Chapter 4
Experimental Results

4.1 Test Images

In an image compression system, one of the main difficulties is how to choose the suitable images for us to evaluate. In this paper, several images that have been mentioned in Chapter 3 are used. They include Lena, Peppers, Baboon, House, Airplane, Man, Aerial, Grass, Barbara, Boat, Fruits, Goldhill, Straw, Text, and Resolution Chart images. Each image is of size 256×256 with 256 grayscale, and is shown in Appendix A.

4.2 Comparisons of the Compression Results

Haar Wavelet (HW), Daubechies Wavelet (DW), Coiflet Wavelet (CW), and Biorthogonal Wavelet (BW) are wavelet families used in our experiments. And the compression ratios we use are 10:1, 30:1 and 50:1.

Table. 4-1 shows the PSNR values of Lena image using different wavelet families and different number of decompositions. Compression results of all test images are shown in Appendix B. The shaded areas in these tables represent better compression results comparatively, so suitable wavelet families and number of decompositions can be found. In Appendix B, we only list the results of some appropriate wavelet families and number of decompositions, which are DW1 (Haar Wavelet) with D = 5,6,8, DW2 with D = 4,5,6, DW5 with D = 4,5, BW2.2 with D = 5,6, CW2 with D = 4,5, and CW3 with D = 4,5.

WAVELET	N	COMPRESSION RATIO			D
		10:1	30:1	50:1	
DW	1 (HW)	32.82	26.78	24.11	3
		33.04	27.45	25.55	4
		33.05	27.46	25.57	5
		33.06	27.48	25.62	6
		33.07	27.51	25.67	8
	2	34.62	28.01	24.84	3
		34.76	28.68	26.61	4
		34.75	28.71	26.69	5
		34.72	28.66	26.65	6
		34.66	28.58	26.54	8
	5	35.09	27.84	23.35	3
		34.85	28.21	25.86	4
		34.66	27.98	25.69	5
		34.47	27.66	25.29	6
		34.16	27.09	24.47	8
		33.74	26.32	23.41	10
	10	32.72	26.10	23.63	4
		31.80	25.22	23.00	5
		31.26	24.50	22.35	6
		30.15	23.38	20.95	8
BW	2.2	35.33	28.46	24.71	3
		35.37	29.16	27.16	5
		35.30	29.06	27.01	6

		35.17	28.86	26.67	8
	3.3	34.21	26.91	23.20	3
		34.19	27.60	25.27	5
		34.06	27.42	25.03	6
		33.92	27.08	24.49	8
	6.8	34.99	26.77	21.89	3
		34.17	27.26	24.70	5
		33.72	26.86	24.40	6
		32.56	25.05	22.62	8
CW	2	34.88	28.25	25.78	4
		34.66	28.15	25.87	5
		34.41	27.74	25.45	6
	3	34.44	27.51	24.67	4
		34.02	27.13	24.51	5
		33.55	26.60	23.84	6
	4	33.07	26.00	22.92	4
		32.41	25.35	22.44	5
		31.80	24.70	21.92	6
	5	32.21	24.82	21.23	4
		30.81	24.03	21.03	5
		30.16	23.48	20.55	6

Table. 4-1. PSNR values of compression results (Lena).

Fig. 4-1 shows an example of the reconstructed Lena image using different wavelets and different number of decompositions, and compression ratio = 30:1.


Original Lena image.


HW, *D* = 8, PSNR = 27.51


DW2, *D* = 5, PSNR = 28.71


DW5, *D* = 4, PSNR = 28.21


BW2.2, *D* = 5, PSNR = 29.16

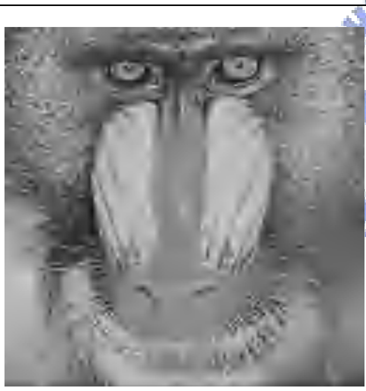

CW2, *D* = 4, PSNR = 28.25

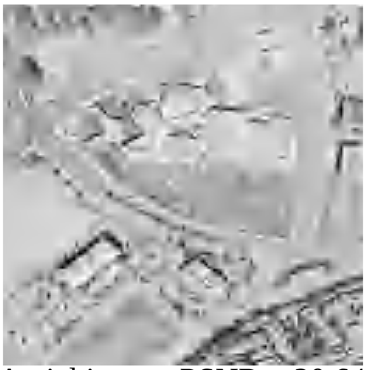
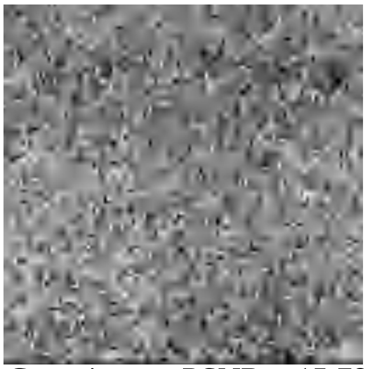
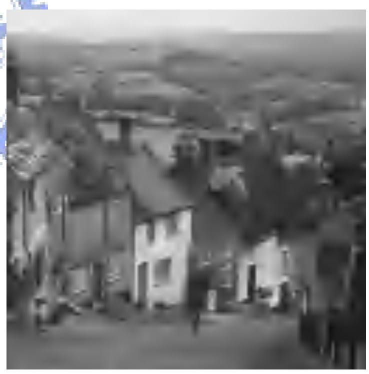

CW3, *D* = 4, PSNR = 27.51

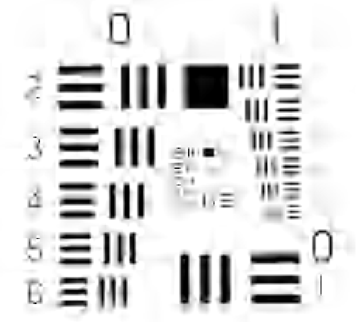
Fig. 4-1. Reconstructed Lena image using some wavelet filters. (CR=30:1)

4.2.1 Different Image Contents

Fig. 4-2 shows different reconstructed images using the same wavelet (BW2.2) and the same number of decompositions (D = 5), also the same compression ratio (CR = 50:1).

 Lena image. PSNR = 27.16	 Peppers image. PSNR = 26.17
 Baboon image. PSNR = 22.63	 House image. PSNR = 29.13
 Airplane image. PSNR = 24.57	 Man image. PSNR = 23.14

 Aerial image. PSNR = 20.64	 Grass image. PSNR = 15.78
 Barbara image. PSNR = 24.68	 Boat image. PSNR = 24.48
 Fruits image. PSNR = 26.99	 Goldhill image. PSNR = 26.24
 Straw image. PSNR = 19.47	 Text image. PSNR = 13.10



Resolution Chart image. PSNR = 19.34

Fig. 4-2. Reconstructed images using BW2.2 and *D* = 5. (CR = 50:1)

It can be seen that the PSNR values will be quite different even we use the same conditions (the same wavelet family, the same number of decompositions, and the same compression ratio). [Fig. 4-3] This is because that different image contents will affect PSNR values. So the standard evaluation criterion PSNR is not suitable when we want to compare images with different contents.

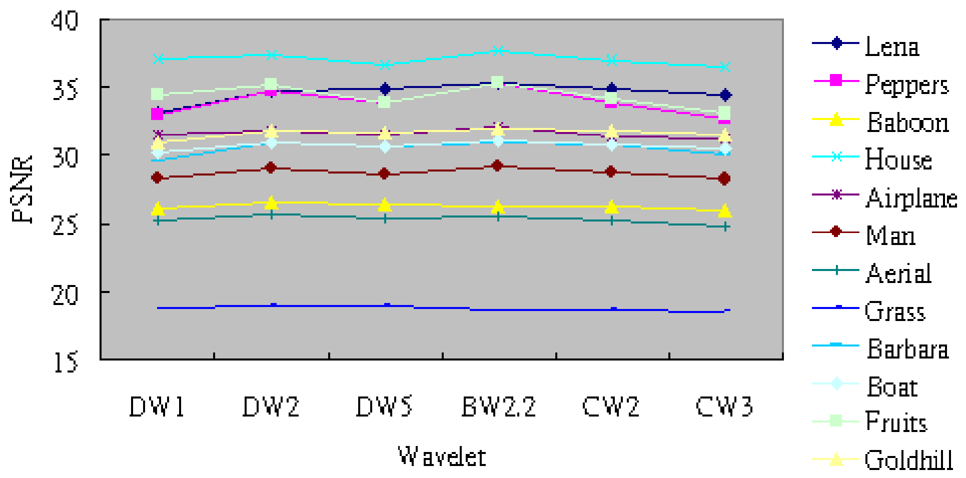
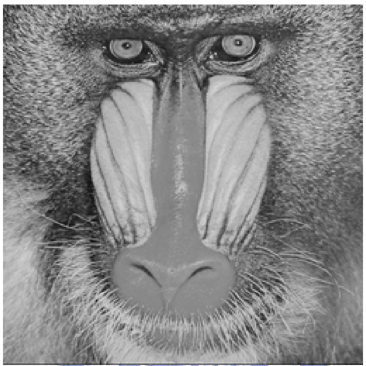


Fig. 4-3. PSNR values of different images. (CR = 10:1)

4.2.2 Different Number of Decompositions

Fig. 4-4 shows comparison of reconstructed Baboon images using the same wavelet and the same compression ratio, but different number of decompositions. The number of decompositions determines the resolution of the lowest level in wavelet domain. So it can be found that image quality is better for higher number of decompositions because resolving important DWT coefficients will be more successfully, and HVS is less sensitive to the removal of smaller details.



Original Baboon image.

D = 3, PSNR = 21.90

D = 4, PSNR = 22.60

D = 5, PSNR = 22.63

D = 6, PSNR = 22.58

Fig. 4-4. Comparison of reconstructed Baboon image using BW2.2 with different number of decompositions. (CR = 50:1)

On the other hand, the PSNR value tends to saturate for lager number of decompositions. The PSNR value will be on the downside if the number of decompositions is larger than the optimal one. Also, larger number of decompositions will cause the coding algorithm inefficiently. Therefore, optimal number of decompositions should be considered about image quality and computational complexity. Fig. 4-5 shows the PSNR values of Baboon image with different number of decompositions using BW2.2.

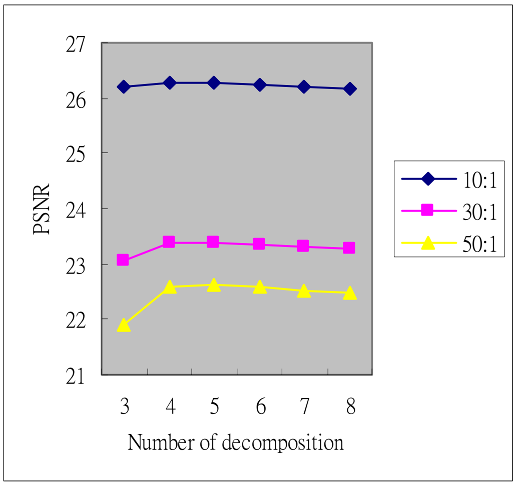


Fig. 4-5. Different number of decompositions using BW2.2. (Baboon)

4.2.3 Different Filter Orders

To find out how the filter orders affect image quality, Fig. 4-6 (a) and (b) show two kinds of wavelet families applied on Lena image. They show that no matter what the number of decompositions is, the PSNR value decreases while the filter order increases. So larger filter orders do not imply better PSNR values or visual picture quality. Fig. 4-7 shows another example using Grass image.

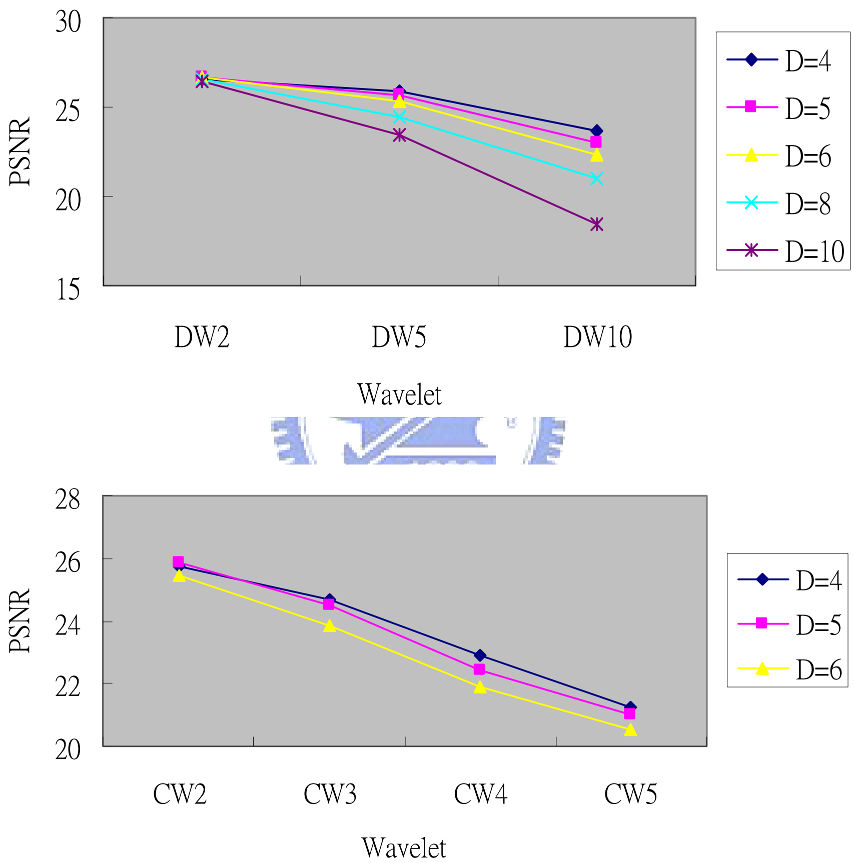


Fig. 4-6. Comparisons of different filter orders. (CR = 50:1, Lena) (a) DW. (b) CW.

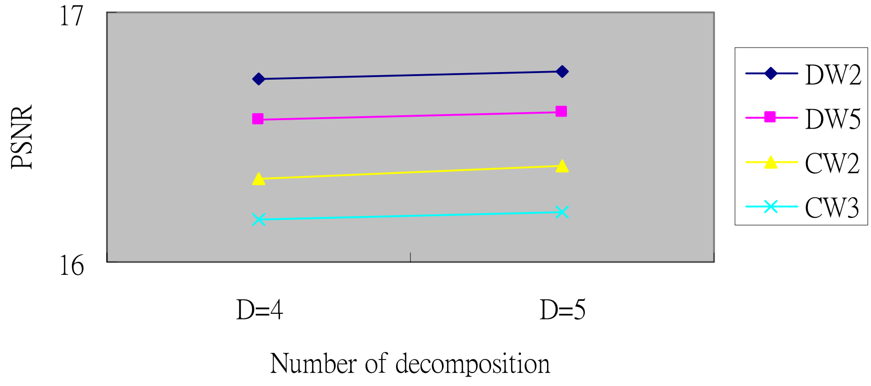


Fig. 4-7. Comparisons of different filter orders. (CR = 30:1, Grass)

Fig. 4-8 shows an example of Lena image using CW with different filter orders. The number of decompositions used here is all four and compression ratio is 30:1. We can clearly see that the worst PSNR value is caused by CW5 and the visual picture quality is also the worst. So it explains again that larger filter orders do not imply better PSNR values or better visual picture quality.

Original Lena image.

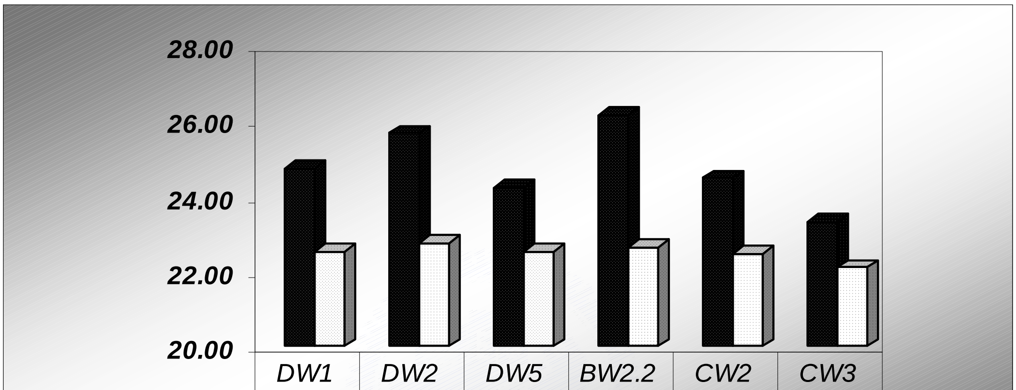
 CW2, PSNR = 28.25	 CW3, PSNR = 27.51
 CW4, PSNR = 26.00	 CW5, PSNR = 24.82

Fig. 4-8. Comparison of reconstructed Lena image using CW with different filter orders. (D = 4, CR = 30:1)

4.2.4 Different Wavelets

As mentioned in section 3.1, choice of wavelet function is significant for coding performance in an image compression system. Nevertheless, the choice should be adjusted according to different image contents. So in this section, we select two different types of images, Peppers and Baboon, to do the comparison. Baboon image contains larger number of small details and lower spatial redundancy (i.e. with higher spectral activity) that makes compression more difficult. Peppers image is quite the other way.

Fig. 4-9 shows different wavelet functions applied on these two images. We can find that Baboon image is insensitive to the choice of wavelets because the PSNR values are similar. On the other hand, coding performance of images with moderate spectral activity is more sensitive to the choice of wavelets. So, one way to choose the better wavelet is to select the optimal wavelet applied on images with moderate spectral activity. This wavelet will also cause good results for other types of images. And this is why Lena image is often used in a compression system.



	DW1	DW2	DW5	BW2.2	CW2	CW3
■ Peppers	24.72	25.66	24.24	26.17	24.47	23.31
□ Baboon	22.53	22.77	22.54	22.63	22.46	22.09

Fig. 4-9. Different wavelets applied on Peppers and Baboon images. (CR = 50:1)

4.2.5 Different Compression Ratios

By the data in Appendix B, we can find out a phenomenon that when applying the same wavelet family and the same filter order on the same image, the optimal number of decompositions tends to increase as compression ratio is on the rise, and the optimal number of decompositions tends to decrease as compression ratio is going down. For example, when we apply DW5 on Goldhill image, the optimal number of decompositions is four when compression ratios are 10:1 and 30:1 (Lower CR). But while compression ratio is 50:1 (Higher CR), the optimal number of decompositions is five. And similar conditions also occur on other images.

4.3 Selection of Proper Wavelets

When we apply one specific wavelet function with one specific filter order on an image, the optimal number of decompositions can be found. Then, for each image with different compression ratios, the statistics of the PSNR values will tell us the proper filter order and proper number of decompositions in one specific wavelet family. The compression results of our experiments are shown in Appendix B.

In this paper, compression ratios we use are 10:1, 30:1 and 50:1. From the compression results shown in Appendix B, we discover that the PSNR values using HW, DW, CW, and BW on the same image only have little difference. So the coding performances are comparable by the PSNR criteria while compression ratio is under 50:1.

Fig. 4-10 shows the PSNR values of different compression ratios 10:1, 30:1 and 50:1, respectively. We find that the appropriate wavelets, filter orders, and number of decompositions of Lena, Peppers, House, Airplane, Man, Barbara, Boat, Fruits, and Goldhill images are similar. They are HW with D = 8, DW2 with D = 4 or 5, BW2.2 with D = 5, and CW2 with D = 4 or 5.

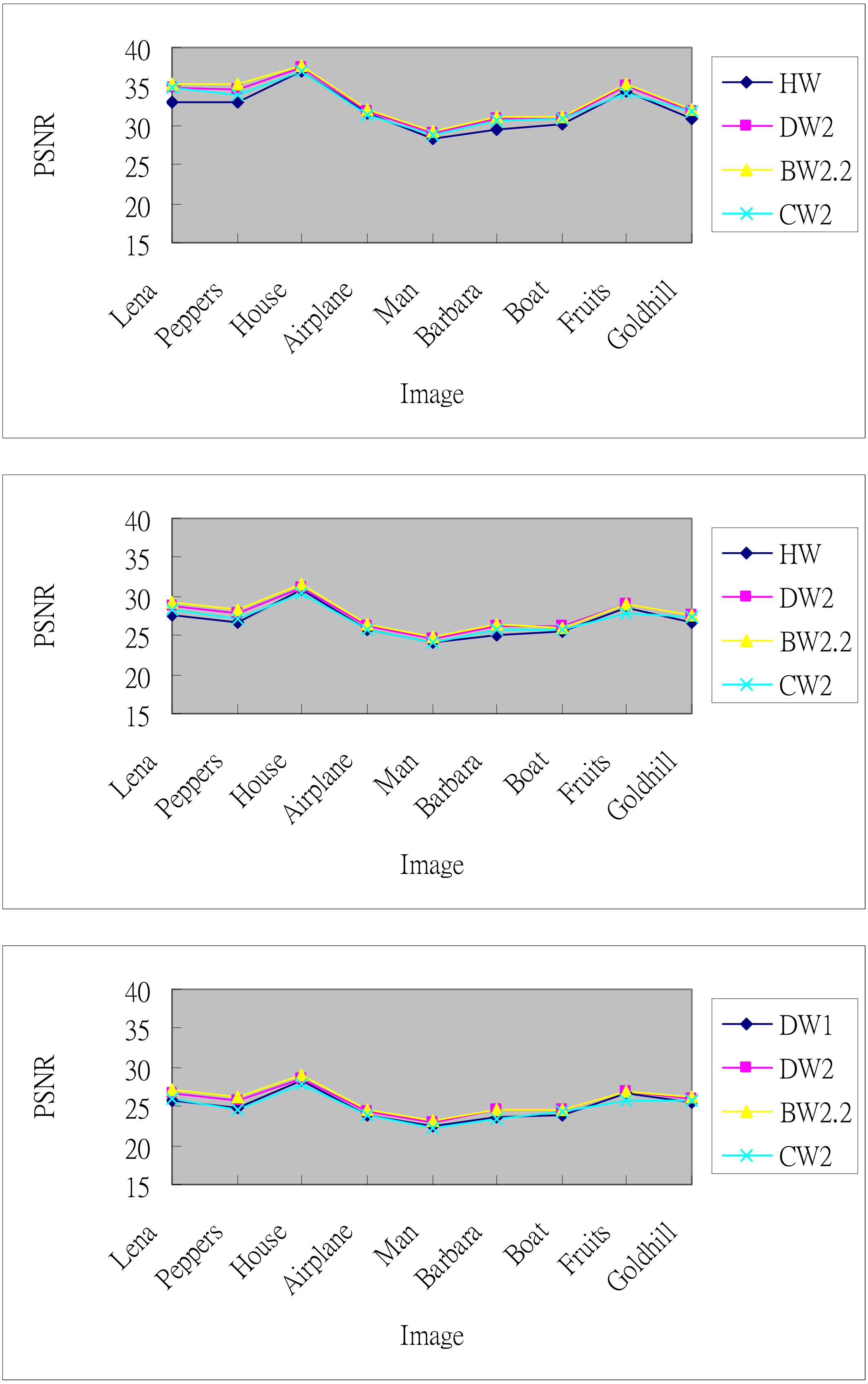


Fig. 4-10. PSNR values using appropriate wavelets.

(a) CR = 10:1 (b) CR = 30:1 (c) CR = 50:1

Among these images, although the PSNR values are close using different wavelets on an image, BW family that filters with order two in decomposition and order two in reconstruction (BW2.2) almost gives the best PSNR values. Two examples of Lena and Fruits images are shown in Fig. 4-11 and Fig. 4-12.

Fig. 4-11. Reconstructed Lena images using appropriate wavelets. (CR = 50:1)

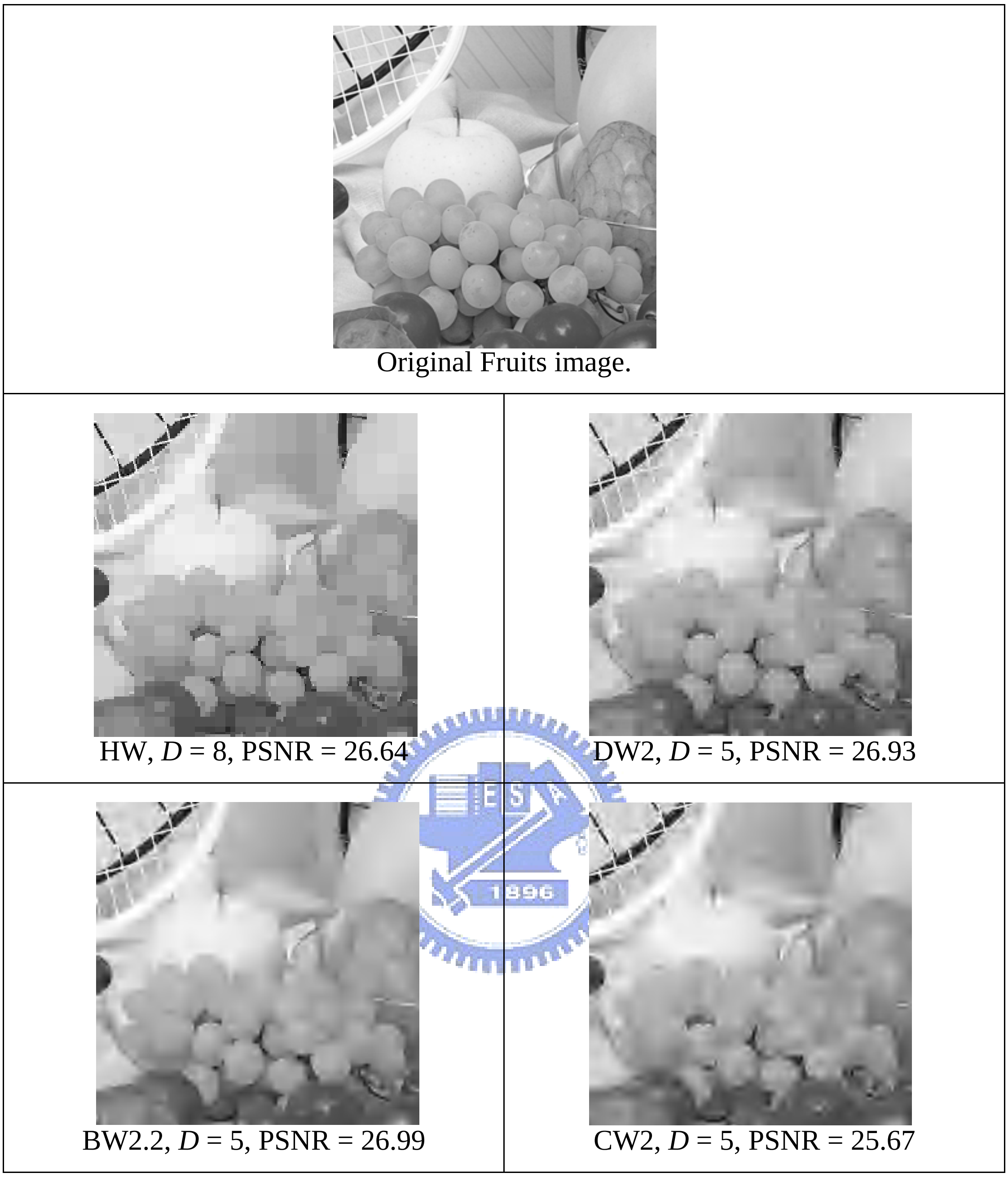


Fig. 4-12. Reconstructed Fruits images using appropriate wavelets. (CR = 50:1)

From these two figures above, we can find that the visual picture quality is also best for BW2.2. Besides, we easily see that HW causes obvious blocking effect. This artifact makes bad visual picture quality, and cannot be evaluated using the PSNR evaluation criteria. So PQS is another way to evaluate visual picture quality. Fig. 4-13 shows the comparison of PQS using different wavelet families on these images at compression ratio 10:1. Note that PQS values of some images are negative, and not shown in the figure. From PQS we can see that BW2.2 indeed outperforms other wavelet families. Moreover, both HW and CW2 have worse results.

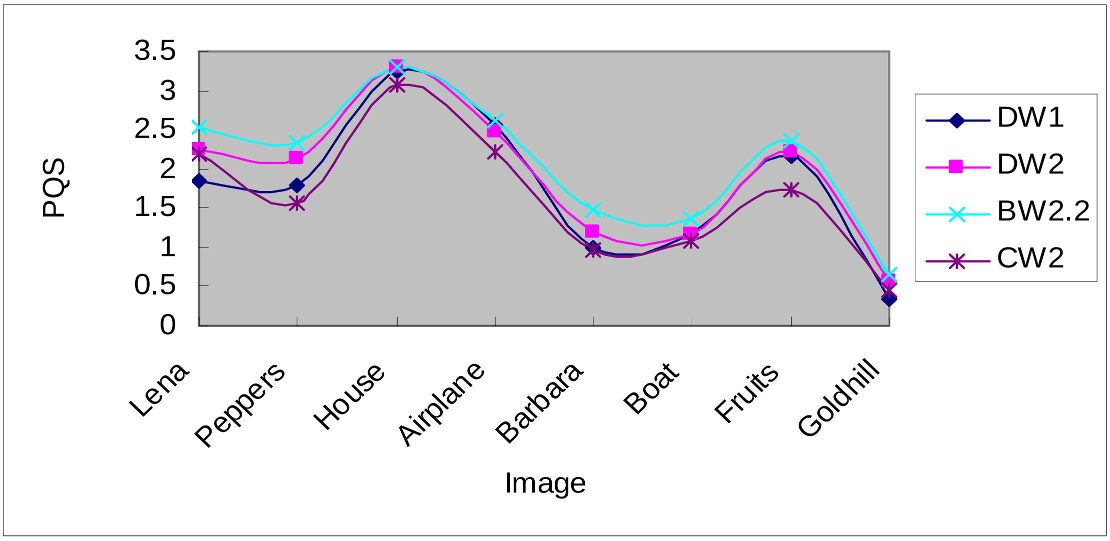
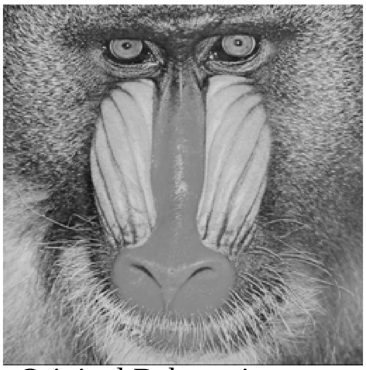


Fig. 4-13. PQS of each image using appropriate wavelets. (CR = 10:1)

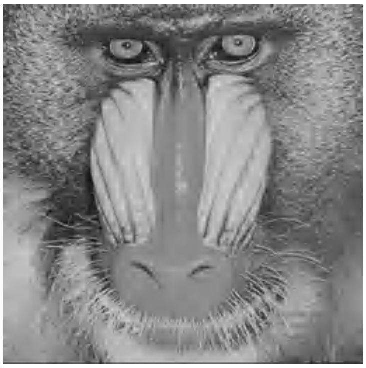
Using BW2.2 we can get good PSNR values and good visual picture quality in most images, but there exist some exceptions. From the results shown in Appendix B, using DW2 with number of decompositions five is better than using BW2.2 on Baboon, Aerial, Grass, and Straw images. The common point of these images is that they usually contain large number of small details and low spatial redundancy, such as texture images. This type of images is more difficult for a compression system to deal with. From Fig. 4-2, it can be discovered that the PSNR values of these images are relatively small.

Two examples of Baboon and Grass images using BW2.2 and DW2 with three different compression ratios are shown in Fig. 4-14 and Fig. 4-15. Comparing with BW2.2, DW2 causes not only better PSNR values but also better visual picture quality.

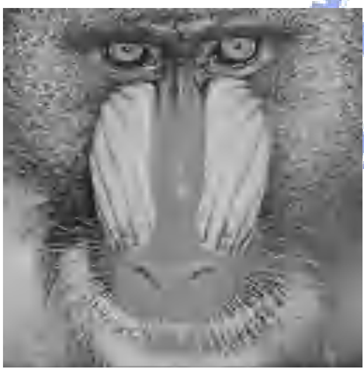


Original Baboon image.

BW2.2,*D*=5,PSNR=26.28,PQS=0.52(10:1)



DW2,*D*=5,PSNR=26.54,PQS=0.54 (10:1)



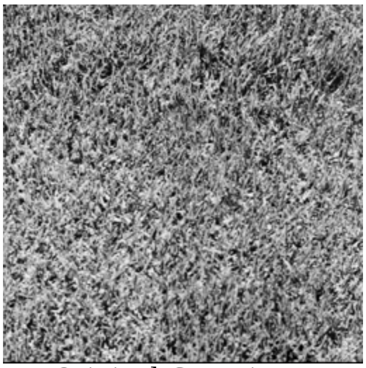
BW2.2, *D*=5, PSNR=23.39 (30:1)

DW2, *D*=5, PSNR=23.59 (30:1)

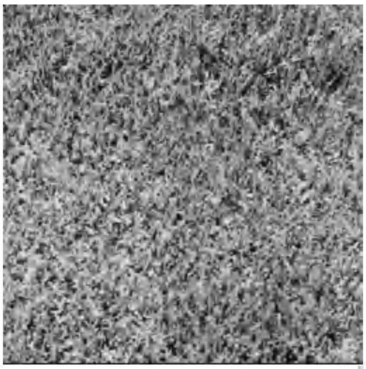
BW2.2, *D*=5, PSNR=22.63 (50:1)

DW2, *D*=5, PSNR=22.78 (50:1)

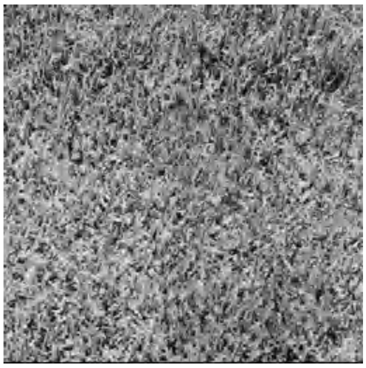
Fig. 4-14. Comparisons using BW2.2 and DW2 with different CRs (Baboon).



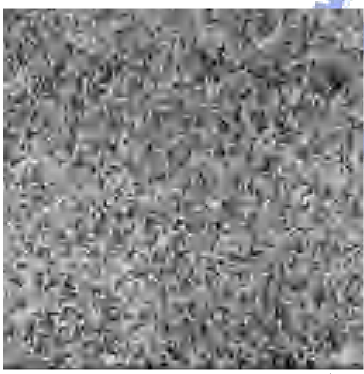
Original Grass image.



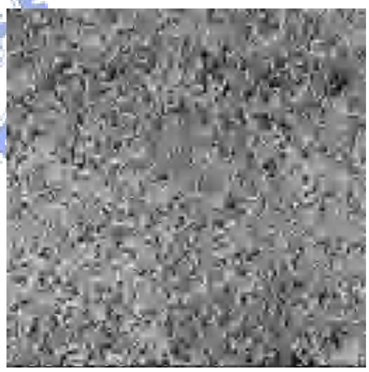
BW2.2,*D*=5,PSNR=21.46,PQS=0.77(5:1)



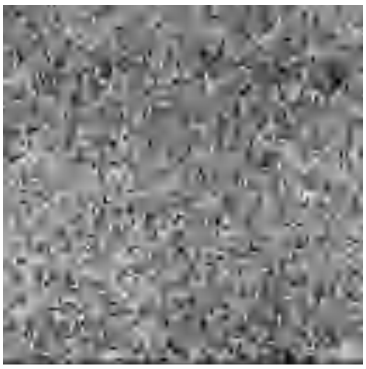
DW2,*D*=5,PSNR=21.62,PQS=0.85(5:1)



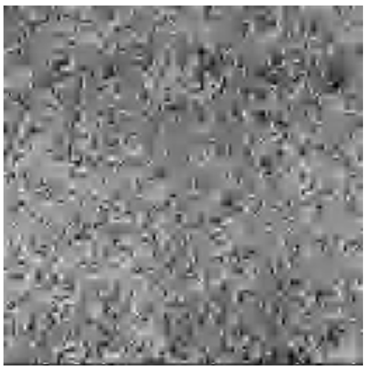
BW2.2, *D*=5, PSNR=16.43 (30:1)



DW2, *D*=5, PSNR=16.76 (30:1)



BW2.2, *D*=5, PSNR=15.78 (50:1)



DW2, *D*=5, PSNR=16.13 (50:1)

Fig. 4-15. Comparisons using BW2.2 and DW2 with different CRs (Grass).

Another type of images is pure binary text images. We choose Text and Resolution Chart images to experiment. Fig. 4-16 shows the comparisons of Text image using different wavelet families and different number of decompositions. And Fig. 4-17 shows an example of Resolution Chart image. Both the figures show that HW family with number of decompositions five gives best PSNR values and best visual picture quality.

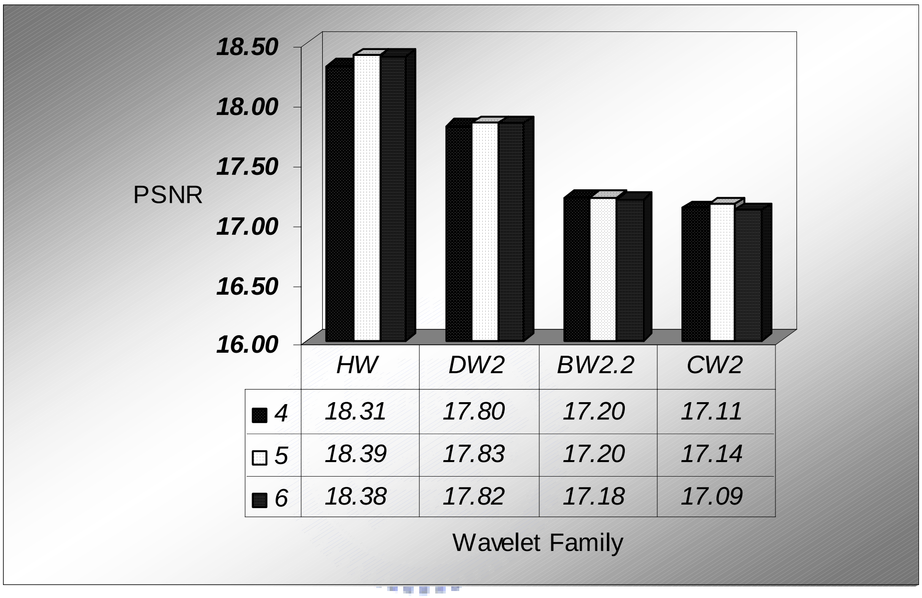
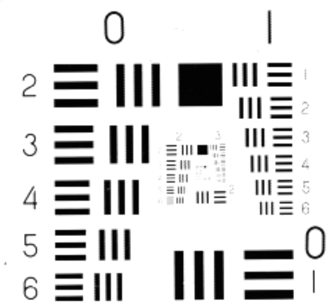


Fig. 4-16. Comparisons of Text image. (CR = 10:1)



Original Resolution Chart image.

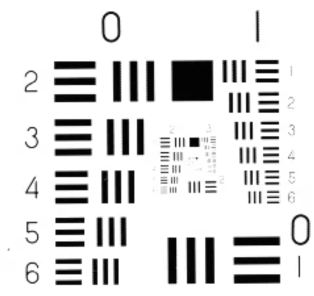
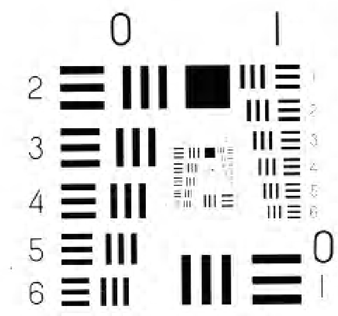
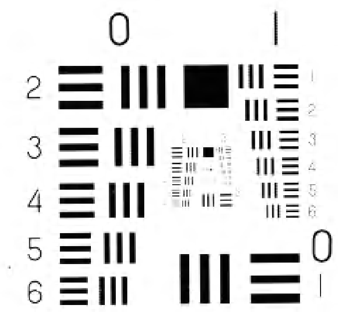
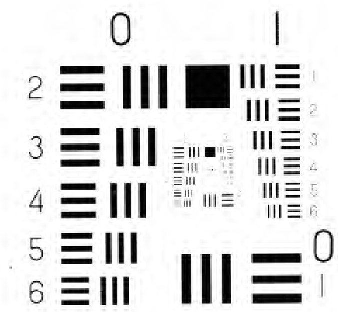
 HW, *D*=5, PSNR=43.91, PQS=4.61	 DW2, *D*=5, PSNR=32.49, PQS=2.42
 BW2.2, *D*=5, PSNR=35.68, PQS=3.44	 CW2, *D*=5, PSNR=32.80, PQS=2.05

Fig. 4-17. Comparisons using different wavelet families.

(CR = 10:1, Resolution Chart)

4.4 Resolutions of Images

In our experiments, the test images we choose are all of size 256×256. Fig. 4-18 shows an example of Lena image, using the same wavelet, number of decompositions and compression ratio on 256×256, 512×512 and 1024×1024 images. It is obviously found that the PSNR values and visual picture quality of the reconstructed image depend on resolutions of the original image, and larger images have better results. This is because DWT gives better results for higher number of decompositions, larger images can provide more decompositions. But oppositely the computational complexity is relatively high.

 Original Lena image	 256×256, PSNR = 27.16
 512×512, PSNR = 31.56	 1024×1024, PSNR = 36.56

Fig. 4-18. Reconstructed Lena images. (BW2.2, D = 5, CR = 50:1)