IMAGE QUALITY OPTIMIZATION BASED ON WAVELET FILTER DESIGN AND WAVELET DECOMPOSITION IN JPEG2000

Do Quan and Yo-Sung Ho

School of Information & Mechatronics
Gwangju Institute of Science and Technology (GIST)
261 Cheomdan-gwagiro (Oryong-dong), Buk-gu, Gwangju 500-712, Korea
E-mail: {viequando,hoyo}@gist.ac.kr

ABSTRACT

In JPEG2000, the Cohen-Daubechies-Feauveau (CDF) 9/7-tap wavelet filter adopted in lossy compression is implemented by the lifting scheme or by the convolution scheme while the LeGall 5/3-tap wavelet filter adopted in lossless compression is implemented just by the lifting scheme. However, these filters are not optimal in terms of Peak Signal-to-Noise Ratio (PSNR) values, and irrational coefficients of wavelet filters are complicated. In this paper, we proposed a method to optimize image quality based on wavelet filter design and on wavelet decomposition. First, we propose a design of wavelet filters by selecting the most appropriate rational coefficients of wavelet filters. These filters are shown to have better performance than previous wavelet ones. Then, we choose the most appropriate wavelet decomposition to get the optimal PSNR values of images.

Keywords: wavelet filter, lifting, filter design, JPEG2000

1. INTRODUCTION

Wavelet, proposed by Grossman and Morlet [1], is known as the dyadic translations and dilations of a particular function, called the mother wavelet. It is also called the first-generation wavelets. Nevertheless, we may use the lifting scheme for generation of wavelets [2]. In this scheme, wavelets are not necessarily translations and dilations of a function, though they have all powerful properties of the first-generation wavelets. It is the lifting scheme and is referred to as the second-generation wavelets in literature.

Using the lifting scheme, Every Finite Impulse Response (FIR) wavelet filter or filter bank can be decomposed into several lifting steps. Statement about perfect reconstruction can be made by Laurent polynomial entries. A lifting step then becomes an elementary matrix that is a triangular matrix with all diagonal entries equal to one.

In the JPEG2000 standard, there are two options for user's choice: the Cohen-Daubechies-Feauveau (CDF) 9/7-tap wavelet filter adopted in lossy compression technique and the LeGall 5/3-tap wavelet filter adopted in lossless compression [3]. In addition, there are four types of decompositions, such as "mallat", "spacl", "packet", and "other" which is defined by user. Different types of wavelet decompositions have different performances in terms of image quality and in terms of PSNR values. Therefore, in this paper, we examine all decompositions in JPEG2000 to find the most appropriate decomposition in order to get the optimal PSNR values of images. Then, we concentrate on the design of optimal wavelet filters used in the lossy compression technique as another way to optimize image quality.

There are two schemes to construct a wavelet filter: the convolution scheme and the lifting scheme. However, since the lifting scheme can greatly reduce the number of wavelet decompositions and reconstructions, the lifting scheme is preferred to the convolution scheme.

With the lifting scheme, there have been several proposed wavelet filters with different coefficients based on the CDF 9/7-tap wavelet filter. In these filters, a parameter α is used to find their coefficients. Daubechies first used the lifting scheme and factoring method with irrational number α=-1.586134342… to find coefficients of the wavelet filter [4]. This filter is referred to the CDF 9/7-tap wavelet filter. Guangjun proposed a simple 9/7-tap wavelet filter based on the lifting scheme with α = -1.5 [5]. Compared with the CDF 9/7-tap wavelet filter, this proposed filter has the same performance in terms of PSNR value, but the computational complexity is much lower. Liang used a temporary parameter t=1.25 [6] to generate the filter (for the CDF 9/7-tap wavelet filter, t=1.230174…). This filter is also proved to have the same performance with lower computational complexity than the CDF 9/7-tap wavelet filter.

Although the filters proposed by Guangjun and Liang slightly outperform the CDF 9/7-tap wavelet filter, we argue that their performances are not optimal. The question is whether there is any other value of α and the corresponding coefficients of wavelet filters which give the same or even better performance with lower computational complexity than the CDF 9/7-tap wavelet filter. In this paper, we address this problem. Especially, we design 9/7-tap wavelet filters by examining the whole possible range for α (i.e. from the negative infinite to the positive infinite) to find the optimal value of α for filters' best performance. We then compute the optimal coefficients for the 9/7-tap wavelet filters from the optimal α. Therefore, based on the construction theorem of the biorthogonal wavelet and on the lifting scheme, we find the optimal wavelet filters to get better performance than previous schemes in terms of PSNR values and in terms of computational complexity.

2. WAVELET DECOMPOSITIONS AND WAVELET FILTERS IN JPEG2000

2.1 Wavelet Decompositions

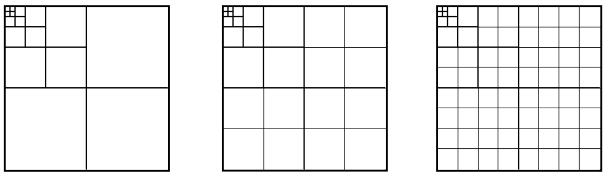


Fig. 1: Structure of different decompositions

There are four types of wavelet decompositions in JPEG2000. First, the "Mallat" decomposition is the most popular scheme in wavelet compression implementations [7]. Second, the "spacl" decomposition was proposed by Signal Processing and Coding Lab. at the University of Arizona. Third, the "packet" decomposition is quite effective for compression of synthetic aperture radar imagery [8]. Finally, "other" decomposition is similar to the "mallat" decomposition.

2.2 Numerical Analysis

In wavelets, the forward transform uses two analysis filters including a low-pass filter h, and a high-pass filter g followed by subsampling. On the other hand, the inverse transform first upsamples and then uses two synthesis filters including a low-pass filter $\tilde{h}$ and a high-pass $\tilde{g}$ [4],[6].

In the z-domain, h can be expressed as [4]:

$$h(z) = \sum_{k=k_b}^{k_e} h_k z^{-k}, \tag{1}$$

where k_b (and respectively k_e) is the smallest (and respectively the largest) integer number for which h_k is nonzero.

The functions of h and g in the ω-domain are defined as:

$$H(\omega) = h_0 + 2\sum_{n=1}^{L_1} h_n \cos n\omega, \tag{2}$$

and

$$G(\omega) = g_0 + 2\sum_{n=1}^{L_2} g_n \cos n\omega, \tag{3}$$

respectively, where in the design of the CDF 9/7-tap wavelet filter, L_1 is 4 and L_2 is 3.

These functions may be rewritten as [5]:

$$H(\omega) = \sqrt{2}\left(\frac{1+e^{-j\omega}}{2}\right)^{N} P(\omega), \tag{4}$$

$$G(\omega) = \sqrt{2}\left(\frac{1+e^{-j\omega}}{2}\right)^{\tilde{N}} \tilde{P}(\omega), \tag{5}$$

where $P(\omega)$ and $\tilde{P}(\omega)$ are polynomials of $e^{-j\omega}$; N and $\tilde{N}$ are the number of the vanishing moments of the wavelet and its dual, respectively. In the CDF 9/7-tap wavelet, N and $\tilde{N}$ are taken by $N = \tilde{N} = 4$. In our design of 9/7-tap wavelet filters, $N = 2$ and $\tilde{N} = 4$.

If $H(\omega)$ and $G(\omega)$ construct a biorthogonal wavelet, the normalized condition must be satisfied as:

$$H(0) = \sqrt{2}\,; \quad G(0) = \sqrt{2} \tag{6}$$

Combining Eq. (6) with Eq. (2) and Eq. (3), we have:

$$\begin{cases} h_0 + 2(h_1 + h_2 + h_3 + h_4) = \sqrt{2} \\ g_0 + 2(g_1 + g_2 + g_3) = \sqrt{2} \end{cases}. \tag{7}$$

Substituting $\omega = 0$ into $H(\omega)$ of Eq. (2) and into $G(\omega)$ of Eq. (3) results in:

$$h_0 + 2(-h_1 + h_2 - h_3 + h_4) = 0. \tag{8}$$

$$g_0 + 2(-g_1 + g_2 - g_3) = 0. \tag{9}$$

Then, taking the second derivative of Eq. (2) results in:

$$2(-g_1 + 4g_2 - 9g_3) = 0 \tag{10}$$

The polyphase matrix $P_a(z)$ which presents the filter pair (h,g) is

$$P_a(z) = \begin{bmatrix} h_e(z) & g_o(z) \\ h_o(z) & g_e(z) \end{bmatrix}, \tag{11}$$

where h_e contains the even coefficients of h, and h_o contains the odd coefficients as:

$$h_e = \sum_k h_{2k} z^{-k} \text{ and } h_o = \sum_k h_{2k+1} z^{-k}. \tag{12}$$

Therefore, the polyphase matrix $P_a(z)$ can be written as:

$$P_a(z) = \begin{bmatrix} h_0 + h_2(z+z^{-1}) + h_4(z^2+z^{-2}) & g_1(1+z^{-1}) + g_3(z+z^{-2}) \\ h_1(z+1) + h_3(z^2+z^{-1}) & -g_0 - g_2(z+z^{-1}) \end{bmatrix}. \tag{13}$$

Additionally, $P_a(z)$ can be factorized into 5 matrices as [4]:

$$P_a(z) = \begin{bmatrix} \xi & 0 \\ 0 & -\frac{1}{\xi} \end{bmatrix} \begin{bmatrix} 1 & \delta(1+z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \gamma(1+z^{-1}) & 1 \end{bmatrix} \begin{bmatrix} 1 & \beta(1+z) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \alpha(1+z^{-1}) & 1 \end{bmatrix}. \tag{14}$$

Comparing Eq. (13) and Eq. (14), we conclude that

$$\begin{cases} h_0 = (1 + 2\alpha\beta + 2\alpha\delta + 2\gamma\delta + 6\alpha\beta\gamma\delta)\xi \\ h_1 = (3\beta\gamma\delta + \beta + \delta)\xi \\ h_2 = (\alpha\beta + \alpha\delta + \gamma\delta + 4\alpha\beta\gamma\delta)\xi \\ h_3 = \beta\gamma\delta\xi \\ h_4 = \alpha\beta\gamma\delta\xi \end{cases}, \tag{15}$$

and

$$\begin{cases} g_0 = \dfrac{2\beta\gamma + 1}{\xi} \\ g_1 = -\dfrac{3\alpha\beta\gamma + \alpha + \gamma}{\xi} \\ g_2 = \dfrac{\beta\gamma}{\xi} \\ g_3 = -\dfrac{\alpha\beta\gamma}{\xi} \end{cases} \tag{16}$$

Finally, using Eq. (7), Eq. (8), Eq. (9), and Eq. (10), we have:

$$
\begin{cases}
\beta = -\dfrac{1}{4(1+2\alpha)^2} \\
\gamma = -\dfrac{(1+2\alpha)^2}{1+4\alpha} \\
\delta = \dfrac{1}{16}\left(4 - \dfrac{2+4\alpha}{(1+2\alpha)^4} + \dfrac{1-8\alpha}{(1+2\alpha)^2}\right) \\
\xi = \dfrac{2\sqrt{2}(1+2\alpha)}{1+4\alpha}
\end{cases}
\tag{17}
$$

In our proposed method, α is examined in the $(-\infty;+\infty)$ range to find the optimal value for the 9/7-tap wavelet filters in terms of computational complexity and in terms of performance. With each α , the (β,γ,δ,ξ) set is determined by Eq. (17) and then the coefficients of *h* and *g* are computed by Eq. (15) and Eq. (16), respectively. In this way, we will find the optimal α based on the maximum value of PSNR (i.e. $PSNR_{max}$) of the corresponding 9/7-tap wavelet filter and the optimal wavelet filter for each experimental image and compression ratio.

3. PROPOSED METHOD

This part presents a proposed method of wavelet filter design. Since β, γ, δ, and ξ depend on α by Eq. (17), we can get different values for β, γ, δ, and ξ by changing α in the $(-\infty;+\infty)$ range. Then, the coefficients of the 9/7-tap wavelet filters are computed using Eq. (15) and Eq. (16). For each filter, we find the corresponding PSNR value. Consequently, α has an optimal value when PSNR value is maximum (i.e., $PSNR_{max}$).

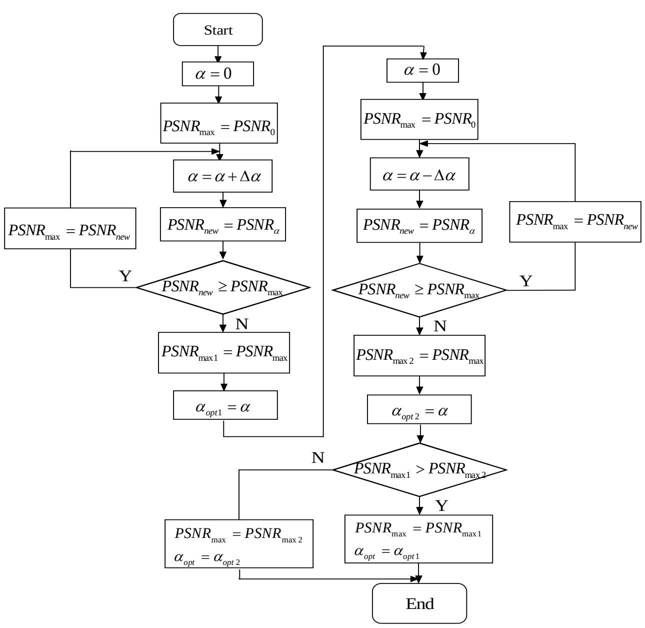


Fig. 2: Method to find $PSNR_{max}$ and optimal α.

Figure 2 is the flow chart of our proposed method. We examine α in its whole range. First, α is examined in the negative side, and then it is examined in the positive side. In each side, we find a local $PSNR_{max}$ and a locally optimal α. After that, we compare the value of $PSNR_{max}$ in both sides. The higher $PSNR_{max}$ is considered as the final $PSNR_{max}$ and its corresponding α is the final optimal α. With this α, we achieve the optimal coefficients of the 9/7-tap wavelet filters.

The shape of PSNR for each 9/7-tap wavelet filter is shown in Fig. 3 as a function of α.

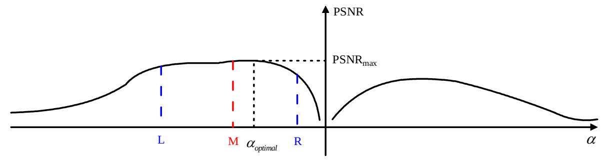


Fig. 3: Shape of PSNR as a function of α.

To decrease the search time for finding optimal α, we use the bi-section algorithm. Suppose we have α in two initial positions Left (L) and Right (R), we compare the PSNR value of Middle (M) position with PSNR value of (L) and (R). After that, we update R or L by M. These steps are iterated until PSNR reaches its maximum value. Figure 4 summarizes these main steps of the bisection method.

1. s ← PSNR(L).
2. M ← (L+R)/2.
3. If PSNR(M) > s, then L ← M. Else R ← M.
4. Return to step 2 unless R – L is small enough.

Fig. 4: Bisection method.

4. EXPERIMENTAL RESULTS

We conducted experiments on the images of the USC image database [9] and some JPEG2000 test images [10]. In addition, the proposed algorithm was implemented on VM9.0 [11] as a reference software of JPEG2000.

4.1 Wavelet Filter Design

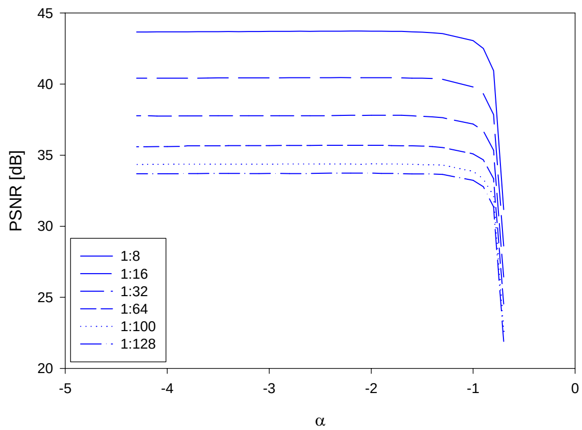
The shapes of PSNR and the improvement of PSNR value for different images are quite similar. Therefore, we only described representative images in this part, such as “GIRL”, “HOUSE”, “PEPPERS”, and “FAXBALLS” images in the databases.

4.1.1 PSNR Computation with Different α

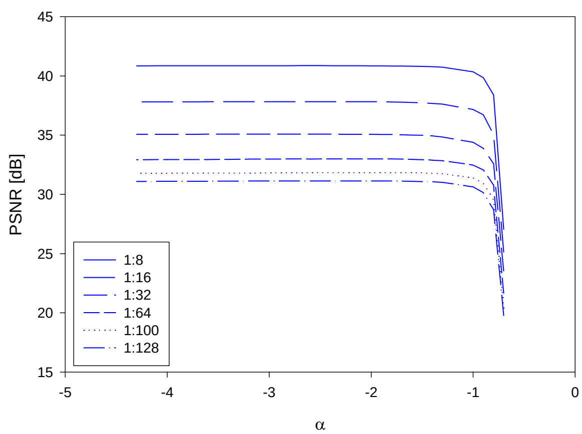
By testing images in the USC image database, we get different PSNR results. The step size of α is 0.1. The potentially optimal α has been drawn in Fig. 5. As it can be easily seen, the optimal α is generally in the negative side.

By our experiments, in the negative side of α value, when α decreases from zero to infinitive negative number, PSNR increases. However, at certain value of α, the PSNR stops increasing. After this period, PSNR decreases when α continues decreasing. When α reaches the negative infinite, PSNR value is very small and remains constant.

In the positive side of α value, when α increases from zero to infinitive positive number, the PSNR first increases. At certain value of α, PSNR does not change even α continues increasing. After that, PSNR decreases when α increases. When α goes to the positive infinite, PSNR is very small and remains constant. Because the range of α is in the $(-\infty;+\infty)$ range, we only draw potentially optimal α in the negative side in Fig. 5.



a)



b)

Fig. 5: PSNR survey with different compression ratios for "GIRL" a) and "HOUSE" b) images.

4.1.2 Find The Optimal α

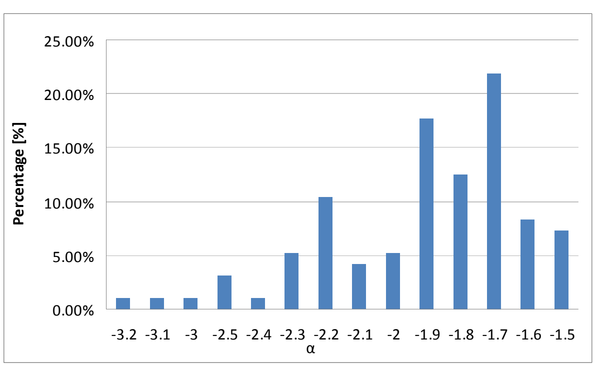


Fig. 6: Distribution of optimal α for $PSNR_{max}$

Each image in the database is tested with 6 different compression ratios including 1:8, 1:16, 1:32, 1:64, 1:100, and 1:128. It is obvious that different images have different optimal α. Even for an image, the optimal α is usually not the same for different compression ratios. Therefore, we have an optimal α range for all images of the database, rather than only one number. Figure 6 represents the optimal α distribution for $PSNR_{max}$.

4.1.3 Comparison with Other 9/7-tap Wavelet Filters

We also implemented the previous 9/7-tap wavelet filters. We used α=-1.586134342… for the CDF 9/7-tap wavelet filter and α=-1.5 for Guangjun and Liang 9/7-tap wavelet filters. Especially, by our proposed method, we find optimal α and optimal wavelet filter, whose PSNR value is better than previous 9/7-tap wavelet filters.

Table 1: PSNR comparison

Image	Bitrate [bpp]	JPEG2000 PSNR1 [dB] (α_1=-1.586134342)	Guangjun PSNR2 [dB] α_2=-1.5	Proposed PSNR [dB]	$\Delta PSNR_1$ [dB]	$\Delta PSNR_2$ [dB]
GIRL (α_{opt}=-2.203)	0.125	35.66	35.63	35.69	+0.03	+0.06
	0.25	37.76	37.73	37.78	+0.04	+0.07
	0.5	40.42	40.42	40.45	+0.03	+0.03
	1	43.68	43.68	43.73	+0.05	+0.08
HOUSE (α_{opt}=-2.322)	0.125	32.95	32.93	33	+0.05	+0.07
	0.25	35	34.99	35.08	+0.08	+0.09
	0.5	37.75	37.72	37.82	+0.07	+0.1
	1	40.82	40.8	40.86	+0.04	+0.06
PEPPERS (α_{opt}=-2.5)	0.125	34.91	34.9	34.95	+0.04	+0.05
	0.25	37.69	37.68	37.69	0	+0.01
	0.5	41.02	40.99	41.07	+0.05	+0.08
	1	44.88	44.85	44.95	+0.07	+0.1
FAXBALLS (α_{opt}=-2.3)	0.125	38.65	38.61	38.76	+0.11	+0.15
	0.25	41.61	41.58	41.69	+0.08	+0.11
	0.5	45.3	45.27	45.38	+0.08	+0.11
	1	50.2	50.14	50.31	+0.11	+0.17

Table 1 shows the PSNR improvement with optimal α compared with previous 9/7-tap wavelet filters. With the optimal α, the improvement of PSNR is presented in $\Delta PSNR_1$ and $\Delta PSNR_2$. The changes are calculated by

$$\Delta PSNR = PSNR(proposed) - PSNR(reference)\left[dB\right] \quad (18)$$

Additionally, PSNR values of the filters with α_2=-1.5 are quite similar to PSNR values of the CDF 9/7-tap wavelet filter with α_1=-1.586134342 [5], [6]. This can be verified from the result of table 1.

Beside the improvement of PSNR, we can also see that α has quite simpler value than the value of α in the CDF 9/7-tap wavelet filter, which is an irrational number.

4.2 Wavelet Decompositions

We experimented on five images from USC database. They are LENNA, BABOON, BIRD, GRANDMA, and MAN. These images are decomposed through four types of decompositions: "mallat", "spacl", "packet", and "other". Additionally, these conditions are used for both 5/3-tap wavelet filter in lossless compression and 9/7-tap wavelet filter in lossy compression. Finally, we use VM9.0 as a reference software of JPEG2000.

4.2.1 PSNR of Different Decompositions

The different decompositions are calculated based on Eq. (18). To find appropriate wavelet decomposition for getting the optimal PSNR values of images, we choose the worst decomposition as a reference. Then we examine differences of PSNR values of different decompositions from the decomposition reference as the following tables.

Table 2: PSNR of different decompositions for 5/3-tap wavelet filter.

Image	Bitrate [bpp]	Mallat PSNR1 [dB]	Spacl PSNR2 [dB]	Other PSNR3 [dB]	Packet PSNR4 [dB]	$\Delta PSNR_1$ [dB]	$\Delta PSNR_2$ [dB]	$\Delta PSNR_3$ [dB]
LENNA	0.125	29.08	29.01	29.05	25.28	+3.8	+3.73	+3.77
	0.25	31.76	31.78	31.76	27.93	+3.83	+3.85	+3.83
	0.5	34.53	34.43	34.53	31.23	+3.3	+3.2	+3.3
	1	37.36	37.08	37.36	35.52	+1.84	+1.56	+1.84
BABOON	0.125	21.23	21.24	21.23	21.23	0	+0.01	0
	0.25	22.77	22.75	22.74	22.74	+0.03	+0.01	0
	0.5	25.02	24.94	25.02	24.86	+0.16	+0.08	+0.16
	1	28.51	28.38	28.51	28.03	+0.48	+0.35	+0.48
BIRD	0.125	32.63	32.25	32.25	31.84	+0.79	+0.41	+0.41
	0.25	36.3	36.1	36.3	35.45	+0.85	+0.65	+0.85
	0.5	40.11	39.56	40.06	38.62	+1.49	+0.94	+1.44
	1	42.95	42.43	42.95	41.11	+1.84	+1.32	+1.84
GRANDMA	0.125	35.14	35.08	35.14	34.89	+0.25	+0.19	+0.25
	0.25	36.68	36.62	36.66	36.39	+0.29	+0.23	+0.27
	0.5	38.34	38.25	38.34	37.73	+0.61	+0.52	+0.61
	1	40.64	40.24	40.64	39.54	+1.1	+0.7	+1.1
MAN	0.125	26.09	26.07	26.08	26.04	+0.05	+0.03	+0.04
	0.25	28.49	28.43	28.46	28.35	+0.14	+0.08	+0.11
	0.5	31.39	31.31	31.32	31.06	+0.33	+0.25	+0.26
	1	34.87	34.65	34.86	34.08	+0.79	+0.57	+0.78

Table 3: PSNR of different decompositions for 9/7-tap wavelet filter.

Image	Bitrate [bpp]	Mallat PSNR1 [dB]	Spacl PSNR2 [dB]	Other PSNR3 [dB]	Packet PSNR4 [dB]	$\Delta PSNR_1$ [dB]	$\Delta PSNR_2$ [dB]	$\Delta PSNR_3$ [dB]
LENNA	0.125	29.55	29.51	29.55	29.45	+0.1	+0.06	+0.1
	0.25	32.4	32.49	32.29	32.4	+0.11	+0.2	+0.11
	0.5	35.19	35.24	35.19	34.95	+0.24	+0.29	+0.24
	1	38.07	37.98	38.07	37.77	+0.3	+0.21	+0.3
BABOON	0.125	21.57	21.56	21.57	21.55	+0.02	+0.01	+0.02
	0.25	23.12	23.17	23.12	23.14	-0.02	+0.03	-0.02
	0.5	25.42	25.5	25.42	25.4	+0.02	+0.1	+0.02
	1	28.94	28.83	28.94	28.63	+0.31	+0.2	+0.31
BIRD	0.125	33.1	33.05	33.1	32.17	+0.93	+0.88	+0.93
	0.25	37.25	37.11	37.07	36.34	+0.91	+0.77	+0.73
	0.5	41.08	40.95	41.08	40.17	+0.91	+0.78	+0.91
	1	44.41	44.34	44.4	43.71	+0.7	+0.63	+0.69
GRANDMA	0.125	35.48	35.48	35.46	35.29	+0.19	+0.19	+0.17
	0.25	37.2	37.2	37.12	37	+0.2	+0.2	+0.12
	0.5	39	38.96	39	38.76	+0.24	+0.2	+0.24
	1	41.69	41.52	41.69	41.26	+0.43	+0.26	+0.43
MAN	0.125	26.63	26.6	26.58	26.49	+0.14	+0.11	+0.09
	0.25	29.07	29	29	28.87	+0.2	+0.13	+0.13
	0.5	32	32.12	32	31.83	+0.17	+0.29	+0.17
	1	35.54	35.48	35.54	35.12	+0.42	+0.36	+0.42

Table 2 and table 3 show that the best decomposition is the “mallat” decomposition while the worst decomposition is the “packet” decomposition. These tables also present the improvements of the “mallat”, “spacl”, and “other” decompositions compared to the “packet” decomposition in terms of $\Delta PSNR_1$ and $\Delta PSNR_2$, and $\Delta PSNR_3$, respectively. Additionally, the maximum PSNR improvement through choosing wavelet decomposition is significantly up to 0.93dB for 9/7-tap wavelet filter in lossy compression and up to 3.85dB for 5/3-tap wavelet filter in lossless compression. Based on our experiments, we can choose the most appropriate decomposition for our image compression application of JPEG2000.

4.2.2 Optimal PSNR for Different Decompositions

We count the numbers of maximum PSNR values for different decompositions and different bitrates. As a result, we have a statistic as shown in Fig. 7.

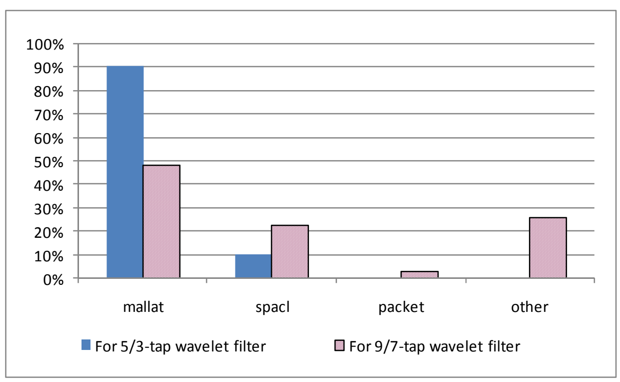
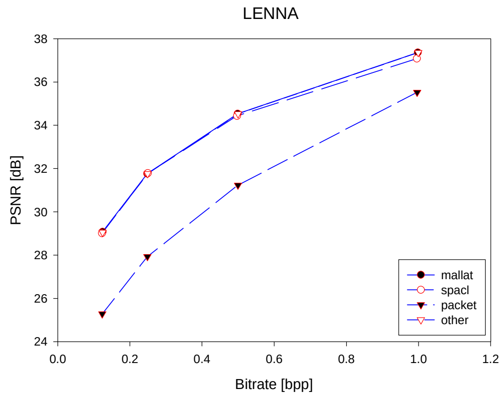


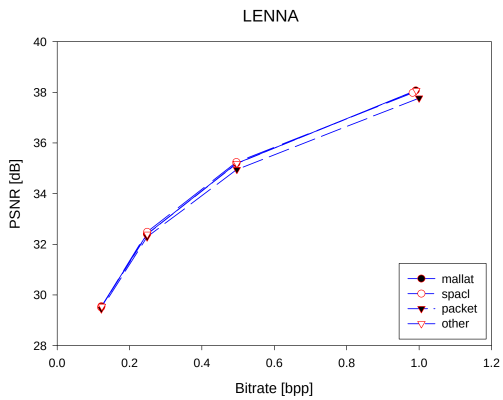
Fig. 7: Optimal PSNR for different decompositions

4.2.3 Rate-Distortion (RD) Curves

Figure 8 and Fig. 9 show the RD curves for different decompositions of “LENNA” and “BIRD” images.

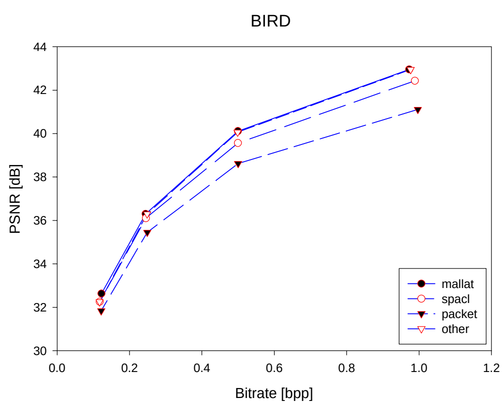


a) For 5/3-tap wavelet filter

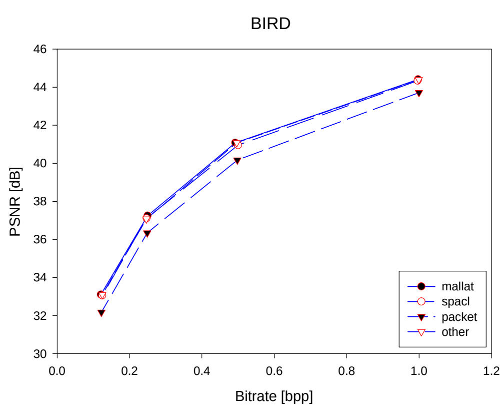


b) For 9/7-tap wavelet filter

Fig. 8: RD curves of different decompositions (LENNA)



a) For 5/3-tap wavelet filter



b) For 9/7-tap wavelet filter

Fig. 9: RD curves of different decompositions (BIRD)

5. CONCLUSIONS

In this paper, we proposed a method to optimize image quality based on wavelet filter design and on wavelet decomposition. Using the lifting scheme, we proposed a method to design the optimal 9/7-tap wavelet filters. We also found out the range of optimal α value, which was used to find the coefficients of the filters, and PSNR as a function of α. Using our proposed method, the complexity of wavelet filters is significantly reduced since their irrational coefficients are replaced by rational coefficients. Additionally, the PSNR are improved. We also found the most appropriate wavelet decomposition to get the optimal PSNR values of images. As a result, the maximum PSNR difference of the most appropriate wavelet decomposition is distinguishable up to 0.93 dB for 9/7-tap wavelet filter in lossy compression and up to 3.85 dB for 5/3-tap wavelet filter in lossless compression.

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REFERENCES

[1] J. Morlet and A. Grossmann, "Decomposition of hardy functions into square integrable wavelets of constant shape," SIAM Journal of Mathematical Analysis, Vol. 15, Issue 4, pp. 723-736, 1984.

[2] W. Sweldens, "The lifting scheme: a construction of second generation wavelets," SIAM Journal on Mathematical Analysis, Vol. 29, pp. 511-546, 1996.

[3] D. S. Taubman, and M. W. Marcellin, *JPEG2000 Image Compression Fundamentals, Standards and Practice*, Kluwer Academic Publishers, 2002.

[4] I. Daubechies and W. Sweldens, "Factoring wavelet transforms into lifting steps," Journal of Fourier Analysis and Applications, Vol. 4, No. 3, 1998.

[5] Z. Guangjun, C. Lizhi, and C. Huowang, "A simple 9/7-tap wavelet filter based on lifting scheme," International Conference on Image Processing, Vol. 2, pp. 249-252, 2001.

[6] D. Liang, L. Cheng, Z. Zang, "General construction of wavelet filters via a lifting scheme and its application in image coding," Optical Engineering, Vol. 42, No. 7, pp. 1949-1955, 2003.

[7] "JPEG 2000 Part I Final Draft International Standard FDIS15444-1:2000," *ISO/IEC JTC1/SC29/WG1 N1876*, August 2000.

[8] A. Przelaskowski, "Performance evaluation of JPEG2000-like data decomposition schemes in wavelet codec," International Conference on Image Processing, Vol. 3, pp. 788-791, 2001.

[9] http://sipi.usc.edu/database/

[10] http://www.jpeg.org/

[11] "JPEG2000 Verification Model 9.0 (VM9.0, reference software)," *ISO/IEC JTC1/SC29/WG1 N2131*, April 2001.