VISUALLY LOSSLESS COMPRESSION BASED ON JPEG2000 FOR EFFICIENT TRANSMISSION OF HIGH RESOLUTION COLOR AERIAL IMAGES

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ABSTRACT

Aerial image collections have experienced exponential growth in size in recent years. These high resolution images are often viewed at a variety of scales. When an image is displayed at reduced scale, maximum quantization step sizes for visually lossless quality become larger. However, previous visually lossless coding algorithms quantize the image with a single set of quantization step sizes, optimized for display at the full resolution level. This implies that if the image is rendered at reduced resolution, there are significant amounts of extraneous information in the codestream. Thus, in this paper, we propose a method which effectively incorporates multiple quantization step sizes, for various display resolutions, into the JPEG2000 framework. If images are browsed from a remote location, this method can significantly reduce bandwidth usage by only transmitting the portion of the codestream required for visually lossless reconstruction at the desired resolution. Experimental results for high resolution color aerial images are presented.

Keywords: JPEG2000, visually lossless coding, JPIP, human visual system.

1. INTRODUCTION

With recent advances in sensing and imaging technology, the sizes of aerial image collections are exponentially growing. Generally, since a great deal of effort is expended in acquiring these images, lossless image compression is preferred. However, typical numerically lossless compression methods, those offering perfect reconstruction fidelity, offer only limited compression performance. Therefore, visually lossless methods, which increase performance by removing information which does not contribute to visual quality, are gaining interest [1].

JPEG2000, a wavelet-based image compression standard, has several advantages in compressing and transmitting high-resolution aerial images [2]. First of all, the codestream for a single image encoded using JPEG2000 is inherently structured to support many types of scalability. Without the need for re-encoding the image, it allows the end user to obtain image products from arbitrary components having various resolutions, qualities and spatial extents, all from a single compressed file. Furthermore, when browsing images from a remote location, the JPEG2000 Interactive Protocol (JPIP), described in Part-9 of the JPEG2000 standard, may be used to transmit only the portion of the codestream required to reconstruct the region of interest [3–5].

This paper presents an efficient visually lossless coding algorithm based on JPEG2000, fully preserving the aforementioned features. Visually lossless coding is achieved by keeping the quantization step sizes of the subbands smaller than the visibility thresholds obtained from our previous psychophysical experiments [6]. Since high resolution images are often displayed at various scales and the visibility thresholds tend to increase as the scale decreases, we propose a method of applying multiple visibility thresholds within a subband for high resolution color images, extending our previous work on monochrome images [7]. By selectively truncating the codestream according to the optimal visibility threshold, as determined by the current display resolution, the proposed method, along with JPIP, can significantly reduce the transmitted bitrate, while preserving visually lossless quality.

2. INTERACTIVE TRANSMISSION OF IMAGES USING JPIP

JPIP is a connection-oriented network communication protocol which facilitates efficient transmission of images using the characteristics of scalable JPEG2000 codestreams. A user can interactively browse spatial regions of interest, at desired resolutions, by retrieving only the corresponding minimum required portions of codestreams.

Selection of a desired resolution is based on the dyadic tree-structured wavelet transform embedded in JPEG2000. A K level dyadic wavelet decomposition yields $K + 1$ display resolutions. Figure 1 shows the reconstruction procedure of multi-resolution images from a wavelet transformed image for $K = 2$. The lowest resolution level $\mathcal{R}_0$ corresponds to the lowest resolution image LL_2. The next lowest resolution level $\mathcal{R}_1$ together with LL_2 can be used to render the next to lowest resolution image LL_1. Finally $\mathcal{R}_2$, together with LL_1, yields the original image LL_0. In general, resolution level $\mathcal{R}_r$ together with the image $LL_{K-(r-1)}$ can be used to synthesize the image LL_{K-r}.

To facilitate spatial random access, JPEG2000 defines precincts, which are collections of codeblocks belonging to a spatial supporting region. Figure 2 illustrates the relationship between precincts and codeblocks. A subband is partitioned into codeblocks, which are the smallest geometric structure in JPEG2000, and a precinct for LL_{K-r} consists of codeblocks from $\mathcal{R}_r$ corresponding to a spatial region in LL_{K-r}. Each precinct for every quality layer (quality layer is described in the following section) constructs one packet, the basic unit of codestream formation, together with header information.

Figure 3 shows a block diagram of the JPIP remote image browsing system. First, the client

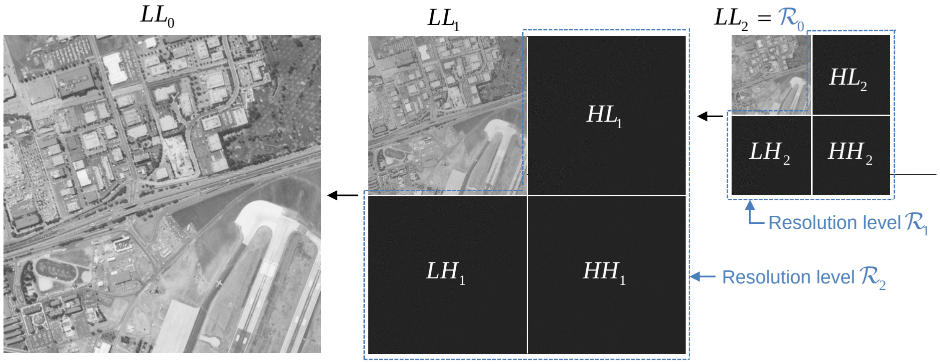

Figure 1. Reconstruction procedure of multi-resolution images from a wavelet transformed image for $K = 2$.

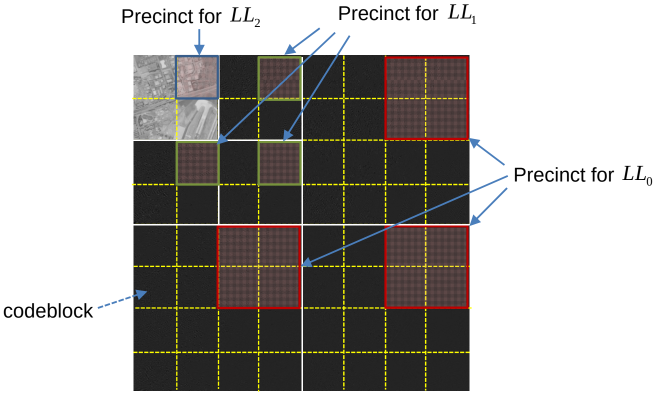

Figure 2. Precincts and codeblocks ($K = 2$).

requests a spatial region, resolution, image components of interest using a simple descriptive syntax to the server. In response to the client's request, the server collects the necessary packets from the JPEG2000 codestream and sends them to the client. The client decodes the received packets and renders the image. Through a graphic user interface (GUI) on the client-side, a user can request different regions, resolutions, components, and qualities at any time.

Among multiple client requests, a considerable portion of packets may be duplicated. To avoid retransmission of those packets, the client may employ a cache. Received packets are stored in the cache and then decoded, and the server maintains a cache model which keeps track of the client's cache. If a request is found to contain a duplicated part, the server does not send the duplicated part and the client decodes it from the cache. This can dramatically reduce transmitted bits per request.

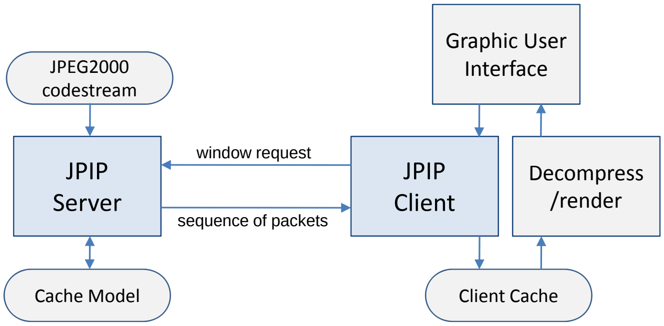

Figure 3. Client-server interaction in a JPIP remote image browsing system.

3. MULTI-RESOLUTION VISUALLY LOSSLESS COLOR IMAGE CODING

3.1. MULTI-RESOLUTION VISIBILITY THRESHOLDS

In irreversible compression in Part I of the JPEG2000 standard, the RGB color space is converted, by the irreversible color transform (ICT), to the YCbCr color space, which is a more efficient representation for compression. Compression is mainly achieved via quantization of each color component, independently transformed by the 9/7 wavelet transform. However, numerical losses caused by the quantization produce compression artifacts in the reconstructed image. In [6], to obtain the maximum compression performance without introducing visible compression artifacts, the maximum quantization level was measured through psychophysical experiments for the YCbCr color space. This maximum quantization level is referred to as the visibility threshold, and depends significantly on the subband. In particular, the thresholds for the luminance component are affected by the distribution of wavelet coefficients within the subband, defined by

$$t_{\theta,k} = a_{\theta,k} \cdot \sigma^2_{\theta,k} + b_{\theta,k} \tag{1}$$

where θ and k are the orientation and decomposition level of the subband, respectively. $\sigma^2_{\theta,k}$ is the variance of wavelet coefficients within the subband. The linear parameters $a_{\theta,k}$ and $b_{\theta,k}$, measured for five decomposition levels ($K = 5$), are listed in Table 1. For the LL subband, we use a fixed threshold value 0.63 since the variance of the subband is usually much larger than that of other subbands and the distortion is less affected by the variance change.

subband	$a_{\theta,k}$	$b_{\theta,k}$	**subband**	$a_{\theta,k}$	$b_{\theta,k}$
HH,1	105.67×10^{-4}	4.85	HH,4	10.16×10^{-4}	0.47
HL/LH,1	46.03×10^{-4}	1.98	HL/LH,4	7.75×10^{-4}	0.36
HH,2	19.94×10^{-4}	0.92	HH,5	7.91×10^{-4}	0.36
HL/LH,2	13.84×10^{-4}	0.64	HL/LH,5	7.16×10^{-4}	0.33
HH,3	11.04×10^{-4}	0.51			
HL/LH,3	10.83×10^{-4}	0.50			

Table 1. Linear parameters $a_{\theta,k}$ and $b_{\theta,k}$.

Compared to the thresholds for the luminance components, the visibility thresholds for the chrominance components are generally larger. This is because the human visual system (HVS) is less sensitive to color change than to luminance change. Also, the variance in the chrominance components is much less than that in the luminance, so the variance change is not significant. Thus, we use fixed threshold values, determined based on the average statistics, as the visibility thresholds for the chrominance components. The chrominance thresholds are shown in Table 2. These visibility thresholds were measured at a viewing distance of 60 cm and a display visual resolution of 35.62 pixels/degree, which is a typical office environment. Under these viewing conditions, an image quantized with these visibility thresholds exhibits visually lossless quality.

subband	**Cb**	**Cr**	**subband**	**Cb**	**Cr**
HH,1	24.72	15.49	HH,4	4.95	1.25
HL/LH,1	14.50	6.35	HL/LH,4	3.26	0.69
HH,2	14.77	7.40	HH,5	1.05	0.56
HL/LH,2	6.36	2.60	HL/LH,5	1.05	0.58
HH,3	11.55	2.57	LL, 5	1.32	0.66
HL/LH,3	4.03	1.23			

Table 2. Visibility thresholds for chrominance components.

The visibility threshold is a function of spatial frequency. When an image is displayed at a different resolution level, the spatial frequency of each subband is also changed. Therefore, the visibility threshold should be applied depending on the display resolution [8]. When a reduced resolution image, $LL_{K-r}, 0 \leq r < K$, is displayed on the monitor, the subbands of resolution $\mathcal{R}_r$ are playing the role of the highest frequency subbands, normally played by $\mathcal{R}_K$. Similarly, the subbands of resolution $\mathcal{R}_{r-1}$ are playing the role normally played by those from resolution $\mathcal{R}_{K-1}$, and so on. In general, resolutions $\mathcal{R}_j, 0 < j \leq r$ are behaving as resolutions $\mathcal{R}_j, K-r < j \leq K$, respectively. Finally, $\mathcal{R}_0 = LL_K$ is playing the role of LL_{K-r}. Therefore, to have visually lossless quality of the displayed image LL_{K-r}, the quantization step sizes used for $\mathcal{R}_j, 0 < j \leq r$ should be those normally used for $\mathcal{R}_j, K-r < j \leq K$ for displaying a visually lossless LL_0. In other words, the visibility thresholds for subband (θ, k) when reduced resolution image LL_{K-r} is displayed are given by

$$\hat{t}_{\theta,k}(r) = \begin{cases} t_{\theta,k-(K-r)} & \text{if } k > (K-r) \\ \infty & \text{otherwise} \end{cases} \tag{2}$$

where $t_{\theta,k}$ is the threshold of subband (θ, k) required to have visually lossless quality when the full resolution image LL_0 is displayed. Since the subbands of resolution $\mathcal{R}_j, j > r$ are not needed to display LL_{K-r}, their thresholds are infinite. As mentioned above LL_K plays the role of LL_{K-r}, necessitating an LL_K threshold for each r. These additional thresholds for the YCbCr components are measured using the same method described previously and are listed in Table 3. Figure 4 illustrates the discussion above for $K = 2$.

k	**Y**	**Cb**	**Cr**	k	**Y**	**Cb**	**Cr**
0	2.82	12.30	8.83	3	0.96	2.31	2.00
1	2.22	6.35	3.70	4	0.77	1.63	1.00
2	1.11	2.69	2.10	5	0.66	1.32	0.66

Table 3. Visibility thresholds for LL subbands.

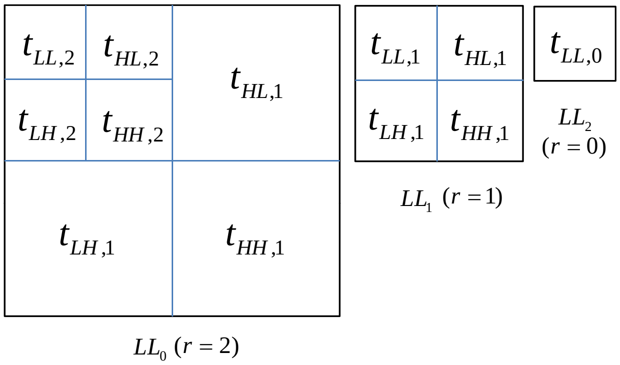

Figure 4. Visibility thresholds $\hat{t}_{\theta,k}(r)$ at three display resolutions ($K = 2$).

3.2. VISUALLY LOSSLESS QUALITY LAYERS

An image is normally quantized with a single set of thresholds, which have been optimized for the full display resolution. However, within the same subband the visibility threshold increases with spatial frequency (i.e., lower resolution images have higher visibility thresholds). This means that if the image is displayed at a reduced resolution, there will be unneeded information transmitted in the codestream. By exploiting the (quality) layer functionality of JPEG2000 to include multiple visibility thresholds for each subband, we are able to overcome this inefficiency.

In JPEG2000, a layer contains a collection of consecutive coding passes from each codeblock in a precinct. Beginning with the lowest (quality) layer $\mathcal{Q}_0$, image quality is successively improved by the incremental contributions of subsequent quality layers. In typical JPEG2000 encoder implementations, each quality layer is constructed to have near-optimal quality at full resolution for a given bitrate, with the aid of post-compression rate-distortion optimization (PCRD-opt) [9].

In the work described here, the quality layers are tied to resolutions, so that $\mathcal{Q}_0$ provides "just" visually lossless reconstruction of LL_K. The addition of $\mathcal{Q}_1$ enables just visually lossless reconstruction of LL_{K-1}, and so on. In this multi-resolution visually lossless coding scheme, quality layer $\mathcal{Q}_r$ is defined such that the maximum quantization distortion for subband (θ, k) is just smaller than the visibility threshold $\hat{t}_{\theta,k}(r)$, which is the optimal threshold value when reduced resolution image LL_{K-r} is displayed. Thus, when image LL_{K-r} is displayed, only quality layers $\mathcal{Q}_j, 0 \le j \le r$ need be decoded.*

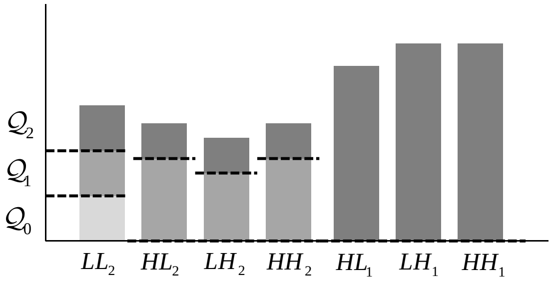

Figure 5. Quality layers for three display resolutions ($K = 2$).

Figure 5 shows an example of quality layers generated for three display resolutions ($K = 2$). The smallest display resolution LL_2 needs only quality layer $\mathcal{Q}_0$ for visually lossless quality. At the next resolution, an additional quality layer $\mathcal{Q}_1$ is decoded. At full resolution, the information from the final quality layer $\mathcal{Q}_2$ is incorporated. The advantages of the proposed scheme are clear from this figure. For example, when displaying LL_2, a straightforward treatment would discard HL_2 through HH_1 for considerable savings. However, it would retain the unneeded portions ($\mathcal{Q}_1$ and $\mathcal{Q}_2$) of LL_2. The savings of our scheme can be significant as demonstrated below.

4. EXPERIMENTAL RESULTS

The proposed multi-resolution visually lossless coding algorithm is implemented in Kakadu v.6.2.1 [10]. Experimental results are presented for four high resolution 24-bit color aerial images, provided by the Cartographic Institute of Catalonia (ICC) [11], as shown in Figure 6. The image dimensions are listed in Table 4. Images are encoded in the position-component-resolution-layer (PCRL) progression order with precinct dimension 128 × 128. This spatial progression is particularly useful for streaming using JPIP in low memory systems. A 5-level 9/7 wavelet transform ($K = 5$) is used and six quality layers are generated for multi-resolution visually lossless coding.

Figure 6. High resolution 24-bit color aerial images used in the experiment.

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[*] Of course, these quality layers can be subdivided to provide quality progressivity at each resolution.

Image	Dimension (H×W)	Numerically Lossless	Visually Lossless	Gain
1	4954 × 7149	14.5610	3.3272	77.15%
2	4900 × 7000	14.7256	3.4032	76.89%
3	4800 × 7200	12.9205	2.8316	78.08%
4	5000 × 7200	13.0459	2.8107	78.46%
Average		13.8133	3.0932	77.64%

Table 4. Bitrates comparison between numerically lossless coding and visually lossless coding for 24-bit color images.

Table 4 demonstrates the compression performance of our visually lossless coding scheme, compared with numerically lossless coding. Without any perceivable quality degradation at full resolution, our visually lossless coding scheme achieves an average bitrate of 3.09 bits-per-pixel (bpp) resulting in a compression ratio of 7.76:1, which is approximately 20% of the bitrate required for numerically lossless coding scheme.

Table 5 shows the bitrates of decoded data for our two visually lossless coding methods. The first method, used as benchmark, employs the methods from [6] to yield a visually lossless image optimized for display at full resolution. The resulting codestream contains a single quality layer. Such a codestream can be decoded (visually losslessly) at lower resolutions, achieving significant bitrate savings. This benchmark is referred to below as the single-layer method. The second method, proposed in this paper, is referred to as the multi-layer method. It should be noted that multiple layers could be included in the first method, having arbitrarily chosen bitrates as is common in conventional JPEG2000 encoding. However, there would generally be no way of knowing which layers to decode in order to achieve visually lossless performance.

Image	method	LL_5	LL_4	LL_3	LL_2	LL_1	LL_0
1	single	0.0120	0.0391	0.1264	0.4217	1.3427	3.3272
	multi	0.0057	0.0192	0.0716	0.2673	1.0231	3.3405
	gain	52.46%	50.82%	43.32%	36.61%	23.80%	−0.40%
2	single	0.0123	0.0411	0.1328	0.4404	1.3870	3.4032
	multi	0.0059	0.0198	0.0737	0.2782	1.0500	3.4166
	gain	51.96%	51.93%	44.51%	36.84%	24.30%	−0.40%
3	single	0.0125	0.0404	0.1263	0.4057	1.2780	2.8316
	multi	0.0058	0.0189	0.0693	0.2529	0.9920	2.8448
	gain	54.12%	53.20%	45.11%	37.65%	22.38%	−0.46%
4	single	0.0117	0.0399	0.1286	0.4213	1.2979	2.8107
	multi	0.0053	0.0190	0.0705	0.2640	1.0038	2.8239
	gain	55.18%	52.51%	45.17%	37.32%	22.66%	−0.47%
Average gain		53.43%	52.11%	44.53%	37.11%	23.29%	−0.43%

Table 5. Bitrates of the single-resolution and multi-resolution visually lossless coding methods.

The rates shown in Table 5 are in bpp calculated for the dimension of the full resolution image. For display of the reduced resolution image $LL_{5-r}, 0 \leq r < 5$, the single-resolution method requires decoding all subband data in $\mathcal{R}_0$,$\mathcal{R}_1$,...,$\mathcal{R}_{r-1}$, while the multi-resolution method need only decode up to quality layer $\mathcal{Q}_r$ of the same subbands. The multi-resolution method requires a slightly higher bitrate at full resolution than does the single-resolution method (due to the overhead associated with the layer information). However, visually lossless quality is achieved at lower resolutions with much smaller bitrates. As can be seen from the table, improvements in effective compression ratio are more than 2:1 at lower resolutions.

Table 6 shows total data transferred via the JPIP server, while remotely browsing the compressed images. For a fair comparison between the two coding methods, each image is browsed with the same sequence of browsing operations and the same display window. The sequence of browsing operations consists of zoom-in, zoom-in, pan, pan, zoom-in, pan, pan, zoom-in, pan and pan. The displayed image locations are the same for both methods. The viewing application shows the lowest resolution level when the image is first opened in order to overview the entire image. In the case of the multi-resolution method, the viewing application selects the quality layer appropriate to the resolution level. The results suggest that the multi-resolution method can achieve significant reductions in bandwidth, as compared to the single-resolution method. In particular, more pan operations at lower resolution levels is expected to provide much improved performance, as indicated in Table 5.

Image	Single	Multi	Gain
1	1119.7 KB	921.8 KB	17.67%
2	1128.0 KB	945.4 KB	16.19%
3	1081.9 KB	881.8 KB	18.50%
4	1057.7 KB	861.2 KB	18.58%
Average	1096.8 KB	902.6 KB	17.71%

Table 6. JPIP data transfer statistics collected while remotely browsing the compressed images.

5. CONCLUSIONS

We have presented a visually lossless coding method for high resolution color aerial images, with additional visibility thresholds for LL subbands of Cb and Cr components. Considering that a high resolution image is typically displayed at various resolutions, multiple visibility thresholds are applied within a subband via the quality layer functionality of JPEG2000. This method allows for visually lossless decoding at a variety of resolutions, using only a portion of the full resolution codestream. In the remote image browsing experiment using JPIP, images encoded by the proposed method provide a significant reduction in transmitted data without any degradation of image quality, compared to visually lossless encoded images only at full resolution. Furthermore, since the proposed method is implemented within Part-1 of the JPEG2000 standard, the codestream is decodable by any JPEG2000 decoder and the various other functionalities of JPEG2000 are preserved.

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