geq T_k$, $T=T_k$. do:
   (i) Loop if $C_{i,j} \geq T$ and $bit\_left_{i,j}>0$ do:
   Output '1' and set $C_{i,j} = C_{i,j} - T$,
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.
   (ii) Loop if $C_{i,j} < T$ and $bit\_left_{i,j}>0$ do:
   Output '0'.
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.
   (iii) if $C_{i,j} \geq T$ and $bit\_left_{i,j}>0$ do:
   Output '1' and set $C_{i,j} = C_{i,j} - T$,
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.

3. *Significant Pass:*
   If $T_k > 0$, for each coefficient $C_{i,j}$ do:
   If $|C_{i,j}|<T_k$ and $bit\_left_{i,j} = 0$ do:
   Output '0'.
   If $T_k \leq |C_{i,j}|<2T_k$ and $bit\_left_{i,j} = 0$ do:
   (a) Output '1', $bit\_left_{i,j}=\log_2(T_k)$.
   (b) Output sign symbol 'S'.
   (c) Set $C_{i,j} = |C_{i,j}| - T_k$, $T= T_k>>1$,
   (d) If $bit\_left_{i,j} >0$, do: (*First-time Refinement*)
   (i) Loop if $C_{i,j} \geq T$ and $bit\_left_{i,j}>0$ do:
   Output '1' and set $C_{i,j} = C_{i,j} - T$,
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.
   (ii) Loop if $C_{i,j} < T$ and $bit\_left_{i,j}>0$ do:
   Output '0'.
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.
   (iii) if $C_{i,j} \geq T$ and $bit\_left_{i,j}>0$ do:
   Output '1' and set $C_{i,j} = C_{i,j} - T$,
   Set $T=T>>1$ and $bit\_left_{i,j}$ --.

4. Set $k=k+1$ and $T_k=T_{k-1}>>1$.

5. If $T_k > 0$, then go to Step 2.

Note: In-place recursive refinement; No Zerotree root analysis.

4. CONTEXT MODELS USED IN LMP-SZC

The purely context modeling on image spatial domain like Wu (CALIC) [14], Weinberger *et al.* (LOCO-I) [15] and Golchin *et al.* [16] eliminates the computation overhead in (multi-resolution) decomposition, and can achieve nearly or even better results in lossless/nearly lossless coding than that of the transform coding. We can see that the proper adaptation of context modeling is essential to achieve better image coding, in either domain.

LMP-SZC starts with scanning the coarsest subband, which is with both parent and children absent, and then applies Z-scanning from coarse to fine across scale. We then adopt the conventional parent-and-children relationship, different from Egger *et al.*[12], for context modeling. In addition, the Z-scanning manner assumes that the magnitudes of coefficients tend to decay with frequency so that our context modeling technique can base on these 2 fundamental locating of the context.

As mentioned in Section 3, there are 3 parts using different context models in the LMP-SZC. When a coefficient with magnitude greater than the current threshold, as shown in Figure 4, it will firstly take up a symbol '1' or '0' for notifying the significant under a significant-context model. The by-product of a significant symbol 'S' will then be coded using a sign-context model. After the significant pass, the multi-partitioning algorithm follows. Whatever which type of trunk in residue 'r', either 0's or 1's, a 2-dimensional context model will be used to the context. Therefore, there will be 3 types of modeling technique involved in at the end of the SAQ+MP, prior to the adaptive entropy coder (huffman or arithmetic).

Below are the 3 kinds of models used in our proposed algorithm in which the sign/significant (SS) information are used for modeling the context.

(a) Significant-Context Modeling, 39 Models.

In Figure 5, the significant information of x is being arithmetic coded conditioned on the local variance of the adjacent coefficients' SS information. Since human visual system (HVS) is sensitive to horizontal and vertical information, we add the horizontal and vertical SS values, and both the difference of the diagonals.

i.e. $$m = (a+b+c+d) + |f-h| + |g-e|$$
$$\text{if } p \text{ exists, then } m = m + 13p. \quad (3)$$

(b) Sign-Context Modeling, maximum 16 Models.

Since sign information are essential in addition to magnitude of the real coefficients and directly affect both the PSNR and human perception on reconstructed images, the sign information of x, as shown in Figure 6, is coded only conditioned the four sensible neighborhoods to our HVS. Firstly, by selecting the most recent neighborhoods, vertically and then horizontally, to have a higher weighting. Secondly, using the MS-VLI representation [11] to make the maximum of models under control.

$$m = 1 + MS(a2^6 + b2^4 + c2^2 + d) \qquad (4)$$

(c) 2-D Multi-Partitioning-Context Modeling, maximum 9×Layer Models.

In order to provide the proper model during refinement, the local variance as well as the parental local variance, if any, were exploited. The models used in refinement is a 2-dimensional structure (*9*, *Layer*) conditioned as shown in Figure 7. Firstly, we get the minimum value of the mean of parental SS information, if any. Then, the model for the selected model at this layer of $bit\_left_{i,j}$ is selected. Therefore, 2 types of starting position can be selected for the coefficients which is signified for further refinement. One always starts at (*m*, *0*). The other one starts at (*m*, $maxbit_{i,j}$-$bit\_left_{i,j}$). Experiment shows the former one achieve better results. (*Layer* is the maximum number of bits used to represent for the largest symbols.)

$$m = \frac{1}{8}\sum_{\substack{i,j=-1 \\ i \neq j}}^{1} a_i$$

if p exists,

$$\text{then } m = 3\min(2, \frac{1}{2}\sum_{i=1}^{2} p_i) + \min(2, m) \qquad (5)$$

P.S. All models used to conditionally code the context adjacent to and parental of *x* can take up the advantages of non-causal SS information, unlike using the coefficients or pixels themselves. Thus, it may be also a factor of getting high coding efficiency for the similar manipulation of lifting mechanism in wavelet transform.

5. EXPERIERMENT RESULTS

Three types of imagery are selected for comparison purposes. They are two JPEG-2000 testing images (seismic and target), five 8-bit natural images of size 512×512 and three medical images of 3 different sizes used for comparison in lossless coding performance. From Table 1 and 2, it is shown that our proposed LMP-SZC achieves better lossless compression performance than that of the S+P [11]*, CREW [4] , EZL [12], LJPEG [6] and the coders tested in [10] for the 3 kinds of testing images.

CoDec	LMP-SZC	S+P*	CREW	EZL	LJPEG
Barbara	4.67	---	---	---	5.67
Lax	5.78	---	5.97	---	6.02
Lena	4.17	4.19	4.35	4.43	4.70
Man	4.54	---	4.73	---	4.88
Woman1	4.68	---	4.82	---	5.06
Seismic	2.85	---	---	---	3.09
Target	2.75	---	---	---	3.09

Table 1. Compression performance of the proposed LMP-SZC with S+P, CREW, EZL and LJPEG on natural images (512×512).

Compared with other embedded lossless coder S+P, our proposed algorithm can achieve a better lossless coding result as shown in Table 1. The lossy performance, however, may be slightly interior due to the trade-off with the lossless results. For example, S+P* gives about 35.6dB at 0.4bpp while LMP-SZC gives 31.14dB at 0.4bpp. We chose to sacrifice lossy performance to lossless one because, in many applications like medical image database, lossy decoding is mainly used for data searching and thus the lossy performance is not as important as the lossless performance.

CoDec	LMP-SZC	Denecker *et al.*.	LJPEG
Mammogram 1024×1024	1.11	---	1.91
Angio-chest 512×512	2.76	3.23	3.49
MR-chest 256×256	4.50	4.71	5.12

Table 2. Compression performance of the proposed coder LMP-SZC with LJPEG and the coders tested in [10] on medical images.

***Note,** Method 3 in Said et al.[11] is an embedded lossless coder based on SPIHT [3].*

5. CONCLUSION

A new embedded Lossless wavelet coder called LMP-SZC was proposed. By dynamically adjusting the partitions based on the space-frequency domain coefficients, it achieves simpler complexity and superior coding efficiency as compared with the other coder in embedded lossless mode, without the time-consuming zerotree root analysis.

REFERENCES

[1] Y. Huang, H. M. Driezen, and N. P. Galatsanos, "Prioritized DCT for Compression and Progressive Transmission of Images", *IEEE Trans., Image Processing,* vol. 1, no. 4 , October 1992.

[2] Jerome Shapiro, "Embedded Image Coding Using Zerotrees of Wavelet Coefficients", *IEEE Trans. Signal Processing,* vol 41, no. 12, pp.3445-3462, December 1993.

[3] A. Said and W. A. Pearlman, "A New, Fast, and Effieient Image Codec Based on Set Partitioning in Hierarchical Trees", *IEEE Trans., Circuits and Systems for Video Technology,* vol. 6, no. 3, pp. 243-250, June 1996.

[4] A. Zandi, J. D. Allen, E. L. Schwartz, M. Boliek, "CREW: Compression with Reversible Embedded Wavelets " 9 November 1994, CRC-TR-9436, *IEEE Data Compression Conference*, Snowbird, UT, March 1995.

[5] D. Taubman and A. Zakhor, "Multirate 3-D Subband Coding of Video", *IEEE Trans., Image Processing,* vol. 3, no. 3, pp. 572-588, 1994.

[6] G. K. Wallace, "The JPEG Still Picture Compression Standard", *Communications of the ACM*, vol. 34, no. 4, pp. 30-40, April 1991.

[7] A. R. Galderbank, I. Daubechies, W. Sweldens, B-L. Yeo. "Lossless Image Compression Using Integer to Integer Wavelet Transforms", *Conf. on Image Proc.*, IEEE Press, 1997.

[8] W. Sweldens, "The Lifting Scheme: A New Philosophy in Biorthogonal Wavelet Constructions", *Wavelet Applications in Signal and Image Processing III*, A. F. Laine and M. Unser, SPIE~2569, pp. 68-79, 1995.

[9] W. Sweldens, "The lifting scheme: construction of second generation wavelets", *SIAM J. Math. Anal.*,No 2, Vol 29, pp. 511-546, 1997.

[10] K. Denecker, S. Van Assche, W. Philips, and I. Lemahieu, "State of the art concerning lossless medical image coding", *Proceedings of the PRORISC IEEE Benelux Workshop on Circuits, Systems and Signal Processing (J.-P. Veen, ed.), (Mierlo, NL),* pp. 129-136, STW Technology Foundation, Nov. 1997.

[11] A. Said and William A. Pearlman, "An Image Multiresolution Representation for Lossless and Lossy Compression", *IEEE Trans. Image Proc.* vol. 5. no. 9, September 1996.

[12] O. Egger and M. Kunt, "Embedded Zerotree Based Lossless Image Coding", *Proc. IEEE ICIP'95*, Washington, DC, vol. 3. pp. 616-619.

[13] H.J. Wang, Y.L. Bao, C.C. Jay Kuo and H. Chen, "Multi-Threshold Wavelet Codec (MTWC)", *JPEG 2000 Contribution, ISO/IEC JTC1/SC29/WG1 N819*, Convergence Phase Meeting, Geneva Swiss, March 1998.

[14] X. Wu, "Lossless Compression of Continuous-tone Images via Context Selection, Quantization, and modeling" *IEEE Trans. Image Proc.* Vol.6, No.5, pp 656-664, May, 1997.

[15] M. J. Weinberger, G. Seroussi, G. Sapiro, "LOCO-I: A Low Complexity, Context-Based, Lossless Image Compression Algorithm", *Proc. IEEE Data Compression Conference*, Mar-Apr, 1996.

[16] F. Golchin, K. K. Paliwal, "A Lossless Image Coder with Context Classification, Adaptive Prediction and Adaptive Entropy Coding", *Conf. On Acoustic, Speech, and Signal Proc.*, IEEE Press, Vol.5, pp. 2545-2548, 1998.

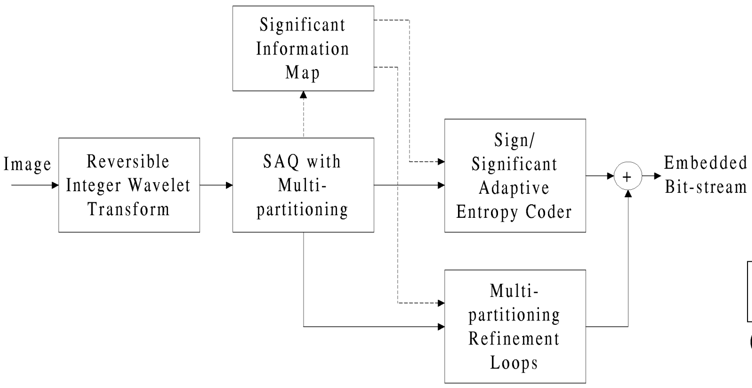

Figure 1. The Block diagram of LMP-SZC

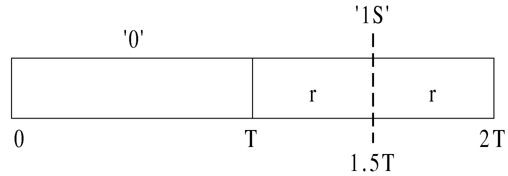

Figure 4. Significant and Refinement Map

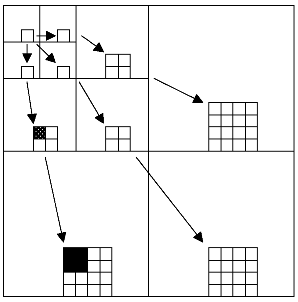

Figure 2. Parent-Children relationship spanned in the frequency-space domain

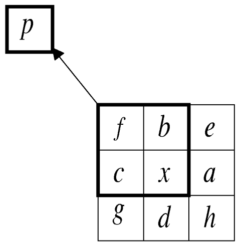

Figure 5. Context model for significant *x*.

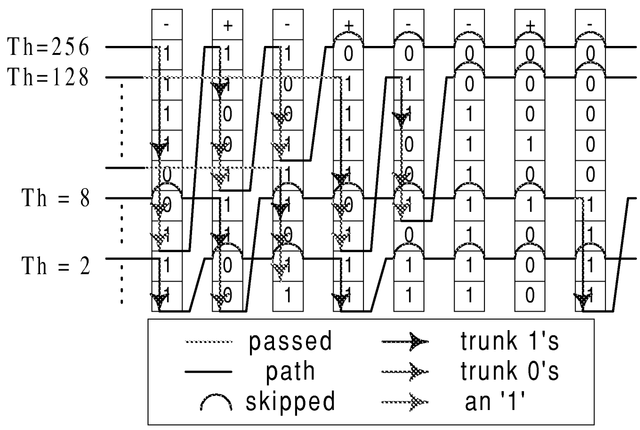

Figure 3. Multi-Partitioning Dynamic Scanning

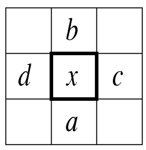

Figure 6. Context model for sign at *x*

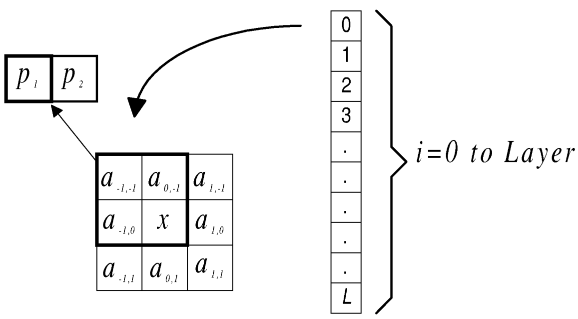

Figure 7. 2-Dimensional Context model for refinement Layer