A New Optimum-Word-Length-Assignment (OWLA) Multiplierless Integer DCT for Unified Lossless/Lossy Image Coding

Somchart CHOKCHAITAM[1] and Masahiro IWAHASHI[2]

[1]Department of Electrical Engineering, Thammasat University, Bangkok, Thailand
[1]E-mail:csomchar@engr.tu.ac.th
[2]Department of Electrical Engineering, Nagaoka University of Technology, Nagaoka city, Niigata, Japan

ABSTRACT

Recently, we proposed a new multiplierless 1D Int-DCT modified from our existing Int-DCT by approximating floating multiplications to bit-shift and addition operations. The multiplierless 1D Int-DCT can be well operated both lossless coding and lossy coding. However, our multiplierless 1D Int-DCT is not focused on how to assign word-length for floating-multiplier approximation as short as possible for reduction of hardware complexity. In this report, we propose a new Optimum-Word-Length-Assignment (OWLA) multiplierless Int-DCT. The new OWLA multiplierless 1D Int-DCT is not only inexpensive hardware complexity but also well operated in both lossless coding and lossy coding. Simulation results confirm an effectiveness of the proposed OWLA multiplierless 1D Int-DCT.

Key words: Integer-DCT, lossless, lossy, image compression, multiplierless, Optimum-Word-Length-Assignment (OWLA)

1. INTRODUCTION

The Discrete Cosine Transform (DCT) [1] is an important transform used in many coding standards such as lossy JPEG [2] for a still image coding and MPEG [3] for a moving image coding. However, its coding system is limited to only lossy coding because distortion of decoded image is unavoidable with this lossy algorithm.

The Integer DCT (Int-DCT) [4-10] have been designed from the conventional lossy DCT to be a lossless transform. The Int-DCT-based coding system can provide not only lossy coding with a compatibility with the conventional DCT for a high compression ratio but also lossless coding for a high quality decoded image.

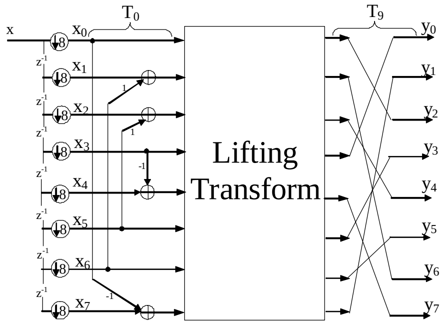
So far, many kinds of the Int-DCT [4-10] including our proposed Int-DCT have been proposed with different advantages and disadvantages. In our research, our first proposed floating 1D Int-DCT was proposed with an objective to reduce rounding effects by minimizing number of rounding operations because rounding effects increase a variance of total errors in a decoded image [12]. However, hardware complexity of our existing floating Int-DCT is high because many floating multipliers are required.

Recently, we proposed 1D multiplierless Int-DCT improved from our first proposed 1D Int-DCT by removing its multipliers by approximating floating multiplications to bit shift and addition operations. The proposed multiplierless 1D Int-DCT can be well operated both lossless coding for a high quality decoded image and lossy coding for a compatibility with the conventional DCT-based coding system. However, our multiplierless 1D Int-DCT is not focused on how to assign word-length for floating-multiplier approximation as short as possible for reduction of hardware complexity.

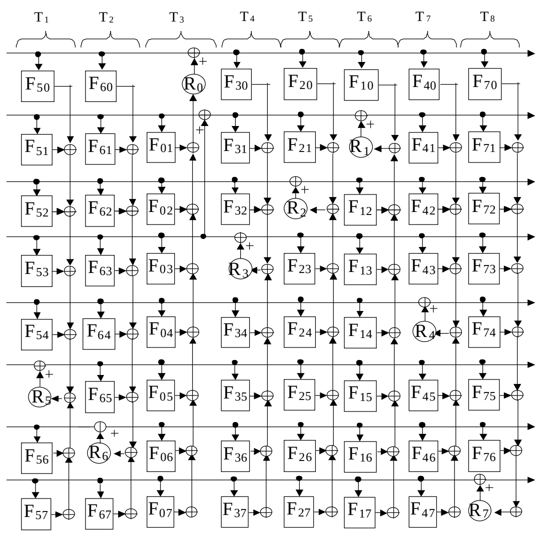
In this report, we propose a new Optimum-Word-Length-Assignment (OWLA) multiplierless Int-DCT. The new OWLA multiplierless 1D Int-DCT is not only inexpensive hardware complexity but also still well operated in both lossless coding and lossy coding. Simulation results confirm an effectiveness of the proposed OWLA multiplierless 1D Int-DCT.

2. OUR EXISTING MULTIPIERLESS 1D INT-DCT

2.1 Our Floating 1D Int-DCT (F Int-DCT)[9]



(a) Our floating 8-point Int-DCT



(b) Signal processing of lifting transformation

Fig. 1 *Our floating 1D Int-DCT (F Int-DCT)*

In previous report, our floating 1D 8-point Int-DCT [9] was introduced to emphasize on reducing rounding error and it's also applied an optimum quantization step to optimize quantization error [13]. The first proposed 1D Int-DCT was designed by applying a simple concept of rounding operation and lifting structure [11] under a constraint that a determinant of a transform matrix must equal one. The floating 1D Int-DCT requires only 8 rounding operations as illustrated in Fig. 1. Filter coefficients operated from subband i^{th} to subband j^{th} (F_{ij}) are floating values illustrated as the follows:

$$\begin{bmatrix} F_{00} & F_{01} & F_{02} & F_{03} & F_{04} & F_{05} & F_{06} & F_{07} \\ F_{10} & F_{11} & F_{12} & F_{13} & F_{14} & F_{15} & F_{16} & F_{17} \\ F_{20} & F_{21} & F_{22} & F_{23} & F_{24} & F_{25} & F_{26} & F_{27} \\ F_{30} & F_{31} & F_{32} & F_{33} & F_{34} & F_{35} & F_{36} & F_{37} \\ F_{40} & F_{41} & F_{42} & F_{43} & F_{44} & F_{45} & F_{46} & F_{47} \\ F_{50} & F_{51} & F_{52} & F_{53} & F_{54} & F_{55} & F_{56} & F_{57} \\ F_{60} & F_{61} & F_{62} & F_{63} & F_{64} & F_{65} & F_{66} & F_{67} \\ F_{70} & F_{71} & F_{72} & F_{73} & F_{74} & F_{75} & F_{76} & F_{77} \end{bmatrix} = \tag{1}$$

$$\begin{bmatrix} 0 & 0.2071 & -0.2071 & -1 & -0.5 & 0 & 0 & 0.5 \\ 0.0733 & 0 & -0.3536 & -1.2803 & 0.5 & 0 & 0 & 0 \\ 0.4142 & 0.8284 & 0 & -1.9142 & 0.4142 & 0 & 0 & 0 \\ 0.5858 & 0.1716 & 0.4142 & 0 & 0.5858 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -0.7071 & 0.7351 & -0.1989 \\ 0 & -0.0994 & -0.5 & 0 & 0.2832 & 0 & 0.1989 & -0.4239 \\ 0 & -0.5 & 0 & 0 & -0.3536 & -0.1913 & 0 & -0.3536 \\ 0 & 0 & 0 & 0 & 0.1913 & 0.8155 & 0.5665 & 0 \end{bmatrix}$$

We can calculate the transform matrix (**$IDCT_P$**) of the proposed Int-DCT [9] as

$$\mathbf{IDCT_P} = \begin{bmatrix} 0.2929 & 0.2929 & 0.2929 & 0.2929 & 0.2929 & 0.2929 & 0.2929 & 0.2929 \\ 0.4809 & 0.4078 & 0.2725 & 0.0956 & -0.0956 & -0.2725 & -0.4078 & -0.4809 \\ 0.5 & 0.2071 & -0.2071 & -0.5 & -0.5 & -0.2071 & 0.2071 & 0.5 \\ 0.4239 & -0.0994 & -0.5 & -0.2832 & 0.2832 & 0.5 & 0.0994 & -0.4239 \\ 0.3536 & -0.3536 & -0.3536 & 0.3536 & 0.3536 & -0.3536 & -0.3536 & 0.3536 \\ 0.2725 & -0.481 & 0.0956 & 0.4078 & -0.4078 & -0.0956 & 0.481 & -0.2725 \\ 0.2133 & -0.5152 & 0.5152 & -0.2134 & -0.2134 & 0.5152 & -0.5152 & 0.2133 \\ 0.0995 & -0.2832 & 0.4239 & -0.5 & 0.5 & -0.4239 & 0.2832 & -0.0995 \end{bmatrix} \tag{2}$$

Similarly, we can calculate the **$IDCT_x$** matrix of the other conventional 1D Int-DCTs as

$$\mathbf{IDCT_X} = \begin{bmatrix} 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} & 1/\sqrt{8} \\ c_1(1) & c_1(3) & c_1(5) & c_1(7) & c_1(9) & c_1(11) & c_1(13) & c_1(15) \\ c_2(1) & c_2(3) & c_2(5) & c_2(7) & c_2(9) & c_2(11) & c_2(13) & c_2(15) \\ c_3(1) & c_3(3) & c_3(5) & c_3(7) & c_3(9) & c_3(11) & c_3(13) & c_3(15) \\ c_4(1) & c_4(3) & c_4(5) & c_4(7) & c_4(9) & c_4(11) & c_4(13) & c_4(15) \\ c_5(1) & c_5(3) & c_5(5) & c_5(7) & c_5(9) & c_5(11) & c_5(13) & c_5(15) \\ c_6(1) & c_6(3) & c_6(5) & c_6(7) & c_6(9) & c_6(11) & c_6(13) & c_6(15) \\ c_7(1) & c_7(3) & c_7(5) & c_7(7) & c_7(9) & c_7(11) & c_7(13) & c_7(15) \end{bmatrix} \tag{3}$$

where function $c_i(m)$ is defined from

$$c_i(m) = \cos(i * m * \pi/16)/2 \tag{4}$$

We can write a relation between the transform matrix of the proposed Int-DCT from eq. (2) and that of the existing one from eq. (3) by

$$\mathbf{IDCT_x} = \begin{bmatrix} 1.1716 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.2437 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.6863 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.0396 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0396 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.9621 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9618 \end{bmatrix} \mathbf{IDCT_p} \tag{5}$$

2.2 Our Existing Multiplierless Int-DCT (M Int-DCT)[10]

Our existing Multiplierless Int-DCT is improved our floating 1D Int-DCT by approximating floating multiplications to bit shift and addition operations. In previous report, the same 8 word-length is applied to all filter coefficients. To achieve that goal, filter coefficients operated from subband i^{th} to subband j^{th} (F_{ij}) are approximated to 8-bit-word-length assignment as the follows:

$$\begin{bmatrix} F_{00} & F_{01} & F_{02} & F_{03} & F_{04} & F_{05} & F_{06} & F_{07} \\ F_{10} & F_{11} & F_{12} & F_{13} & F_{14} & F_{15} & F_{16} & F_{17} \\ F_{20} & F_{21} & F_{22} & F_{23} & F_{24} & F_{25} & F_{26} & F_{27} \\ F_{30} & F_{31} & F_{32} & F_{33} & F_{34} & F_{35} & F_{36} & F_{37} \\ F_{40} & F_{41} & F_{42} & F_{43} & F_{44} & F_{45} & F_{46} & F_{47} \\ F_{50} & F_{51} & F_{52} & F_{53} & F_{54} & F_{55} & F_{56} & F_{57} \\ F_{60} & F_{61} & F_{62} & F_{63} & F_{64} & F_{65} & F_{66} & F_{67} \\ F_{70} & F_{71} & F_{72} & F_{73} & F_{74} & F_{75} & F_{76} & F_{77} \end{bmatrix} = \tag{6}$$

$$\frac{1}{256} * \begin{bmatrix} 0 & 53 & -53 & -256 & -128 & 0 & 0 & 128 \\ 19 & 0 & -91 & -327 & 128 & 0 & 0 & 0 \\ 106 & 212 & 0 & -490 & 106 & 0 & 0 & 0 \\ 149 & 43 & 106 & 0 & 149 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -181 & 188 & -51 \\ 0 & -25 & -128 & 0 & 73 & 0 & 51 & -109 \\ 0 & -128 & 0 & 0 & -91 & -49 & 0 & -91 \\ 0 & 0 & 0 & 0 & 49 & 209 & 145 & 0 \end{bmatrix}$$

Filter coefficients in eq.(6) can be operated by only shift and addition operations. For example, F_{01} can be operated as the follows:

$$F_{01} = \frac{53}{256} = \frac{32}{256} + \frac{16}{256} + \frac{4}{256} + \frac{1}{256} = \frac{1}{8} + \frac{1}{16} + \frac{1}{64} + \frac{1}{256} = \frac{1}{2^3} + \frac{1}{2^4} + \frac{1}{2^6} + \frac{1}{2^8} \tag{7}$$

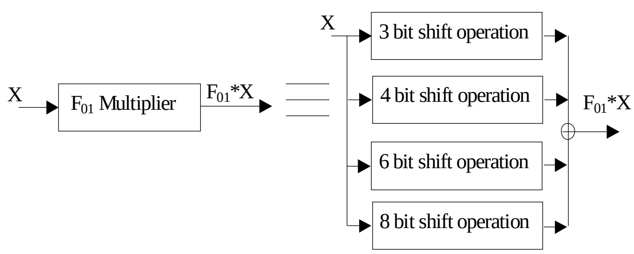


***Fig. 2** Approximation floating multiplication to bit shift and addition operations*

From eq.(7), we can replace F_{01} multiplication to summation of results from 3 bit shift, 4 bit shift, 6 bit shift, and 8 bit shift operations as illustrated in Fig. 2. Therefore, it requires 205 bit shift operations and 116 addition operations to perform 1D Multiplierless Int-DCT.

From filter coefficients in eq.(6), the transform matrix (**IDCT**) of the multiplierless Int-DCT is

$$\mathbf{IDCT}_P = \begin{bmatrix} 0.2910 & 0.2885 & 0.2936 & 0.2949 & 0.2910 & 0.2936 & 0.2885 & 0.2910 \\ -0.4782 & -0.4068 & -0.2729 & -0.0957 & 0.0957 & 0.2729 & 0.4089 & 0.4782 \\ 0.5000 & 0.2070 & -0.2070 & -0.5000 & -0.5000 & -0.2070 & 0.2070 & 0.5000 \\ 0.4258 & -0.0977 & -0.5000 & -0.2852 & 0.2852 & 0.5000 & 0.1016 & -0.4258 \\ -0.3500 & 0.3617 & 0.3524 & -0.3575 & -0.3500 & 0.3524 & 0.3617 & -0.3500 \\ 0.2740 & -0.4813 & 0.0957 & 0.4100 & -0.4100 & -0.0957 & 0.4806 & -0.2740 \\ -0.2102 & 0.5183 & -0.5156 & 0.2132 & 0.2156 & -0.5156 & 0.5183 & -0.2102 \\ 0.0994 & -0.2844 & 0.4238 & -0.4973 & 0.4973 & -0.4238 & 0.2811 & -0.0994 \end{bmatrix} \quad (8)$$

3. A NEW OPTIMUM-WORD-LENGTH-ASSIGNMENT MULTIPLIERLESS INTEGER DCT

Recently, we proposed the "SNR sensitivity" [9] defined as an effect of the finite word length expression on a quality of the decoded image. In this report, we apply the SNR sensitivity to design a new optimum-word-length-assignment multiplierless Int-DCT as the follows:

3.1 The Optimum Word Length Assignment Method

In this report, we optimize word-length assignment of 26 floating multiplier coefficients in our Int-DCT as illustarte d in table 1. First, the 26 floating multiplier coefficient F_{ji}, is expressed as h_k, (k=0,1,…,25), by

$$h_k = (-1)^{B_0} \cdot \sum_{j=1}^{\infty} B_j 2^{-j}, \qquad k = 0,1,\Lambda,25 \quad (9)$$

where B_j (j=0,1,…) is 0 or 1. Under the finite word length expression in this report, h_k is truncated into W_k [bit] b inary value h_k'. Namely,

$$h_k' = (-1)^{B_0} \cdot \sum_{j=1}^{W_k} B_j' 2^{-j}, \qquad k = 0,1,\Lambda,25 \quad (10)$$

Value Δh_k is defined as a difference between value h_k and binary value h_k' as

$$\Delta h_k = h_k - h_k' \quad (11)$$

Then, we calculate errors generated from finite word length allocation ($\mathbf{N_{TF}}$) in the decoded image [] as

$$\mathbf{N_{TF}} = \sum_{k=0}^{25} (\mathbf{S_{Hk}} \cdot \Delta h_k) \quad (12)$$

where the $\mathbf{S_{Hk}}$ called "SNR sensitivity" is defined as an effect of the finite word length expression on a quality of the decoded image. Next, we calculate the "relative SNR sensitivity" (SR_k) by

$$SR_k = \frac{\|\mathbf{S_{Hk}}\|}{\prod_{p=0}^{25} \sqrt[15]{\|\mathbf{S_{Hp}}\|}}, \qquad k = 0,1,\Lambda,25 \quad (13)$$

The optimum-word-length assignment is given by the relative SNR sensitivity SR_k as follows.

$$\Delta W_k = W_k - \overline{W} = \log_2 \frac{\|\mathbf{S_{Hk}}\|}{\overline{\|\mathbf{S_{Hk}}\|}} = \log_2 SR_k \quad (14)$$

$k = 0,1,\Lambda,25$

3.2 A New Optimum-Word-Length-Assignment Multiplierless Integer DCT (OWLA Int-DCT)

In our previous report, we found that an optimum word length assignment depending on input signal. To find an optimum word length assignment of our existing multiplierless Int-DCT, AR(1) model is applied as representative input for image data. We theoretically calculate the optimum-word-length assignment by applying the AR(1) model with correlation coefficient ρ=0.8 as an input signal, which its frequency spectrum is

$$\left| X(e^{jw}) \right| = \frac{1-\rho}{\sqrt{1+\rho^2 - 2\rho \cdot \cos\omega}} \quad (15)$$

Table 1 illustrates the optimum-word-length assignment (ΔW_k) of our existing multiplierless Int-DCT based on the AR(1) model with correlation coefficient ρ=0.8. Examples of number of assigned bits are shown in table 1. Notice that at least 1 bit must be assigned to represent floating multiplier coefficients.

Table 1 The optimum-word-length-assignment results based on AR(1) model with ρ=0.8

F_{ji}	h_k	ΔW_k	No. of assigned bits when 4 bits (average)	No. of assigned bits when 8 bits (average)
F_{51}	h_0	2.3148	6	10
F_{54}	h_1	-1.0599	3	7
F_{56}	h_2	0.2963	4	8
F_{57}	h_3	1.8883	6	10
F_{64}	h_4	-1.0318	3	7
F_{65}	h_5	-1.0714	3	7
F_{67}	h_6	1.9164	6	10
F_{01}	h_7	2.8824	7	11
F_{02}	h_8	2.1805	6	10
F_{30}	h_9	0.3346	4	8
F_{31}	h_{10}	3.6008	7	11
F_{32}	h_{11}	2.8988	7	11
F_{34}	h_{12}	-0.3415	3	7
F_{20}	h_{13}	-0.815	3	7
F_{21}	h_{14}	2.4512	6	10
F_{23}	h_{15}	2.0749	6	10
F_{24}	h_{16}	-1.4911	2	6
F_{10}	h_{17}	-1.0443	3	7
F_{12}	h_{18}	-3.7779	1	5
F_{13}	h_{19}	1.8456	6	10
F_{45}	h_{20}	-1.595	2	6
F_{46}	h_{21}	-3.3595	1	5
F_{47}	h_{22}	1.3927	5	9
F_{74}	h_{23}	-5.5894	1	5
F_{75}	h_{24}	-1.5679	2	6
F_{76}	h_{25}	-3.3324	1	5

4. Simulation Results

We confirm an effectiveness of our new optimum-word-length-assignment (OWLA) multiplierless Int-DCT by comparing its coding performances to those of our conventional multiplierless Int-DCT in term lossless coding performance, lossy coding performance, and a compatibility with the conventional Int-DCT.

4.1 Lossless coding

In this report, some of standard images are applied to confirm an effectiveness of the proposed 1D Int-DCT not only in lossy coding and but also in lossless coding. The first order entropy rate [13] in this report is defined from

$$H = -\sum_{s} P_s \log_2 P_s \tag{16}$$

where P_s indicates probability of a symbol *s*. From results in table 2, total entropy rates of our first proposed Int-DCT are the best but its hardware complexity is the highest too. Considered on the same assigned bits, total entropy rates of the proposed OWLA multiplierless Int-DCT is better than that of the existing multiplierless Int-DCT.

Table 2 Total entropy rate (bpp) for lossless coding

Image name	F Int-DCT	M Int-DCT		OWLA Int-DCT	
		4 bits	8 bits	4 bits	8 bits
Couple	4.4307	4.5682	4.4337	4.4829	4.4288
Aeirl	5.7767	5.8691	5.7783	5.8537	5.7773
Girl	4.6902	4.8445	4.6998	4.7536	4.6921
Chest-X Ray	6.1383	6.1815	6.1394	6.1836	6.1411
Moon	5.0662	5.1398	5.0692	5.1184	5.0664
Barbara	4.862	5.1037	4.8754	4.9843	4.8604
Average	5.1606	5.2845	5.1659	5.2294	5.1610

4.2 Lossy coding

In this section, the 1D Int-DCTs are applied in both analysis and synthesis filter. We also applied the optimum quantization step [13] given by

$$\frac{\Delta_b}{\Delta_k} = \frac{\|G_k\|}{\|G_b\|} \tag{17}$$

where Δ_b ,Δ_k denotes quantization step size in b^{th} subband and k^{th} subband, respectively. $\|G_b\|$ is calculated from

$$\|G_b\| = \sqrt{\sum_{k_2}\sum_{k_1} g_b^2(k_1,k_2)} \tag{18}$$

and $g_b(k_1,k_2)$ are filter coefficients of the synthesis filter G_b. From results in table 3 and table 4, PSNR of a decoded image based on F Int-DCT, M Int-DCT 8 bits and OWLA Int-DCT 8 bits are the same results but those are better than those of low hardware-complexity Int-DCT such as our M Int-DCT 4 bits and our OWLA Int-DCT 4 bits. Considered on the same assigned bits, PSNR of a decoded image based on our OWLA Int-DCT is slightly better than that of our M Int-DCT.

Table 3 PSNR of a decoded image at 4 bpp.

Image name	F Int-DCT	M Int-DCT		OWLA Int-DCT	
		4 bits	8 bits	4 bits	8 bits
Couple	49.4	48.5	49.4	49.2	49.4
Aeirl	45.3	45.0	45.3	44.9	45.3
Girl	48.1	47.6	48.1	47.9	48.1
Chest-X Ray	44.0	43.5	44.0	43.5	44.0
Moon	47.6	47.3	47.6	47.3	47.6
Barbara	47.7	47.5	47.7	47.5	47.7
Average	47.0	46.6	47.0	46.7	47.0

Table 4 PSNR of a decoded image at 1 bpp.

Image name	F Int-DCT	M Int-DCT		OWLA Int-DCT	
		4 bits	8 bits	4 bits	8 bits
Couple	37.8	36.8	37.8	37.4	37.8
Aeirl	29.1	28.3	29.1	28.4	29.1
Girl	36.4	35.5	36.4	36.0	36.4
Chest-X Ray	27.2	26.8	27.2	26.8	27.2
Moon	33.8	33.3	33.8	33.4	33.8
Barbara	34.3	32.9	34.3	33.6	34.3
Average	33.1	32.3	33.1	32.6	33.1

4.3 A compatibility with the conventional Int-DCT

In this section, we illustrate a compatibility with the conventional DCT by applying our conventional Int-DCT as an analysis filter and the Int-DCT as a synthesis filter. From results in table 5 and table 6, PSNR of a decoded image based on the conventional Int-DCT is the best but its hardware complexity is the hisghest too. Considered on the same assigned bits, PSNR of a decoded image based on the proposed OWLA multiplierless Int-DCT is significantly better than that of the existing multiplierless Int-DCT (especially 4 assigned bits) because of finite-word-length effects. These results confirm an effectiveness of our proposed OWLA multiplierless Int-DCT.

Table 5 PSNR of a decoded image at 4 bpp.

Image name	F Int-DCT	M Int-DCT		OWLA Int-DCT	
		4 bits	8 bits	4 bits	8 bits
Couple	50.7	32.7	48.0	41.2	49.4
Aeirl	46.0	30.4	44.6	35.7	45.0
Girl	49.2	30.9	46.7	40.8	48.0
Chest-X Ray	44.2	30.1	43.2	33.4	43.8
Moon	49.4	34.5	47.0	40.8	47.5
Barbara	48.5	30.0	46.1	35.4	47.3
Average	48.0	31.4	45.9	37.9	46.8

Table 6 PSNR of a decoded image at 1 bpp.

Image name	F Int-DCT	M Int-DCT		OWLA Int-DCT	
		4 bits	8 bits	4 bits	8 bits
Couple	37.8	31.6	37.6	36.3	37.7
Aeirl	29.0	26.8	28.9	28.3	28.9
Girl	36.4	29.9	36.3	35.5	36.4
Chest-X Ray	27.2	25.5	27.1	26.5	27.2
Moon	33.8	31.3	33.8	33.1	33.8
Barbara	34.4	28.7	34.1	31.9	34.2
Average	33.1	29.0	32.9	31.9	33.0

From results in this report, overall coding performances of our proposed OWLA multiplierless Int-DCT is better than those of existing multiplierless Int-DCTs. However, overall coding performances of our proposed OWLA multiplierless Int-DCT is worse than that of our existing floating Int-DCT because it's trading off between hardware complexity and coding performance.

5. Conclusion

In this report, a new OWLA multiplierless 1D Int-DCT was proposed for unified lossless/lossy coding. A OWLA new multiplierless 1D Int-DCT does not require any floating multiplier and it's considered word-length for floating-multiplier approximation as short as possible, so its hardware complexity is not so high. Moreover, its coding performance is still good comparing to those of our floating Int-DCT that its hardware complexity is high. Simulation results confirm an effectiveness of the proposed OWLA Int-DCT.

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