A New Wavelet Lifting Scheme for Image Compression Applications

Guoan Yang and Shugang Guo

Institute of Artificial Intelligence and Robotics of Xi'an Jiaotong University
No.28 West Xianning Road, 710049, Xi'an, China
{Guoan, Yang}gayang@aiar.xjtu.edu.cn
http://www.aiar.xjtu.edu.cn
{Shugang, Guo}sgguo@aiar.xjtu.edu.cn

Abstract. A new lifting scheme of 7/5 biorthogonal wavelet filter banks (BWFB) which include BT 7/5 filter banks of Brislawn and Treiber for image compression applications is presented in this paper. The functional relations between all coefficients of the 7/5 BWFB and their lifting parameters with respect to a one free lifting parameter are derived. Moreover, all coefficients of 7/5 BWFB and their lifting parameters are rational numbers, compared to CDF 9/7 filter banks of Cohen, Daubechies and Feauveau with irrational coefficients in JPEG2000 standard, 7/5 BWFB not only have advantage of easy computation but also are very suitable for VLSI hardware implementation. Finally, two 7/5 BWFB namely 7/5 BWFB-1 and 7/5 BWFB-2 are proposed. The experimental results show that the peak signal-to-noise ratio (PSNR) of the reconstructed images using 7/5 BWFB-1 and 7/5 BWFB-2 is 0.1dB less than CDF 9/7 filter banks but is higher 1.2dB than LT 5/3 filter banks of LeGall and Tabatabai within compression ratio 100:1. Therefore, the 7/5 BWFB-1 and 7/5 BWFB-2 are the ideal replacement of CDF 9/7 filter banks in the JPEG2000 standard for image compression applications.

1 Introduction

The design of the wavelet filter and the algorithm of compression coding are two most important factors in JPEG2000 image compression systems [1]. Since CDF 9/7 filter banks [2] developed by Cohen, Daubechies and Feauveau have linear phase and excellent image compression performance, they have been applied most widely in the image compression applications. However, there is a common complaint about CDF 9/7 filter banks by some researchers that their coefficients are irrational number and thus requires a floating-point implementation. This will not only increase the computational complexity but also bring a great disadvantage to VLSI hardware implementation. The purpose of our study is to find a new wavelet filter banks with rational coefficients whose the image compression performances are close to CDF 9/7 filter banks and better than LT 5/3 filter banks of LeGall and Tabatabai. Sweldens et al have presented the lifting scheme [3][4] in 1996 that is called as the second generation wavelet,

N. Zheng, X. Jiang, and X. Lan (Eds.): IWICPAS 2006, LNCS 4153, pp. 465–474, 2006.

and is an entirely spatial construction of wavelet. The lifting scheme for fast wavelet transform has many characteristics that are suitable for the VLSI hardware implementation. For example, the lifting scheme doesn't refer to the Fourier transformation, which leads to a speedup of 2 times faster than the Mallat algorithm based on convolution; it allows for an in-place implementation of the fast wavelet transform, this means the wavelet transform can be calculated without allocating auxiliary memory; all operations within one lifting step can be done entirely in parallel while the only sequential part is the order of the lifting operations; it is particularly easy to build nonlinear wavelet transform, a typical example is a wavelet transform that maps integers to integers, such transform is important for hardware implementation and lossless image coding; it allows for adaptive wavelet transforms, this means one can start the analysis of a function from the coarsest levels and then build the finer levels by refining only in the areas of interest; the multiresolution analysis for classical wavelet transform is inherited.

This paper constructs a class of biorthogonal 7/5 wavelet filter banks (BWFB), and also presents a kind of structure and implementation of the 7/5 BWFB for the lifting scheme of fast wavelet transform. In addition, it is found that when the lifting parameter for the 7/5 BWFB is 0.05 and 0.08, the performance for image compression turns out to be better than other situations, we named them as 7/5 BWFB-1 and 7/5 BWFB-2 in this paper that are recommended in JPEG2000 standard part 2. [5]-[7]. Finally, in order to verify the image compression performances of 7/5 BWFB-1 and 7/5 BWFB-2, we have developed the system of the image compression that supports the 7/5 BWFB-1 and 7/5 BWFB-2 as well as the CDF 9/7 and LT 5/3 filter banks.

The present paper is organized as follows. In section 2, the lifting scheme using Euclidean algorithm on two channel filter banks is introduced. In section 3, lifting implementation for fast wavelet transform using 7/5 BWFB is carried out. Section 4 provides both 7/5 BWFB-1 and 7/5 BWFB-2 for JPEG2000 image compression coding, and experimental results are discussed. Finally, in section 5, we conclude the paper.

2 The Lifting Scheme for 7/5 BWFB

2.1 Two Channel Filter Banks for 7/5 BWFB

We consider a two channel filter banks as shown in Fig.1, suppose a symmetric 7/5 BWFB, and $\{H_0(z), G_0(z)\}$ denotes low pass filters and $\{H_1(z), G_1(z)\}$ denotes high pass filters for analysis and synthesis stage respectively.

The low pass filters of 7/5 BWFB are given by

$$\begin{cases} H_0(z) = h_0 + h_1(z + z^{-1}) + h_2(z^2 + z^{-2}) + h_3(z^3 + z^{-3})) \\ G_0(z) = g_0 + g_1(z + x^{-1}) + g_2(z^2 + z^{-2}) \end{cases} \tag{1}$$

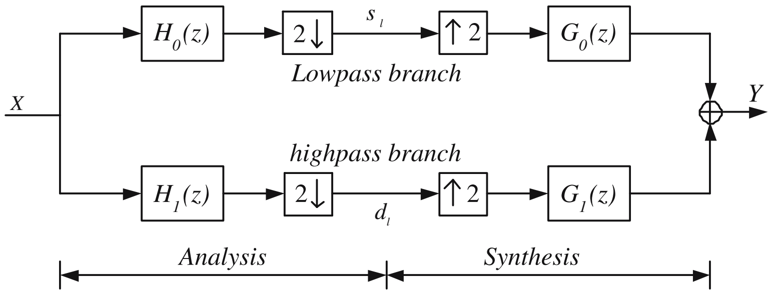

Fig. 1. Two channel filter banks

The polyphase representation of the lowpass analysis filter $H_0(z)$ and the lowpass synthesis filter $G_0(z)$ for 7/5 BWFB are given by

$$\begin{cases} H_{0e}(z) = h_0 + h_2(z + z^{-1}) \\ H_{0o}(z) = h_1(z + 1) + h_3(z^2 + z^{-1}) \end{cases} \tag{2}$$

$$\begin{cases} G_{0e}(z) = g_0 + g_2(z + z^{-1}) \\ G_{0o}(z) = g_1(z + 1) \end{cases} \tag{3}$$

Where $H_{0e}(z)$ and G_{0e} contains the even coefficients, and H_{0o} and G_{0o} contains the odd coefficients. Thus we can build the decomposition based on the Euclidean algorithm [8] with a focus on applying it to wavelet filtering.

2.2 Lifting Scheme of 7/5 BWFB

Here take two Laurent polynomials $a(z)$ and $b(z)$ with the restricts that $a(z)$ and $b(z) \neq 0$ with $|a(z)| \geq |b(z)|$. Then there always exist a Laurent polynomial $q(z)$ (i.e. quotient) with $|q(z)| = |a(z)| - |b(z)|$, and a Laurent polynomial $r(z)$ (i.e. remainder) with $|r(z)| < |b(z)|$ to make the equation reasonable. We denote this as: $q(z) = a(z)/b(z)$ and $r(z) = a(z)\%b(z)$. First let $a_0(z) = H_{0e}(z)$ and $b_0(z) = H_{0o}(z)$, then iterate the following steps starting from $i = 0$

$$\begin{cases} a_{i+1}(z) = b_i(z) \\ b_{i+1}(z) = a_i(z)\%b_i(z) \end{cases} \tag{4}$$

Note that in case $|H_{0o}(z)| > |H_{0e}(z)|$, the first quotient $q_1(z)$ is zero. We thus obtain the Euclidean decomposition as follows

$$Step1 \quad \begin{cases} a_1(z) = b_0(z) = H_{0o} = h_1(z + 1) + h_3(z^2 + z^{-1}) \\ b_1(z) = a_0(z)\%b_0(z) = H_{0e}(z) = h_0 + h_2(z + z^{-1}) \\ q_1(z) = 0 \end{cases} \tag{5}$$

$$Step2 \quad \begin{cases} a_2(z) = b_1(z) = H_{0e} = h_0 + h_2(z + z^{-1}) \\ b_2(z) = a_1(z)\%b_1(z) = s_2(1 + z) \\ q_2(z) = t_2(1 + z) \end{cases} \tag{6}$$

$$Step3 \quad \begin{cases} a_3(z) = b_2(z) = s_2(1+z) \\ b_3(z) = a_2(z)\%b_2(z) = s_3 \\ q_3(z) = t_3(1+z^{-1}) \end{cases} \tag{7}$$

$$Step4 \quad \begin{cases} a_4(z) = b_3(z) = s_3 \\ b_4(z) = a_3(z)\%b_3(z) = s_4 = 0 \\ q_4(z) = t_4(1+z) \end{cases} \tag{8}$$

In the equations above, s_i is the lifting parameter and t_i is the dual lifting parameter, which are as follows

$$\begin{cases} s_1 = 0, \quad t_1 = 0 \\ s_2 = h_1 - h_3 - h_0 h_3/h_2, \quad t_2 = h_3/h_2 \\ s_3 = h_0 - 2h_2, \quad t_3 = h_2^2/[h_1 h_2 - (h_0 + h_2)h_3] \\ s_4 = 0, \quad t_4 = [(h_1 - h_3)h_2 - h_0 h_3]/[(h_0 - 2h_2)h_2] \end{cases} \tag{9}$$

3 Implementation of Lifting Scheme for 7/5 BWFB

Using the method described above, this section will provides the implementation of lifting scheme for 7/5 BWFB. Here the factorization of filter pair $\{H_{0e}, H_{0o}\}$ are as follows

$$\begin{bmatrix} H_{0e}(z) \\ H_{0o}(z) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ q_2(z) & 1 \end{bmatrix} \begin{bmatrix} 1 & q_3(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ q_4(z) & 1 \end{bmatrix} \begin{bmatrix} s_3 \\ 0 \end{bmatrix} \tag{10}$$

Set $\alpha = t_2$, $\beta = t_3$, $\gamma = t_4$, $K = s_3$, so the polyphase matrix for the 7/5 BWFB can be expressed as

$$\begin{aligned} \tilde{P}(z) &= \begin{bmatrix} h_0 + h_2(z + z^{-1}) & g_1(1 + z^{-1}) \\ h_1(z+1) + h_3(z^2 + z^{-1}) & -g_0 - g_2(z + z^{-1}) \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ q_2(z) & 1 \end{bmatrix} \begin{bmatrix} 1 & q_3(z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ q_4(z) & 1 \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & 1/K \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ \alpha(1+z) & 1 \end{bmatrix} \begin{bmatrix} 1 & \beta(1+z^{-1}) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \gamma(1+z) & 1 \end{bmatrix} \begin{bmatrix} K & 0 \\ 0 & 1/K \end{bmatrix} \end{aligned} \tag{11}$$

So we have

$$\begin{cases} h_0 = (1 + 2\beta\gamma)K \\ h_1 = [\alpha(1 + \beta\gamma) + \gamma(1 + 2\alpha\beta)]K \\ h_2 = \beta\gamma K \\ h_3 = \alpha\beta\gamma K \\ g_0 = (1 + 2\alpha\beta)/(2K) \\ g_1 = -\beta/(2k) \\ g_2 = \alpha\beta/(2k) \end{cases} \tag{12}$$

We start with a sequence $x = \{x_j | j \in \mathbb{Z}\}$ and denote the result of applying the lowpass filter $H_0(z)$ and downsampling as a $s = \{s_j | j \in \mathbb{Z}\}$, and sequence

$s^{(i)}$ and $d^{(i)}$ are used to denotes the intermediate values computed during lifting. Then Lazy wavelet are given by

$$s_i^{(0)} = x_{2i}, \quad d_i^{(0)} = x_{2i+1}$$

Finally, the factorization leads to the following implementation of the forward transform

$$\begin{aligned}
&s_l^{(1)} = s_l^{(0)} + \alpha(d_l^{(0)} + d_{l-1}^{(0)}) \\
&d_l^{(1)} = d_l^{(0)} + \beta(s_l^{(1)} + s_{l+1}^{(1)}) \\
&s_l^{(2)} = s_l^{(1)} + \gamma(d_l^{(1)} + d_{l-1}^{(1)}) \\
&s_l = K s_l^{(2)} \\
&d_l = d_l^{(1)}/K
\end{aligned}$$

The implementation of the inverse transform are as follows

$$\begin{aligned}
&s_l^{(2)} = s_l/K \\
&d_l^{(1)} = K d_l \\
&s_l^{(1)} = s_l^{(2)} - \gamma(d_l^{(1)} + d_{l-1}^{(1)}) \\
&d_l^{(0)} = d_l^{(1)} - \beta(s_l^{(1)} + s_{l+1}^{(1)}) \\
&s_l^{(0)} = s_l^{(1)} - \alpha(d_l^{(0)} + d_{l-1}^{(0)})
\end{aligned}$$

The lifting structure of the 7/5 BWFB is shown in Fig.2.

From Equation (12) and normalization condition for the 7/5 BWFB we can get

$$\beta = -1/[2(1+2\alpha)], \quad \gamma = (1-4\alpha^2)/4, \quad K = 1/(1+2\alpha) \tag{13}$$

Equation (13) shows that β, γ, K can be all expressed by a free parameter α. We consider now using the algorithm of approximation and Hölder regularity [9][10] to find a compactly supported 7/5 BWFB which will satisfy the perfect reconstruction (PR) condition. In the 7/5 category this leaves a single unused degree of freedom $\alpha = 0.05$ and $\alpha = 0.08$ that have an excellent image compression performances than other situations, and they are defined as 7/5 BWFB-1 and 7/5 BWFB-2. The structure of 7/5 BWFB for lifting scheme is plotted as in Fig.2. The coefficients of 7/5 BWFB-1 and 7/5 BWFB-2 and corresponding lifting parameters are shown in Table.1-Table.4.

4 Experiment and Discussion

In order to verify the performances of image compression for 7/5 BWFB-1 and 7/5 BWFB-2, we have developed a new image compression system based on JPEG2000 standard, it not only supports both CDF 9/7 filter and LT 5/3 filter banks but also supports both 7/5 BWFB-1 and 7/5 BWFB-2 through improves Jasper1.701.0 version in JPEG2000 standard. In addition, a great deal

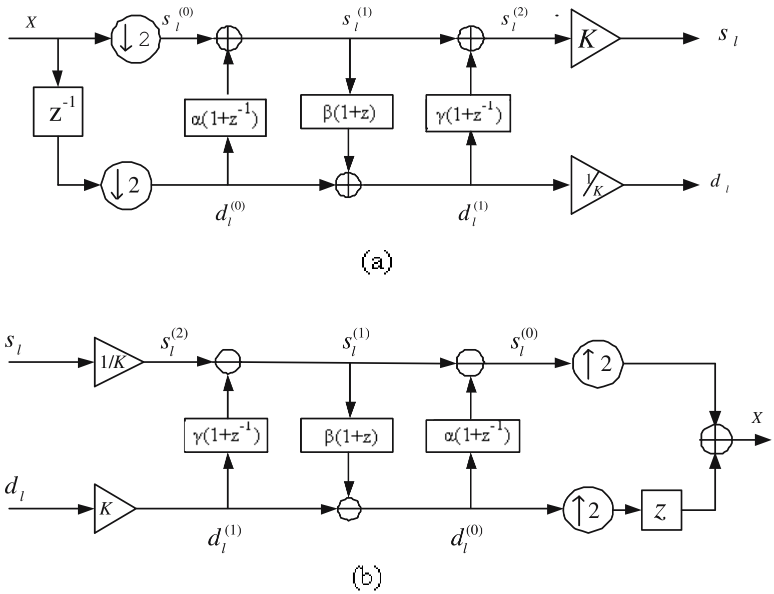

Fig. 2. The structure of 7/5 BWFB for lifting scheme (a) the decomposition (b) the reconstruction

Table 1. The coefficients of the 7/5 BWFB-1

n	$h_i(analysis)$	$g_i(synthsis)$
0	31/44	21/40
±1	449/1760	1/4
±2	-9/88	-1/80
±3	-9/1760	

Table 2. The lifting parameters of the 7/5 BWFB-1

parameters	values
α	1/20
β	-5/11
γ	99/400
K	11/10

of gray bitmaps in standard test image library were tested using 5 levels of wavelet decomposition and scalar quantization and EBCOT coding algorithm [11][12]. The objective coding results with PSNR in dB for standard 512×512 pixel and 8bits depth Peppers.bmp, Lena.bmp, Goldhill.bmp, Baboon.bmp and Women.bmp testing images were tabulated in Table.5-Table.9. The differences

Table 3. The coefficients of the 7/5 BWFB-2

n	$h_i(analysis)$	$g_i(synthsis)$
0	79/116	27/50
±1	373/1450	1/4
±2	-21/232	-1/50
±3	-21/2900	

Table 4. The lifting parameters of the 7/5 BWFB-2

parameters	values
α	2/25
β	-175/406
γ	609/2500
K	29/25

of PSNR values for the reconstructed image between 7/5 BWFB-1 and CDF 9/7 filter banks were represented as Δ_{1D}, similarly, the differences between 7/5 BWFB-2 and CDF 9/7 filter banks were represented as Δ_{2D}, the differences between 7/5 BWFB-1 and LT 5/3 filter banks were represented as Δ_{1L}, the differences between 7/5 BWFB-2 and LT 5/3 filter banks were represented as Δ_{2L}. It is easy to find from table.5-Table.9 that the performances of the image compression for 7/5 BWFB-1 and 7/5 BWFB-2 are very close to CDF 9/7 filter banks and also is much better than LT 5/3 filter banks. Moreover, we compared PSNR values of reconstructed image using different filters in Fig.3, and the abscissa denotes compression ratio which is integral power for 2, the ordinate denotes PSNR values of the reconstructed image. It is illustrated that PSNR values of the reconstructed image using 7/5 BWFB-1 is only 0.1dB less than the CDF 9/7 filter banks, but 1.2dB higher than the LT 5/3 filter banks about testing image Woman.bmp in Fig.3. However, when the compression ratio (C.R.) is greater than 100:1, the compression performances using 7/5 BWFB-1 is 0.01dB less than the LT 5/3 filter banks. The subjective comparisons of the

Table 5. PSNR evaluation for the Peppers.bmp in dB

C.R.	CDF 9/7	LT 5/3	7/5 BWFB-1	7/5 BWFB-2	Δ_{1D}	Δ_{2D}	Δ_{1L}	Δ_{2L}
4:1	43.1083	41.3481	42.6307	42.7673	-0.4476	-0.3410	+1.2826	+1.4192
8:1	38.2030	37.5476	37.9269	37.9936	-0.2761	-0.2094	+0.3793	+0.4460
16:1	35.7832	35.2654	35.4361	35.4170	-0.3471	-0.3662	+0.1707	+0.1516
32:1	33.4908	33.0552	33.0767	33.0125	-0.4141	-0.4783	+0.0215	-0.0427
64:1	30.7161	30.3354	30.3600	30.2256	-0.3561	-0.4905	+0.0246	-0.1098
100:1	28.4688	28.2567	28.0892	28.1015	-0.3796	-0.3673	-0.1675	-0.1552
128:1	27.5009	27.2342	27.2028	27.1584	-0.2981	-0.3425	-0.0314	-0.0758

Table 6. PSNR evaluation for the Lena.bmp in dB

C.R.	CDF 9/7	LT 5/3	7/5 BWFB-1	7/5 BWFB-2	Δ_{1D}	Δ_{2D}	Δ_{1L}	Δ_{2L}
4:1	42.9495	41.1995	42.3858	42.4764	-0.5637	-0.4731	+1.1863	+1.2769
8:1	38.0703	37.3410	37.6658	37.6953	-0.4045	-0.3750	+0.3248	+0.3543
16:1	35.1721	34.4984	34.6425	34.6254	-0.5296	-0.5467	+0.1441	+0.1270
32:1	32.3538	31.7087	31.7193	31.7408	-0.6345	-0.6130	+0.0106	+0.0321
64:1	29.5526	28.9618	29.0785	29.0370	-0.4741	-0.5156	+0.1167	+0.0752
100:1	27.7308	27.2636	27.2375	27.2836	-0.4933	-0.4472	-0.0261	+0.0200
128:1	26.8370	26.4218	26.5133	26.4455	-0.3237	-0.3915	+0.0915	+0.0237

Table 7. PSNR evaluation for the Goldhill.bmp in dB

C.R.	CDF 9/7	LT 5/3	7/5 BWFB-1	7/5 BWFB-2	Δ_{1D}	Δ_{2D}	Δ_{1L}	Δ_{2L}
4:1	39.5641	38.6910	39.0016	39.1366	-0.5625	-0.4275	+0.3106	+0.4456
8:1	35.0873	34.5923	34.8390	34.9030	-0.2483	-0.1843	+0.2467	+0.3107
16:1	32.3438	31.9067	32.0199	32.0405	-0.3239	-0.3033	+0.1132	+0.1338
32:1	30.0213	29.6347	29.7234	29.8100	-0.2979	-0.2113	+0.0887	+0.1753
64:1	28.1324	27.8516	27.8709	27.9310	-0.2615	-0.2014	+0.0193	+0.0794
100:1	26.9970	26.5792	26.7023	26.7312	-0.2947	-0.2658	+0.1231	+0.1520
128:1	26.3435	26.1060	26.1177	26.0853	-0.2258	-0.2582	+0.0117	-0.0477

Table 8. PSNR evaluation for the Baboon.bmp in dB

C.R.	CDF 9/7	LT 5/3	7/5 BWFB-1	7/5 BWFB-2	Δ_{1D}	Δ_{2D}	Δ_{1L}	Δ_{2L}
4:1	34.8018	34.1268	34.2124	34.2179	-0.5894	-0.5839	+0.0856	+0.0911
8:1	29.0705	28.6222	28.4054	28.4574	-0.6651	-0.6131	-0.2168	-0.1648
16:1	25.5388	25.0646	25.1061	25.2201	-0.4327	-0.3187	+0.0415	+0.1555
32:1	23.1835	22.8077	22.8375	22.8973	-0.3460	-0.2862	+0.0298	+0.0896
64:1	21.6200	21.3188	21.2840	21.3689	-0.3360	-0.2511	-0.0348	+0.0501
100:1	20.8802	20.6963	20.7797	20.8718	-0.1005	-0.0084	+0.0834	+0.1755
128:1	20.6537	20.4250	20.5121	20.5506	-0.1416	-0.1031	+0.0871	+0.1256

reconstructed image were demonstrated in Fig.4 at compression ratio 16:1 with the testing image Women.bmp. The compression performances using the 7/5 BWFB-1 and 7/5 BWFB-2 are almost identical with CDF 9/7 filter banks.

We can see easily from this paper that compression performances using the CDF 9/7 filter banks are always better than 7/5 BWFB-1, 7/5 BWFB-2 and LT 5/3 filter banks when compression ratios is less than 100:1, 0.1-0.6dB higher than 7/5 BWFB-1 and 7/5 BWFB-2, and 0.5-1.4dB higher than LT 5/3 filter banks. When compression ratio are 100:1 and over, the compression performance using LT 5/3 filter banks are little better than 7/5 BWFB-1 and 7/5 BWFB-2 by about 0.05-0.1 dB. In addition, when testing image includes much information for low frequency such as Woman.bmp bitmap, PSNR values of reconstructed

Table 9. PSNR evaluation for the Women.bmp in dB

C.R.	CDF 9/7	LT 5/3	7/5 BWFB-1	7/5 BWFB-2	Δ_{1D}	Δ_{2D}	Δ_{1L}	Δ_{2L}
4:1	45.8728	44.4178	45.4255	45.5494	-0.4473	-0.3234	+1.0077	+1.1316
8:1	39.1503	38.1474	38.7211	38.8229	-0.4292	-0.3274	+0.5737	+0.6755
16:1	34.5551	33.9244	34.1463	34.2185	-0.4088	-0.3366	+0.2219	+0.2941
32:1	31.4530	31.0521	31.2834	31.3065	-0.1696	-0.1465	+0.2313	+0.2544
64:1	29.5272	29.1728	29.2553	29.2425	-0.2719	-0.2847	+0.0825	+0.0697
100:1	28.2210	27.9241	27.9271	27.8405	-0.2939	-0.3805	+0.0030	-0.0836
128:1	27.3979	27.2418	27.1850	27.1185	-0.2129	-0.2794	-0.7391	-0.1233

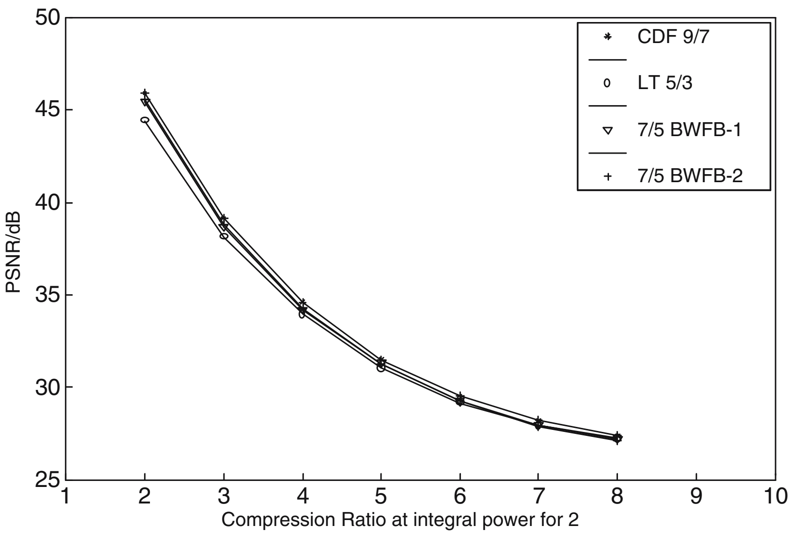

Fig. 3. The objective comparison of compression performance using different filter

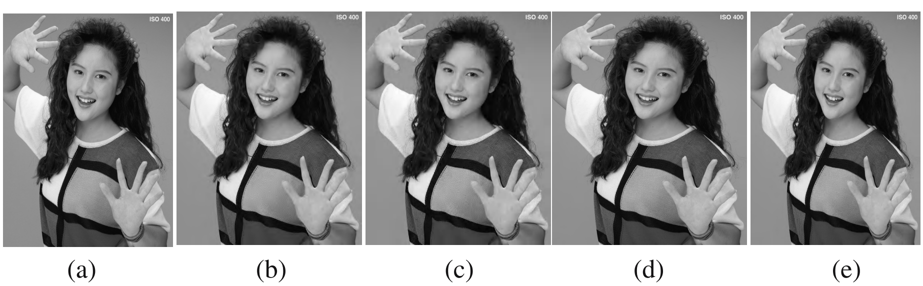

Fig. 4. The compression performance comparison using different filter (a) original image (b) CDF 9/7 filter banks (c) LT 5/3 filter banks (d) 7/5 BWFB-1 (e) 7/5 BWFB-2

image reduce slowly with the increase of the compression ratio because loss for low frequency is very little. However, when testing image includes many information for high frequency, for example Babbon.bmp bitmap, PSNR values for reconstructed image reduce quickly with the increase of the compression ratio because loss for high frequency is very much.

5 Conclusions

The lifting scheme and implementation structure of 7/5 BWFB-1 and 7/5 BWFB-2 are derived in detail. In addition, the 7/5 BWFB-1 and 7/5 BWFB-2 with rational coefficients whose performances of image compression are highly close to CDF 9/7 filter banks have been obtained. Finally, we can concluded that the image compression performances using 7/5 BWFB-1 and 7/5 BWFB-2 based on JPEG2000 standard will be better than CDF 9/7 filter banks in terms of computational complexity and VLSI hardware implementation.

Acknowledgements

This work is supported by the national science foundation of China (No.60021302, No.60405004).

References

1. ISO/ IEC 15444-1, ITU-T RT800,2003, JPEG2000 image coding system, part 1.
2. Cohen, A, Daubechies, I, Feauveau, J.C, Biorthogonal bases of compactly supported wavelets, Commun Pure Appl Math,Vol.45, (1992) 485-560
3. Sweldens, W, The lifting scheme: a custom-design construction of biorthogonal wavelets, Applied and computational Harmonic Analysis, Vol. 3, (1996) 186-200
4. Sweldens, W, The lifting scheme: A construction of second generation wavelets, SIAM J Math Anal, Vol.29, No.2, (1997) 511-546
5. ISO/ IEC, 15444-2, ITU-TR T800, 2004, JPEG2000 image coding system, part 2.
6. Guoan Yang, Nanning Zheng, et al, Research on cluster of 7/5-tap wavelet filters and their image compression performances, Journal of Xi'an Jiaotong University, Vol.39, No.6, (2005) 628-632
7. Guoan Yang, Nanning Zheng,et al, Extensible JPEG2000 image compression systems, IEEE ICIT2005 conference proceeding, December 14-17, HongKong, (2005)1376-1380
8. Daubechies, I, Sweldens, W, Factoring wavelet transforms into lifting steps, Fourier analysis and applications,Vol.4, No.3, (1998) 247-269
9. Antonini, M, Barlaud, M, Mathieu, P, Daubechchies, I, Image coding using wavelet transform, IEEE Trans on Image processing, Vol.1, No.2, (1992) 205-220
10. Unser, M, Blu, T, Mathematical properties of the JPEG2000 wavelet filters, IEEE Trans on Image processing, Vol.12,No.9, (2003) 1080-1090
11. Bilgin, A, Sementilli, P.J, Sheng, F, et al, Scalable image coding using reversible integer wavelet transforms, IEEE Trans on Image Processing, Vol.9, No.11, (2000) 1972-1977
12. Taubman, D, High performance scalable image compression with EBCOT, IEEE Trans on Image processing, Vol.9, No.7, (2000) 1158-1170