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Image coding using blocked zerotree

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Abstract A blocked zerotree coding algorithm for compression of subband image is proposed. Significance of blocks with respect to a certain threshold are coded with a set of transition rules for the significance of blocks. Significant blocks are quantized by vector quantization. The basic idea for this coding approach are: 1) Subband images are coded by blocks, 2) Important blocks based on the significance of blocks are coded and quantized, 3) Multiband codebook which is composed of sub-codebooks dedicated for each threshold and subband level is adapted to produce good reproduction vectors for vector quantization. The compression results are similar to Shapiro's zerotree coding even though ours are obtained without entropy coding of bit streams from blocked zerotree encoder. If an entropy coding is applied to the bitstream, PSNR will be improved.

1. Introduction

Image transmission will be one of the future data services offered over multimedia communication services. One latent problem with digital images is that a large number of bits are required for representing the images, and that a large bandwidth is required for transmission. Therefore, in order to use the spectrum efficiently, image data must be compressed before transmission. To meet increasing demand of image and video data in the future multimedia services, the need for developing more efficient coding techniques for the various applications is more and more increased.

Since the application two-dimensional subband coding to image compression by Woods and O'Neil [1], many coding schemes have been proposed for image coding [2]-[4]. Recently, a zerotree coding scheme was introduced by Shapiro [5] for coding the subband coefficients. This coding scheme was developed in recognition of the difficulty in achieving efficient bit rate reductions for significant coefficients via significance prediction. In this paper, a blocked zerotree coding technique for the coding of images is proposed. The proposed coding scheme is a generalized technique of the zerotree coding scheme.

In our proposed technique, subband coefficients are divided into blocks, and the significance of blocks are represented by zerotree. Significant blocks with respect to a threshold are choose according to their importance. The significance of blocks is coded using a set of state transition rules by predicting next state of a block. Vector quantization with the multiband codebook is applied to the significant blocks in order to quantize all the coefficients in each block. Since the blocks are selected by threshold value based on the magnitude of subband coefficients in blocks, sub-codebooks dedicated for each threshold and each subband level are generated. These sub-codebooks are merged together to form a multiband codebook. The encoder can terminate the encoding process at any point if a target rate or a distortion rate is met. This can be done since the produced bit streams are embedded codes. This technique can be applied to many applications such as progressive image transmission and image browsing. It is also applicable to the multilayer transmission for the different quality of services, and to the protection of channel noise in wireless communications.

This paper is organized as follows: Section 2 gives an overview of subband coding and vector quantization. In section 3, blocked zerotree coding scheme is proposed and image compressing technique using blocked zerotree is presented. Experimental results are discussed in section 4. The conclusions are summarized in section 5.

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2. Subband Coding and Vector Quantization

The fundamental idea of subband coding is to divide the frequency band of the signal into a number of subbands using a bank of bandpass filters. The subband coded images can be coded more efficiently than the coding of original image since coding can be performed separately for each subband. Subband coding is very flexible coding scheme since it allows appropriate bit allocation to the subbands. An image is first filtered and downsampled to generate a set of subband images. As a result, each of the subband image contains a limited range of spatial frequencies. This process of filtering and subsampling is termed analysis stage. The analysis filter banks should have ideal frequency responses which are nonoverlapping, but contiguous, and have unity gain over their bandwidths. In order to compress the image, subbands are then coded using some coding techniques. Bit streams which represent the quantized values may be entropy coded for further compression. Image reconstruction is accomplished by inverting the compression operations. This process is termed synthesis stage. In the synthesis stage, upsampling and an appropriate filtering is performed to reconstruct the subband imaged. These reconstructed subband images are added together for the reconstruction of the image.

The key elements of subband coding systems are 1) the analysis and synthesis filter banks and 2) the coding strategies in order to code the subband coefficients. There are two approaches in the quantization of subband decomposed images: 1) quantization of each subband independently and 2) quantization across subbands by exploiting dependencies between subbands. For the coding of the baseband in the first approach, differential PCM [1], transform coding [6], and vector quantization [7] have been widely used. A variety of approaches which explore the dependencies of subbands are reported using vector quantization [3] and zerotree coding [5].

Vector quantization [8] is a generalization of scalar quantization. VQ is a process in which data to be encoded are decomposed into vectors. Each vector is then compared with a collection of code vectors. In vector quantization, compression is obtained by using a codebook with respectively small number of codevectors compared to the number of vectors in an image. Designing a good codebook to represent the input vectors is the key of vector quantization. Codebooks are typically generated by using a training set of data that are representative of the data to be encoded. The algorithm generally used to generate codebook is the Linde-Buzo-Gray(LBG) algorithm [9] which is generalization of the Lloyd-Max algorithm for scalar quantization.

3. Blocked Zerotree Coding of images

In order to achieve low bit rate coding, a large number of bits must be used to encode significant subband coefficients. Shapiro [5] proposed zerotree coding technique that is a coding technique based on the prediction of the insignificant coefficients across subbands. The fundamental idea of zerotree coding is based on the hypothesis that if a subband coefficient has the magnitude less than a threshold, then all coefficients corresponding to the same spatial location with the similar orientation at all lower level bands are likely to be as well with respect to threshold.

The blocked zerotree coding is a vectorized algorithm of zerotree coding scheme. Each subband is decomposed into blocks such that each block consists of $p \times q$ coefficients. Each block can be a node of a zerotree. Dependencies within the subbands as well as among the subbands are explored in the blocked zerotree coding approach. Blocks in the blocked zerotree coding are coded in the order of the importance of the blocks to yield meaningful code at the beginning of the bit stream. Using this embedded code, the encoder can stop encoding at any target bit rate or distortion rate. Similarly, the decoder can stop decoding at the point when the reconstructed image is at the desired target rate. The importance of a block can be determined in many ways such as using the magnitude of the coefficients in the block, mean value of the magnitude of the coefficients in the block, or some other decision criteria such as variance of the block. The simplest method to decide the importance of a block is that a block is significant if the magnitude of any coefficient in the block is greater than or equal to a threshold. For our blocked zerotree coding scheme, the magnitude of coefficient is adopted in order to determine the significance of a block.

A block at the next upper level is called the parent block, and all blocks corresponding to the same spatial location at the next lower level of similar orientation are called children blocks. Each parent block has four children blocks in the next lower level since our subband decomposition is accomplished by 2×2 band system. Similarly, four blocks in the lower subband level has same parent block in the next upper subband level. For a given parent block, the set of all blocks at all lower levels of similar orientation corresponding to the same location are called descendant blocks. A block B_i at subband level i has four descendant blocks at the subband level $i-1$, 16 descendant blocks at the subband level $i-2$, and so on. Similarly, for a given child block, the set of blocks at all higher levels of similar orientation corresponding to the same location are called ancestor blocks. Note that baseband is not included in our blocked zerotree coding. The size of the blocks in the subbands can be any size of $p\times q$ coefficients. But blocks in similar spatial orientation should have same size across subband levels. In our blocked zerotree coding algorithm, the block size is 2×2, and the block size is same through all subbands.

The significance map of blocks can be efficiently represented as a string of symbols with three-symbol alphabets. The three symbols considered in our coding algorithm are 1) blocked zerotree root, 2) isolated blocked zero, and 3) significant block. A block B is said to be significant block with respect to the given threshold T if the magnitude of any coefficients in the block is greater than or equal to T. If all coefficients in the block have magnitudes less than T, this block is said to be insignificant block. Given a threshold T, a block B is said to be an element of a blocked zerotree if itself and all of its descendant blocks are insignificant with respect to T. A block which is an element of blocked zerotree is said to be blocked zerotree root if it is not the descendant block of a previously found blocked zerotree root for threshold T. By coding the blocked zerotree root, coding of the descendants of blocked zerotree root is also accomplished inherently since descendants of the blocked zerotree root are also insignificant blocks. In this way bits for coding the elements of a blocked zerotree can be avoided. Isolated zero block is an insignificant block which has some significant blocks in its descendant blocks. If a block is significant block, this block is quantized by a quantization method and resulting bits are coded.

The scanning order of the blocks are important since the information about the location of current scanning block can be implied in the scanning order. From HL subband in the highest subband level, a scanning of the blocks is performed in such a way that no child block is scanned before its parent block. For the subbands in the same subband level, after whole blocks in a subband is scanned, scanning of blocks in other subbands are started. For an N-level subband system, the scan begins with the blocks in the HL_N subband followed by scanning the blocks in the subband LH_N and HH_N. The scanning is, then, move to other subbands in the next lower level $N-1$ with the same order of HL_{N-1}, LH_{N-1}, and HH_{N-1} until subbands HL_1, LH_1, and HH_1 are scanned. Since the scanning order is known to the encoder and decoder, the information about the location of the significant block is implied in the coding of significance of the block. As a result, no bits are spent for coding the location of the scanned blocks. Bits send to the decoder are the bits needed to represent significance of the blocks, and bits needed for quantization of the significant blocks. By introducing block coding in the zerotree coding, the bits needed for coding the significant coefficients can be reduced by a factor of $p\times q$.

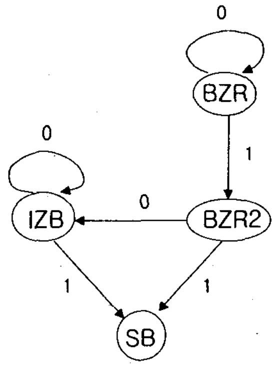
In order to code significance map of blocks, the state transition rule is investigated instead of direct coding of the significance of blocks. The significance of each block is checked with respect to the threshold T_i for the iteration i for all the subband levels where $T_i = T_0,\ T_0/2,\ \ldots,\ 1$. T_0 is the initial threshold and $T_0 = 2x$ in our coding system where x is an positive integer. In each iteration with T_i, all the blocks in all the subbands are scanned in order to check the significance of the blocks with respect to a threshold T_i. This iteration of scanning is continued until the target rate is met. If a block is significant with respect to the threshold T_i, quantization of the block is performed at the iteration i. This block is marked as scanned block, and it will not be scanned any more. When a block is isolated zero block with respect to current threshold T_i, the possible significances of the block with respect to the next threshold T_{i+1} are isolated zero block or significant block. If a block is blocked zerotree root with respect to the current threshold T_i, the possible significances with respect to the next threshold are blocked zerotree root or not blocked zerotree root (significant block or isolated zero block).

These observations lead to the development of an state transition rules with four states. The state of a block is defined based on the significance of a block with respect to the current threshold T_i and significance of a block with respect to the next threshold T_{i+1} if the significance of a block is blocked zerotree root or isolated zero block. Otherwise, the state of a block is defined based on the significance of a block with respect to the current threshold T_i. We defined four states for the transition of significance of blocks as below:

- significant block(SB): the magnitude of any coefficients in a block is greater than or equal to the current threshold T_i.
- isolated zero block(*IZB*): an insignificant block with respect to the current threshold T_i but one or more descendant blocks are significant blocks.
- blocked zerotree root(*BZR*): a blocked zerotree root for the current threshold T_i, and it is also the block-zero tree root with respect to the next threshold T_{i+1}.
- blocked zerotree root but not blocked zerotree root at the next threshold (*BZR2*): a blocked zerotree root for the current threshold T_i, but it will not be a blocked zerotree root (isolated block-zero or significant block) for the next threshold T_{i+1}.

At the initial iteration with initial threshold T_0, initial state of each block is assigned by above definitions. Each state is then encoded by two bits such that BZR is coded by "00", IZB by "01", BZR2 by "10", and SB by "11". After assigning a state to the block, that block is marked as scanned block for the current iteration i. If a block is a descendant block of a BZR, the state of this block is not coded although the state of this block is assigned at the initial threshold T_0, since the state of this block can be implied in the coding of its tree root block. The SB is the destination state in the state transition. After reaching state SB at the iteration i, this block will not be scanned any more at any iteration j where $j > i$. The scanning of blocks for the assignment of states is continued until all blocks are scanned with the scanning order.

In the iteration i with threshold T_i where $i > 0$, information of the state of a block is represented by state transition rules. If a block is in BZR state, the next possible state is BZR or BZR2. The next possible state of BZR2 is IZB or SB. If the state of a block is IZB, the next state should be IZB or SB. Since all these states have two transitions for the next state we can code these state transitions using only one bit. The state transitions and bit assignment for the coding of these transitions are shown in <Fig. 1>. For the coefficients in the lowest subband level, two symbols such as block-zero and significant block are used since coefficients in the lowest level have no descendant blocks.



<Figure 1>. State transition diagram and bit assignment for coding the state transition.

Before starting iteration i, blocks whose state are not SB are marked as unscanned blocks. Blocks marked as unscanned block are scanned at the iteration i with threshold T_i until all blocks are scanned. After scanning a block, the state of a block is assigned by state transition rules and state transition of the block is coded. If the new state of a block is SB, coefficients of the block is quantized using multiband vector quantization following coding of state transition. The blocked zerotree coding algorithm with vector quantization is summarized as below:

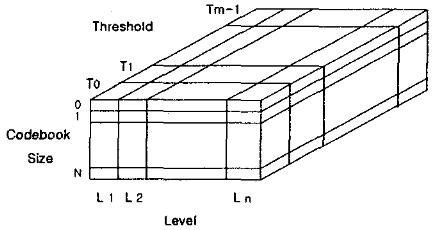
1. At the initial threshold T_0: assign state of the block according to the significance of the blocks. If the block is the zerotree root, assign states of all descendant blocks as BZR or BZR2 based on the significance of block with T_1. If a block is significant block, perform vector quantization to the significant block.

2. At threshold T_i, $i > 0$:
   1) If the block was not the SB at the threshold T_{i-1}, decide current state with thresholds T_i and T_{i+1}, and code the state of the block according to state transition rules. Quantize a block using vector quantization if the block is significant block.
   2) repeat step 2-(1) for all blocks whose previous states were not SB.

3. repeat step 2 until bit rate is satisfied.

The multiband codebook consists of many sub-codebooks dedicated for each threshold and subband level. Different sub-codebooks are provided for each subband levels. For each subband level, sub-codebooks are also supplied for all threshold values. The number of sub-codebooks for each threshold is the same as the number of levels in subband coding system. Total number of sub-codebooks is $n_T \times n_L$ where n_T is the number of thresholds and n_L is the number of levels. Each sub-codebook is generated using LBG algorithm. The global codebook is composed of three-dimensional array, $C = f(T, L, S)$ where T is threshold value, L is level number, and S is size of sub-codebook.

Since a threshold $T_i = T_{i-1}/2$, values of codevectors in sub-codebooks for a threshold T_i is less than $T_{i-1}/2$ and greater than or equal to T_i. When $T=1$ and block size is four, the possible number of codewords in codevector is only 81. We can code these vectors with at most 7 bits. The structure of codebook is shown in <Fig 2>. With this multiband codebook, we can reduce quantization errors between the original block and the reproduced block. Sub-codebooks for each different threshold and level may have same codebook size and vector dimensions, or different codebook size and vector dimensions. A multiband codebook can be obtained by assembling all of these resulting sub-codebooks. Each sub-codebook has a low distortion level. Since, in zerotree coding, only important block is coded, our codebook size can be relatively large. These larger size codebooks enable us to produce good quality of reconstructed image at the given bit rate.

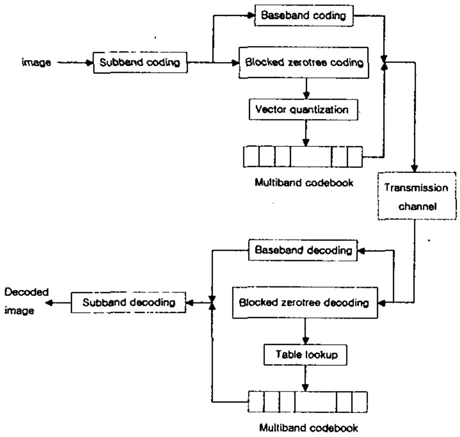


<Figure 2>. The Three-dimensional structure of multiband codebook.

4. Experimental Results

The blocked zerotree coder was applied to the 512×512 8 bpp gray images "Lena". Blocked zerotree coding system used in our experiments is illustrated in <Fig. 3>. Ten-band (three-level) subband coding is applied to the input image. Johnston's 24-tap QMF filter [10] is used to generate subband images in our coding system. The baseband image of size 64×64 is sent directly without coding. High frequency subbands $HL_3, LH_3, HH_3, \ldots, HH_1$ are coded using coding system. If a block is significant block, this block is vector quantized with multiband codebook. Initial threshold of

$T_0 = 32$ was used. After then threshold $T_i = T_{i-1}/2$, where $i > 0$, were used.



<Figure 3>. Encoding/decoding scheme of the blocked zerotree coding system.

At the initial state assignment with T_0, initial state of each block is assigned. During the scanning, the information whether a block is already scanned or not is recorded. If a block's state is BZR or BZR2, all descendant blocks are recorded as scanned blocks and states of these blocks are assigned for each block. If a block is marked as scanned block, the block is not scanned again during the same iteration. After finishing the iteration i, blocks are marked as unscanned block except significant block with respect to the threshold T_i for the next iteration $i+1$. After iteration with initial threshold T_0, state of each block is coded by state transition rules. Note that bits needed to code state of each block is 2 bits for initial threshold and 1 bit after then.

If a block is SB, coefficients in this block are quantized using vector quantization with multiband codebook. Multiband codebook consists of sub-codebooks for different thresholds and different subband levels. In our system, 18 sub-codebooks are provided since 3-level subband systems is adopted and 6 threshold values 32, 16, 8, 4, 2, and 1 are used. For the initial threshold 32, a block is significant block if magnitude of any coefficients in the block is greater than or equal to 32. Similarly for the threshold T_i where $i > 0$, a block is significant block if magnitude of any coefficients in the block is greater than or equal to T_i and less than T_{i-1}. Codebooks are obtained using the Linde-Buzo-Gray (LBG) algorithm based on a set of 28 training images. Since codebooks are provided for each threshold and subband levels, lots of training images may be needed. For the vector quantization, 2×2 vector dimension is used for all threshold and levels. Codebook size of 1024 is used when threshold $T > 1$, otherwise codebook size of 64 is used. Codebook sizes and vector dimensions for each threshold and subband level are shown in <Table 1>.

For the implementation of this coding algorithm, it is assumed that codebook size and vector dimension are known to encoder and decoder. The resulting bit streams after coding consist of bits for block information and bits resulting from vector quantization. The measurement for compression performance used are compression ratio and peak signal-to-noise ratio (PSNR). The compression ratio is defined as

$$R = b_o / b_c \qquad (1)$$

where R is compression ratio, b_o is the number of bits in the original image, and b_c is the number of bits in the compressed image. PSNR is computed as

$$PSNR = 20 \log_{10} \frac{255}{\mathrm{RMSE}} \qquad (2)$$

RMSE(root mean squared error) is defined as

$$\mathrm{RMSE} = \sqrt{\frac{1}{MM} \sum_{i=1}^{N} \sum_{j=1}^{M} (f(i,j) - \hat{f}(i,j))^2} \qquad (3)$$

where $f(i,j)$ is a original image and $\hat{f}(i,j)$ is the reconstructed image, and $M \times N$ is the size of image.

Threshold	Subband levels		
	3	2	1
32	1024 (2×2)	1024 (2×2)	1024 (2×2)
16	1024 (2×2)	1024 (2×2)	1024 (2×2)
8	1024 (2×2)	1024 (2×2)	1024 (2×2)
4	1024 (2×2)	1024 (2×2)	1024 (2×2)
2	1024 (2×2)	1024 (2×2)	1024 (2×2)
1	64 (2×2)	64 (2×2)	64 (2×2)

<Table 1>. Codebook size and vector dimension for each threshold and subband level where vector dimensions are indicated by $p \times q$ blocks.

The resulting PSNR of Lena image are 31.46 dB, 35.77 dB, and 38.61 dB for 0.25 bpp, 0.5 bpp, and 1.0 bpp, respectively. Coding results for Lena are summarized in <Table 2>. Detailed block information for each threshold and level is shown in <Table 3>.

bit rate	RMSE	PSNR (dB)
1.0	8.96	38.61
0.5	17.22	35.77
0.25	46.49	31.36

<Table 2>. Coding results for 512×512 Lena image

At the initial iteration with the initial threshold T_0, small number of significant blocks are detected and most of blocks are elements of zerotree. Note that blocks in the lowest subband level have only two symbols, significant block and zero block. The number of zero blocks in lowest level is indicated in the column IZB. As threshold is decreased, the number of significant blocks and isolated zero blocks are increased. At the iterations with larger thresholds, only small number of bits for coding the significance of blocks (block significance map) are needed, since most of blocks are elements of zerotree. However, if the value of threshold is decreased, we need a large number of bits to represent block significance map, since elements of zero tree are greatly decreased. These results are obtained without entropy coding of bit streams from blocked zerotree encoder. If an entropy coding is applied to the bit streams, and baseband image is coded by some compression techniques, PSNR will be higher than these results.

5. Conclusions

An image compression technique based on tree coding of subband images is proposed. Images are transformed by subband coding to decorrelate image data. Subband images are then grouped as square blocks. Information about the location of blocks and their significance when compared against a threshold is coded by the blocked zerotree coding algorithm. Coded bit streams are ordered in importance of blocks. Significant blocks are quantized by vector quantization. Some features of this approach are block tree coding by predicting insignificance across scales, approximation by vector quantization, and use of multiband codebook. This coding technique allows termination of encoding at any bit rate since coding is accomplished in an embedded fashion. The results of proposed scheme are similar to Shapiro's [5] that are resulted from zerotree coding and successive approximation of significant coefficients followed by adaptive arithmetic coding even though we did not code coefficients by entropy coding. Our results are better than Tsern's pyramid vector quantization of subband coefficients [11]. The difference between ours and Shapiro's is that 1) our scheme is blocked version of Shapiro's zerotree coding. 2) we introduced state diagram transition and bit assignment for coding the state transition. The PSNR of proposed scheme will be higher than presented results if an entropy coding is applied to the bit streams, and baseband image is coded by some compression techniques. Our approach has advantages in many application, particularly for progressive image transmission, image browsing, layered transmission of image data.

T	L	subbands									totals
		HL			LH			HH			
		SB	BZR	IZB	SB	BZR	IZB	SB	BZR	IZB	
32	3	31	952	41	2	1019	3	3	1021	0	6144
	2	54	226	8	4	16	0	0	12	0	6784
	1	13	0	235	0	0	16	0	0	0	7312
16	3	147	771	75	52	923	47	56	951	14	10348
	2	311	586	61	105	286	9	60	232	0	11998
	1	286	0	1405	22	0	450	1	0	239	14401
8	3	218	568	60	119	734	117	138	767	60	17182
	2	450	863	146	338	579	134	315	629	24	20660
	1	1283	0	2262	459	0	1843	124	0	1471	28102
4	3	182	225	221	189	367	295	166	453	208	30408
	2	617	1129	635	524	986	671	500	989	420	36879
	1	2793	0	3893	2427	0	3660	1415	0	3640	54707
2	3	217	7	222	241	10	411	209	14	438	56476
	2	1190	113	1333	1167	222	1696	1016	331	1818	65362
	1	7789	0	3656	7893	0	4535	7827	0	5469	102531
1	3	203	0	26	346	0	75	352	0	100	103633
	2	1365	0	109	1743	0	215	1886	0	319	109270
	1	4031	0	189	5149	0	434	6508	0	509	126090

<Table 3>. Number of blocks of different thresholds and levels, and bit budget for the coding of block information of subband coded Lena image, where T is threshold and L is levels: Numbers in columns indicate the number of blocks. Note that Level 1 has two symbols, SB and IZB, and levels higher than level 1 have three symbols, SB, BZR, IZB.

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