A Hybrid Scheme Using Improved SPIHT and Huffman Coding for Lossless Image Compression

Xiao YANG, Xueyou YANG

1. State Key Laboratory of Precision Measuring Technology & Instruments, Tianjin University, Tianjin, 300072, China, jackyang996@163.com

Abstract

In order to improve the coding performance of image lossless compression, a hybrid lossless compression scheme based on modified Set Partitioning in Hierarchical Trees (SPIHT) and Huffman coding is proposed. The lower magnitude bit-planes, whose corresponding magnitude thresholds are less than 8, and the sign bit-plane are scanned node by node in the fixed order, and the bit sequence obtained by scanning the bit-planes is further processed by Huffman coder to remove the statistical redundancy. The other bit-planes, namely the higher magnitude bit-planes, are sorted by the modified SPIHT partitioning structure, which could improves the coding efficiency of sorting pass by means of grouping more nodes together. Experimental results show the proposed algorithm has reduced its bit-rate by 0.13bit/pixel-0.35bit/pixel for gray images and by 0.72bit/pixel-1.25bit/pixel for color images as compared with those of the original SPIHT algorithm. Furthermore, the modified scheme retains the progressive transmission property of SPIHT coder. It is concluded that the proposed method efficiently reduces the redundancy existing in the original SPIHT coder and is fit for lossless image compression.

Keywords: SPIHT, The Sign Bit-Plane, Huffman Coder, Lossless Compression, Reversible Wavelet Transform

1. Introduction

With the rapid development of image coding techniques, lossless compression has been extensively used in many image processing applications, especially in which image is required for further processing[1], such as medical image, remote sensing image, and so on. However, the traditional lossless compression algorithms, including Run-length coding, arithmetic coding and LZW coding, couldn’t meet the demand of the performance asked by many frontier research fields because of their lower compression ratio [2-3]. Consequently, it is necessary for researchers to develop an efficient lossless compression method.

Recently, the wavelet transforms have attracted many interests of researchers and been adopted in JPEG2000, the newest still image compression standard. Compared with the traditional lossless coding methods, the wavelet transforms could efficiently remove the information redundancy held in natural images and describe the image detail in different frequency resolutions using multi-resolutions analysis [4-6]. Therefore, wavelet based image coding methods could effectively and simply process the transformed images using scalar quantization on hierarchical structures of wavelet coefficients. The Embedded Zerotree Wavelet (EZW) algorithm, proposed by Shapiro, is the first image coding method using such a quantization scheme [7]. EZW algorithm introduced the notion of zerotree and realized embedded image coding. Due to the attractive progressive transmission property, EZW algorithm quickly grew in popularity as a means to develop lossless compression systems [4]. No longer after, Said and Pearlman proposed a new coding technique, called Set Partitioning in Hierarchical Trees (SPIHT) [8], which is similar in the quantization method to EZW. SPIHT could organize and encode wavelet coefficients more effectively by extending zerotree to a new tree structure, called Spatial Orientation Tree (SOT). Consequently, SPIHT has better performances than EZW in lossless compression and is viewed as one of the most excellent lossless image compression algorithms [9-11].

Experimentally, three parts of SPIHT deficiency have been realized from the image lossless coding. In the first part, SPIHT doesn’t utilize the correlation among all sign bits to decorrelate the statistic redundancy of the sign bit-plane in the lowest frequency sub-band, because the sign bit of every wavelet coefficient is coded immediately and separately after the coefficient is labeled as significant. In the second part, SPIHT wastes a lot of bits to encode the coefficients in the highest pyramid level
because of the inefficiency existing in the original SOT. In the third part, the feature of bit distribution in the lower magnitude bit-planes increases appreciably the coding uncertainty and is not fit to organize these coefficients using the SOT structure.

In this paper, several new technologies are proposed, with the objective to solve the deficiency of SPIHT coder and improve lossless compression performance of images. The first modification involves the sign bit-plane where all sign bits of wavelet coefficients, as a whole bit-plane, are reorganized in the specific sequence and encoded to reduce the statistic redundancy of the symbol sequence in the lowest frequency sub-band using Huffman algorithm. The second improvement is motivated by the fact that the coefficients in the highest pyramid level have strong correlation. Thus, all high-frequency coefficients and most low-frequency coefficients in the highest pyramid level can also be encoded using the list of insignificant sets (LIS) to decrease the output frequencies of redundancy bits. The third idea is that the bit sequence at the lower magnitude bit-planes, obtained in fixed scan-order, could be processed by Huffman method to improve the lossless compression rate. Experiment results indicate that the proposed method achieves higher compressing performance as compared with traditional SPIHT for all tested images in terms of lossless coding bit-rate.

The rest of this paper is organized as follow: in Section 2, the original SPIHT algorithm is described, Section 3 analyses the existing problems in lossless compression based on SPIHT and introduces the proposed modifications to the original SPIHT. The valuable experiment results are shown in Section 4, the last section concludes this paper.

2. The overview of SPIHT algorithm

In this Section, we describe a brief overview of the SPIHT algorithm. SPIHT coder orders the wavelet coefficients by magnitude and bit-plane. The most significant magnitude bit-plane could firstly be ordered and encoded to yield the largest decrease in the rate-distortion of the reconstructed image, and the most insignificant magnitude bit-plane could lastly be processed to provide the detail information for the reconstructed image. The SPIHT coder includes a sequence of sorting and refinement passes applied with decreasing magnitude thresholds.

In the sorting pass, the coefficients that exceed and equal to the current magnitude threshold are labeled significant and insignificant otherwise. When a coefficient is firstly labeled as significance, the sign of the coefficient is immediately outputted. If the sign of the significant coefficient is positive, SPIHT coder outputs “1”. Conversely, it transmits “0” to the bit stream. When the insignificant nodes are coded, SPIHT coder scans the coefficient in the fixed order, which saves a lot of bits by partitioning the nodes in the subsets that contain many insignificant coefficients for the current magnitude threshold. After all coefficients are scanned in this sorting pass, SPIHT coder starts to process the refinement pass [12-14].

In the refinement pass, the significant coefficients, except those have been coded in the last sorting pass, are perfected with a certain threshold.

In the original SPIHT algorithm, three lists, including the list of significant pixels (LSP), the list of insignificant pixels (LIP) and the list of insignificant sets (LIS), are used to reserve and update the positions of ordering nodes. Initially, the elements of the highest pyramid level are added to the LIP, the LIS is the roots of the SOT and the LSP is set as the empty list. The method firstly orders all coefficients in the LIP, and encodes the descants of coefficients in the LIS. After sorting the elements in LIP and LIS, SPIHT refines the LSP coefficients and halves the quantization threshold for the next pass until the magnitude threshold equals to 0.

3. The proposed method for lossless image compression

The modified method mainly includes the coding of the sign bit-plane, the coding of the higher magnitude bit-planes and the coding of the lower magnitude bit-planes. In the proposed algorithm, the signs of all coefficients, as a whole bit-plane, are encoded to decrease the statistic redundancy. According to the magnitude threshold, all magnitude bit-planes are divided into two parts: the higher magnitude bit-planes and the lower magnitude bit-planes. For the higher magnitude bit-planes, the new SOT structure could more efficiently order and encode these wavelet coefficients. For the lower magnitude bit-planes, the modified coder scans these bits in the fixed order and encodes them using
Huffman algorithm to increase its coding efficiency.

3.1 The coding of the sign bit-plane

Experimentally, the signs of most wavelet coefficients located in the low frequency sub-band are positive in transformed images. As shown in Table 1, take five 512×512-8bit gray images after n-level 5/3 wavelet decomposition for example, the ratios of positive coefficients to total coefficients in the lowest frequency sub-band is very high, more than 97%. Consequently, if the sign of each coefficient is transmitted into the bit stream separately according to the original SPIHT algorithm, the strong correlation existing in the lowest frequency sub-band couldn’t be used to improve the coding efficiency of the sign bit-plane.

<table>
<thead>
<tr>
<th>n-level 5/3 wavelet decomposition</th>
<th>Lena</th>
<th>Barb</th>
<th>Gold-hill</th>
<th>Boat</th>
<th>Peppers</th>
</tr>
</thead>
<tbody>
<tr>
<td>n=3</td>
<td>99.5%</td>
<td>99.9%</td>
<td>100%</td>
<td>97.8%</td>
<td>98.0%</td>
</tr>
<tr>
<td>n=4</td>
<td>99.1%</td>
<td>99.7%</td>
<td>100%</td>
<td>98.1%</td>
<td>97.8%</td>
</tr>
</tbody>
</table>

In order to resolve the coding drawback of the coefficients signs in original SPIHT algorithm, by taking 3-level wavelet transform as an example, the modified method divides all coefficients into four blocks according to the similarity of wavelet coefficients in the same spatial orientation sub-bands (shown in Figure 1): the low-frequency block LL (LL3), the detail blocks in the vertical direction LH (LH1, LH2 and LH3), the detail blocks in the horizontal direction HL (HL1, HL2 and HL3) and the detail blocks in the diagonal direction HH (HH1, HH2 and HH3). The signs of wavelet coefficients in the low-frequency block are firstly processed one by one in the raster scan order, then the coefficient signs of the detail blocks in the vertical direction and in the horizontal direction, finally the coefficients signs of the detail blocks in the diagonal direction. If the sign of the coefficient scanned in above order is positive, the coder outputs “1”, and transmits “0” if the sign is negative. However, nothing is transmitted to the bit stream if the coefficient equals to zero, since the coefficients, which is equivalent to zero, could be decoded without the sign bit for lossless image compression. The processing sequence could obviously increase the output frequencies of “FF”, because the ratio of positive coefficients to total coefficients in the low frequency sub-band is close to 100%. After all blocks are processed, the Huffman coder is used to remove the statistic redundancy existing in the sign bit-stream.

Figure1. The dividing of wavelet sub-bands and the scan order of sign bit-plane

3.2 The modification of the SOT structure

In the original SPIHT coder, the significant bits are used to reduce the distortion of the reconstructed images and the insignificant bits are only used to transmit the position information of the insignificant coefficients to the decoder. From this perspective, the SOT structure is inefficient for describing...
insignificant information in the highest pyramid level, because only a small percentage of bits are used to describe the significant information. In this paper, a new SOT structure is proposed to increase the proportion of significant information in the bit stream.

In the sorting pass of SPIHT algorithm, the coefficients in LIP is ordered and encoded one by one, whereas the nodes in LIS is processed set by set [15], composed of four neighboring coefficients. Hence, the LIP is not very efficient in coding small wavelet coefficients. For instance, if four neighboring coefficients are insignificant, four bits would be required to code the information in LIP, whereas only one bit is required in LIS. Thus, if some very small coefficients, such as the ones located in the high-frequency sub-bands, are added to the LIP, SPIHT coder sends many redundancy bits denoting the insignificance of these coefficients to the decoder for many passes. However, such an phenomenon has existed in the original SOT structure (shown in Figure 2(a)), because the coefficients of three high-frequency sub-bands in the high pyramid level are inputted to LIP for sorting and coding in the initialization of SPIHT.

Another problem of SOT structure is that all coefficients of the lowest frequency sub-band (sub-band LL_n for n-level wavelet transform) are also added to the LIP and analyzed coefficient by coefficient. Experimentally, it has been noticed during the lowest frequency sub-bands of different test images that there are a lot of blocks with a size of 2×2 (denoted using S0) where coefficient absolute values are close to each other (within the same threshold interval) and smaller than the maximum of quantization thresholds (see Table 2). Hence, if the coefficients of each block are encoded using LIP, four bits are required to code the information for the higher magnitude thresholds. However, if using LIS, three bits are saved in every pass for the higher magnitude the thresholds.

<table>
<thead>
<tr>
<th>The name of the test images</th>
<th>n = 3</th>
<th>n = 4</th>
<th>n = 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lena</td>
<td>56.71</td>
<td>52.34</td>
<td>47.62</td>
</tr>
<tr>
<td>Barbara</td>
<td>52.19</td>
<td>48.35</td>
<td>45.18</td>
</tr>
<tr>
<td>Gold-hill</td>
<td>60.26</td>
<td>55.16</td>
<td>51.37</td>
</tr>
</tbody>
</table>

(a) Spatial orientation tree of the SPIHT algorithm (b) Modified SPIHT partitioning structure

Figure 2. The modification of spatial orientation tree

Obviously, SPIHT coder dramatically wastes bits in the initial iterations as the original SOT structure utilizes the LIP to organize all coefficients of tree roots one by one. Based on the observation, we suggest adding more coefficients to the LIS. Therefore, the modified SOT structure is proposed: the sub-band LL_n is divided to four sub-bands LL_{n+1}, LH_{n+1}, HL_{n+1} and HH_{n+1} in a virtual way. In the modified SOT structure, the pixels in the virtual sub-band LL_{n+1} are the tree roots and also form many groups with a size of 2×2. However, their offspring branching rule is different. In each set of the virtual sub-band LL_{n+1}, one of four coefficients (denoted by the star in Fig.2(b)) has no descants and the others have the direct descants which correspond to the pixels of the same spatial orientation of the set in the others virtual sub-bands. In the other sub-bands, every coefficient has direct descants which correspond to the nodes of the same spatial orientation in the next finer level of the pyramid.

In the modified SOT structure, all coordinates of the tree roots are added into the LIP, all
coefficients of the other virtual sub-bands are added into the LIS as the sets of type A. Furthermore, in order to increase the coding efficiency of the coefficients in $LL_n$, the nodes of the tree roots which have offspring in the virtual sub-band $LL_{n+1}$ are also added to the LIS. Compared with the original SOT structure, the new structure has two effects. Firstly, it decreases the output frequency of redundancy bits in such a way that more coefficients could be grouped together to capture the insignificant information efficiently. Secondly, it reduces the initial length of LIP and LIS. The shorter initial length of LIP and LIS accelerates the first sorting pass and also improves the sorting efficiency.

3.3 The coding method of the lower magnitude bit-planes

The efficiency of SPIHT in terms of lossless compression performance depends on the probability of the significant information within each bit-plane [16], because the SOT structure organizes and encodes the wavelet coefficients using the correlation of insignificant information at the high frequency sub-bands with the same spatial orientation. Hence, the compression performance of SPIHT coder certainly decreases if the probability of the significant coefficients increases. However, for transformed images, the proportion of the significant coefficients increases with the decrease of magnitude threshold (see Figure 3), thereby resulting in the reduction of coding efficiency of SPIHT coder in the lower magnitude bit-planes, which correspond to the lower magnitude thresholds.

As analyzed above, SOT structure, including the modified structure, isn’t suitable for processing the coefficients in the lower magnitude bit-planes, thus a new scheme is proposed to process these coefficients. According to Fig.3, it could be concluded that the proportion of the significant information rapidly increases from average 16.8% to average 42.3% (more than 25%) when the quantization threshold is less than 8. Hence, the bit-planes whose corresponding magnitude thresholds are less than 8 are defined as the lower magnitude bit-planes. The main reason of the rapid increase of the proportion in the lower magnitude bit-planes is that the high frequency coefficients have lower magnitudes and appear more frequently in the lower magnitude bit-planes. If these bit-planes are encoded using the original SPIHT coder, much additional bits, which aren’t necessary for image reconstruction, are transmitted into the bit stream. Therefore, in the new scheme, the bit sequence of the lower magnitude bit-planes could be captured with checking for every bit one by one instead of checking for the significance information set by set. If the bit checked is “1” in the current bit-plane, the scheme outputs “1”, and transmits “0” to the code stream if the bit checked is “0” in the current bit-plane.

The distribution properties of wavelet coefficients in the same spatial orientation sub-bands are similar, thus the scanning order of the lower magnitude bit-planes is the same as the sign bit-plane (see Fig.1). After all bits of three lower magnitude bit-planes are scanned and outputted, the bit sequence is encoded to improve the coding performance using Huffman coder.
3.4 The processing flow of the proposed method

Base on the medication mentioned above, the processing flow of the proposed method is shown as follow:

1. The original images are captured from the standard image test database;
2. The reversible 5/3 wavelet filter is chosen to transform the original images;
3. The sign bit-plane is scanned in the fixed order and the sign sequence is further treated by Huffman algorithm;
4. The higher magnitude bit-planes, whose corresponding thresholds are more than 8, are encoded by the SPIHT coder with modified SOT structure;
5. The remaining magnitude bit-planes, namely the lower magnitude bit-planes, are outputted in the order used in the sign bit-planes and the bit sequence is also encoded using Huffman method;

If all coefficients are transmitted or the modified coder achieves the lossless compression of all image, the proposed coder ends the procession.

4. Experiment results and Discussion

In this section, the comparison results between the proposed method and the original SPIHT algorithm and the feature of progressive transmission are presented. The tested images include the gray images and the color images represented using the YUV color space. The performance of lossless compression is measured using the bit per pixel (bpp), since the reconstructed images have no distortion by comparison with the original images. The bpp is denoted by

\[ \text{bpp} = \frac{\text{bits/pixel numbers of original image}}{\text{compression ratio}} \]  

Figure3. The correspondence between the proportion of the significant coefficients and the threshold after 3-level 5/3 wavelet transform
where

\[
\text{compression ratio} = \frac{\text{original image size}}{\text{compressed image size}}
\]  

(2)

4.1 The compression performance of gray images

Some natural images are used to evaluate the compression performance of the proposed method, and the results are compared with the original SPIHT. The test images with a size of 512×512 include a great variety of content: “Lena”, “Boat”, “Barb”, “Gold-hill” and “Baboon”. All test images are compressed losslessly using the 3-level reversible 5/3 filter. The experimental results of gray images are shown in Table 3, where the symbol “-” denotes that the proposed method consumes fewer bits to encode the whole gray image than the SPIHT coder.

As reported in Table 3, the proposed algorithm outperforms SPIHT coder in the bit per pixel for all tested images. Note that the best improvement by the proposed method has been obtained for “Baboon”, because the rate of the significant coefficients exploited by the modification of the lower magnitude bit-planes is the highest (more than 40%) and more coefficients in the higher magnitude bit-planes are grouped together to reduce the number of redundancy bits. The improvements captured for gray images changes between 0.13bpp and 0.35bpp. Overall, the proposed method is proved to be effective in improving the performance of gray image lossless compression.

<table>
<thead>
<tr>
<th>Method</th>
<th>Lena</th>
<th>Barb</th>
<th>Boat</th>
<th>Gold-hill</th>
<th>Baboon</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIHT</td>
<td>4.6875</td>
<td>4.9806</td>
<td>4.7626</td>
<td>5.1984</td>
<td>6.3191</td>
</tr>
<tr>
<td>The proposed method</td>
<td>4.4203</td>
<td>4.8560</td>
<td>4.6073</td>
<td>4.8871</td>
<td>5.9766</td>
</tr>
<tr>
<td>Gain between SPIHT and the proposed method</td>
<td>-0.2672</td>
<td>-0.1246</td>
<td>-0.1553</td>
<td>-0.3113</td>
<td>-0.3425</td>
</tr>
</tbody>
</table>

4.2 The tested results of the color images

A true color image is made up of three primary colors: red, green and blue. However, an ideal color space should meet some requirement that most energy of color image could be focused on the specified component and there is a small correlation among all components of the color image. Hence, in this paper, the RGB color space is converted to YUV, which could concentrate 90% energy of the whole image on the luminance component and remove the correlation among chrominance components of the true color image.

The lossless coding method of color images consists of a reversible color transform from RGB to YUV, a 5/3 integer wavelet transform and an encoder. After converting RGB to YUV, each color component is decomposed using the 3-level 5/3 integer wavelet filter and separately encoded by the proposed coder. The true color images with a size of 512×512, including “Lena”, “Boat”, “Baboon” and “Gold-hill”, are tested to measure the effectiveness of the proposed coder. The test results of color images are reported in Table 4, where the symbol “-” denotes that the proposed method consumes fewer bits to encode the whole color image than the SPIHT coder.

<table>
<thead>
<tr>
<th>Method</th>
<th>Lena</th>
<th>Boat</th>
<th>Baboon</th>
<th>Gold-hill</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPIHT</td>
<td>14.9062</td>
<td>15.4308</td>
<td>19.3174</td>
<td>16.5713</td>
</tr>
<tr>
<td>The proposed method</td>
<td>14.0149</td>
<td>14.7146</td>
<td>18.0721</td>
<td>15.5943</td>
</tr>
<tr>
<td>Gain between SPIHT and the proposed method</td>
<td>-0.8913</td>
<td>-0.7162</td>
<td>-1.2453</td>
<td>-0.9767</td>
</tr>
</tbody>
</table>

According to the table 4, it is clearly implied that the coding performance of the proposed coder is also superior to SPIHT for all tested color images. On average, the proposed method outperforms the SPIHT coder by 0.72bpp-1.25bpp for the color images in the bit per pixel. Therefore, this coder is also
an excellent lossless compression scheme for the color images.

4.3 The progressive transmitting prosperity of the proposed method

Although all bit-planes of the transformed image are divided into three parts to encode these wavelet coefficients: the sign bit-plane, the higher magnitude bit-planes \( T \geq 8 \) and the lower magnitude bit-planes \( T<8 \). However, all coefficients are processed from a bit-plane to another bit-plane. Consequently, the progressive transmitting prosperity is reserved in the proposed method. Figure 4 shows the progressive transmission prosperity of the proposed coder with respect to the different thresholds.

![Progressive transmission illustration using the proposed coder operating on Lena](image)

**Figure 4.** Progressive transmission illustration using the proposed coder operating on Lena

5. Conclusions

Image lossless compression is necessary for many applications where perfect accuracy is required, such as medical image, remote sensing image and so on. In this paper, an improved method based on SPIHT and Huffman coding is presented. The method divides bit-planes into several categories, and each category could be encoded separately according to its bit distribution character. In addition, the progressive property of SPIHT is maintained. The results show that bit-rates of all international standard images have reduced by 0.13bpp-0.35bpp for gray images and by 0.72bpp-1.25bpp for color images. Therefore, it is obtained that the proposed method efficiently improves the lossless compression performance of all images, including gray images and true color images.

6. Acknowledgement

This work is supported by the National Natural Science Foundation of China under Grant No. 50735003.
7. References


