Lossless/Lossy Coding Gain To Evaluate Coding Performance of the Lossless/Lossy Wavelet

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ABSTRACT

In this report, we propose lossless/lossy coding gain as a new objective criterion to theoretically evaluate lossless and lossy coding performance of the lossless/lossy wavelet (LLW). The proposed lossless/lossy coding gain consists of three parameters: "*lossless coding gain*", "*quantization-lossy coding gain*" and "*rounding errors*". Performances of 15 kinds of the LLW are measured with two-dimensional (2D) octave-decomposition. Some standard images are applied as input signals to evaluate coding performance of the LLW.

Key words: lossless, lossy, wavelet, coding gain, rounding error, evaluation

1. INTRODUCTION

The JPEG-2000 [1] has been discussed as a new international standard that contains two operation modes – lossless mode and lossy mode. So far, some lossless/lossy wavelets (LLWs) [2]–[7] are proposed as the JPEG-2000 candidates. The LLW can be used not only as a lossless coding but also as lossy coding because of including the *"rounding"* operations. Some researchers [7]-[8] have been investigating the LLW in term of lossless compression performance and lossy compression performance separately; however a new objective measure to evaluate lossless and lossy compression performance based on the same hypothesis should be a great benefit.

Recently, we proposed the "*lossless coding gain*" [9] as an objective criterion to theoretically evaluate performance of the LLW. The relationship between the "lossless coding gain" and the existing "coding gain (lossy coding gain)" is explicitly described. It becomes possible to theoretically evaluate lossless-lossy unified coding methods of the LLW under the unified criterion – "lossless coding gain" and "lossy coding gain". However, the errors generated by rounding operations are neglected in our previous report.

In this report, we propose lossless/lossy coding gain as a new objective criterion to theoretically evaluate lossless and lossy coding performance of the LLW under the unified criterion. The lossless/lossy coding gain consists of three parameters: "lossless coding gain", "quantization-lossy coding gain" and "rounding errors". Relation among those three parameters is clearly illustrated. Rounding errors are newly considered to determine lossy coding performance of the LLW at high bit rate. We measure compression performances of 15 kinds of the well-known LLW under lossless/lossy coding gain by applying some standard images as input signals. The analysis part of coding system in this report is based on 2D octave-decomposition as shown in section 2.

2. THE LOSSLESS/LOSSY WAVELET (LLW)

We analyze analysis part and synthesis part of the one-dimensional (1D) LLW in section 2.1 and 2.2, respectively. Then, our analysis is extended to two-dimensional (2D) octave-decomposition in section 2.3.

In this report, we use z-transform expression defined by

$$X(z)=\sum_{k=0}^{K-1} x(k)\, z^{-k} \tag{1}$$

where x(k) denotes signal's intensity and its value for image signal is given in "integer". We analyze all signals in this report under the following assumptions: (1) All filters are linear and time-invariant filters (2) Correlations between each of the errors and the signals are zero (statistical independence), and (3) their power spectrums are approximately flat.

We renamed the LLW according to the numbers of taps in low-passed and high-passed filters as indicated in the first row from left in table 1. The parameters in i^{th} lifting structure of each LLW as shown in table 1 are

$$P_i(z)=\sum_{k=-3}^{3} a_{ki} z^k \tag{2}$$

Table 1. Parameters of JPEG-2000 candidates.

LWT	i	a_{3i}	a_{2i}	a_{1i}	a_{0i}	a_{-1i}	a_{2i}	a_{-3i}
2/2	1	-	-	-	-1	-	-	-
[2], [5]	2	-	-	-	1/2	-	-	-
2/6-T	1	-	-	-	-1	-	-	-
[3], [4]	2	-	-	-	1/2	-	-	-
	3	-	-	-1/4	-	1/4	-	-
2/10	1	-	-	-	-1	-	-	-
[7]	2	-	-	-	1/2	-	-	-
	3	-	3/64	-11/32	-	11/32	-3/64	-
6/14	1	-	-	-	-1	-	-	-
[7]	2	-	-	-1/16	1/2	1/16	-	-
	3	-	1/16	-3/8	-	3/8	-1/16	-
5/3	1	-	-	-1/2	-1/2	-	-	-
[4]-[7]	2	-	-	-	1/4	1/4	-	-
13/3	1	-	-	-1/2	-1/2	-	-	-
[6]	2	-	1/128	-5/128	9/32	9/32	-5/128	1/128
9/3-K	1	-	-	-1/2	-1/2	-	-	-
[6]	2	-	-	1/256	63/256	63/256	1/256	-
9/7-M	1	-	1/16	-9/16	-9/16	1/16	-	-
[4]-[7]	2	-	-	-	1/4	1/4	-	-
9/3-S	1	-	-	-1/2	-1/2	-	-	-
[4], [6]	2	-	-	-3/64	19/64	19/64	-3/64	-
13/7-C	1	-	1/16	-9/16	-9/16	1/16	-	-
[6], [7]	2	-	-	-1/16	5/16	5/16	-1/16	
13/11	1	-3/256	25/256	-150/256	-150/256	25/256	-3/256	-
[4], [5]	2	-	-	-	1/4	1/4	-	-
13/7-T	1	-	1/16	-9/16	-9/16	1/16	-	-
[5], [7]	2	-	-	-1/32	9/32	9/32	-1/32	-
5/11-C	1	-	-	-1/2	-1/2	-	-	-
[5], [7]	2	-	-	-	1/4	1/4	-	-
	3	-	-	1/16	-1/16	-1/16	1/16	-
9/7-F	1	-	-	-203/128	-203/128	-	-	-
[5], [7]	2	-	-	-	-217/4096	-217/4096	-	-
	3	-	-	113/128	113/128	-	-	-
	4	-	-	-	1817/4096	1817/4096	-	-
5/11-A	1	-	-	-1/2	-1/2	-	-	-
[7]	2	-	-	-1/16	1/2	1/16	-	-
	3	-	1/16	-3/8	-	3/8	-1/16	-

2.1 Analysis Part and Its Equivalent Expression

In this section, we investigate analysis (encoding) part of the 1D LLW. Analysis part of the 1D LLW in the left side of fig. 1 can be expressed by an equivalent expression in the right side of fig. 1. The analysis filters $H_L(z)$ and $H_H(z)$ in the right side of fig. 1 are

$$\begin{pmatrix} H_L(z) \\ H_H(z) \end{pmatrix} = \begin{pmatrix} 1 & P_4(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ P_3(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & P_2(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ P_1(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 \\ z \end{pmatrix} \quad (3)$$

and rounding errors $R_{L,A}(z)$ and $R_{H,A}(z)$ in analysis part are

$$\begin{pmatrix} R_{L,A}(z) \\ R_{H,A}(z) \end{pmatrix} = \begin{pmatrix} 1 & P_4(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ P_3(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & P_2(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ R_1(z) \end{pmatrix} + \begin{pmatrix} 1 & P_4(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ P_3(z^2) & 1 \end{pmatrix} \begin{pmatrix} R_2(z) \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & P_4(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ R_3(z) \end{pmatrix} + \begin{pmatrix} R_4(z) \\ 0 \end{pmatrix} \quad (4)$$

where $R_i(z)$ denotes additive noises generated from i^{th} rounding operation of analysis part of the 1D LLW.

In lossless mode, the band signals $Y_0(z)$ and $Y_1(z)$ are entropy coded without any quantization. In lossy mode, before the entropy coding, the band signals are quantized with step size ($\alpha_b S_Y$) by

$$\begin{pmatrix} Y'_0(z) \\ Y'_1(z) \end{pmatrix} = \begin{pmatrix} Y_0(z)/(\alpha_0 S_Y) \\ Y_1(z)/(\alpha_1 S_Y) \end{pmatrix} \quad (5)$$

where the S_Y is a quantization step size and two parameters α_b, b=0,1, are determined in section 3.2. Note If the LLW is performed by double or triple lifting structure, parameters in extended lifting structure are set to be zero as shown in table 1.

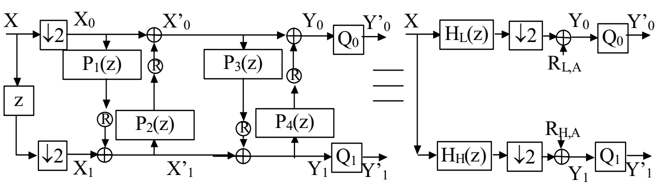

Fig. 1 Analysis part of the 1D LLW and its equivalent expression.

2.2 Synthesis Part and Its Equivalent Expression

Synthesis part of the 1D LLW in the left side of fig. 2 is also replaced by an equivalent expression in the right side of fig. 2. The synthesis filters $G_L(z)$ and $G_H(z)$ in the right side of fig. 2 are

$$\begin{pmatrix} G_L(z) \\ G_H(z) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -P_1(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & -P_2(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -P_3(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & -P_4(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ z^{-1} \end{pmatrix} \quad (6)$$

and rounding errors $R_{L,S}(z)$ and $R_{H,S}(z)$ in synthesis part are

$$\begin{pmatrix} R_{L,S}(z) \\ R_{H,S}(z) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -P_1(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & -P_2(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -P_3(z^2) & 1 \end{pmatrix} \begin{pmatrix} R'_4(z) \\ 0 \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ -P_1(z^2) & 1 \end{pmatrix} \begin{pmatrix} 1 & -P_2(z^2) \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 0 \\ R'_3(z) \end{pmatrix} + \begin{pmatrix} 1 & 0 \\ -P_1(z^2) & 1 \end{pmatrix} \begin{pmatrix} R'_2(z) \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ R'_1(z) \end{pmatrix} \quad (7)$$

where $R'_i(z)$ denotes additive noises generated from i^{th} rounding operation of synthesis part of the 1D LLW.

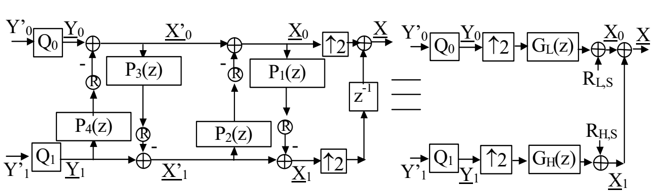

Fig. 2 Synthesis part of the 1D LLW and its equivalent expression.

2.3 The Coding System for LLW Evaluation

The coding system for LLW evaluation is based on 2D octave decomposition as shown in fig. 3. Namely, input signal (X_I) is divided into 10 subbands: "Y_{HL1}", "Y_{LH1}", "Y_{HH1}" for 1st stage, "Y_{HL2}", "Y_{LH2}", "Y_{HH2}" for 2nd stage and "Y_{LL3}", "Y_{HL3}", "Y_{LH3}", "Y_{HH3}" for 3rd stage. We denote {LL3, LH3, HL3, HH3, LH2, HL2, HH2, LH1, HL1, HH1} as {0, 1, 2, …, 9}, respectively.

The coding system in fig. 3 is replaced by its equivalent expression in the left side of fig. 4. The filter parameters in fig. 4 can be written in term of filter parameters of the 1D LLW in eq. (3) and eq. (6). Similarly, rounding errors in an equivalent expression in fig. 4 can be written in term of rounding errors in eq. (4) and eq. (7). For example, filter parameters in its equivalent expression of HL2 subband are

$$H_5(z_1, z_2) = H_L(z_1) H_L(z_2) H_H(z_1^2) H_L(z_2^2) \quad (8)$$

$$G_5(z_1, z_2) = G_L(z_1) G_L(z_2) G_H(z_1^2) G_L(z_2^2) \quad (9)$$

and rounding errors in its equivalent expression are

$$R_{5,A}(z_1, z_2) = R_{L,A}(z_1) H_L(z_2) H_H(z_1^2) H_L(z_2^2) + R_{L,A}(z_2) H_H(z_1^2) H_L(z_2^2) + R_{H,A}(z_1^2) H_L(z_2^2) + R_{L,A}(z_2^2) \quad (10)$$

$$R_{5,S}(z_1, z_2) = R_{L,S}(z_2^2) G_H(z_1^2) G_L(z_2) G_L(z_1) + R_{H,S}(z_1^2) G_L(z_2) G_L(z_1) + R_{L,S}(z_2) G_L(z_1) + R_{L,S}(z_1) \quad (11)$$

where z_1 and z_2 denote horizontal and vertical dimension respectively. Q_i in fig. 4 denotes errors generated from quantization and Up/Down sampling factor w_p in fig. 4 is

$$w_p = \begin{cases} 64 & \text{for } p = 0,1,2,3 \\ 16 & \text{for } p = 4,5,6 \\ 4 & \text{for } p = 7,8,9 \end{cases} \quad (12)$$

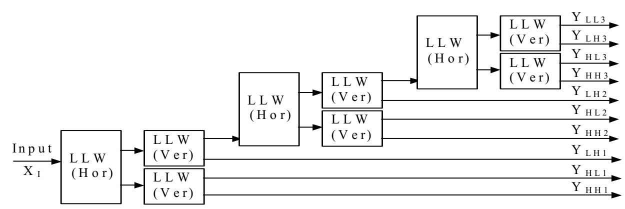

Fig. 3 2D Octave decomposition of the LLW.

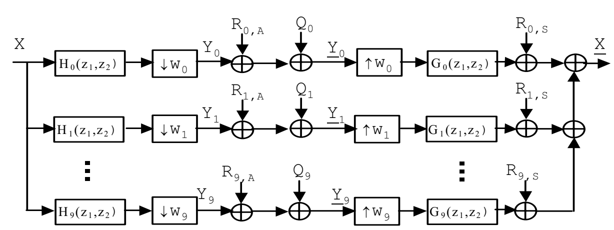

Fig. 4 The equivalent expression of the LLW in fig. 3.

3. LOSSLESS/LOSSY CODING GAIN

In this section, we propose lossless/lossy coding gain as a new objective criterion. The lossless/lossy coding gain consists of three parameters: "*lossless coding gain*", "*quantization-lossy coding gain*" and "*rounding errors*".

3.1 Lossless Coding Gain[9]

There are two kinds of the lossless coding gain: "*bit-rate-lossless coding gain*" and "*variance-lossless coding gain*" Firstly, we define bit-rate-lossless coding gain (C_{LSL}) to evaluate system's performance as a ratio between the total bit rate of PCM (B_{PCM}) and that of lossless coding (B_{LSL}) by

$$C_{LSL} = 20\log_{10}\frac{2^{B_{PCM}}}{2^{B_{LSL}}} \tag{13}$$

This can be expressed as a bit rate difference:

$$\begin{aligned} C_{LSL} &= 20(\log_{10}2)\left(B_{PCM} - B_{LSL}\right) \\ &\approx 6.02\left(B_{PCM} - B_{LSL}\right) \end{aligned} \tag{14}$$

It becomes obvious that 6 [dB] improvement of the new criterion (C_{LSL}) means 1 [bpp] bit rate reduction in lossless coding. The total bit rate B_{LSL} [bpp] can be written in term of a variance of the band signal ($\sigma^2_{y_b}$) and a constant value fixed by signal's probability density function (γ_{y_b}) as

$$B_{LSL} = \log_2 \prod_{b=0}^{9} \left(\gamma_{y_b}\sqrt{\sigma^2_{y_b}}\right)^{w_b^{-1}} \tag{15}$$

Similarly, the bit rate of PCM is also estimated by the signal's variance as

$$B_{PCM} = \log_2 \gamma_x \sqrt{\sigma_x^2} \tag{16}$$

Next, we define variance-lossless coding gain (C^*_{LSL}) from

$$C^*_{LSL} = 10\log_{10}\frac{\sigma_X^2}{\prod_{b=0}^{9}\left(\sigma^2_{y_b}\right)^{w_b^{-1}}} \tag{17}$$

Using eq. (13) – eq. (17), we can find relation between bit-rate-lossless coding gain (C_{LSL}) and variance-lossless coding gain (C^*_{LSL}) from

$$C_{LSL} = 20\log_{10}\frac{2^{B_{PCM}}}{2^{B_{LSL}}} = C^*_{LSL} + c_1 \tag{18}$$

where c_1 is constant depending on signal's probability density function as

$$c_1 = 20\log_{10}\frac{\gamma_X}{\prod_{b=0}^{9}\left(\gamma_{y_b}\right)^{w_b^{-1}}} \tag{19}$$

Hence, evaluation results of variance-lossless coding gain C^*_{LSL} is similar to evaluation results of bit-rate-lossless coding gain C_{LSL}. However, the C^*_{LSL} has an advantage because the total bit rate of signal is not necessary to be computed.

3.2 Quantization-Lossy Coding Gain

In this section, we consider relation between the "*lossless coding gain*" in eq. (18) and the "*lossy coding gain*" [2] defined by

$$C_{LSY} = 10\log_{10}\frac{\sigma^2_{PCM}}{\sigma^2_{LSY}} \tag{20}$$

where σ^2_{PCM} denotes variance of total errors in PCM coding and σ^2_{LSY} denotes variance of total errors in lossy coding calculated from

$$\sigma^2_{LSY} = \sigma^2_Q + \sigma^2_R \tag{21}$$

where σ^2_Q, and σ^2_R denote variances of total errors generated from quantization operations and rounding operations, respectively.

Next, we define quantization-lossy coding gain from conventional lossy coding gain neglected rounding error. The quantization-lossy coding gain can be applied as an objective criterion to measure lossy coding performance of the LLW in low bit rate when rounding errors are relatively small comparing to quantization errors. Then, we can find that relationship between quantization-lossy coding gain $C_{LSY,Q}$ and lossless coding gain C^*_{LSL} [9] is

$$C_{LSY,Q} = C^*_{LSL} + c_1 - \Omega \tag{22}$$

where

$$\Omega = 10\log_{10}\theta = 10\log_{10}\frac{\sum_{b=0}^{9}\left(\alpha_b^2\right)w_b^{-1}\cdot\left\|G_b\right\|^2}{\prod_{c=0}^{9}\left(\alpha_c^2\right)^{w_c^{-1}}} \tag{23}$$

Next, we minimize the Ω in eq. (23). The Ω is based on 3 parameters: α_b, G_b, and w_b. The filter G_b depends on the LLW, so we calculate the optimum quantization step size (α_b) to minimize Ω. From solving the following differential equation

$$\frac{\partial\Omega}{\partial\alpha_b} = 0 \ \ ; \text{ for } \forall\,\alpha_b \tag{24}$$

, we find the optimum quantization steps given [9] by

$$\alpha_b = \frac{\left\|G_0\right\|}{\left\|G_b\right\|}, \quad b = 0,1,\cdots,9 \tag{25}$$

where

$$\left\|G_b\right\| = \sqrt{\sum_{k_2}\sum_{k_1} g_b^2(k_1,k_2)} \tag{26}$$

As a result, we find that eq. (25) should be applied to the quantization of the band signals. In this case (optimum bit allocation), eq. (23) becomes

$$\Omega_{opt} = 10\log_{10}\prod_{b=0}^{9}\left(\left\|G_b\right\|^2\right)^{w_b^{-1}} \tag{27}$$

3.3 Rounding Errors

However, rounding errors cannot be neglected at high bit rate when quantization errors are relatively small comparing to rounding errors. Based on the assumptions mentioned in the previous section, variance of rounding errors of analysis part in eq. (4) is calculated from

$$\begin{aligned}\begin{pmatrix}\sigma^2_{R_{L,A}} \\ \sigma^2_{R_{H,A}}\end{pmatrix} &= \begin{pmatrix}1 & \left\|P_4(z^2)\right\|^2 \\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 \\ \left\|P_3(z^2)\right\|^2 & 1\end{pmatrix}\begin{pmatrix}1 & \left\|P_2(z^2)\right\|^2 \\ 0 & 1\end{pmatrix}\begin{pmatrix}0 \\ \sigma^2_{R_1}\end{pmatrix} + \\ &\begin{pmatrix}1 & \left\|P_4(z^2)\right\|^2 \\ 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 \\ \left\|P_3(z^2)\right\|^2 & 1\end{pmatrix}\begin{pmatrix}\sigma^2_{R_2} \\ 0\end{pmatrix} + \begin{pmatrix}1 & \left\|P_4(z^2)\right\|^2 \\ 0 & 1\end{pmatrix}\begin{pmatrix}0 \\ \sigma^2_{R_3}\end{pmatrix} + \begin{pmatrix}\sigma^2_{R_4} \\ 0\end{pmatrix}\end{aligned} \tag{28}$$

where

$$\sigma^2_{R_1} = \sigma^2_{R_2} = \sigma^2_{R_3} = \sigma^2_{R_4} = \frac{1}{12} \tag{29}$$

Similar to eq. (28), we can calculate variance of rounding errors of the equivalent expressions from eq. (7), eq. (10) and eq. (11). Next, we can calculate variance of rounding error in the coding system for LLW evaluation from

$$\sigma^2_R = \sum_{i=0}^{9}\frac{\sigma^2_{Ri,A} * \left\|G_i\right\|}{w_i} + \sum_{i=0}^{9}\frac{\sigma^2_{Ri,S}}{w_i} \tag{30}$$

where $\sigma^2_{Ri,A}$ and $\sigma^2_{Ri,S}$ denote variance of i^{th} rounding error in analysis part and synthesis part, respectively. Finally, the conventional lossy coding gain is determined from eq. (20) – eq. (22) as

$$C_{LSY} = \frac{\sigma^2_{PCM}}{10^{-(C^*_{LSL}+c_1-\Omega)}\,\sigma^2_{PCM} + \sigma^2_R} \tag{31}$$

From eq. (31), it's implied that lossy coding performance in high bit rate (when quantization errors are relatively small comparing to rounding errors) mainly depends on variance of rounding errors. Therefore, variance of rounding errors can be used as a criterion to measure lossy coding performance of the LLW in high bit rate.

As a conclusion, we propose lossless/lossy coding gain consisting of three parameters. The lossless coding gain and quantization-lossy coding gain are varied depending on image inputs; whereas, variance of rounding errors is constant depending on parameters of the LLW. The lossless coding gain is applied as an objective criterion to measure lossless coding performance of the LLW. The quantization-lossy coding gain and variance of rounding errors are applied as objective criteria to measure lossy coding performance of the LLW in low bit rate and high bit rate, respectively.

4. SIMULATION RESULTS

In this report, we apply lossless/lossy coding gain to evaluate coding performance of the LLW. The 256 * 256 monochrome standard images with 8 bits/pixels are applied as input signals using the following images: "Couple", "Aerial", "Girl", "Chest (x-ray), "Moon", "Barbara", "Cartoon", "Flower", "Basketball", "Plant", "Barbara2", and "Lena". The lossless/lossy coding gain is summarized in table 2. Notice that C_{LSL}, C^*_{LSL} and $C_{LSY,Q}$ in table 2 are calculated from averaged over all standard images as mentioned.

Table 2. Lossless/lossy coding gain.

LLW name	C_{LSL} (average)	C^*_{LSL} (average)	Ω_{opt}	$C_{LSY,Q}$ (average)	σ_R^2
2/2	5.95	6.37	0	6.37	0.656
2/6-T	6.43	7.77	0.175	7.6	0.847
2/10	6.51	7.91	0.333	7.58	0.872
6/14	6.51	7.77	0.071	7.7	0.813
5/3	6.59	8.20	0.429	7.77	0.666
13/3	6.58	8.15	0.341	7.81	0.664
9/3-K	6.6	8.21	0.445	7.77	0.666
9/7-M	6.69	8.41	0.568	7.84	0.749
9/3-S	6.57	8.12	0.338	7.78	0.664
13/7-C	6.69	8.38	0.356	8.02	0.745
13/11	6.71	8.38	0.637	7.74	0.789
13/7-T	6.7	8.42	0.409	8.01	0.746
5/11-C	6.69	8.39	0.591	7.8	0.843
9/7-F	6.58	8.14	0.154	7.99	2.171
5/11-A	6.66	8.36	0.499	7.86	0.832

From results in table 2, we conclude the following facts:

1. The results in table 2 confirm high correlation between variance-lossless coding gain and bit-rate-lossless coding gain shown in eq. (17)
2. The "13/11" has the highest variance-lossless coding gain followed by the "13/7-T", "13/7-C" and "5/11-C", respectively. The "13/7-T" has the highest bit-rate-lossless coding gain followed by the "9/7-M", "5/11-C", "13/7-C" and "13/11", respectively. These results are supported by results presented in M.D. Adams's report [7].
3. The "13/7-C" has the highest quantization-lossy coding gain followed by "13/7-T", "9/7-F", "5/11-A", and "9/7-M", respectively. These results are slightly different from results presented in in M.D. Adams's report [7]. This is because optimum bit allocation is applied in this report as shown in eq. (25) – eq. (27).
4. The "2/2" has the lowest variance of rounding errors followed by "13/3", "9/3-S", "9/3-K", and "5/3", respectively. Quantization-lossy coding gain of the "2/2" is not so high, so lossy coding performance of the "2/2" in high bit rate is not the best.

From the previous facts, we suggest the follows:

1. The "13/7-T" and "13/7-C" are appropriate for image applications that are mainly operated in lossless coding and lossy coding in low bit rate.
2. The "13/3" and "9/3-S" are suitable for image applications that are mainly operated in lossless coding and lossy coding in high bit rate.

5. CONCLUSION

In this report, we proposed a new objective criterion to evaluate coding performance of the LLW in both lossless and lossy coding. Our proposed criterion consists of three parameters: "*lossless coding gain*", "*quantization-lossy coding gain*" and "*rounding errors*". We measured coding performance of 15 kinds of the LLW based on two-dimension (2D) octave-decomposition.

From evaluation results, we summarize that the "13/7-T" and "13/7-C" are suitable for image applications mainly operating in lossless coding and lossy coding in low bit rate, whereas the "13/3" and "9/3-S" are appropriate for image applications mainly operating in lossless coding and lossy coding in high bit rate.

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