INTER COLOR AND INTER/INTRA BAND PREDICTION ON REVERSIBLE WAVELET FOR LOSSLESS PROGRESSIVE COLOR CODING

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ABSTRACT

We propose a new lossless progressive color coding of color still images. An image is firstly transformed by reversible Wavelet transform such as S transform due to progressive transmission of image. And we utilize for an improvement of the compression performance not only the inter color correlation but also the inter/intra band correlation of the subbands of reversible wavelet transform. We show three effective predictors to remove that correlations, and it is confirmed by numerical experiment that combination of all the predictions is the best in performance.

1. INTRODUCTION

Numerous attempts have been made toward the new international standards JPEG-LS[1]and JPEG-2000[2]. The JPEG-LS features a non linear predictor which can adapt to local statistics of an image. It has been confirmed that this kind of non linear filters, - MED (Median Edge Detector) [3], GAP (Gradient Adaptive Prediction) [4] and so on was effective for image data compaction. On the other hand, linear filters composed with an integered operator such as "*flooring*" or "*rounding*", - SP transform [5] and TT transform [8], Wavelet transform based on the lifting structure [6], are also attracting many researchers attention because of their inherent advantage for progressive data transmission. For lossless color image coding, however, most of the reports focused on encoding Red, Green and Blue(RGB) color components independently although there exists correlation between the color components (*inter color* correlation).

N.Strobel, et. al. applied linear prediction to RGB color image to utilize the inter color correlation[7]. And M.J.Gormish, et. al.[8] and S.Fukuma , et. al.[9] also developed an effective lossless color coordinate transform for lossless color coding. To attain progressive resolution transmission, a reversible Wavelet (RWT) was adopted and the inter color prediction was applied to subbands of the Wavelet[7]. However there still exists remaining correlation between subbands (*interband* correlation) and also within each of the subbands itself (*intra-band* correlation).

In this report, we propose a new lossless progressive color coding of color still images which utilizes for an improvement of the compression performance not only the inter color correlation but also inter/intra-band correlation of the RWT's subbands. The basic tools of this proposal, RWT and lossless multi-channel prediction (LMP), are summarized in section 2. We show effective three predictions - the intra band, inter band and inter color predictions in section 3. Experimental results for the lossless color image coding are given in section 4. Summary is given in section 5.

2. BASIC TOOLS

2.1. RWT and DPCM

One of the most simple and widely used RWT is a two tap orthogonal transform referred to as the S transform. It decomposes one dimensional input signal $x(m)$, $m \in \{0, 1, \cdots, M-1\}$, with M even, into two band signals $y_L(n)$ and $y_H(n)$, $n \in \{0, 1, \cdots, N-1\} (N = M/2)$ by

$$\begin{pmatrix} y_L(n) \\ y_H(n) \end{pmatrix} = \begin{pmatrix} \mathrm{F}\left[\frac{1}{2} \cdot \{x(2n) + x(2n+1)\}\right] \\ x(2n) - x(2n+1) \end{pmatrix}, \quad (1)$$

where $x(n)$ takes an integer value and $\mathrm{F}[\cdot]$ denotes the "*flooring*" from a real into an integer value. Therefore $y_L(n)$ and $y_H(n)$ have an integer value. Applying equation (1) to the original image $x(m_1, m_2)$ in horizontal and vertical direction, where m_1 and m_2 denote horizontal index and vertical index respectively, we can get four subbands, denoted by $y_{LL}(n_1, n_2)$, $y_{LH}(n_1, n_2)$, $y_{HL}(n_1, n_2)$ and $y_{HH}(n_1, n_2)$. For example, $y_{HL}(n_1, n_2)$

indicates horizontally high passed (H) and vertically low passed (L) version of the input image.

As a result of the S transform, $y_{LH}(n_1, n_2)$, $y_{HL}(n_1, n_2)$ and $y_{HH}(n_1, n_2)$ have both the more reduced variance and the weaker correlation than that of $x(m_1, m_2)$. $y_{LL}(n_1, n_2)$ is a down sampled version of original image with an *anti aliasing filter* and it is firstly transmitted and restored at decoder as a low resolution image (a thumbnail). Since $y_{LL}(n_1, n_2)$ is not decorrelated yet, we apply the non-separable two dimensional DPCM

$$y'_{LL}(n_1, n_2) = y_{LL}(n_1, n_2) - \mathrm{R}\left[\frac{1}{2}\left\{y_{LL}(n_1 - 1, n_2) + y_{LL}(n_1, n_2 - 1)\right\}\right], \quad (2)$$

where $\mathrm{R}[\cdot]$ denotes the "*rounding*" into an integer value. Applying the S transform to RGB color image, we can get four subband signals with three color components as

$$y_b(C; n_1, n_2), C \in \{R, G, B\}, b \in \{LL, LH, HL, HH\}, \quad (3)$$

which is shown in figure 1.

The subbands in equation (3) are almost decorrelated, however, it still contains remaining correlation between the bands (*inter band* correlation) and within each of the bands (*intra-band* correlation). In addition, the correlation between R, G, B (*inter color* correlation) are kept not to be utilized yet, we can exploit this redundancy for more data compression.

2.2. Lossless Multichannel Prediction (LMP)

In this report, we adopt LMP[10] to make the better use of the inter/intra band and inter color correlation still exist in the RWT's subbands, and its block diagram is illustrated in figure 1. The LMP is a multi band non separable two dimensional filter bank and it affects on an input signal as a linear predictor. In this report, in order to remove the remaining correlation effectively, we employ a type of LMP as illustrated in figure 2. The signals in equation (3) are predicted by using subband signals and color components, and the prediction error is produced by

$$y_b{}^*(C; n_1, n_2) = y_b(C; n_1, n_2) - \hat{y_b}(C; n_1, n_2), \quad (4)$$

where

$$\hat{y_b}(C; n_1, n_2) = \mathrm{R}\left[\hat{y_b}^{(IA)}(C; n_1, n_2) + \hat{y_b}^{(IB)}(C; n_1, n_2) + \hat{y_b}^{(IC)}(C; n_1, n_2)\right], \quad (5)$$

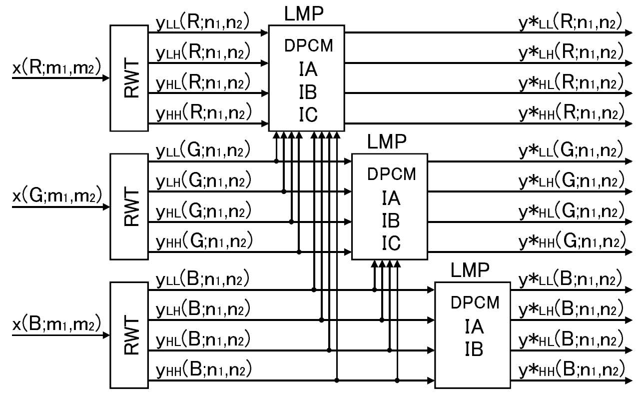

Figure 1: Inter color and intra/inter band prediction with reversible Wavelet and lossless multi-channel prediction

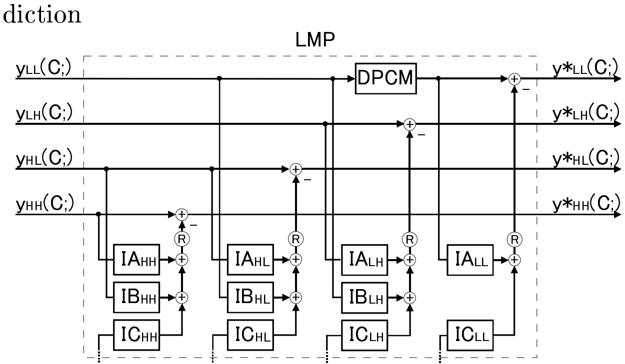

Figure 2: Inter color and intra/inter band predictor for each color $C \in \{R, G, B\}$

and

$$\begin{cases} \hat{y_b}^{(IA)} & \text{IntrA band prediction} \\ \hat{y_b}^{(IB)} & \text{Inter Band prediction} \\ \hat{y_b}^{(IC)} & \text{Inter Color prediction.} \end{cases}$$

See figure 3 for the location of pixels for prediction. Detail of the predictions in equation (5) will be described in the next section.

3. PREDICTION TYPES

3.1. Intra band prediction (IA)

As the "*intra band*" predictor in equation (5), it is used the following causal predictor:

$$\hat{y_b}^{(IA)}(C; n_1, n_2) = \underline{\alpha}_b^T(C) \cdot \underline{e}_b(C; n_1, n_2), \quad (6)$$

where

$\underline{e}_b(C; n_1, n_2) =$

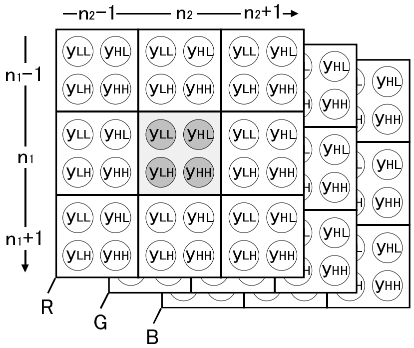

Figure 3: Pixel location for prediction

$$\begin{cases} [y_b(C;n_1-1,n_2), y_b(C;n_1,n_2-1)]^T \\ \qquad\qquad\qquad\qquad \text{for } b \neq LL \\ [y'_{LL}(C;n_1-1,n_2), y'_{LL}(C;n_1,n_2-1)]^T \\ \qquad\qquad\qquad\qquad \text{for } b = LL \end{cases}$$

$$\underline{\alpha}_b(C) = [\alpha_b(C;1), \alpha_b(C;2)]^T,$$

where underlined letter denotes a vector. IA predictor works as to remove the correlation remaining within subband. Determination of the filter coefficients $\{\alpha_b\}$ is described later.

3.2. Inter band prediction (IB)

In this report, we use the following "*inter band*" predictor:

$$\hat{y}_b^{(IB)}(C;n_1,n_2) = \underline{\beta}_b^T(C) \cdot \underline{f}_b(C;n_1,n_2), \qquad (7)$$

where

$$\underline{f}_b(C;n_1,n_2) =$$
$$\begin{cases} [0,0,0] & \text{for b=LL} \\ [y_{LL}(C;n_1-1,n_2), y_{LL}(C;n_1,n_2), \\ \qquad y_{LL}(C;n_1+1,n_2)]^T & \text{for b=LH} \\ [y_{LL}(C;n_1,n_2-1), y_{LL}(C;n_1,n_2), \\ \qquad y_{LL}(C;n_1,n_2+1)]^T & \text{for b=HL} \\ [y_{HL}(C;n_1,n_2), y_{HL}(C;n_1,n_2+1), 0]^T, \\ & \text{for b=HH} \end{cases}$$

and

$$\underline{\beta}_b(C) = [\beta_b(C;1), \beta_b(C;2), \beta_b(C;3)]^T$$

Because the band with the strongest correlation to HH-band is HL-band, IB prediction for HH-band is performed by using only HL-band signal. For HL-band, LL-band signal is used for the prediction since HL-band has a correlation with pseudo HL-band signal generated by LL-band. For LH-band it is the same as for HL-band. For LL-band, IB prediction is not performed, i.e. $\underline{\beta}_{LL} = \underline{0}$, because it can utilize only IB predicted bands and they have very few correlation with LL-band.

3.3. Intra color prediction (IC)

As the "*inter color*" predictor in equation (5), we use following predictor:

$$\hat{y}_b^{(IC)}(C;n_1,n_2) = \underline{\gamma}_b^T(C) \cdot \underline{g}_b(C;n_1,n_2), \qquad (8)$$

where

$$\underline{g}_b(C;n_1,n_2) =$$
$$\begin{array}{ll} [y_b(G;n_1,n_2), y_b(B;n_1,n_2)]^T & \text{for C=R} \\ [y_b(B;n_1,n_2), 0]^T & \text{for C=G} \\ [0,0]^T & \text{for C=B} \end{array}$$

and

$$\underline{\gamma}_b(C) = [\gamma_b(C;1), \gamma_b(C;2)]^T.$$

As the same in case of IB predictor, for IC prediction we don't utilize the signals that have already IC predicted. Therefore, IC prediction for G signal is performed by using only G signal and that for B signal is not performed.

We employ above predictions, IA, IB and IC prediction and its combination in order to improve the compression performance.

3.4. Determination of filter coefficients

In this report, the filter coefficients for a given input image are determined by linear least square method. It is obtained as the solution of the following linear simultaneous equations:

$$\underline{p}_b(C) = \Phi_b^{-1}(C) \cdot \underline{d}_b(C) \qquad (9)$$

where

$$\begin{aligned} \Phi_b(C) &= \sum_{n_1,n_2} \underline{v}_b^T(C;n_1,n_2) \cdot \underline{v}_b(C;n_1,n_2) \\ \underline{d}_b(C) &= \sum_{n_1,n_2} y_b(C;n_1,n_2) \cdot \underline{v}_b(C;n_1,n_2) \\ \underline{p}_b(C) &= \left[\underline{\alpha}_b^T(C), \underline{\beta}_b^T(C), \underline{\gamma}_b^T(C)\right]^T \end{aligned}$$

$$\underline{v}_b(C;n_1,n_2) =$$
$$\left[\underline{e}_b^T(C;n_1,n_2), \underline{f}_b^T(C;n_1,n_2), \underline{g}_b^T(C;n_1,n_2)\right]^T.$$

The above equations can be solved for each colors $C \in \{R,G,B\}$ and each bands $b \in \{LL,LH,HL,HH\}$ independently.

Since the determination of the filter coefficients must be calculated before encoding, two-pass processing is required. And also the obtained filter coefficients must be transmitted to decoder as a "*side information*". Assuming that errors on transmitting digital data are free or perfectly corrected, we can use recursive method such as RLS algorithm [11] to determine the filter coefficients at both encoder and decoder. In this report, we implement the recursive determination of the filter coefficients by RLS algorithm every pixel. If coding is processed in raster scan order and the indices for update are

$$\underline{k} = (n_1, n_2),$$

$$\underline{k}^{(-1)} = \begin{cases} (n_1, n_2 - 1) & \text{for } n_2 \neq 0 \\ (n_1 - 1, N - 1) & \text{for } n_2 = 0 \end{cases},$$

$$\underline{k}^{(+1)} = \begin{cases} (n_1, n_2 + 1) & \text{for } n_2 \neq N - 1 \\ (n_1 + 1, 0) & \text{for } n_2 = N - 1 \end{cases},$$

then the prediction process is below:

Step 0 Initialize the algorithm by setting

$$(n_1, n_2) = (0, 0), \qquad \underline{k} = (0, 0)$$

$$\Phi_b(C; \underline{k}^{(-1)}) = I, \qquad \underline{p}_b^T(C; \underline{k}) = \underline{0}$$

where I denotes identity matrix.

Step 1 Compute the predictor output by

$$\hat{y}_b(C; \underline{k}) = \underline{p}_b^T(C; \underline{k}) \cdot \underline{v}_b(C; \underline{k}),$$

and prediction error for encoding by

$$y_b^*(C; \underline{k}) = y_b(C; \underline{k}) - \mathrm{R}\left[\hat{y}_b(C; \underline{k})\right]$$

or restored subband signal for decoding by

$$y_b(C; \underline{k}) = y_b^*(C; \underline{k}) + \mathrm{R}\left[\hat{y}_b(C; \underline{k})\right].$$

Step 2 Update the filter coefficients by

$$\underline{r}_b(C; \underline{k}) = \frac{\Phi_b(C; \underline{k}^{(-1)}) \cdot \underline{v}_b(C; \underline{k})}{1 + \underline{v}_b^T(C; \underline{k}) \cdot \Phi_b(C; \underline{k}^{(-1)}) \cdot \underline{v}_b(C; \underline{k})}$$

$$\Phi_b(C; \underline{k}) = \left\{ I - \underline{r}_b(C; \underline{k}) \cdot \underline{v}_b^T(C; \underline{k}) \right\} \cdot \Phi_b(C; \underline{k}^{(-1)})$$

$$\underline{p}_b(C; \underline{k}^{(+1)}) = \underline{p}_b(C; \underline{k}) + \underline{r}_b(C; \underline{k}) \cdot y_b^*(C; \underline{k})$$

Step 3 Repeat step1 and 2 for each $C \in \{R, G, B\}$ and $b \in \{LL, LH, HL, HH\}$.

Step 4 Update (n_1, n_2).

Step 5 Repeat from step 1 to 4 until the end of image.

In this algorithm, all filter coefficients are created by only already processed(decoded) pixel, therefore we can decode without side information and we can do at one-pass as well. However, the identical computational precision and the same computational complexity are required for both encoder and decoder.

Table 1: First order entropy [bits/pixel].

Predictor	Image				
	Church	Lenna	Baboon	Couple	average
(1)	6.61	4.89	6.44	4.65	5.64
(2)	6.56	4.81	6.38	4.56	5.58
(3)	6.51	4.72	6.37	4.57	5.54
(4)	6.29	4.62	6.05	4.37	5.33
(5)	6.06	4.41	5.93	4.18	5.15
(6)	6.09	4.40	5.93	4.18	5.15

(1):RWT + DPCM, (2):RWT + DPCM + IA,
(3):RWT + DPCM + IB, (4):RWT + DPCM + IC,
(5):RWT + DPCM + IA/IB/IC,
(6):RWT + DPCM + IA/IB/IC (recursive).

4. EXPERIMENTAL RESULTS

It is used for experiment 24bpp test images of "church" (256 × 256), "lenna" (512 × 512), "baboon" (512 × 512) and "couple" (256 × 256). Experiment is performed on following cases:(1) RWT + DPCM; (2) RWT + DPCM + IntrA band; (3) RWT + DPCM + Inter Band; (4) RWT + DPCM + Inter Color; (5) RWT + DPCM + IntrA/Inter Band + Inter Color; (6) RWT + DPCM + IntrA / Inter Band + Inter Color (recursive method).

Experimental results are listed in table 1 and the measure is first order entropy [bits / pixel]. All filter coefficients are truncated into 8 bit binary data and filter coefficients determined for each image in case (5) are listed in table 2. In this case, the number of filter coefficients is 60 and it means 0.0003 bpp side information for 256 × 256 pixel image data. We can confirm effectiveness of the intra/inter band and inter color prediction from table 1. Especially, in three predictors the performance of the inter color prediction is better than that of the intra/inter band. This results from that intra/inter band correlation is already removed to a certain extent by RWT (S transform), while inter color correlation is not removed. The amount of reduced entropy in proposed method (case (5) and (6)) is about 10 % with compared to case (1).

5. SUMMARY

We proposed a new lossless progressive color coding for color still images. We utilized for an improvement of the compression performance not only the inter color correlation but also the inter/intra band correlation of the RWT's subbands. We showed three effective predictors to remove that correlations. Above predictions, the inter color prediction was relatively effective for the images used in this report. And it was confirmed by experiment that the combination of all the predictions was the best in performance.

6. REFERENCES

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Table 2: Filter coefficients of the predictor.

Band	Coef.	Image			
		Church	Lenna	Baboon	Couple
	$\alpha(R;1)$	0.086	0.141	0.000	0.078
	$\alpha(R;2)$	0.063	0.063	0.102	0.156
	$\alpha(G;1)$	0.055	0.242	-0.070	0.055
	$\alpha(G;2)$	-0.008	0.031	0.008	0.070
LL	$\alpha(B;1)$	0.102	0.313	-0.070	0.344
	$\alpha(B;2)$	-0.102	-0.047	0.023	0.102
	$\gamma(R;1)$	0.820	0.789	0.891	0.930
	$\gamma(R;2)$	0.000	-0.211	-0.258	-0.055
	$\gamma(G;1)$	0.781	1.070	0.820	0.969
	$\alpha(R;1)$	-0.383	-0.297	-0.078	-0.141
	$\alpha(R;2)$	0.070	0.055	0.117	0.156
	$\alpha(G;1)$	-0.281	-0.250	-0.078	-0.109
	$\alpha(G;2)$	0.023	0.008	0.102	0.148
	$\alpha(B;1)$	-0.508	-0.289	-0.258	-0.203
	$\alpha(B;2)$	0.047	0.008	0.320	0.266
	$\beta(R;1)$	-0.367	-0.367	-0.141	-0.195
LH	$\beta(R;2)$	0.328	0.227	0.133	0.086
	$\beta(R;3)$	0.063	0.148	0.000	0.117
	$\beta(G;1)$	-0.234	-0.367	-0.102	-0.164
	$\beta(G;2)$	0.102	0.289	0.109	0.070
	$\beta(G;3)$	0.156	0.078	-0.008	0.094
	$\beta(B;1)$	-0.500	-0.422	-0.313	-0.344
	$\beta(B;2)$	0.219	0.164	0.102	0.117
	$\beta(B;3)$	0.297	0.266	0.219	0.234
	$\gamma(R;1)$	0.422	0.281	0.820	0.570
	$\gamma(R;2)$	0.078	-0.063	-0.164	0.063
	$\gamma(G;1)$	0.563	0.555	0.828	0.680
	$\alpha(R;1)$	0.125	0.133	0.070	0.117
	$\alpha(R;2)$	-0.109	-0.188	-0.148	-0.234
	$\alpha(G;1)$	0.141	0.141	0.016	0.133
	$\alpha(G;2)$	-0.461	-0.172	-0.133	-0.172
	$\alpha(B;1)$	0.203	0.211	0.133	0.391
	$\alpha(B;2)$	-0.422	-0.273	-0.445	-0.305
	$\beta(R;1)$	-0.117	-0.250	-0.234	-0.297
HL	$\beta(R;2)$	0.078	0.148	0.188	0.219
	$\beta(R;3)$	0.047	0.094	0.047	0.070
	$\beta(G;1)$	-0.375	-0.219	-0.156	-0.203
	$\beta(G;2)$	0.570	0.070	-0.023	0.156
	$\beta(G;3)$	-0.188	0.148	0.195	0.039
	$\beta(B;1)$	-0.352	-0.344	-0.383	-0.336
	$\beta(B;2)$	0.102	0.133	0.141	0.156
	$\beta(B;3)$	0.273	0.219	0.258	0.203
	$\gamma(R;1)$	0.656	0.406	0.641	0.602
	$\gamma(R;2)$	0.055	-0.047	-0.125	-0.070
	$\gamma(G;1)$	0.703	0.609	0.555	0.695
	$\alpha(R;1)$	-0.250	-0.102	-0.023	-0.047
	$\alpha(R;2)$	-0.094	-0.047	-0.117	-0.133
	$\alpha(G;1)$	-0.242	-0.117	-0.063	-0.070
	$\alpha(G;2)$	-0.320	-0.109	-0.102	-0.117
	$\alpha(B;1)$	-0.313	-0.172	-0.164	-0.070
	$\alpha(B;2)$	-0.281	-0.133	-0.359	-0.102
	$\beta(R;1)$	0.117	-0.078	0.078	-0.117
HH	$\beta(R;2)$	0.102	0.188	-0.047	0.172
	$\beta(G;1)$	0.023	0.023	0.086	-0.109
	$\beta(G;2)$	0.227	0.117	-0.055	0.164
	$\beta(B;1)$	-0.008	-0.039	-0.031	-0.125
	$\beta(B;2)$	0.297	0.250	0.227	0.203
	$\gamma(R;1)$	0.469	0.320	0.602	0.500
	$\gamma(R;2)$	-0.008	-0.055	-0.023	0.039
	$\gamma(G;1)$	0.344	0.469	0.695	0.422