Deep Edge Guided Recurrent Residual Learning for Image Super-Resolution

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Abstract

This supplementary file is consists of following three sections. The first section presents the objective evaluation of DEGREE on Set5 and Set14, and the second section gives subjective evaluation of DEGREE on Set 5, Set14 and BSD100. The third section present some examples of sub-band decomposition.

I. SUBJECTIVE RESULTS

We compare subject results of the proposed DEGREE with recent SR methods on three popular benchmark datasets: Set5 [1], Set14 [2] and BSD100 [3] with scaling factors of 2, 3 and 4. In particular, our proposed DEGREE SR network (DEGREE) is compared with Bicubic interpolation and the following seven state-of-the-art SR methods: ScSR (Sparse coding) [4], Neighbor Embedding (NE+LLE) [5], A+ (Adjusted Anchored Neighborhood Regression) [6], SRCNN [7], TSE-SR (Transformed Self-Exemplars) [8], CSCN (Deep Sparse Coding) [9] and JSB-NE (Joint Sub-Band Based Neighbor Embedding) [10]. All the compared methods are implemented using the public available codes from the authors. The results of the DEGREE network are generated by DEGREE-2, which has 20 layers and 64 channels. The subjective results are shown in Figure 1-14. **Zoom-in view on some important details is presented and highlighted.**
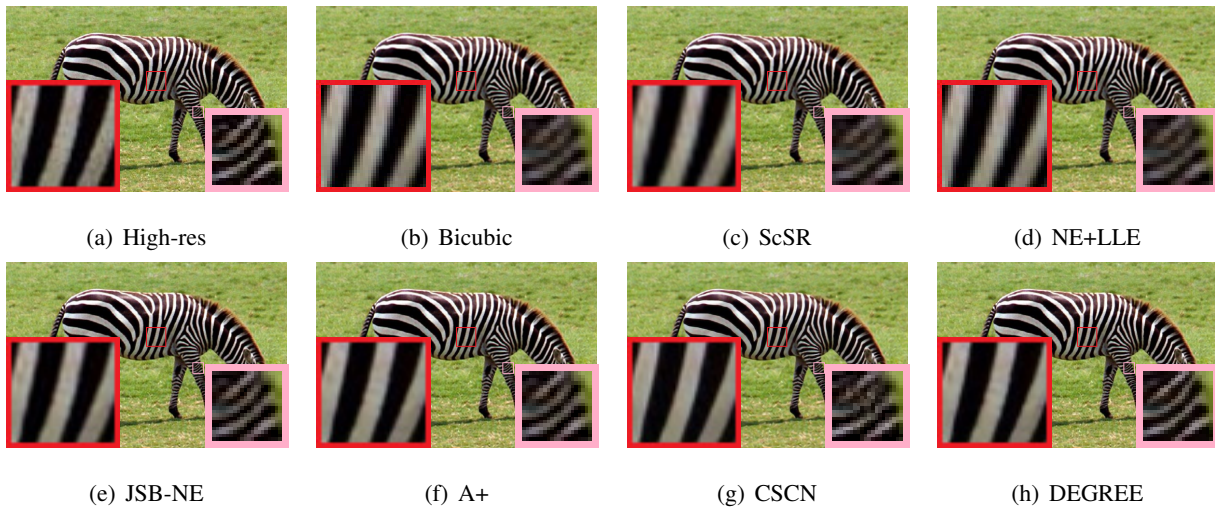
Fig. 1. Visual comparisons between different algorithms for the image *Zebra* (×2). The DEGREE presents sharper stripes without artifacts.

Fig. 2. Visual comparisons between different algorithms for the image *PPT3* (×2). The DEGREE presents clearer texts with fewer artifacts.

(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
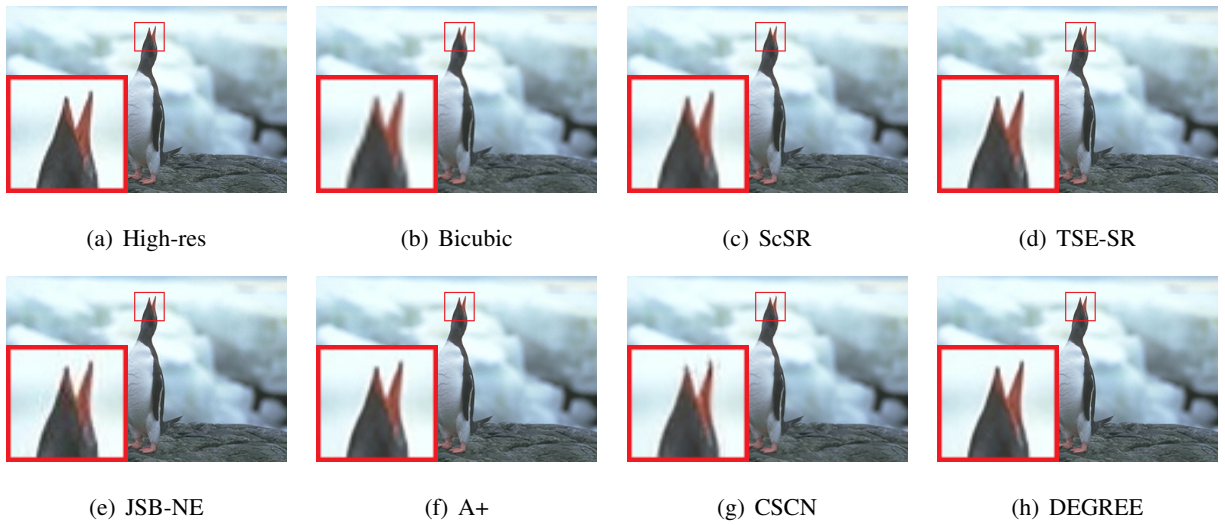
Fig. 3. Visual comparisons between different algorithms for the image *106024* (×2). The results of DEGREE and TSE-SR present the penguin mouth naturally. The former includes fewer artifacts around the boundary of the mouth.

(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR
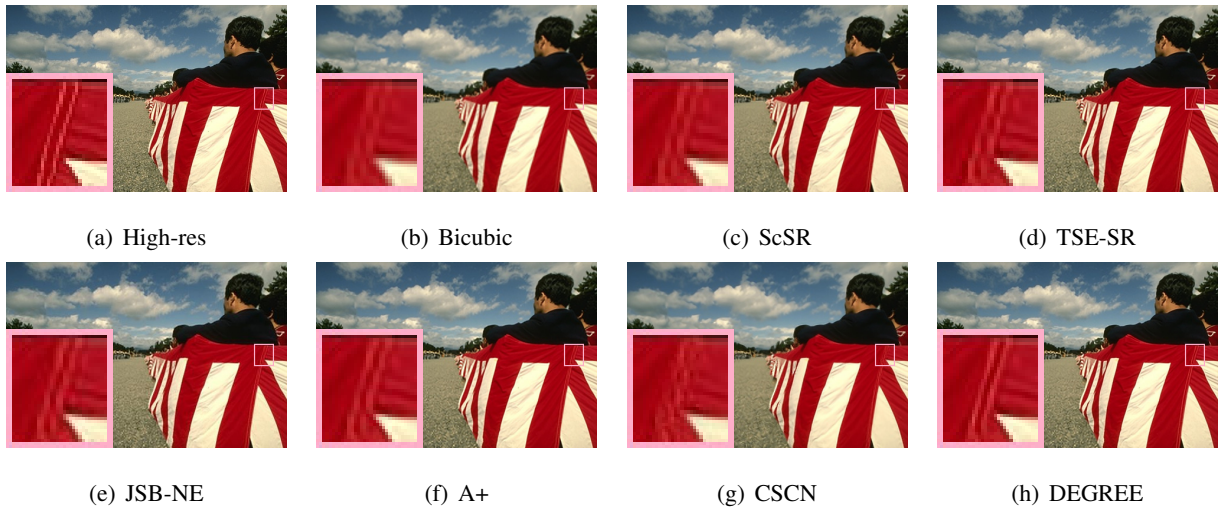
(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE

Fig. 4. Visual comparisons between different algorithms for the image *145086* (×2). The DEGREE presents more straight and long stripe in the flag.

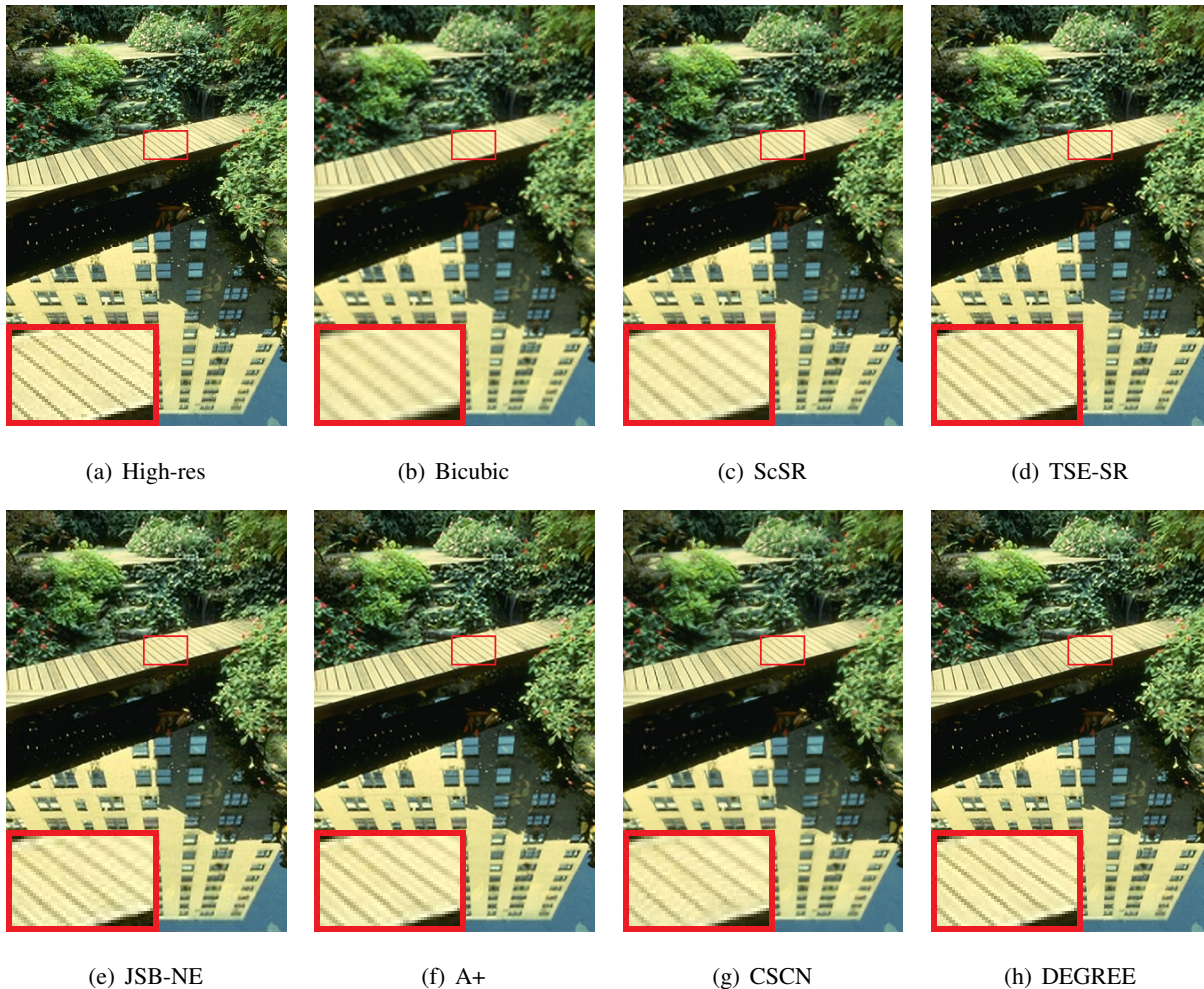| (a) High-res | (b) Bicubic | (c) ScSR | (d) TSE-SR |
| (e) JSB-NE | (f) A+ | (g) CSCN | (h) DEGREE |

Fig. 5. Visual comparisons between different algorithms for the image *148026* (×2). The DEGREE presents more straight and long cracks between boards.

| (a) High-res | (b) Bicubic | (c) ScSR | (d) TSE-SR |
| (e) JSB-NE | (f) A+ | (g) CSCN | (h) DEGREE |
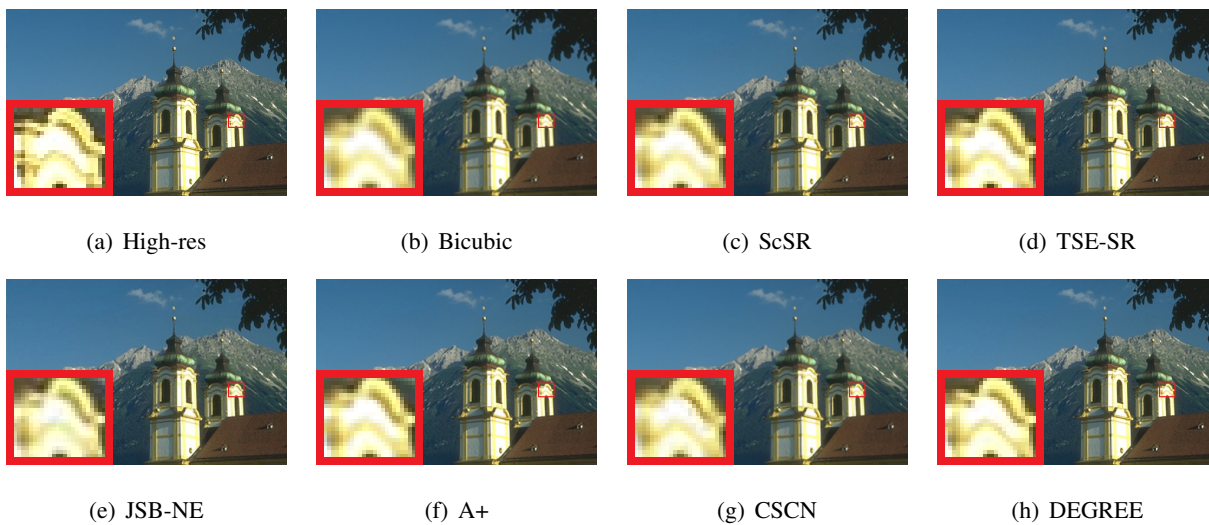
Fig. 6. Visual comparisons between different algorithms for the image *126007* (×2). The DEGREE presents a clearer result.

| (a) High-res | (b) Bicubic | (c) ScSR | (d) TSE-SR |

| (e) JSB-NE | (f) A+ | (g) CSCN | (h) DEGREE |
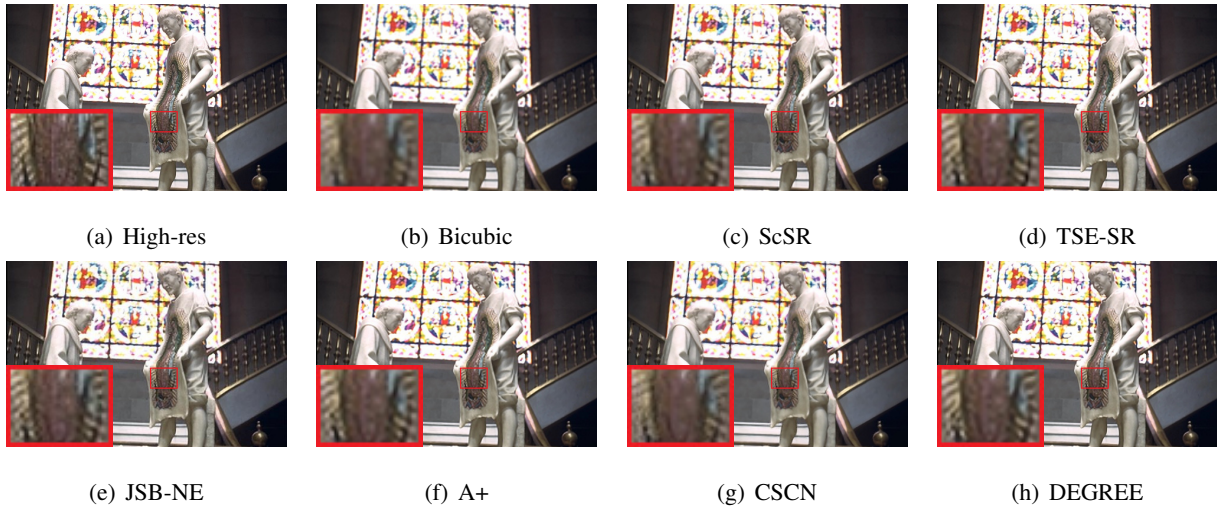
Fig. 7. Visual comparisons between different algorithms for the image *24077* (×2). The DEGREE and TSE-SR present more regular and clear textures.

| (a) High-res | (b) Bicubic | (c) ScSR | (d) TSE-SR |

| (e) JSB-NE | (f) A+ | (g) CSCN | (h) DEGREE |

Fig. 8. Visual comparisons between different algorithms for the image *102061* (×3). The DEGREE shows more obvious and clear spires.

(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
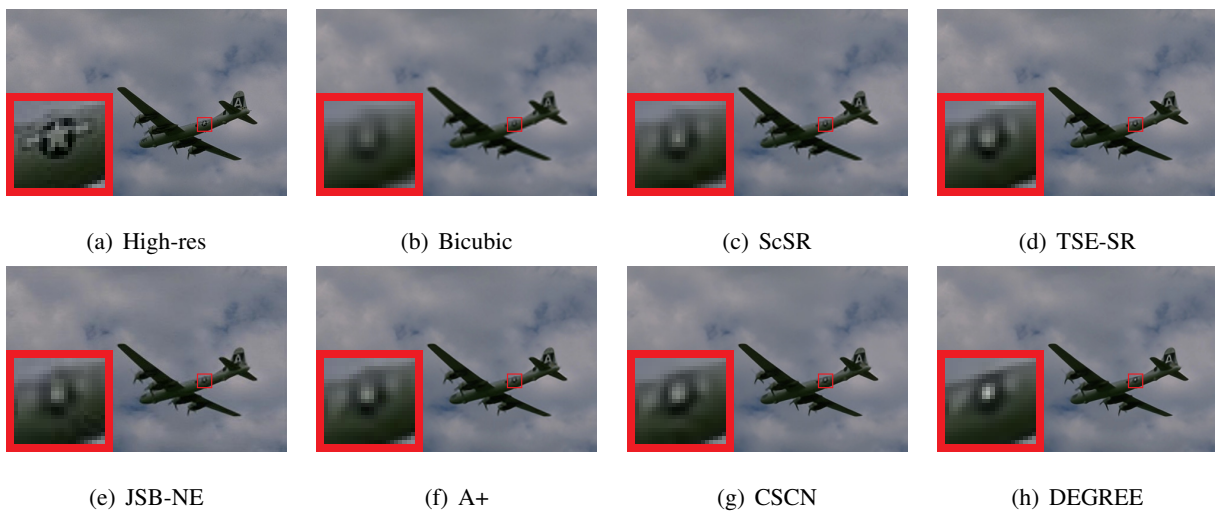
Fig. 9. Visual comparisons between different algorithms for the image *067* (×3). All methods fail to recover the 'Star' symbol. However, the DEGREE recovers a very clear symbol, with a natural look.

(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE

Fig. 10. Visual comparisons between different algorithms for the image *108005* (×3). DEGREE successfully recovers the stripes and textures of the tiger's fur.

(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
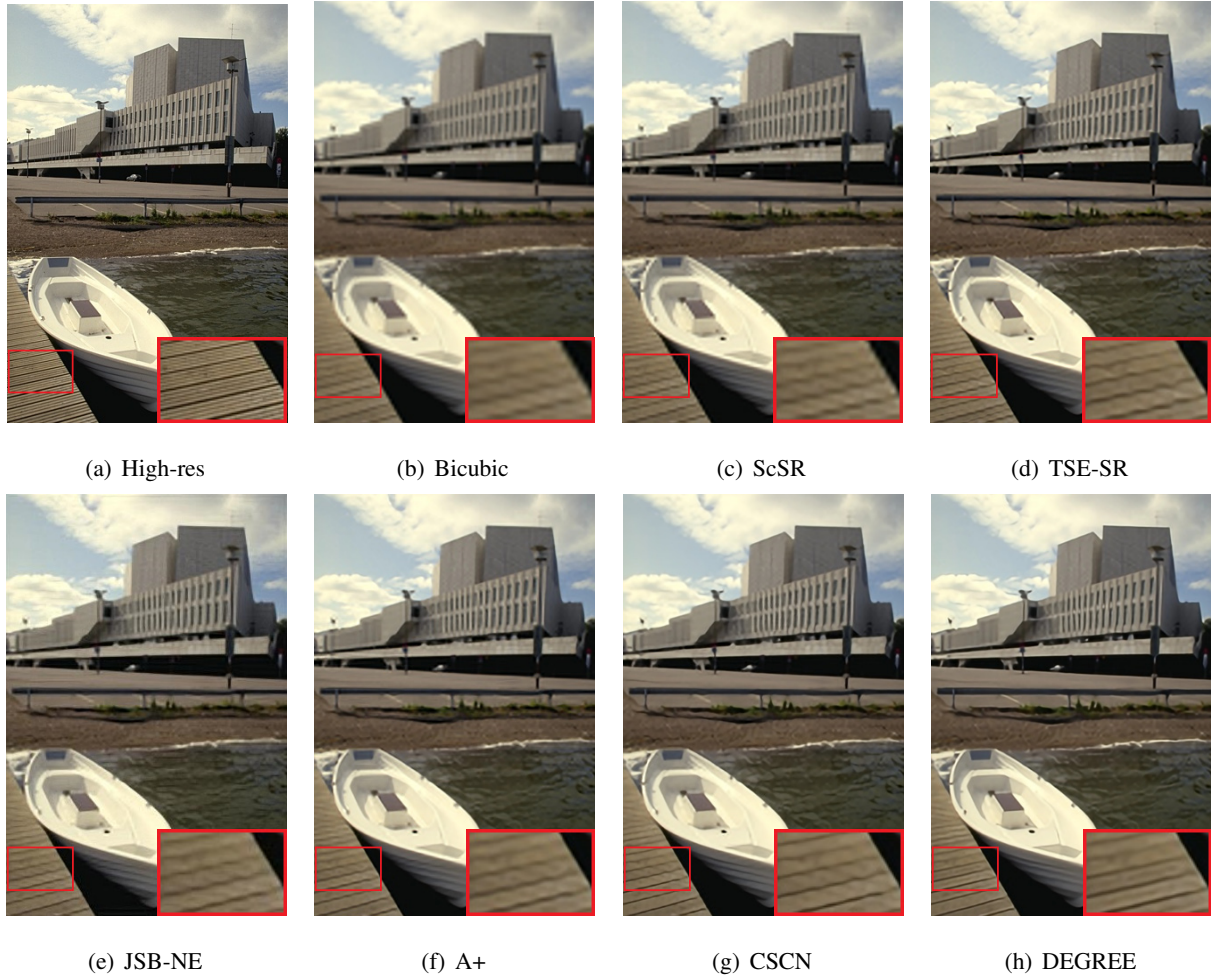
Fig. 11. Visual comparisons between different algorithms for the image *78004* (×3). The DEGREE presents more straight and long cracks between boards.


(a) High-res   (b) Bicubic   (c) ScSR   (d) TSE-SR
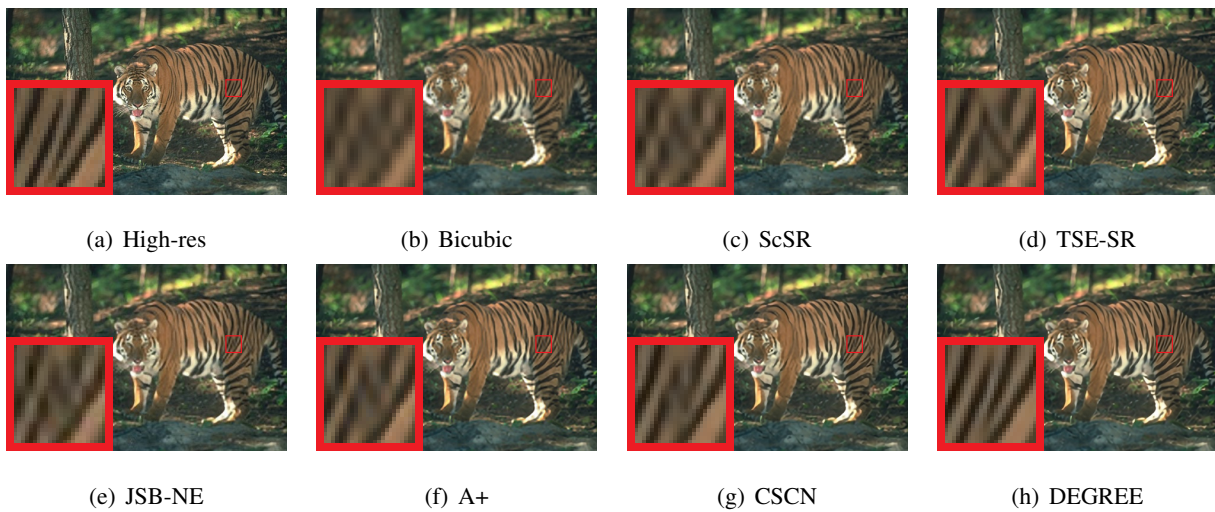
(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
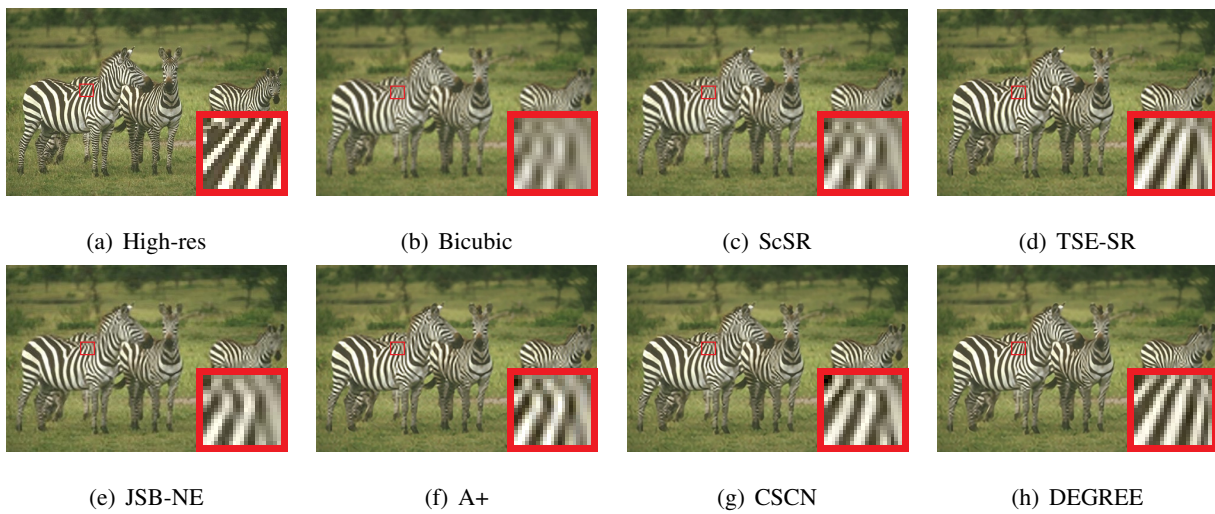
Fig. 12. Visual comparisons between different algorithms for the image *253027* (×3). DEGREE succeeds to recover the stripes and textures of the zebra's fur correctly.

(a) High-res   (b) Bicubic   (c) ScSR   (d) NE+LLE

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
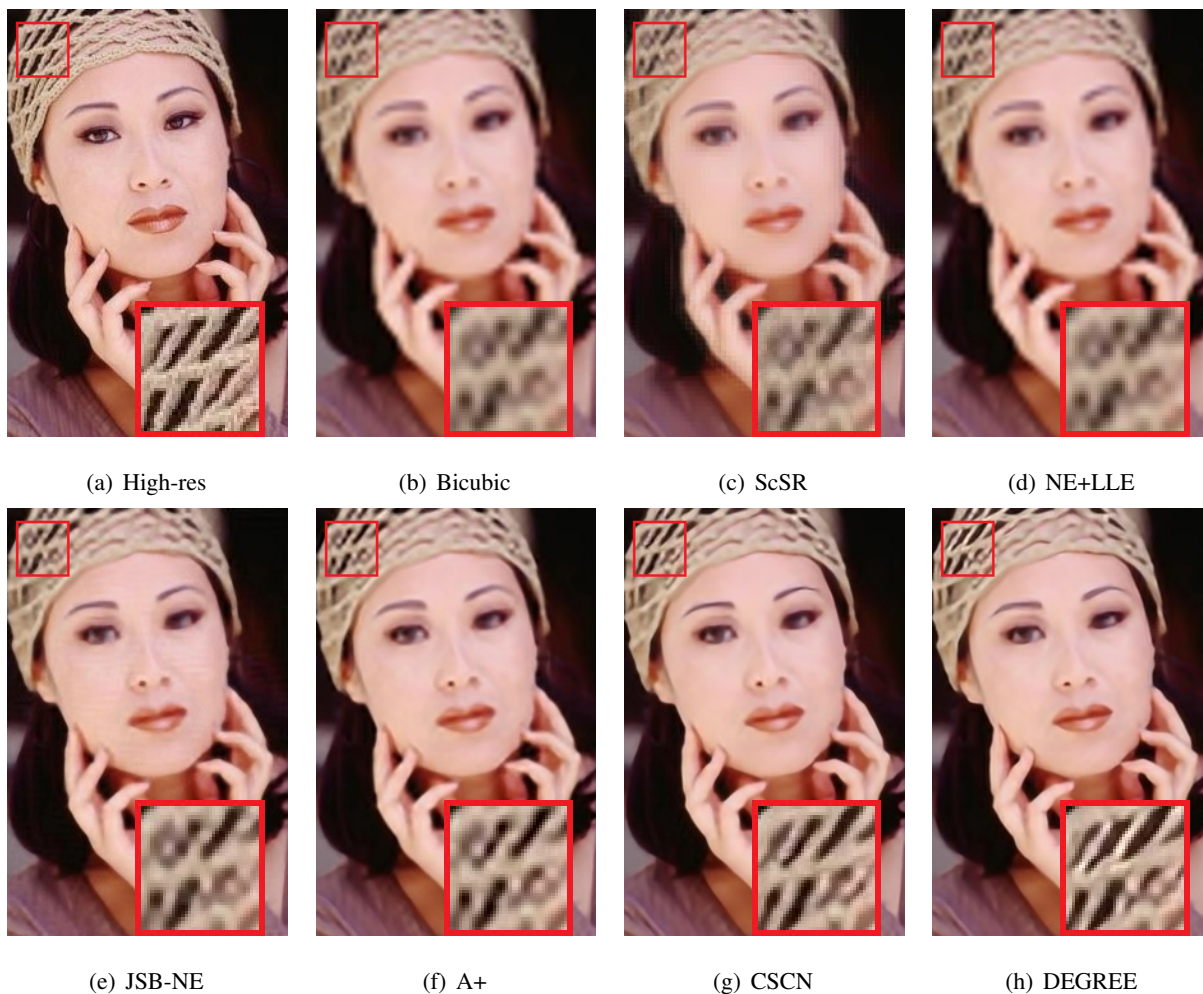
Fig. 13. Visual comparisons between different algorithms for the image *Woman* (×4). The DEGREE presents clearer textures of the headscarf.

(a) High-res   (b) Bicubic   (c) ScSR   (d) NE+LLE

(e) JSB-NE   (f) A+   (g) CSCN   (h) DEGREE
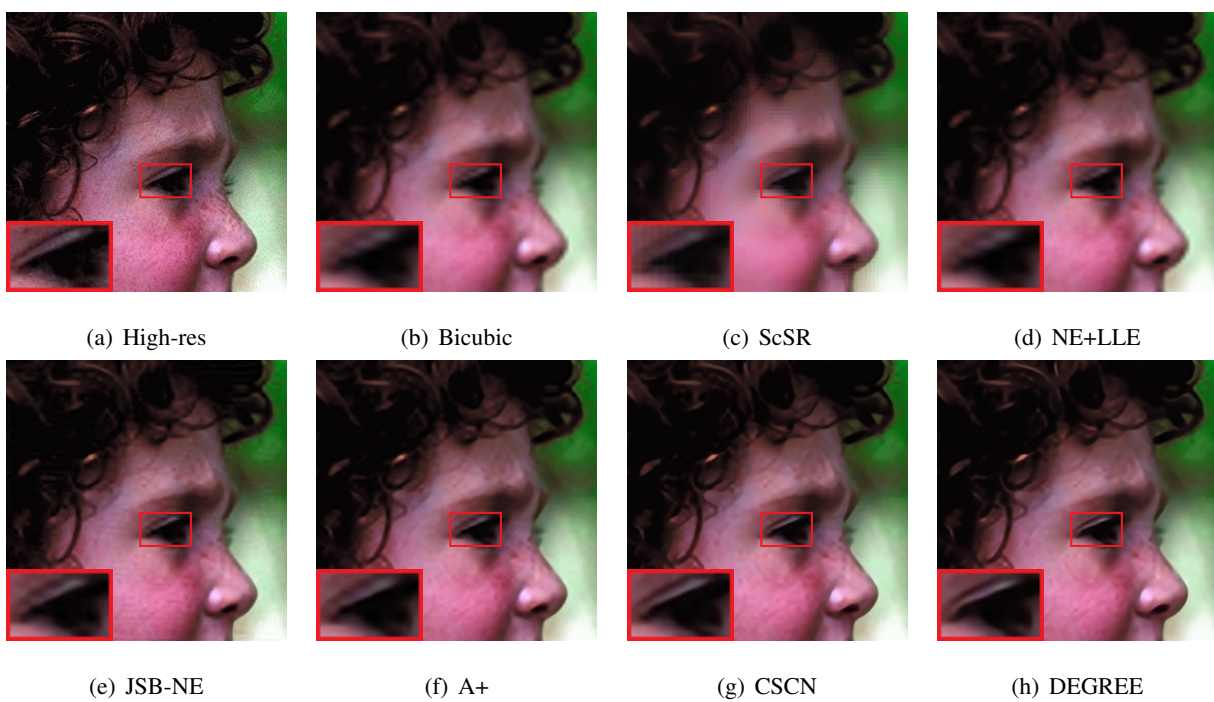
Fig. 14. Visual comparisons between different algorithms for the image *Head* (×4). The DEGREE presents a clearer eyelid.

II. OBJECTIVE RESULTS

We use DEGREE-1 and DEGREE-2 to denote two versions of the proposed model, which have 10 layers, 64 channels and 20 layers, 64 channels respectively. The quality of HR results is measured by Peak Signal-to-Noise Ratio (PSNR) [11] and Structural SIMilarity (SSIM) [12]. The results of the baseline CSCN in ×3 and ×4 enlargement are obtained by the published code with the ×2, ×3 and ×4 concatenation model. The testing is performed on the dataset Set14 and Set5. The results are reported in Table I to VIII. From the tables, one can observe that our proposed DEGREE consistently outperforms baselines.

TABLE I

COMPARISON OF PSNR(DB) RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 2. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	24.86	25.54	25.63	25.51	25.66
Barbara	28.00	28.59	**28.69**	28.50	<u>28.68</u>
Bridge	24.91	25.76	25.87	25.88	27.80
Coastguard	29.13	30.47	30.57	30.68	30.66
Comic	26.02	27.80	28.27	28.29	28.36
Face	34.83	35.64	35.72	35.61	35.67
Flowers	30.37	32.31	33.00	33.00	33.07
Foreman	34.14	36.40	36.93	36.80	36.95
Lena	34.70	36.33	36.58	36.50	36.61
Man	29.25	30.49	30.87	30.81	30.89
Monarch	32.94	35.73	36.99	37.18	37.23
Pepper	34.98	36.41	37.02	37.01	37.00
PPT3	26.95	29.21	30.18	31.39	30.30
Zebra	30.68	33.24	33.65	33.81	33.83
Average	30.13	31.71	32.14	32.21	32.34
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	25.62	25.74	25.67	<u>25.80</u>	**25.83**
Barbara	28.59	28.64	28.43	28.35	28.35
Bridge	27.70	27.84	27.84	<u>27.94</u>	**27.95**
Coastguard	30.49	30.83	30.61	<u>30.80</u>	**30.88**
Comic	28.27	28.52	28.85	<u>29.20</u>	**29.28**
Face	35.62	35.70	35.74	<u>35.80</u>	**35.82**
Flowers	33.03	33.32	33.57	<u>34.08</u>	**34.24**
Foreman	36.20	36.42	36.83	<u>37.33</u>	**37.50**
Lena	36.50	36.64	36.64	<u>36.88</u>	**36.92**
Man	30.82	31.04	31.05	<u>31.31</u>	**31.37**
Monarch	37.18	37.74	38.20	<u>38.97</u>	**39.23**
Pepper	36.75	36.87	36.94	<u>37.28</u>	**37.31**
PPT3	30.40	31.52	30.93	<u>32.33</u>	**32.63**
Zebra	33.29	33.49	33.77	<u>34.05</u>	**34.10**
Average	32.18	32.45	32.50	<u>32.87</u>	**32.96**

TABLE II

COMPARISON OF PSNR(DB) RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 3.

THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST

PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	23.21	23.57	23.62	23.53	23.57
Barbara	26.25	<u>26.69</u>	26.47	**26.94**	26.67
Bridge	23.33	23.96	24.08	24.07	25.08
Coastguard	26.56	27.09	<u>27.29</u>	27.23	27.10
Comic	23.12	24.06	24.40	24.42	24.25
Face	32.82	33.62	33.76	33.73	33.44
Flowers	27.23	28.50	29.05	29.08	28.83
Foreman	31.18	33.24	34.29	34.11	33.99
Lena	31.68	33.09	33.52	33.48	33.22
Man	27.01	27.94	28.29	28.32	28.17
Monarch	29.43	31.11	32.16	32.04	32.05
Pepper	32.41	33.86	34.75	34.80	34.41
PPT3	23.76	25.17	26.18	27.06	25.84
Zebra	26.67	28.58	29.08	29.18	29.04
Average	27.47	28.61	29.07	29.14	28.98
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	23.60	23.67	23.63	<u>23.68</u>	**23.69**
Barbara	26.66	26.55	25.97	26.04	26.03
Bridge	25.07	25.24	25.26	<u>25.28</u>	**25.30**
Coastguard	27.20	**27.36**	27.22	27.25	27.13
Comic	24.39	24.55	24.70	**24.89**	<u>24.85</u>
Face	33.58	33.72	<u>33.80</u>	33.78	**33.83**
Flowers	28.97	29.26	29.53	<u>29.65</u>	**29.83**
Foreman	33.35	33.89	34.51	<u>34.54</u>	**34.74**
Lena	33.39	33.67	33.66	<u>33.79</u>	**33.88**
Man	28.18	28.42	28.50	<u>28.59</u>	**28.66**
Monarch	32.39	32.81	33.54	<u>33.96</u>	**34.20**
Pepper	34.35	34.71	34.97	<u>35.10</u>	**35.17**
PPT3	26.02	27.04	26.98	<u>27.46</u>	**27.68**
Zebra	28.87	29.29	**29.56**	29.47	<u>29.52</u>
Average	29.00	29.30	29.42	<u>29.53</u>	**29.61**

TABLE III

COMPARISON OF PSNR(DB) RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 4. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	22.44	22.69	22.74	22.67	22.68
Barbara	25.15	25.60	25.74	25.69	25.71
Bridge	22.33	22.86	22.97	22.95	23.69
Coastguard	25.48	25.81	25.99	25.92	25.84
Comic	21.69	22.34	22.60	22.55	22.48
Face	31.55	32.24	32.44	32.35	32.17
Flowers	25.53	26.49	26.91	27.14	26.80
Foreman	29.41	30.83	32.24	32.26	32.08
Lena	29.84	31.00	31.42	31.38	31.11
Man	25.70	26.45	26.79	26.81	26.72
Monarch	27.46	28.72	29.41	29.31	29.50
Pepper	30.61	31.98	32.89	33.18	32.70
PPT3	22.03	22.95	23.72	24.86	23.60
Zebra	24.10	25.59	26.02	26.30	26.06
Average	25.95	26.82	27.28	27.38	27.22
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	22.70	22.73	22.70	22.75	**22.77**
Barbara	25.70	**25.76**	25.34	25.51	25.40
Bridge	23.66	23.76	23.74	**23.85**	23.83
Coastguard	25.93	26.04	26.01	**26.15**	26.12
Comic	22.53	22.70	22.63	**22.82**	22.78
Face	32.12	32.38	32.44	32.41	**32.46**
Flowers	26.84	27.14	27.08	27.39	**27.41**
Foreman	31.47	32.14	32.24	32.55	**32.70**
Lena	31.20	31.41	31.45	31.65	**31.73**
Man	26.65	26.89	26.82	27.01	**27.07**
Monarch	29.89	30.22	30.01	30.91	**31.18**
Pepper	32.34	32.98	32.87	33.25	**33.39**
PPT3	23.84	24.80	23.74	24.97	**25.02**
Zebra	25.97	26.09	25.99	**26.48**	26.36
Average	27.20	27.50	27.36	27.69	**27.73**

TABLE IV

COMPARISON OF SSIM RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 2. THE
BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST
PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	0.6976	0.7586	0.7611	0.7623	0.7671
Barbara	0.8413	0.8734	0.8756	0.8740	<u>0.8763</u>
Bridge	0.7591	0.8176	0.8204	0.8252	0.8501
Coastguard	0.7893	0.8447	0.8437	0.8470	0.8492
Comic	0.8496	0.9024	0.9120	0.9140	0.9136
Face	0.8623	0.8838	0.8851	0.8846	0.8858
Flowers	0.8986	0.9290	0.9348	0.9350	0.9352
Foreman	0.9518	0.9670	0.9707	0.9688	0.9695
Lena	0.9112	0.9277	0.9291	0.9286	0.9293
Man	0.8460	0.8804	0.8854	0.8846	0.8864
Monarch	0.9601	0.9730	0.9767	0.9760	0.9761
Pepper	0.9075	0.9193	0.9215	0.9211	0.9212
PPT3	0.9481	0.9698	0.9784	0.9819	0.9786
Zebra	0.9092	0.9398	0.9409	0.9430	0.9430
Average	0.8665	0.8990	0.9025	0.9033	0.9058
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	0.7655	0.7696	0.7689	<u>0.7746</u>	**0.7756**
Barbara	0.8757	0.8759	0.8751	0.8727	**0.8766**
Bridge	0.8470	0.8511	0.8514	<u>0.8555</u>	**0.8565**
Coastguard	0.8452	0.8529	0.8454	<u>0.8491</u>	**0.8501**
Comic	0.9115	0.9146	0.9225	<u>0.9292</u>	**0.9311**
Face	0.8841	0.8861	0.8865	<u>0.8877</u>	**0.8883**
Flowers	0.9337	0.9364	0.9388	<u>0.9439</u>	**0.9453**
Foreman	0.9679	0.9692	0.9695	<u>0.9726</u>	**0.9733**
Lena	0.9288	0.9296	0.9290	<u>0.9316</u>	**0.9318**
Man	0.8843	0.8884	0.8886	<u>0.8943</u>	**0.8956**
Monarch	0.9756	0.9771	0.9772	<u>0.9801</u>	**0.9806**
Pepper	0.9204	0.9214	0.9211	<u>0.9236</u>	**0.9238**
PPT3	0.9741	0.9792	0.9810	<u>0.9865</u>	**0.9877**
Zebra	0.9401	0.9429	0.9408	<u>0.9434</u>	**0.9443**
Average	0.9039	0.9067	0.9069	<u>0.9103</u>	**0.9115**

TABLE V

COMPARISON OF SSIM RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 3. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	0.5439	0.5991	0.6056	0.6043	0.5959
Barbara	0.7531	0.7811	0.7792	**0.7904**	0.7774
Bridge	0.6178	0.6760	0.6832	0.6860	0.7001
Coastguard	0.6149	0.6578	0.6623	0.6605	0.6504
Comic	0.6992	0.7616	0.7790	0.7842	0.7677
Face	0.7984	0.8234	0.8268	0.8268	0.8174
Flowers	0.8013	0.8405	0.8522	0.8547	0.8422
Foreman	0.9058	0.9301	0.9400	0.9380	0.9298
Lena	0.8582	0.8805	0.8849	0.8856	0.8752
Man	0.7500	0.7900	0.7997	0.8018	0.7908
Monarch	0.9198	0.9377	0.9471	0.9469	0.9412
Pepper	0.8704	0.8856	0.8920	0.8928	0.8827
PPT3	0.8816	0.9127	0.9377	0.9480	0.9306
Zebra	0.7959	0.8448	0.8503	0.8524	0.8455
Average	0.7722	0.8086	0.8171	0.8194	0.8105
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	0.6035	0.6111	0.6115	**0.6159**	<u>0.6152</u>
Barbara	0.7810	<u>0.7816</u>	0.7727	0.7748	0.7756
Bridge	0.7050	0.7146	0.7162	**0.7182**	<u>0.7173</u>
Coastguard	0.6588	<u>0.6658</u>	0.6618	**0.6664**	0.6629
Comic	0.7778	0.7844	0.7946	<u>0.8023</u>	**0.8042**
Face	0.8214	0.8269	<u>0.8289</u>	0.8284	**0.8289**
Flowers	0.8475	0.8548	0.8619	<u>0.8648</u>	**0.8674**
Foreman	0.9321	0.9374	0.9422	<u>0.9439</u>	**0.9455**
Lena	0.8827	0.8866	0.8868	<u>0.8888</u>	**0.8899**
Man	0.7940	0.8029	0.8061	<u>0.8091</u>	**0.8110**
Monarch	0.9450	0.9488	0.9534	<u>0.9560</u>	**0.9577**
Pepper	0.8876	0.8915	0.8933	<u>0.8945</u>	**0.8953**
PPT3	0.9194	0.9393	0.9495	<u>0.9531</u>	**0.9578**
Zebra	0.8470	<u>0.8547</u>	0.8541	0.8545	**0.8559**
Average	0.8145	0.8215	0.8238	<u>0.8265</u>	**0.8275**

TABLE VI

COMPARISON OF SSIM RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET14 WITH THE SCALE FACTOR OF 4. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST PERFORMANCE.

Set14	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baboon	0.4522	0.4960	0.5033	0.5028	0.4933
Barbara	0.6863	0.7192	0.7289	**0.7301**	0.7188
Bridge	0.5154	0.5668	0.5749	0.5769	0.5871
Coastguard	0.5222	0.5496	0.5582	0.5509	0.5380
Comic	0.5837	0.6408	0.6603	0.6653	0.6485
Face	0.7519	0.7744	0.7806	0.7788	0.7672
Flowers	0.7216	0.7603	0.7748	0.7820	0.7640
Foreman	0.8664	0.8880	0.9091	0.9087	0.8979
Lena	0.8139	0.8385	0.8455	0.8458	0.8322
Man	0.6763	0.7148	0.7282	0.7307	0.7189
Monarch	0.8808	0.9004	0.9122	0.9129	0.9071
Pepper	0.8372	0.8552	0.8658	0.8697	0.8551
PPT3	0.8219	0.8516	0.8838	0.9080	0.8770
Zebra	0.6857	0.7415	0.7519	0.7573	0.7452
Average	0.7011	0.7355	0.7484	0.7514	0.7393
Set14	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baboon	0.4956	0.5029	0.5008	<u>0.5080</u>	**0.5105**
Barbara	0.7225	<u>0.7293</u>	0.7149	0.7260	<u>0.7293</u>
Bridge	0.5892	0.5990	0.5943	<u>0.6032</u>	**0.6045**
Coastguard	0.5470	0.5563	0.5568	**0.5609**	<u>0.5608</u>
Comic	0.6513	0.6658	0.6633	<u>0.6781</u>	**0.6825**
Face	0.7698	0.7779	<u>0.7810</u>	0.7791	**0.7814**
Flowers	0.7660	0.7791	0.7774	<u>0.7875</u>	**0.7907**
Foreman	0.8971	0.9080	0.9090	<u>0.9143</u>	**0.9165**
Lena	0.8394	0.8436	0.8451	<u>0.8497</u>	**0.8512**
Man	0.7184	0.7300	0.7276	<u>0.7361</u>	**0.7387**
Monarch	0.9126	0.9181	0.9174	<u>0.9261</u>	**0.9291**
Pepper	0.8565	0.8648	0.8647	<u>0.8692</u>	**0.8707**
PPT3	0.8670	0.8928	0.8840	<u>0.9058</u>	**0.9114**
Zebra	0.7455	0.7505	0.7470	**0.7598**	<u>0.7578</u>
Average	0.7413	0.7513	0.7488	<u>0.7574</u>	**0.7597**

TABLE VII

COMPARISON OF PSNR(DB) RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET5 WITH THREE SCALE FACTORS OF

2, 3 AND 4. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND

BEST PERFORMANCE.

Set5	SF	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baby	2	37.07	38.44	38.52	38.45	38.56
Bird	2	36.81	40.06	41.14	41.08	41.07
Butterfly	2	27.43	30.50	32.03	31.79	32.27
Head	2	34.86	35.66	35.77	35.68	35.72
Woman	2	32.15	34.56	35.32	35.33	35.31
Average	2	33.66	35.85	36.56	36.47	36.59
Baby	3	33.91	35.13	35.21	35.19	34.90
Bird	3	32.58	34.62	35.55	35.78	35.06
Butterfly	3	24.04	25.92	27.25	26.92	27.22
Head	3	32.88	33.64	33.77	33.71	33.50
Woman	3	28.56	30.34	31.20	31.50	30.90
Average	3	30.39	31.93	32.60	32.62	32.32
Baby	4	31.78	33.04	33.28	33.10	32.91
Bird	4	30.18	31.86	32.57	32.71	32.19
Butterfly	4	22.10	23.54	24.45	23.94	24.65
Head	4	31.59	32.27	32.52	32.50	32.20
Woman	4	26.47	27.82	28.66	28.98	28.44
Average	4	28.42	29.71	30.30	30.24	30.08
Set5	SF	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baby	2	38.30	38.54	38.39	<u>38.59</u>	**38.63**
Bird	2	40.64	40.91	41.43	<u>42.15</u>	**42.30**
Butterfly	2	32.20	32.75	33.29	<u>34.10</u>	**34.34**
Head	2	35.64	35.72	35.77	<u>35.82</u>	**35.84**
Woman	2	34.94	35.37	35.53	<u>35.81</u>	**35.91**
Average	2	36.34	36.66	36.88	<u>37.29</u>	**37.40**
Baby	3	35.01	35.25	35.05	<u>35.20</u>	**35.34**
Bird	3	34.91	35.48	35.24	<u>36.20</u>	**36.37**
Butterfly	3	27.58	27.95	27.79	<u>29.23</u>	**29.49**
Head	3	33.55	33.71	33.75	<u>33.77</u>	**33.88**
Woman	3	30.92	31.37	31.19	**32.07**	<u>31.87</u>
Average	3	32.39	32.75	32.60	<u>33.29</u>	**33.39**
Baby	4	32.98	33.13	<u>33.22</u>	33.18	**33.23**
Bird	4	31.98	32.52	32.91	<u>32.94</u>	**33.18**
Butterfly	4	25.07	25.46	26.18	<u>26.38</u>	**26.72**
Head	4	32.19	32.44	**32.66**	32.48	<u>32.55</u>
Woman	4	28.21	28.89	<u>29.36</u>	29.30	**29.46**
Average	4	30.09	30.49	30.86	<u>30.88</u>	**31.03**

TABLE VIII

COMPARISON OF SSIM RESULTS AMONG DIFFERENT IMAGE SR METHODS ON SET5 WITH THREE SCALE FACTORS OF 2, 3 AND 4. THE BEST PERFORMANCE IS HIGHLIGHTED IN BOLD AND THE UNDERLINED NUMBERS DENOTE THE SECOND BEST PERFORMANCE.

Set5	SF	Bicubic	ANR	A+	TSE-SR	JSB-NE
Baby	2	0.9427	0.9645	0.9651	0.9642	0.9648
Bird	2	0.9641	0.9845	0.9866	0.9864	0.9857
Butterfly	2	0.8990	0.9515	0.9644	0.9628	0.9637
Head	2	0.7988	0.8838	0.8865	0.8852	0.8860
Woman	2	0.9432	0.9656	0.9695	0.9689	0.9686
Average	2	0.9096	0.9500	0.9544	0.9535	0.9538
Baby	3	0.9039	0.9225	0.9233	0.9235	0.9137
Bird	3	0.9258	0.9490	0.9559	0.9584	0.9503
Butterfly	3	0.8216	0.8718	0.9088	0.9058	0.9060
Head	3	0.8003	0.8240	0.8272	0.8266	0.8284
Woman	3	0.8896	0.9170	0.9288	0.9320	0.9227
Average	3	0.8682	0.8969	0.9088	0.9092	0.9042
Baby	4	0.8567	0.8812	0.8843	0.8825	0.8699
Bird	4	0.8732	0.9027	0.9136	0.9208	0.9037
Butterfly	4	0.7369	0.7890	0.8393	0.8289	0.8388
Head	4	0.7536	0.7764	0.7829	0.7828	0.7695
Woman	4	0.8319	0.8624	0.8821	0.8896	0.8719
Average	4	0.8105	0.8423	0.8604	0.8609	0.8508
Set5	SF	CNN	CNN-L	CSCN	DEGREE-SR-1	DEGREE-SR-2
Baby	2	0.9642	0.9655	0.9637	0.9659	**0.9662**
Bird	2	0.9849	0.9859	0.9861	0.9885	**0.9889**
Butterfly	2	0.9605	0.9648	0.9680	0.9730	**0.9741**
Head	2	0.8840	0.8860	0.8865	0.8876	**0.8883**
Woman	2	0.9670	0.9687	0.9694	0.9720	**0.9725**
Average	2	0.9521	0.9542	0.9547	0.9574	**0.9580**
Baby	3	0.9210	0.9241	0.9203	0.9239	**0.9249**
Bird	3	0.9494	0.9549	0.9540	0.9605	**0.9625**
Butterfly	3	0.9012	0.9098	0.9145	0.9326	**0.9369**
Head	3	0.8215	0.8272	0.8261	0.8286	**0.8298**
Woman	3	0.9236	0.9291	0.9282	0.9363	**0.9368**
Average	3	0.9033	0.9090	0.9086	0.9164	**0.9182**
Baby	4	0.8779	0.8824	**0.8845**	0.8837	0.8835
Bird	4	0.9018	0.9112	0.9189	0.9194	**0.9227**
Butterfly	4	0.8416	0.8566	0.8819	0.8847	**0.8931**
Head	4	0.7726	0.7801	**0.7874**	0.7817	0.7844
Woman	4	0.8710	0.8837	0.8936	0.8935	**0.8965**
Average	4	0.8530	0.8628	0.8732	0.8726	**0.8761**

III. SUB-BANDS VISUALIZATION

In Figure 15 to 17, we visualize the learned features from the bottom feature extraction layer (denoted as 1L) and the nine recurrent time steps (denoted as 1R to 9R). The 1L to 9R sub-images of each figure show the effect of the incremental enhancement of each layer for the final reconstructed result. The results are produced by a DEGREE network with 20 layers for the $\times 2$ testing case. From the visualization results, one can observe that the proposed DEGREE model captures details at different frequencies, similar to decomposition into different frequency sub-bands. The 1L layer enhances the contrast of the given LR image. The 1R-3R layers capture the edge features remarkably. In 4R-8R layers, the sub-bands recover both edges and textures. The 9R layer remedies details. In all, for the whole DEGREE network, previous layers produce edge features at different sub-bands. Later ones include texture features. The "sub-band" of the last layer models the "residual signal".

(a) LR (b) 1L (c) 1R (d) 2R

(e) 3R (f) 4R (g) 5R (h) 6R

(i) 7R (j) 8R (k) 9R (l) Result

Fig. 15.   The visualization of the learned sub-bands in the recovery on *Butterfly* (×2).

(a) LR   (b) 1L   (c) 1R   (d) 2R

(e) 3R   (f) 4R   (g) 5R   (h) 6R

(i) 7R   (j) 8R   (k) 9R   (l) Result
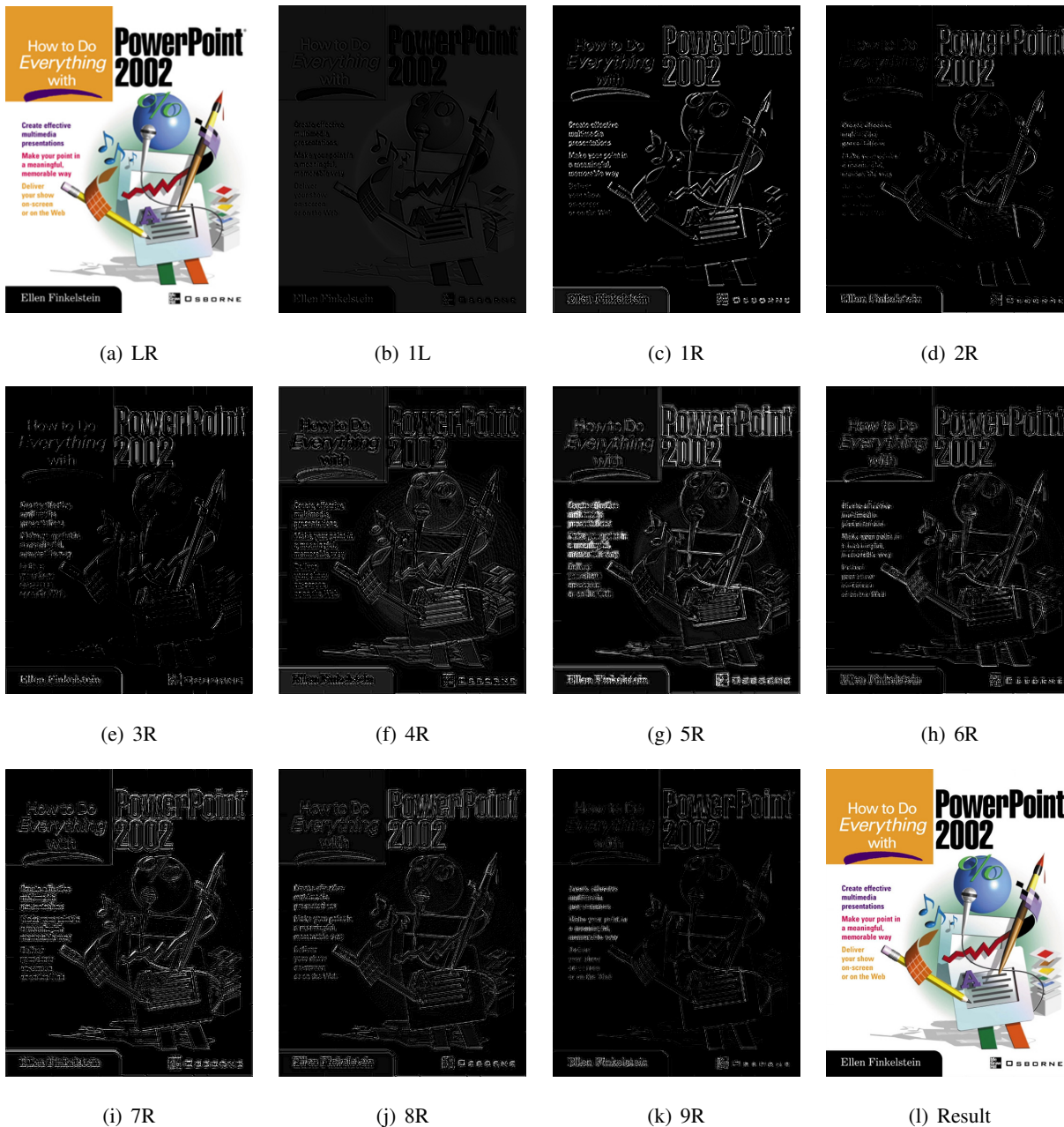
Fig. 16. The visualization of the learned sub-bands in the recovery on *PPT3* ($\times 2$).

(a) LR

(b) 1L

(c) 1R

(d) 2R
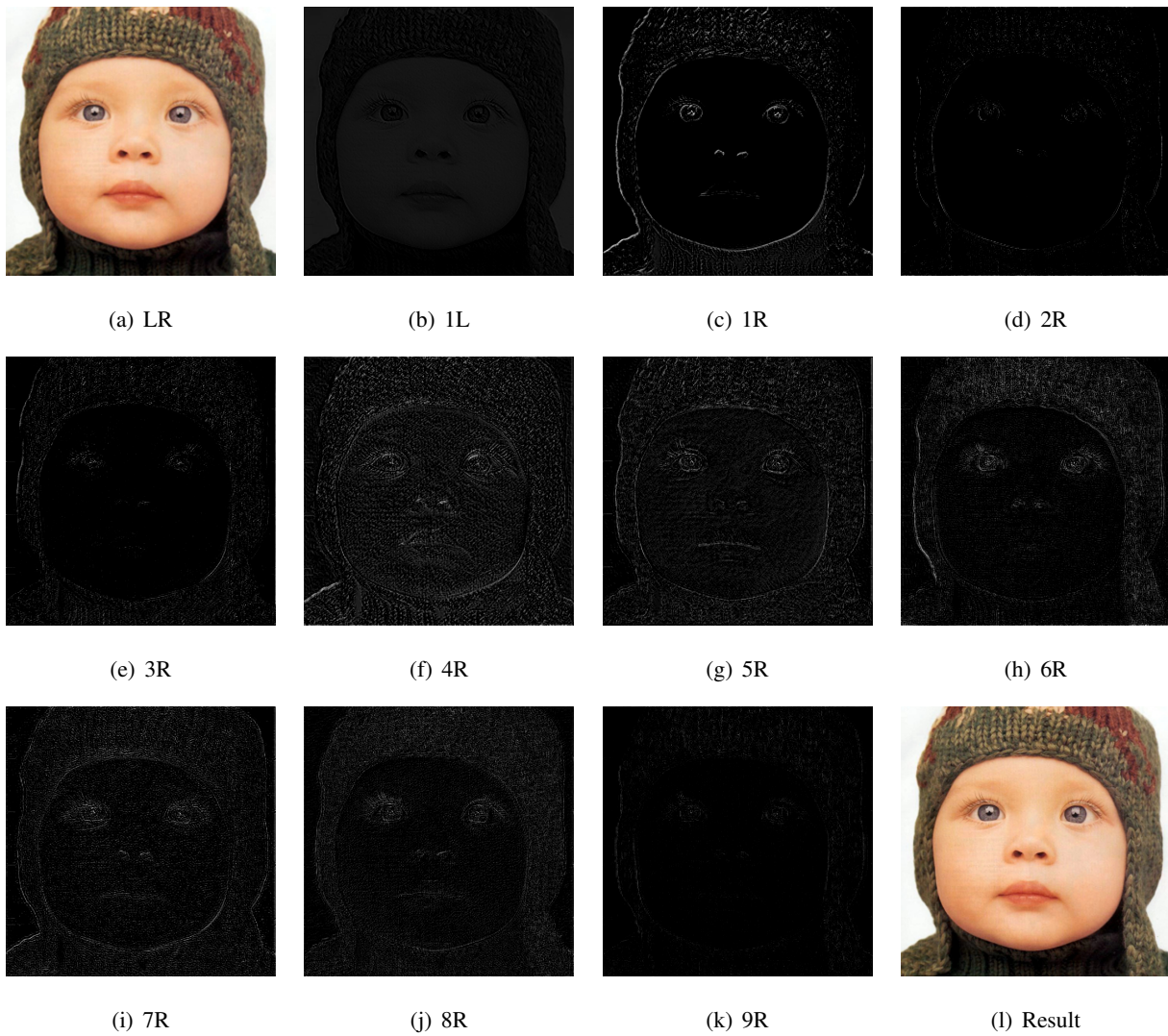
(e) 3R

(f) 4R

(g) 5R

(h) 6R

(i) 7R

(j) 8R

(k) 9R

(l) Result

Fig. 17. The visualization of the learned sub-bands in the recovery on *Baby* (×2).

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