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Embedded Lossless Wavelet-Based Image Coder Based on Successive Partition and Hybrid Bit Scanning

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SUMMARY A simple embedded lossless wavelet-based image coding algorithm called Successive Partition Zero Coder (SPZC), which uses hybrid bit scanning and non-causal adaptive context modelling, is proposed. By successive partition the wavelet coefficients in the spatial-frequency domain, the coefficients are ordered based on their absolute range. The prioritized coefficients are quantized in a successive approximation manner to generate a binary sequence, which is divided into subsources and encoded by arithmetic coder with non-causal adaptive context modelling. This method is suited for progressive image transmission (PIT). Experimental results show that SPZC outperforms other state-of-the-art coders such as SPIHT, CREW and LJPEG, but slightly inferior to ECECOW and CALIC in lossless mode. SPZC is simple in both context modelling and implementation.
key words: *hybrid bit scanning, non-causal context modelling, lossless compression, embedded lossless wavelet coding*

1. Introduction

In recent years, new applications such as telemedicine, archiving images (especially medical images and satellite images), and progressive transmission in lossless mode, require efficient lossless coding algorithms. In the past years, several wavelet-based coding algorithms, such as EZW [1], SPIHT [2], S+P [5], ECECOW [13] and CREW [6] have been proposed. The hierarchical octave structure of the wavelet decomposition provides a better framework for capturing global patterns in the image data, and the multi-resolution property is useful in progressive image transmission (PIT), which transmits the most important coefficients with the largest distortion reduction first. By transmitting the wavelet coefficients in an appropriate manner and successive approximation quantization (SAQ), one can produce an embedded bit-stream for any degree of compression, from lossy to lossless.

In this paper, we propose a hybrid bit scanning method and a non-causal adaptive context modelling, which are used in a simple embedded lossless wavelet-based image coding algorithm called Successive Partition Zero Coder (SPZC). The concept is inspired by Huang's partition priority coding (PPC) for progressive DCT image compression [4]. We adopt the order-by-magnitude transmission property of PPC, embedded coding property of bit-plane and successive approximation quantization (SAQ) to construct a prioritized quantization scheme, which generates long zero run sequence especially in the high frequency subbands. This leads to high coding efficiency since there are long zero runs; thus the adaptive arithmetic coder can generate more accurate local probability distributions, in which the conditional probability for symbols '0' are close to one. Different from other zerotree based algorithms, our algorithm only produces two symbols '0' and '1' instead of four (ZTR, POS, NEG and IZ) in EZW [1]. Small alphabets allow an adaptation algorithm with a short memory to learn quickly and constantly track-changing symbols probabilities, this also accounts for some of the effectiveness of SPZC. Besides, SPZC eliminates the zerotree analysis, which in essence serves as a high-order context model of small wavelet coefficients. Thus, the implementation and context modelling of SPZC are simple.

The bit stream generate by the hybrid bit scanning method is divided into three subsources according to the type of information it carried. This is similar to the MDEC in [4], which is proved not only reduce the entropy of a source, but also reduce the cost of coding. By applying the non-causal adaptive context modelling to each bit stream, SPZC exploits self-similarity and the joint coefficient statistics in the wavelet pyramid [10] and includes part of the future information for better conditional probability estimation. The ability of looking into the future information (detail can be found in Sect. 4) generally reduces the uncertainty of the coefficient being encoded. This is another factor of the high coding efficiency of SPZC. Like other embedded coders such as EZW [1] and SPIHT [2], SPZC adopts the embedded property, which gives any degree of compression with same code-stream. The users/applications can decide to retain the lossless code of an image or to truncate it to a lossy version. Such scheme is useful for progressive image transmission (PIT).

The remainder of this paper focus on hybrid bit scanning method and non-causal adaptive context modelling for the lossless compression and is organized as follows. In the next section, we give a description of the hybrid bit scanning method. In Sect. 3 we describe the simple embedded lossless wavelet-based image cod-

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ing algorithm, Successive Partition Zero Coder (SPZC), which is simple in concept and implementation. Section 4 shows the importance of the non-causal adaptive context modelling, which is used in the arithmetic coder to entropy encode the binary sequence generated by SPZC. Section 5 presents the experimental results for standard image set as well as medical image set. Section 6 concludes the paper.

2. Hybrid Bit Scanning

In baseline JPEG, a DCT coefficient in each transformed block has to be completely encoded before encoding the next coefficient in zig-zag scanning manner. First, bits of the coefficient C_1 denoted by $\{b_0,b_1,\ldots,b_{k-1}\}_b$ in a binary form are encoded from the most significant bit (MSB), i.e. b_{k-1} to the least significant bit (LSB), i.e. b_0, then bits of coefficient C_2 and C_3 and so on. Such coefficient-by-coefficient coding approach can be considered vertical bit scanning. Recently, a concept known as embedded or layered coding was proposed by Jerome Shapiro [1] and further developed by Amir Said [2] and David Taubman [3] in the context of wavelet coding. Those well-known embedded wavelet coders, such as EZW [1], SPIHT [2] and LZC [3], adopted a bit-plane/layered-bit-scanning approach, in which each coefficient is quantized successively. The MSB of all coefficients are grouped together to form one layer and encoded initially. And then it moves to the layer of the second significant bits and so on. Sign bit is encoded after the first non-zero bit of the coefficient. Such bit-plane/layered-bit-scanning approach can be regarded as horizontal bit scanning.

Inspired by Huang's partition priority coding (PPC) for progressive DCT image compression [4] and make use of the embedded coding property of bit-plane and successive approximation quantization (SAQ), we construct a prioritized quantization scheme to generate long zero run especially in the high frequency subbands. The new scanning method is indicated in Fig. 1. For each pass, bits are being scanned horizontally, and then vertically if a non-zero bit (i.e. significant) is encountered. Sign bit is encoded when the coefficient is known as significant. After that, it reverts back to original layer retrieving horizontal direction again. The coefficients being known as significant in previous passes will be skipped. For instance, in Fig. 1, bit streams of the first and second passes are {1+10110, 0, 1−00001, 0, 0, 0, 0, 0} and {1 − 0100, 1+0101, 1+0100, 0, 1+0010, 0} respectively. Such an oriental switching between horizontal and vertical bit scanning is classified as hybrid bit scanning.

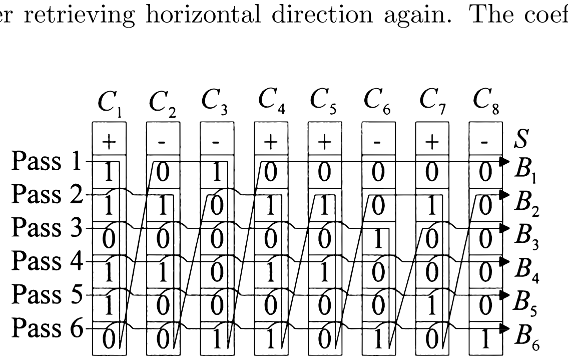


Fig. 1 Horizontal and vertical bit scanning order.

Unlike the vertical bit scanning used in JPEG, which adopt zig-zag scanning as the ordering controller, the ordering method in our hybrid bit scanning is based on the absolute range; therefore, SPZC sorts the coefficients more accurately according to their importance. Furthermore, different from conventional horizontal bit scanning, in which the most important coefficients can only be fully refined until the last bit plane was received, our hybrid bit scanning refine the significant coefficients immediately when it was found.

3. Successive Partition Zero Coder (SPZC)

In PPC [4], the transformed coefficients $C_{i,j}$ are ordered by magnitude so that the largest coefficients, which contain most energy are encoded first. Such magnitude ordering based on prioritized coding scheme is suitable for progressive image transmission (PIT), since it codes and transmits the largest transformed coefficients, which capture the most important characteristics of images first. The basic idea of SPZC is to divide the transformed coefficient magnitude range R into several variable-sized partitions $\{P_n\}$ successively. The lower bound of each partition is restricted to power of 2 i.e. 2^b and used as a control parameter to handle the order-by-magnitude transmission. By successive partition and hybrid bit scanning the wavelet coefficients in the spatial-frequency domain, the coefficients are ordered based on their absolute range and quantized successively to form a binary sequence with long zero run.

For example, let $\{P_0, P_1, P_2,\ldots, P_N\}$ be the partitions on the magnitude range R of the transformed coefficient $C_{i,j}$ where $0 \leq\mid C_{i,j} \mid\leq R$, such that P_n are disjoint, nonempty, varying size $(Size(P_i) = 2Size(P_{i+1}))$ and bounded by 2^{b-1} to 2^b. If $b = \log_2[\max(\mid C_{i,j} \mid)] = 8$, then the partition set is $\{P_0 = \{255,\ldots,128\}, P_1 = \{127,\ldots,64\}, P_2 = \{63,\ldots,32\},\ldots,P_7 = \{1,0\}\}$. Actually, each P_n can be viewed as a quantization pass. In each pass, if $\mid C_{i,j} \mid\in P_c$, i.e. $T_k \leq\mid C_{i,j} \mid< 2T_k$ where T_k is the lower bound of P_c , it is identified as significant, then symbol '1' is encoded followed by the sign bit 'S' to indicate its position and significance. After that, the residue $d_{ij} = [\mid C_{ij} \mid -T_k]$ is refined. If $\mid C_{i,j} \mid\notin P_c$, i.e. $\mid C_{i,j} \mid< T_k$, symbol '0' is encoded to indicate its insignificance in current pass P_c. The coefficient $C_{i,j}$ encoded in the quantization pass P_c will never be encoded again.

The algorithm is summarized as the following:

1. Set layer $k = 0$ and lower bound $T_k = 2^{b-1}$, where

$b = \log_2[\max(| C_{i,j} |)]$

2. For each coefficient $C_{i,j}$ do
   - 2.1 If $| C_{i,j} | < T_k$ then output '0'
   - 2.2 If $T_k \leq | C_{i,j} | < 2Tk$ then
     - 2.2.1 Output '1S,' where 'S' is the sign bit,
     - 2.2.2 Set $d_{ij} = |C_{i,j}| - T_k, k' = k + 1$ and $T = T_k/2$,
     - 2.2.3 For each bit layer i.e. while $k' < b$, do
       - 2.2.3.1 If $d_{ij} < T$ then output '0'
       - 2.2.3.2 If $d_{ij} \geq T$ then output '1' and set $d_{ij} = d_{ij} - T$
       - 2.2.3.3 Set $T = T/2$ and $k' = k' + 1$
3. Set $T_{k+1} = T_k/2$ and $k = k + 1$
4. If $k < b$, then go to Step 2

It seems that SPZC generates three symbols, '0,' '1' and 'S.' However, since the sign bit 'S' is binary event (positive or negative), it can be represented by symbol '0' and '1' as well. Therefore, SPZC only generates two symbols '0' and '1' instead of four in EZW [1]. The output symbols are entropy encoded by the arithmetic coder [14]. Since the alphabet size is two, it is fast in arithmetic coding, as the arithmetic coder only needs to maintain and update a single probability distribution table with two parameters. Moreover, each time a symbol is entered, the time it took to calculate new intervals becomes shorter; that is because for the binary case, there is only one endpoint change when a new bit is entered. This accounts for some of the effectiveness of the SPZC.

4. Non-causal Adaptive Context Modelling

From Wu's and Golchin's works [8], [9], we concluded that proper context modelling which is used to estimate the conditional probability distributions $p(x_{i+1}|x_1, \ldots, x_i)$ of x_{i+1} in a finite sequence $x_1, x_2, \ldots, x_n$ is essential to achieve higher coding efficiency in arithmetic coder. Context modelling of SPZC is simple. It is based on two fundamental properties: 1) z-scanning from coarse to fine resolution across scale assume that the magnitudes of coefficients tend to decay with frequency [1]; 2) the conventional parent-and-children relationship (Fig. 4 of [1]) and self-similarity and joint coefficient statistics of the wavelet pyramid [10]. Unlike most of the well-known embedded coders, which use coefficients' magnitude to form a context for conditional probability estimation, SPZC uses coefficients' significance status (positive significant, negative significant and unknown) to estimate the conditional probability of current coefficient $C_{i,j}$. The significance status of $C_{i,j}$'s eight neighbors, three cousins and one parent shown in Fig. 2(a) are included to form a non-causal context modelling for the conditional probability estimation. Such non-causal context modelling may be

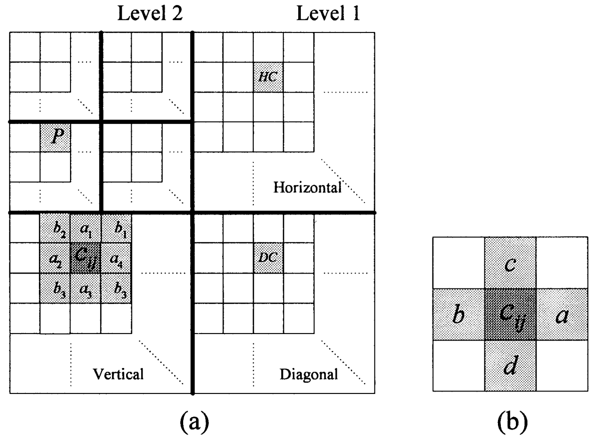
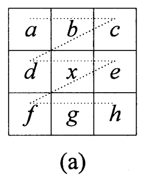


Fig. 2 (a) Context members of coefficient $C_{i,j}$. (b) Context members of sign bit of coefficient $C_{i,j}$.



a	b	c	d	x	e	f	g	h	
+	-	-	+	-	+	-	+	-	
1	0	0	0	0	1	0	1	0	Pass 1
1	1	0	1	1	1	0	1	1	Pass 2
0	0	0	0	0	0	1	0	0	Pass 3
1	1	1	1	0	1	0	0	0	Pass 4
1	0	0	0	1	0	0	1	0	Pass 5
0	0	1	1	1	0	1	0	1	Pass 6

(a) (b)

Fig. 3 (a) Neighbor coefficients of current coefficient x, if z-scanning method is applied, coefficient a, b, c and d will be visited before x i.e. past information of x, while e, f, g and h are the future information of x. (b) The binary representation of the coefficients.

one of the factors of getting high coding efficiency for similar manipulation of lifting mechanism in wavelet transform. In addition, the orientations of different subbands naturally lend an adaptive context modelling.

By using the non-causal adaptive context modelling, not only the past information, but also part of the future information are included. The ability of looking into the future information generally reduces the uncertainty of the coefficient being encoded. Figure 3 shows the ability of looking into the future information of SPZC. Figure 3(a) shows a set of neighbor coefficients of current coefficient x. If z-scanning method is applied, coefficient a, b, c and d will be visited before x i.e. past information of x, while e, f, g and h are the future information of x. Figure 3(b) shows the binary representation of the coefficients. At the beginning, the encoder sets the significance status of each coefficient to unknown. It updates the status of the coefficient during encoding process. For instance, in Fig. 3, coefficient x will be encoded as significant in pass 2. When encoding x, significance status of a, b and d are already available since they are encoded in pass 1 or just encoded. For the future information, only the value of e and g are available since they are encoded in pass 1. Coefficient c, f and h are not available in pass 2, their significance status remain unknown. The decoding process is as same as the encoding process.

Figure 2(a) shows the set U of context of the significant bit use in SPZC:

1. if $C_{i,j}$ exists in horizontal orientation or vertical orientation then
   $U = \{a_i, b_i, P, DC | i = 1, 2, 3, 4\}$ or
2. if $C_{i,j}$ exists in diagonal orientation then
   $U = \{a_i, b_i, P, HC, VC | i = 1, 2, 3, 4\}$

The future information refers to $\{a_3, a_4, b_3, b_4, HC, DC\}$, where DC stands for diagonal coefficient, HC stands for horizontal coefficient and VC represents vertical coefficient. Their status information are available in the immediate previous layer.

Hung's et al. [4] proved that the entropy of a source and cost of coding are reduced if it is partitioned into subsources with different probability distribution. In view of this, we divide the bit stream generated by the SPZC in each bit plane into three substreams, namely significant bit stream (the first non-zero bit of each coefficient $C_{i,j}$), refinement bit stream (binary representation of $|C_{ij}| - T_k$) and sign bit stream as well, according to the type of information it carried. The significant bit stream and the sign bit stream are encoded and conditioned to different contexts. However, as the binary representation of the transformed coefficients are randomly distributed, the refinement bit stream is encoded with single adaptive model. Therefore, there are two types of modelling, significant bit modelling and sign bit modelling. Magnitude-Set Variable-Length Integer (MS-VLI) Representation in [5] is used to limit the number of adaptive models in order to avoid 'context dilution' when count statistics must spread over too many contexts, which affects the accuracy of the corresponding estimates. Therefore, maximum number of context model for the significant bit is 9 and maximum number of context model for the sign bit is 15. In the follow subsections, $MS(x)$ is used as an operator of Magnitude-Set Variable-Length Integer (MS-VLI) Representation.

4.1 Significant Bit Modelling

The first non-zero bit of $C_{i,j}$ is encoded conditioned to the local and global variance of its adjacent, neighboring cousins (Horizontal Cousin, Vertical Cousin and Diagonal Cousin) and parent coefficient's significance status as shown in Fig. 2(a). Since Human Visual System (HVS) is sensitive to horizontal and vertical orientation, the conditioning descriptor is defined as:

1. if $C_{i,j}$ exists in Horizontal or Vertical subband

$$m = MS\left(3\sum_{i=1}^{4} a_i + 2\sum_{j=1}^{4} b_j + 3DC\right)$$

2. if $C_{i,j}$ exists in Diagonal subband

$$m = MS\left(3\sum_{i=1}^{4} a_i + 2\sum_{j=1}^{4} b_j + 3(HC + VC)\right)$$

if parent exists

$$m = MS(m + 3p) \qquad (1)$$

4.2 Sign Bit Modelling

Sign bits are essential to the real value of coefficients and directly affect the PSNR and human visual perception on the reconstructed image. However, many researchers seem to ignore this. Up to now, except for the CREW [6] and ECECOW [13], most wavelet image coders leave the sign uncoded. In order to further improve the coding efficiency, sign bit of $C_{i,j}$ in the SPZC is encoded conditioned to its four adjacent coefficients as shown in Fig. 2(b), which are sensitive to HVS. The conditioning descriptor is defined as:

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

5. Experimental Results

S+P [5] transformation is applied to the original image throughout our experiments. In order to evaluate the proposed algorithm, three sets of test images are chosen for comparison. The first set is JPEG standard test images; the second set is JPEG 2000 test images, Seismic and Target, where all of the images in set one and set two are 512×512 except Gold and Hotel which are 720×576; the last set includes twelve medical images with different sizes and types. All of the three sets of test images are 8-bit in depth. We compare SPZC with other state-of-the-art lossless image coders, SPIHT [2], CREW [6], ECECOW [13], LJPEG [11] and CALIC [8] in term of their lossless compression efficiency. Among them, CALIC and LJPEG are un-embedded, predictive coding algorithm without progressive transmission capability as SPZC does.

Table 1 and Table 2 show that, SPZC outperforms

Table 1 Compression comparison of SPZC with SPIHT, CREW, ECECOW, LJPEG and CALIC on natural images in term of bit per pixel (bpp).

Image	Embedded				Unembedded	
	SPZC	SPIHT	CREW	ECECOW	LJPEG	CALIC
Lena	4.145	4.182	4.512	4.090	4.694	4.171
Airplane	3.915	3.965	4.319	–	4.403	3.808
Boat	4.077	4.288	4.504	3.860	4.663	4.001
Peppers	4.551	4.679	4.718	–	4.978	4.491
Barbara	4.677	4.815	5.077	4.570	5.491	4.470
Baboon	5.927	6.160	6.212	–	6.381	5.987
Gold	4.544	4.627	4.762	4.420	4.985	4.456
Hotel	4.504	4.613	4.885	4.380	5.063	4.346
Lax	5.745	5.850	5.970	–	6.025	5.625
Seismic	2.887	2.894	–	–	3.083	2.960
Target	2.748	2.646	–	–	3.085	2.291
Average	4.338	4.439	–	–	4.805	4.237

Table 2 Compression comparison SPZC with SPIHT, LJPEG and CALIC on medical images in term of bit per pixel (bpp).

Imgae	Type	SPZC	SPIHT	LJPEG	CALIC
Mammogram 2048 × 2048	X-ray	1.154	1.274	1.962	1.095
x-ray 2048 × 1680	X-ray	2.254	2.312	2.627	2.199
cr 1744 × 2048	X-ray	3.231	3.300	3.592	3.221
mr_head_p 256 × 256	MRI	4.035	4.022	4.539	3.872
mr_head_w 256 × 228	MRI	3.764	3.796	4.436	3.647
mr_thorax 256 × 256	MRI	4.474	4.520	5.120	4.452
ct_abdomen_fr 512 × 512	CT	1.824	1.868	2.062	1.650
ct_abdomen_tr 256 × 256	CT	3.307	3.297	3.755	3.141
ct_head 512 × 450	CT	2.163	2.243	2.751	1.925
angio 512 × 512	ANG	3.105	3.133	3.487	3.072
echo 720 × 504	U-sound	2.935	3.012	3.637	2.706
Pet 414 × 414	PET	4.542	4.627	4.134	4.037
Average		3.066	3.117	3.509	2.918

SPIHT, CREW, and LJPEG in compressing both natural and medical images, but inferior to CALIC and ECECOW (2.32% and 3.05% respectively) due to the complex context modelling, context selection and quantization and different conditional entropy coding used in CALIC and ECECOW. As, Wu [13] pointed out that the good performance of ECECOW is soly due to high order adaptive context modelling. Therefore the inferiority of SPZC is reasonable. In contrast, the cost of good performance of ECECOW is its high complexity compare to SPZC. For natural images, SPZC gain 2.28% in lossless compression efficiency over SPIHT. Compare to LJPEG, SPZC is far superior, it gains 9.72% in lossless compression efficiency. The results of CREW are quoted from [12]. Since the CREW codec is not available, thus the JPEG 2000 test images can't be compared. However, for the rest of the natural images, SPZC gains 6.39% in lossless compression efficiency. For medical images, SPZC has 1.64% gain over SPIHT and 12.62% over LJPEG in term of lossless compression efficiency. Those results are promising and comparative with the state-of-the-art embedded lossless wavelet-based image coding algorithms published in the literature.

6. Conclusion

A simple embedded lossless wavelet-based image coding algorithm called Successive Partition Zero Coder (SPZC), which using hybrid bit scanning and non-causal adaptive context modelling, is proposed. The proposed method is simple in concept and implementation but achieving promising lossless compression efficiency as compared with some conventional bit-plane scanning methods. The construction of SPZC is inspired by Hung's partition priority coding. However, we go further to exploit the self-similarity of wavelet decomposition in both spatial and frequency domain. Compare with other wavelet based coders, small alphabets in the arithmetic encoding, non-causal adaptive context modelling, which includes future information for context modelling and source division are the major factors accounting for the gain of compression efficiency of SPZC. Elimination of zerotree analysis lead to simple implementation of SPZC. Experimental results show that SPZC outperforms other embedded coders in term of coding efficiency. The advantages of SPZC are simple implementation, high coding efficiency, allow lossy and lossless image compression and the potential application in lossless achieve large images database, e.g., medical images. However, the rate-distortion of the proposed method is not as good as others at this moment (PSNR=32.22 dB for 0.5 Bit/Pixel with image Lena). In view of this, further improvement of the lossy compression efficiency while maintaining its lossless compression efficiency is under investigation with the use of bit-plane scanning method for the first few layers and then switch to the proposed hybrid bit scanning method.

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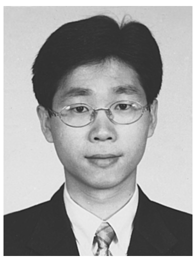

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