# "KXNet: A Model-Driven Deep Neural Network for Blind Super-Resolution": Supplementary Material

Jiahong Fu<sup>1</sup>, Hong Wang<sup>2</sup>, Qi Xie<sup>\*1</sup>, Qian Zhao<sup>1</sup>, Deyu Meng<sup>1</sup>, and Zongben Xu<sup>1</sup>

<sup>1</sup> Xi'an Jiaotong University, Shaanxi, P.R. China jiahongfu@stu.xjtu.edu.cn, {xie.qi, timmy.zhaoqian, dymeng, zbxu}@mail.xjtu.edu.cn <sup>2</sup> Tencent Jarvis Lab, Shenzhen, P.R. China hazelhwang@tencent.com <sup>3</sup> Pazhou Lab, Guangzhou, P.R. China

**Abstract.** In this supplementary material, we provide more details about the optimization algorithm, network module design, and execute more ablation experiments to illustrate the effectiveness of our method. Furthermore, we compare with unsupervised blind super-resolution for blur kernel estimation.

#### 1 Details of Model Optimization

In this section, we provide a detailed derivation in Section 3.2 of the main text. As we shown in the main text, the optimization problem for blind super-resolution can be mathematically expressed as:

$$\min_{\boldsymbol{K},\boldsymbol{X}} \left\| \boldsymbol{Y} - (\boldsymbol{X} \otimes \boldsymbol{K}) \downarrow_{\mathbf{s}} \right\|_{F}^{2} + \lambda_{1} \phi_{1}(\boldsymbol{K}) + \lambda_{2} \phi_{2}(\boldsymbol{X})$$
s.t.  $\boldsymbol{K}_{j} \geq 0, \sum_{j} \boldsymbol{K}_{j} = 1, \forall j,$ 
(1)

where we aim to estimate a blur kernel  $\mathbf{K} \in \mathbb{R}^{p \times p}$  and an HR image  $\mathbf{X} \in \mathbb{R}^{H \times W}$  from an observed LR image  $\mathbf{Y} \in \mathbb{R}^{h \times w}$ ;  $\phi_1(\mathbf{K})$  and  $\phi_2(\mathbf{X})$  represent the regularization terms for delivering the prior knowledge of blur kernel and HR image, respectively.  $\lambda_1$  and  $\lambda_2$  are trade-off regularization parameters. We also introduce the non-negative and equality constraints for every element  $\mathbf{K}_j$  of blur kernel  $\mathbf{K}$  to alleviate the non uniqueness of the solution.

As mentioned in Section 3.2 of the main text, we use the proximal gradient algorithm [1] to solve the alternate optimization problem of X and K. The details are provided as follows:

Updating blur kernel K: The blur kernel K can be updated by solving:

$$\boldsymbol{K}^{(t)} = \arg\min_{\boldsymbol{K}} Q_1\left(\boldsymbol{K}, \boldsymbol{K}^{(t-1)}\right), \qquad (2)$$

<sup>\*</sup> Corresponding author.

#### 2 Jiahong Fu et al.

where  $\mathbf{K}^{(t-1)}$  denotes the updating result after the last iteration, and  $Q_1(\mathbf{K}, \mathbf{K}^{(t-1)})$  is a quadratic approximation of the objective function Eq. (1) with respect to  $\mathbf{K}$ , mathematically expressed as:

$$Q_{1}\left(\boldsymbol{K},\boldsymbol{K}^{(t-1)}\right) = f\left(\boldsymbol{K}^{(t-1)}\right) + \frac{1}{2\delta_{1}}\left\|\boldsymbol{K}-\boldsymbol{K}^{(t-1)}\right\|_{F}^{2} + \left\langle\boldsymbol{K}-\boldsymbol{K}^{(t-1)},\nabla f\left(\boldsymbol{K}^{(t-1)}\right)\right\rangle + \lambda_{1}\phi_{1}(\boldsymbol{K}),$$
(3)

where  $f(\mathbf{K}^{(t-1)}) = \left\| \mathbf{Y} - (\mathbf{X}^{(t-1)} \otimes \mathbf{K}^{(t-1)}) \downarrow_{\mathbf{s}} \right\|_{F}^{2}$  and  $\delta_{1}$  denotes the stepsize parameter. Then Eq. (2) is equivalent to:

$$\min_{\boldsymbol{K}} \left\| \boldsymbol{K} - \left( \boldsymbol{K}^{(t-1)} - \delta_1 \nabla f \left( \boldsymbol{K}^{(t-1)} \right) \right) \right\|_F^2 + \lambda_1 \delta_1 \phi_1(\boldsymbol{K})$$
s.t.  $\boldsymbol{K}_j \ge 0, \sum_j \boldsymbol{K}_j = 1, \forall j,$ 
(4)

It's solution can then be easily expressed in close-form as [4]:

$$\boldsymbol{K}^{(t)} = \operatorname{prox}_{\lambda_1 \delta_1} \left( \boldsymbol{K}^{(t-1)} - \delta_1 \nabla f\left( \boldsymbol{K}^{(t-1)} \right) \right), \tag{5}$$

where  $\operatorname{prox}_{\lambda_1\delta_1}(\cdot)$  is the proximal operator dependent on the regularization term  $\phi_1(\cdot)$  with respect to  $\mathbf{K}$ ; the specific form of  $\nabla f(\mathbf{K}^{(t-1)})$  is complicated. For ease of calculation by transforming the convolutional operation in  $f(\mathbf{K}^{(t-1)})$  into matrix multiplication, as shown in the main text, we have:

$$\nabla f\left(\boldsymbol{k}^{(t-1)}\right) = \left(D_{\mathbf{s}} U_f\left(\boldsymbol{X}^{(t-1)}\right)\right)^{\mathrm{T}} \operatorname{vec}\left(\boldsymbol{Y} - \left(\boldsymbol{X}^{(t-1)} \otimes \boldsymbol{K}^{(t-1)}\right) \downarrow_{\mathbf{s}}\right), \tag{6}$$

where  $U_f(\mathbf{X}^{(t-1)}) \in \mathbb{R}^{HW \times p^2}$  are the unfolded result of  $\mathbf{X}^{(t-1)}$ ;  $D_s$  denotes the downsampling operator which is corresponding to the operator  $\downarrow_s$ , and achieves the transformation from the size HW to the size hw. Thus, the result  $D_s U_f(\mathbf{X}^{(t-1)})$ ;  $\nabla f(\mathbf{k}^{(t-1)}) \in \mathbb{R}^{p^2 \times 1}$ ;  $\nabla f(\mathbf{K}^{(t-1)}) = \text{vec}^{-1}(\nabla f(\mathbf{k}^{(t-1)}))$ ;  $\text{vec}^{-1}(\cdot)$  is the reverse vectorization;

**Implementation of**  $D_{\mathbf{s}}U_f(\cdot)$ : With Pytorch<sup>4</sup> framework, we can directly perform "torch.nn.function.unfold" with  $stride = \mathbf{s}$  on  $\mathbf{X}^{(t-1)} \in \mathbb{R}^{H \times W}$  to get  $(D_{\mathbf{s}}U_f(\mathbf{X}^{(t-1)}))^{\mathrm{T}} \in \mathbb{R}^{p^2 \times hw}$ , and execute "torch.permute" to get  $D_{\mathbf{s}}U_f(\mathbf{X}^{(t-1)}) \in \mathbb{R}^{hw \times p^2}$ .

Updating HR image X: Similarly, the quadratic approximation of the problem in Eq. (1) with respect to X is:

$$Q_{2}\left(\boldsymbol{X},\boldsymbol{X}^{(t-1)}\right) = h\left(\boldsymbol{X}^{(t-1)}\right) + \frac{1}{2\delta_{2}}\left\|\boldsymbol{X}-\boldsymbol{X}^{(t-1)}\right\|_{F}^{2} + \left\langle\boldsymbol{X}-\boldsymbol{X}^{(t-1)},\nabla h\left(\boldsymbol{X}^{(t-1)}\right)\right\rangle + \lambda_{2}\phi_{2}(\boldsymbol{X}),$$
(7)

<sup>&</sup>lt;sup>4</sup> https://pytorch.org/



Fig. 1. Illustration of the gradient adjuster. The solid line represents the gradient adjustment process.



**Fig. 2.** (1) The exploited ResNet for the proximal network  $\operatorname{proxNet}_{\theta_k^{(t)}}(\cdot)$ . (2) The exploited ResNet for the proximal network  $\operatorname{proxNet}_{\theta_k^{(t)}}(\cdot)$ 

where  $h(\mathbf{X}^{(t-1)}) = \|\mathbf{Y} - (\mathbf{X}^{(t-1)} \otimes \mathbf{K}^{(t)}) \downarrow_{\mathbf{s}} \|_{F}^{2}$ ;  $\nabla h(\mathbf{X}^{(t-1)}) = \mathbf{K}^{(t)} \otimes_{\mathbf{s}}^{\mathrm{T}}$  $(\mathbf{Y} - (\mathbf{X}^{(t-1)} \otimes \mathbf{K}^{(t)}) \downarrow_{\mathbf{s}})$ ;  $\delta_{2}$  denotes the stepsize parameter. Then the equivalent optimization problem is:

$$\min_{\boldsymbol{X}} \left\| \boldsymbol{X} - \left( \boldsymbol{X}^{(t-1)} - \delta_2 \nabla h\left( \boldsymbol{X}^{(t-1)} \right) \right) \right\|_F^2 + \lambda_2 \delta_2 \phi_2(\boldsymbol{X}), \tag{8}$$

Similarly, we can easily deduce the updating rule for X as:

$$\boldsymbol{X}^{(t)} = \operatorname{prox}_{\lambda_2 \delta_2} \Big( \boldsymbol{X}^{(t-1)} - \delta_2 \boldsymbol{K}^{(t)} \otimes_{\mathbf{s}}^{\mathrm{T}} \Big( \boldsymbol{Y} - (\boldsymbol{X}^{(t-1)} \otimes \boldsymbol{K}^{(t)}) \downarrow_{\mathbf{s}} \Big) \Big),$$
(9)

where  $\operatorname{prox}_{\lambda_2 \delta_2}(\cdot)$  is the proximal operator dependent on the regularization term  $\phi_2(\cdot)$  with respect to  $\boldsymbol{X}$ .

#### 2 Details of Network Module Design

In this section, we provide more details of network design, including the gradient adjuster,  $\operatorname{proxNet}_{\theta_{L}^{(t)}}(\cdot)$  and  $\operatorname{proxNet}_{\theta_{T}^{(t)}}(\cdot)$ .

**Gradient adjuster**. As stated in Section 4.1 of the main text, we adopt an adjuster to the gradient  $G_x^{(t)}$ , which alleviate the unevenness issue. As shown in

 Table 1. Average PSNR/SSIM of adopting different strategies for X-net on synthesized

 testing sets. KXNet\* presents without gradient adjuster and concatenating strategy.

Method	Noise	Urban100 [7]		BSD100 [10]		Set14 [14]		Set5 [3]	
		PSNR	SSIM	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM
$\mathrm{KXNet}^*$	0	27.55	0.8425	29.71	0.8293	30.45	0.8532	33.63	0.9213
KXNet(ours)	0	28.33	0.8627	30.21	0.8456	<b>31.14</b>	0.8672	34.59	0.9315
$KXNet^*$	5	26.51	0.7957	28.21	0.7580	29.01	0.7951	31.82	0.8829
KXNet(ours)	5	26.88	0.8056	28.33	0.7615	29.22	0.7993	32.07	0.8864
KXNet*	15	25.25	0.7433	26.82	0.6946	27.53	0.7402	29.84	0.8422
$\mathrm{KXNet}(\mathrm{ours})$	10	25.45	0.7500	26.87	0.6959	27.59	0.7422	29.93	0.8449

Fig. 1, the residual image  $\boldsymbol{E}_x^{(t)}$  are deconvolved with blur kernel  $\boldsymbol{K}^{(t)}$  to obtain the gradient  $\boldsymbol{G}_x^{(t)}$ . We can clearly find that due to the "uneven overlap" phenomenon with transposed convolution, the obtained gradient  $\boldsymbol{G}_x^{(t)}$  is corrupted with unexpected grid-like artifacts. These kinds of artifacts can be detrimental to image restoration for it is neither smooth nor natural. To alleviate the unevenness issue, we introduce the  $\boldsymbol{K}^{(t)} \otimes_{\mathbf{s}}^{\mathrm{T}} \mathbf{1}$  to calculate the degree of uneven overlap and element-wisely divide  $\boldsymbol{G}_x^{(t)}$  with  $\boldsymbol{K}^{(t)} \otimes_{\mathbf{s}}^{\mathrm{T}} \mathbf{1}$  to get an adjusted gradient,  $\hat{\boldsymbol{G}}_x^{(t)}$ . As illustrated in Fig. 1,  $\hat{\boldsymbol{G}}_x^{(t)}$  has more precise textures and edges than  $\boldsymbol{G}_x^{(t)}$ , which will improve the recovery performance of X-net.

**Proximal Network Architecture**. As stated in the main text, the proximal network  $\operatorname{proxNet}_{\theta_k^{(t)}}(\cdot)$  and  $\operatorname{proxNet}_{\theta_x^{(t)}}(\cdot)$   $(t = 0, 1, \dots, T)$  are two shallow ResNets. Fig. 2 shows the architectural details of  $\operatorname{proxNet}_{\theta_k^{(t)}}(\cdot)$  and  $\operatorname{proxNet}_{\theta_x^{(t)}}(\cdot)$ , respectively. For each Resblock in each stage in  $\operatorname{proxNet}_{\theta_k^{(t)}}(\cdot)$ , we simply adopt the same structure.  $\operatorname{proxNet}_{\theta_x^{(t)}}(\cdot)$  also uses the same strategy. It is worth noting that we also adopted the residual in residual (RIR) structure [16] here, which is very effective for single image super-resolution problems.

#### 3 Ablation studies

In this section, we will provide the ablation studies about the gradient adjuster and concatenating  $\mathbf{X}^{(t-1)}$  and  $\hat{\mathbf{G}}_x^{(t)}$  as the input of the proximal network proxNet $_{\theta_x^{(t)}}(\cdot)$ . In this part, the setting of the experiment is the same as setting 2 for scale factor 2 in the main text. We adopt the PSNR and SSIM computed on Y channel in the YCbCr space for quantitative analysis. As shown in Table 1, if we do not perform gradient adjuster and concatenate  $\mathbf{X}^{(t-1)}$  and  $\hat{\mathbf{G}}_x^{(t)}$ as the input of the proximal network  $\operatorname{proxNet}_{\theta_x^{(t)}}(\cdot)$ , then the performance will be greatly reduced. The above experiments verify the effectiveness of gradient adjuster and concatenation strategy.

Method (x2)	K-Net+USRNet [15]	KXNet
PSNR / SSIM Speed (seconds)	29.37 / 0.8250 1.38	$29.71 \ / \ 0.8354 \\ 0.47$

Table 2. Compared to USRNet on Set14.

### 4 Compare with the Non-Blind Super-Resolution Unfolding Method.

Here we mainly compare with the SOTA of the non-blind super-resolution unfolding method, USRNet[15]. Firstly, our method targets the blind super-resolution problem, i.e., the blur kernel is unknown, while USRNet targets the non-blind super-resolution problem. Therefore, USRNet has no function of estimating the blur kernel and handling the blur kernel unknown cases. Secondly, compared with USRNet, the X-Net we constructed has the following advantages: 1) Simpler operators. When updating  $X^{(t)}$ , USRNet involves multiple Fourier transforms and division operations, which will increase the computational complexity, especially during the gradient backpropagation process. Comparatively, KXNet only contains convolutions and ReLu operations, which are evidently simpler to calculate. Thus, the inference speed of KXNet is much faster, as illustrated in Table 2. 2) More stable results. KXNet is built according to a proximal gradient descent algorithm, and the updating of X and K are both performed by gradient descent and ResNet, which adjusts X and K by adding a relatively small residue. This updating manner is very stable, ensuring that X and Kdon't change very much through network stages. In comparison, the manner for updating X in USRNet could always be hardly guaranteed to be stable, for the Fourier transforms and inverse Fourier transforms tend to make the updating results more unpredictable. To verify this point, we replace our X-Net with USRNet, i.e., combining K-Net with USRNet (denoted K-Net+USRNet), and conduct experiments under the same setting with KXNet. The experimental results are shown in the following Table 2. We controlled the number of stages of KXNet so that the parameters of the two methods are almost the same, and the advantage of KXNet can be evidently observed.

 Table 3. Performance comparison between SeaNet/ENLCA and KXNet on Set14.

Method (x2)	SeaNet [5]	ENLCA [13]	KXNet
PSNR	29.50	18.35	31.14
SSIM	0.8262	0.5077	0.8672

#### 5 Compare with other Super-Resolution Method.

We further compare with the latest super-resolution algorithms, SeaNet [5] and ENLCA [13]. Thus, we conduct experiments under the same setting with KXNet, and the final results are shown in Table 3.

#### 6 Jiahong Fu et al.

Method         Scale         Urban100 [7]         BSD100 [10]         Set14 [14]         Set51 PSNR         SSIM											
Bicubic         PSNR         SSIM         PSNR         SSIM         PSNR         SSIM         PSNR         SSIM         Level           Bicubic         23.00         0.6656         25.85         0.6769         25.74         0.7085         27.68         0.8047           RCAN [16]         23.22         0.6791         20.63         0.6896         25.92         0.7217         27.85         0.8097           DASR [12]         x2         26.65         0.8106         28.84         0.7955         29.44         0.8224         32.50         0.8661         31.40         0.8291           KXNet(ours)         28.33         0.6627         30.21         0.8466         31.14         0.8672         34.40         0.8291           Bicubic         21.80         0.6004         24.47         0.6274         24.28         0.6564         25.78         0.7555           IKC [6]         x3         25.20         0.7575         27.39         0.7766         31.70         0.8940           KXNet(ours)         26.37         0.8035         28.15         0.7603         31.70         0.8940           KCAN [16]         19.84         0.5307         23.16         0.7647         27.28         0.7603<	Method	Scale	Urbar	100 [7]	BSD1	.00 [10]	Set1	4 [14]	Set	5 [3]	Noise
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	mounou	beare	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM	PSNR	SSIM	Level
DR.	Bicubic		23.00	0.6656	25.85	0.6769	25.74	0 7085	27.68	0.8047	
Inc. rs [10]         20.32         27.46         0.8401         29.85         0.8303         20.52         0.1211         21.33         0.9305           DASR [12]         x2         26.65         0.8401         29.85         0.8410         31.03         0.86224         32.50         0.8961           DAN [9]         27.30         0.8497         30.09         0.6254         24.28         0.6546         25.78         0.8555           RCAN [16]         21.38         0.6042         24.47         0.6224         24.28         0.6546         25.78         0.7555           RCAN [16]         21.38         0.6042         24.47         0.6224         24.28         0.6546         24.35         0.7663         28.69         0.7660         3.873         0.8733         0           DAN [9]         25.82         0.7855         27.88         0.7663         28.69         0.7600         3.8746         0.8803           KXNet(ours)         26.37         0.8035         23.17         0.6082         2.372         0.6973           IKC [6]         x4         24.33         0.721         27.98         0.7600         30.53         0.8455           DAN [9]         24.91         0.741 <t< td=""><td>BCAN [16]</td><td></td><td>20.00</td><td>0.6701</td><td>26.03</td><td>0.6806</td><td>25.02</td><td>0.7000</td><td>27.85</td><td>0.8005</td><td></td></t<>	BCAN [16]		20.00	0.6701	26.03	0.6806	25.02	0.7000	27.85	0.8005	
Int C [0]         x2         21:40         0.6301         28:50         0.6303         0.5014         32:50         0.8229           DAN [9]         27:93         0.8497         30.09         0.8410         31.03         0.8647         34.40         0.9291           KXnet(ours)         28:33         0.6627         30.21         0.8466         31.14         0.8672         34.59         0.9315           Bicubic         21:80         0.6084         24:48         0.6254         24:28         0.6546         25:78         0.7555           DAN [16]         21:80         0.6084         24:47         0.6299         24:07         0.6606         26:37         0.8036         32:53         0.8533           DAN [9]         25:82         0.7555         27:38         0.7602         27:45         0.6322         24:35         0.7086           RCAN [16]         19:84         0.5307         23:10         0.5729         22:38         0.5967         23:72         0.6973           Bicubic         20:88         0.5600         24:35         0.6303         24:35         0.6933         0.8455           DAN [9]         24:30         0.7214         27.08         0.7729         24:35	IKC [6]		20.22	0.8401	20.05	0.0000	20.52	0.9614	22.00	0.0000	
	DASP [19]	$\mathbf{x}^2$	27.40	0.8401	29.60	0.8390	20.44	0.8014	20.59	0.9229	
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	DASK [12] DAN [0]		20.00	0.8100	20.04	0.7903	29.44	0.8224	24.40	0.8901	
RANKet(0018)       23.33       0.6028       0.521       0.63024       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6312       0.6666       25.78       0.7575       0.7379       27.96       0.7727       30.90       0.8723       0         DAN [9]       25.82       0.7855       27.88       0.7672       29.04       0.6082       23.35       0.9034         KXNet(ours)       26.37       0.8035       28.15       0.7672       29.04       0.6086       32.53       0.9034         KXNet(ours)       26.37       0.8035       23.75       0.5827       23.8       0.6607       23.72       0.66973         JASR [12]       x4       24.20       0.7105       24.30       0.6692       27.48       0.6526       27.39       0.7738         RCAN [16]       12.8       0.6747       27.08       0.7659       30.99       0.8815         Bicubic       22.89       0.6401       25.65       0.6428       27.79       0.7738       0.7738         RCAN [16]       21.80	KXNet(ouro)		21.90	0.8497	20.09	0.8410	91 14	0.8047	24.40 24.50	0.9291	
Datemole RCAN [16]         21.80         0.0044         24.40         0.0344         24.24         0.0346         24.25         0.0346         24.25         0.0346         24.25         0.0346         24.27         0.0346         24.25         0.0346         24.27         0.0346         24.28         0.0346         24.27         0.0346         25.36         0.7572         30.91         0.8753         0.8853         0.0344         24.28         0.7805         21.79         0.0727         30.91         0.8723         0           DAN [9]         25.82         0.7855         27.88         0.7603         28.69         0.7398         23.75         0.6903         24.35         0.7086           RCAN [16]         19.84         0.5007         23.10         0.5729         22.38         0.5967         23.2         0.6903         24.89         0.7308         23.75         0.8803           DAN [9]         24.20         0.7150         26.64         0.6903         25.59         0.733         0.733         0.733         0.733         0.733         0.733         0.733         0.733         0.733         0.8815         0.6403         25.59         0.6401         25.65         0.6480         25.59         0.6402         25.9<	Diaubia		20.00	0.6021	24.69	0.6450	01.14	0.6546	01 70	0.9313	-
RCA (i [10]       21.35       0.0042       24.41       0.0042       24.01       0.00005       31.60       0.8853       0         DAN [9]       25.36       0.7575       27.39       0.7737       27.96       0.7727       30.90       31.60       0.8853       0         KXNet(ours)       26.37       0.8035       28.15       0.7672       29.04       0.8036       22.35       0.7086         Bicubic       20.88       0.5507       23.17       0.6082       24.35       0.7086         RCAN [16]       19.84       0.5307       23.10       0.5729       23.37       0.6973       0.8503         DASR [12]       X4       24.20       0.7150       26.43       0.6093       25.55       0.6880       25.30       0.8455         DAN [9]       24.91       0.7491       26.92       0.7186       27.69       0.7093       31.23       0.8718         Bicubic       22.89       0.6401       25.65       0.6498       25.55       0.6480       25.99       0.733       0.7336         RCAN [16]       22.88       0.5966       25.43       0.6460       26.89       0.7333       0.8718         DAN [9]       26.64       0.7964 <td< td=""><td>DICUDIC DCAN [16]</td><td></td><td>21.60</td><td>0.6044</td><td>24.00</td><td>0.0204</td><td>24.20</td><td>0.6540</td><td>20.10</td><td>0.7555</td><td></td></td<>	DICUDIC DCAN [16]		21.60	0.6044	24.00	0.0204	24.20	0.6540	20.10	0.7555	
IAC, [0]       x3       23.30       0.1620       27.36       0.17475       28.19       0.1805       31.00       0.88733       0         DANR [9]       25.22       0.7575       27.38       0.7603       28.69       0.7969       31.70       0.8940         KXNet(ours)       26.37       0.8085       28.15       0.7672       29.04       0.8036       22.53       0.7066         RCAN [16]       19.84       0.5307       23.10       0.5729       22.38       0.5967       23.72       0.6973         DAN [9]       24.30       0.7241       26.49       0.6903       26.89       0.7306       29.53       0.8455         DAN [9]       24.30       0.7241       26.64       0.6903       26.769       0.7306       29.53       0.8455         Bicubic       22.89       0.6401       25.65       0.6498       25.55       0.6262       27.39       0.7738         RCAN [16]       22.89       0.6506       28.33       0.6160       28.41       0.7767       31.03       0.8680         DASR [12]       x2       25.72       0.7678       27.75       0.7399       27.75       0.7399       27.75       0.7399       27.75       0.7399       <	RCAN [10]		21.38	0.6042	24.47	0.6299	24.07	0.6606	20.03	0.7572	
DAN [9]         25.20         0.7375         27.39         0.7379         27.96         0.7171         0.8940           KXNet(ours)         26.37         0.8035         28.15         0.7672         29.04         0.8036         31.70         0.8940           KXNet(ours)         26.37         0.8035         28.15         0.7672         29.04         0.8032         24.35         0.7086           Bicubic         20.88         0.5602         23.75         0.5827         23.17         0.6082         24.35         0.7086           DASR [12]         x4         24.33         0.7241         26.49         0.6968         27.04         0.7398         29.60         0.8503           DAN [9]         24.91         0.7491         26.92         0.7168         27.69         0.7605         30.99         0.8815           Bicubic         22.89         0.6401         25.65         0.6482         25.55         0.6826         27.39         0.7738           DAN [9]         26.64         0.768         27.76         0.7396         28.10         0.7767         31.23         0.8815           DAN [9]         26.68         0.8056         28.33         0.7615         29.12         0.7833	IKC [6]	x3	25.30	0.7626	27.30	0.7475	28.19	0.7805	31.00	0.8853	0
DAN [9]         25.82         0.7855         27.88         0.7003         28.09         0.7999         31.70         0.8940           KXNet(ours)         26.37         0.8053         28.15         0.7672         29.04         0.8036         32.53         0.9034           Bicubic         20.88         0.5602         23.75         0.5827         23.17         0.6082         24.35         0.7086           DAN [9]         24.20         0.7150         26.43         0.6903         26.89         0.7306         29.53         0.8455           DAN [9]         24.91         0.7141         26.92         0.7168         27.69         0.7600         30.53         0.8745           EkxNet(ours)         25.30         0.7647         27.08         0.7221         27.98         0.7659         30.90         0.8815           Bicubic         22.89         0.601         25.65         0.6492         25.51         0.6482         27.39         0.773           DASR [12]         x2         25.89         0.7739         27.75         0.7366         28.41         0.7767         31.03         0.8648           Bicubic         21.72         0.5889         24.20         0.6045         24.15	DASK [12]		25.20	0.7575	27.39	0.7379	27.90	0.7727	30.91 91 <del>7</del> 0	0.8723	
RANCE(Outrs)         26.37         0.8035         26.13         0.7072         29.04         0.8036         23.53         0.9034           Bicubic         20.88         0.5602         23.17         0.6082         24.35         0.7086           RCAN [16]         19.84         0.5307         23.17         0.6082         23.72         0.60973           DASR [12]         x4         24.30         0.7741         26.49         0.6968         27.04         0.7308         29.53         0.8455           DAN [9]         24.91         0.7441         26.92         0.7168         27.69         0.7000         20.53         0.8746           KXNet(ours)         25.30         0.6741         27.76         0.7456         28.28         0.7738         0.7738           RCAN [16]         22.88         0.5966         25.43         0.6092         25.34         0.6460         26.89         0.7333           DAN [9]         26.64         0.7674         28.14         0.7767         23.00         0.8864           Bicubic         21.72         0.5889         24.52         0.6045         24.15         0.6349         25.59         0.7316           RCAN [16]         21.30         0.7405	DAN [9]		25.82	0.7855	27.88	0.7603	28.69	0.7969	31.70	0.8940	
Bicubic         20.88         0.5002         23.73         0.5827         23.17         0.6082         24.35         0.7086           IKC [6]         x4         24.33         0.7241         26.49         0.6968         27.04         0.7398         29.60         0.8503           DASR [12]         x4         24.30         0.7141         26.49         0.6903         26.89         0.7306         29.53         0.8455           KNet(ours)         25.30         0.7647         27.08         0.7168         27.69         0.7600         30.53         0.8746           KNet(ours)         22.89         0.6401         25.55         0.6498         25.55         0.6826         27.39         0.7738           RCAN [16]         22.89         0.5766         28.43         0.6062         25.43         0.6042         25.43         0.6042         25.34         0.6460         26.89         0.7333           IKC [6]         22.89         0.6761         27.75         0.7396         28.13         0.7761         31.03         0.8843           KXnet(ours)         26.88         0.7964         27.17         0.7161         27.12         0.7316         23.07         0.8842         0.6633         24.55	KANet(ours)		26.37	0.8035	28.15	0.7672	29.04	0.8036	32.53	0.9034	-
RCA [16]       19.84       0.5307       23.10       0.5379       22.38       0.5369       23.12       0.0739       23.12       0.0739         DASR [12]       x4       24.33       0.77241       26.49       0.6963       26.89       0.7306       29.53       0.8455         DAN [9]       25.30       0.7647       27.08       0.7221       27.98       0.7659       30.99       0.8815         Bicubic       22.89       0.6401       25.55       0.6420       25.54       0.6400       26.89       0.7333       31.23       0.8718         DASR [12]       x2       25.89       0.7739       27.76       0.7736       28.41       0.7767       31.03       0.8680         DAN [9]       26.64       0.7664       28.24       0.7571       29.14       0.7765       31.03       0.8680         Bicubic       21.72       0.5889       24.52       0.6049       25.59       0.7316       7.72       0.7736       32.07       0.8864         DASR [12]       x3       25.10       0.7402       26.95       0.7070       27.75       0.7379       29.44       0.8437       5         DASR [12]       x3       25.49       0.7614       27.30	DCAN [1c]		20.88	0.5602	23.70	0.5827	23.17	0.6082	24.30	0.7086	
IAC [6]       x4       24.33       0.7150       20.43       0.6908       27.04       0.7306       29.50       0.8845         DANR [9]       24.91       0.7150       26.43       0.6908       26.89       0.7306       29.53       0.8845         KXNet(ours)       25.30       0.7647       27.08       0.7721       27.98       0.7659       30.99       0.8815         Bicubic       22.89       0.6401       25.55       0.6826       27.39       0.7738         RCAN [16]       22.88       0.5986       25.43       0.6092       25.34       0.6406       26.89       0.7333         IKC [6]       22.57       0.7673       27.76       0.7476       27.68       0.7767       31.03       0.8680         DASR [12]       x2       25.89       0.7739       27.76       0.7476       27.94       32.01       0.8843         KXNet(ours)       26.68       0.8056       28.33       0.7615       29.22       0.7793       31.33       0.8718         RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6399       25.39       0.7128         DAN [9]       25.13       0.7472       20.7172       0.7572	RCAN [10]		19.84	0.5307	23.10	0.5729	22.38	0.5967	23.72	0.6973	
DAN [9]       24.90       0.7491       20.43       0.0903       20.89       0.7600       30.53       0.8746         KXNet(ours)       25.30       0.7747       27.08       0.7221       27.98       0.7659       30.99       0.8815         Bicubic       22.89       0.6401       25.65       0.6498       25.55       0.6860       27.39       0.7738         RCAN [16]       22.88       0.6793       27.76       0.7756       27.75       0.7667       31.03       0.8680         DAN [9]       26.64       0.7964       28.23       0.7712       20.14       0.7767       31.03       0.8684         Bicubic       21.72       0.7588       24.24       0.7571       29.14       0.7767       31.03       0.8684         Bicubic       21.72       0.5889       24.52       0.6045       24.15       0.6349       25.39       0.7316         RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         DAN [9]       25.13       0.7402       27.01       0.7090       27.72       0.7513       30.36       0.8578         KXNet(ours)       20.4906       22.99       0.5365 <td>IKC [6]</td> <td>x4</td> <td>24.33</td> <td>0.7241</td> <td>26.49</td> <td>0.6968</td> <td>27.04</td> <td>0.7398</td> <td>29.60</td> <td>0.8503</td> <td></td>	IKC [6]	x4	24.33	0.7241	26.49	0.6968	27.04	0.7398	29.60	0.8503	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	DASR [12]		24.20	0.7150	26.43	0.6903	26.89	0.7306	29.53	0.8455	
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	DAN [9]		24.91	0.7491	26.92	0.7168	27.69	0.7600	30.53	0.8746	
Bicubic       22.89       0.6401       25.65       0.6492       25.55       0.6826       27.39       0.7738         RCAN [16]       22.88       0.5986       25.43       0.6092       25.34       0.6400       26.89       0.7333         IKC [6]       x2       25.72       0.7678       27.75       0.7396       28.44       0.7767       31.03       0.8680         DAN [9]       26.64       0.7964       28.24       0.7715       21.01       0.8843         KXNet(ours)       26.88       0.8056       28.33       0.7615       29.22       0.7993       32.07       0.8864         Bicubic       21.72       0.5888       24.52       0.6045       24.15       0.6039       25.23       0.7128         IKC [6]       x3       25.01       0.7405       26.95       0.7700       27.59       0.7481       30.36       0.8578         DAN [9]       25.13       0.7472       27.01       0.7090       27.72       0.7572       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5937       24.22       0.6911         BAS N [12]       x4       21.30       0.7672       26.	KXNet(ours)		25.30	0.7647	27.08	0.7221	27.98	0.7659	30.99	0.8815	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Bicubic		22.89	0.6401	25.65	0.6498	25.55	0.6826	27.39	0.7738	
IKC [6]       22       25.72       0.7678       27.75       0.7396       28.28       0.7793       31.23       0.8718         DASR [12]       x2       25.89       0.7793       27.75       0.7396       28.41       0.77954       31.03       0.8680         DAN [9]       26.64       0.7964       28.24       0.7571       29.14       0.7954       32.07       0.8864         Bicubic       21.72       0.5588       24.52       0.6045       24.15       0.6349       25.59       0.7316         RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         DASR [12]       x3       25.01       0.7405       26.65       0.7700       27.59       0.7313       30.36       0.8576         DAN [9]       25.13       0.7472       27.01       0.7090       27.72       0.7513       30.36       0.8577         MXNet(ours)       25.49       0.7614       27.13       0.7109       27.72       0.711       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5937       24.24       0.6633         JASR [12]       x4       24.	RCAN [16]		22.88	0.5986	25.43	0.6092	25.34	0.6460	26.89	0.7333	
DASR [12]       Theorem 25:89       0.7739       27.75       0.7396       28.41       0.7767       31.03       0.8680         DAN [9]       26.64       0.7964       32.01       0.8843       32.07       0.8864         Bicubic       21.72       0.5889       24.52       0.6045       24.15       0.6349       25.59       0.7316         RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         DASR [12]       x3       24.73       0.7300       26.75       0.6957       27.72       0.7379       29.84       0.8437       5         Bicubic       25.49       0.7616       27.13       0.7140       27.92       0.7577       20.711       0.8637         Bicubic       20.82       0.5616       23.63       0.5676       23.07       0.5937       24.22       0.6911         RCAN [16]       19.92       0.4996       22.99       0.5365       22.31       0.5597       23.48       0.6633         IKC [6]       24.02       0.7072       26.03       0.6677       27.10       0.7262       29.55       0.8450         DASR [12]       x4       0.5159       24.48	IKC [6]	x2	25.72	0.7678	27.76	0.7456	28.28	0.7793	31.23	0.8718	
DAN [9]       26.64       0.7964       28.24       0.7571       29.14       0.7954       32.01       0.8843         KXNet(ours)       26.88       0.8056       28.33       0.7615       29.22       0.7993       32.07       0.8864         Bicubic       21.72       0.5889       24.52       0.6045       24.15       0.6349       25.53       0.7128         RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         DAN [9]       25.13       0.7472       27.01       0.7000       27.72       0.7513       30.36       0.8578         KXNet(ours)       25.49       0.7614       27.13       0.7140       27.92       0.7572       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5597       24.48       0.6633         JKC [6]       x4       24.02       0.7027       26.03       0.6664       26.57       0.7129       28.90       0.8275         DASR [12]       x4       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8440         KXNet(ours)       25.45	DASR $[12]$		25.89	0.7739	27.75	0.7396	28.41	0.7767	31.03	0.8680	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	DAN [9]		26.64	0.7964	28.24	0.7571	29.14	0.7954	32.01	0.8843	
Bicubic       21.72       0.5889       24.52       0.6045       24.15       0.6349       25.59       0.7316         RCAN [16]       12.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         IKC [6]       x3       25.01       0.7405       26.95       0.7070       27.59       0.7379       29.84       0.8437       5         DAN [9]       25.13       0.7472       27.01       0.7090       27.72       0.7512       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5937       24.22       0.6911         RCAN [16]       19.92       0.4996       22.99       0.5365       22.31       0.5597       23.48       0.6633         JKC [6]       x4       23.92       0.6982       26.01       0.6664       26.56       0.7119       29.30       0.8404         KXNet(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         Bicubic       22.19       0.5159       24.44       0.5150       24.38       0.5497       23.76       0.4706         IKC [6]       x2 <td>KXNet(ours)</td> <td></td> <td>26.88</td> <td>0.8056</td> <td>28.33</td> <td>0.7615</td> <td>29.22</td> <td>0.7993</td> <td>32.07</td> <td>0.8864</td> <td>-</td>	KXNet(ours)		26.88	0.8056	28.33	0.7615	29.22	0.7993	32.07	0.8864	-
RCAN [16]       21.30       0.5538       24.19       0.5776       23.80       0.6099       25.23       0.7128         IKC [6]       x3       25.01       0.7405       26.95       0.7070       27.59       0.7481       30.53       0.8586         DANS [9]       25.13       0.7472       27.01       0.7090       27.72       0.7573       20.7379       29.84       0.8437         Bicubic       25.49       0.7614       27.13       0.7140       27.92       0.7572       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5977       23.48       0.6633         IKC [6]       24.02       0.7027       26.03       0.6664       26.57       0.7129       28.90       0.8275         DASR [12]       x4       23.92       0.6982       26.01       0.6636       26.46       0.7068       28.69       0.8211         DAN [9]       24.33       0.7167       26.20       0.6752       26.86       0.7219       29.30       0.8404         KXNet(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         DAN [9]       <	Bicubic		21.72	0.5889	24.52	0.6045	24.15	0.6349	25.59	0.7316	5
IKC [6]       x3       25.01       0.7405       26.95       0.7070       27.59       0.7481       30.53       0.8586       5         DAN [9]       25.13       0.7472       27.01       0.7070       27.72       0.7513       30.36       0.8578         KXNet(ours)       25.49       0.7614       27.13       0.7140       27.92       0.7572       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5937       24.22       0.6911         RCAN [16]       19.92       0.4996       22.99       0.5365       22.31       0.5597       23.48       0.6633         JKC [6]       x4       24.02       0.7027       26.03       0.6664       26.57       0.7129       29.50       0.8275         DASR [12]       x4       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         Bicubic       21.9       0.5159       24.44       0.5150       24.38       0.5497       25.72       0.6241         RCAN [16]       21.28       0.3884       22.98       0.8822       2.960       0.4155       23.76       0.4706         KXnet(our	RCAN [16]		21.30	0.5538	24.19	0.5776	23.80	0.6099	25.23	0.7128	
DASR [12]       M3       24.73       0.7300       26.75       0.6957       27.32       0.7379       29.84       0.8437       5         DAN [9]       25.13       0.7472       27.01       0.7090       27.72       0.7513       30.36       0.8578         KXNet(ours)       25.49       0.7614       27.13       0.7140       27.92       0.7572       30.71       0.8637         Bicubic       20.82       0.5461       23.63       0.6664       26.57       0.7129       28.90       0.8275         DASR [12]       x4       24.02       0.7027       26.03       0.6664       26.57       0.7129       28.90       0.8275         DASR [19]       24.33       0.7167       26.20       0.6652       26.86       0.7219       29.30       0.8404         KXNet(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         Bicubic       22.19       0.5159       24.44       0.5150       24.38       0.5497       25.72       0.6241         RCAN [16]       21.28       0.3884       22.98       0.6828       26.93       0.7242       29.21       0.8260         DAN [9]       <	IKC [6]	x3	25.01	0.7405	26.95	0.7070	27.59	0.7481	30.53	0.8586	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	DASR $[12]$		24.73	0.7300	26.75	0.6957	27.32	0.7379	29.84	0.8437	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	DAN [9]		25.13	0.7472	27.01	0.7090	27.72	0.7513	30.36	0.8578	
Bicubic       20.82       0.5461       23.63       0.5676       23.07       0.5937       24.22       0.6911         RCAN [16]       19.92       0.4996       22.99       0.5365       22.31       0.5597       23.48       0.6633         IKC [6]       x4       24.02       0.7027       26.03       0.6664       26.57       0.7129       28.90       0.8275         DASR [12]       v4       23.39       0.6982       26.01       0.6664       26.46       0.7068       28.69       0.8211         DAN [9]       24.33       0.7167       26.20       0.6752       26.86       0.7219       29.30       0.8404         KXNet(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         Bicubic       21.18       0.3884       22.98       0.3822       22.96       0.4155       23.76       0.4706         JKC [6]       x2       24.69       0.7208       26.49       0.6822       27.56       0.7392       29.91       0.8430         KXNet(ours)       25.45       0.7500       26.87       0.6959       27.59       0.7422       29.93       0.8449         Bicubic	KXNet(ours)		25.49	0.7614	27.13	0.7140	27.92	0.7572	30.71	0.8637	_
RCAN [16]       19.92       0.4996       22.99       0.5365       22.31       0.5597       23.48       0.6633         IKC [6]       x4       24.02       0.7027       26.03       0.6664       26.57       0.7129       28.90       0.8275         DASR [12]       x4       23.92       0.6982       26.01       0.6664       26.46       0.7029       28.69       0.8211         MKX et(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8404         KXNet(ours)       24.59       0.7285       26.28       0.6777       27.01       0.7262       29.55       0.8450         Bicubic       22.19       0.5159       24.44       0.5150       24.38       0.5497       25.72       0.6241         RCAN [16]       21.28       0.3884       22.98       0.3822       22.66       0.7129       29.21       0.8260         DAN [9]       25.32       0.7447       26.84       0.6932       27.56       0.7392       29.91       0.8430         KXNet(ours)       25.45       0.7019       25.33       0.6564       26.42       0.7018       28.61       0.8135         Bicubic       21.18	Bicubic		20.82	0.5461	23.63	0.5676	23.07	0.5937	24.22	0.6911	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	RCAN [16]		19.92	0.4996	22.99	0.5365	22.31	0.5597	23.48	0.6633	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	IKC [6]	<b>v</b> 4	24.02	0.7027	26.03	0.6664	26.57	0.7129	28.90	0.8275	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	DASR $[12]$	A 1	23.92	0.6982	26.01	0.6636	26.46	0.7068	28.69	0.8211	
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	DAN [9]		24.33	0.7167	26.20	0.6752	26.86	0.7219	29.30	0.8404	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	KXNet(ours)		24.59	0.7285	26.28	0.6777	27.01	0.7262	29.55	0.8450	
RCAN [16]       21.28       0.3884       22.98       0.3822       22.96       0.4155       23.76       0.4706         IKC [6]       x2       24.69       0.7208       26.49       0.6828       26.33       0.7244       29.21       0.8200         DAN [9]       25.32       0.7447       26.63       0.6841       27.22       0.7392       29.91       0.8322         KXNet(ours)       25.45       0.7500       26.87       0.6959       27.56       0.7422       29.93       0.8449         Bicubic       21.18       0.4891       23.55       0.4961       23.28       0.5289       24.42       0.6119         RCAN [16]       20.22       0.3693       22.20       0.3726       21.99       0.4053       22.85       0.4745         IKC [6]       x3       24.41       0.7019       25.93       0.6564       26.42       0.7018       28.61       0.8135         DAN [9]       24.17       0.7013       25.93       0.6551       26.66       0.7063       28.64       0.8178         KXNet(ours)       24.42       0.7135       25.93       0.6585       26.56       0.7063       28.64       0.8178         Bicubic       20.38       <	Bicubic		22.19	0.5159	24.44	0.5150	24.38	0.5497	25.72	0.6241	
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	RCAN [16]		21.28	0.3884	22.98	0.3822	22.96	0.4155	23.76	0.4706	
DASR [12]       X2       24.84       0.7273       26.63       0.6841       27.22       0.7283       29.44       0.8322         DAN [9]       25.32       0.7447       26.84       0.6932       27.56       0.7392       29.91       0.8430         KXNet(ours)       25.45       0.7500       26.87       0.6959       27.59       0.7422       29.93       0.8449         Bicubic       21.18       0.4891       23.55       0.4961       23.28       0.5289       24.42       0.6119         RCAN [16]       20.22       0.3693       22.20       0.3726       21.99       0.4053       22.85       0.4745         JKC [6]       x3       24.21       0.7019       25.93       0.6664       26.22       0.7018       28.61       0.8135         DAN [9]       24.17       0.7019       25.93       0.6655       26.66       0.7063       28.64       0.8178         Bicubic       24.17       0.7013       25.99       0.6585       26.66       0.7063       28.64       0.8178         Bicubic       20.38       0.4690       22.83       0.4841       22.39       0.5120       23.33       0.5977         RCAN [16]       19.23 <th< td=""><td>IKC [6]</td><td></td><td>24.69</td><td>0.7208</td><td>26.49</td><td>0.6828</td><td>26.93</td><td>0.7244</td><td>29.21</td><td>0.8260</td><td></td></th<>	IKC [6]		24.69	0.7208	26.49	0.6828	26.93	0.7244	29.21	0.8260	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	DASR [12]	X2	24.84	0.7273	26.63	0.6841	27.22	0.7283	29.44	0.8322	
KXNet(ours)       25.45       0.7500       26.87       0.6959       27.59       0.7422       29.93       0.8449         Bicubic       21.18       0.4891       23.55       0.4961       23.28       0.5289       24.42       0.6119         RCAN [16]       20.22       0.3693       22.20       0.3726       21.99       0.4053       22.85       0.4745         DASR [12]       x3       24.21       0.7019       25.93       0.6564       26.42       0.7018       28.61       0.8135         DASR [12]       x3       24.42       0.7013       25.93       0.6551       26.46       0.7014       28.52       0.8147         MXNet(ours)       24.42       0.7135       25.99       0.6585       26.66       0.7063       28.64       0.8178         Bicubic       20.38       0.4690       22.83       0.4841       22.39       0.5102       23.33       0.5977         RCAN [16]       19.23       0.3515       21.47       0.3686       21.05       0.3960       21.77       0.4689         IKC [6]       x4       23.35       0.6665       25.21       0.6238       25.55       0.6683       27.32       0.7867         DAN [9]	DAN [9]		25.32	0.7447	26.84	0.6932	27.56	0.7392	29.91	0.8430	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	KXNet(ours)		25.45	0.7500	26.87	0.6959	27.59	0.7422	29.93	0.8449	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	Bicubic		21.18	0.4891	23.55	0.4961	23.28	0.5289	24.42	0.6119	-
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	RCAN [16]		20.22	0.3693	22.20	0.3726	21.99	0.4053	22.85	0.4745	
DASR [12]       x3       23.93       0.6890       25.82       0.6484       26.27       0.6940       28.27       0.8047       13         DAN [9]       24.17       0.7013       25.93       0.6551       26.46       0.7014       28.52       0.8130         KXNet(ours)       24.42       0.7135       25.99       0.6585       26.66       0.7063       28.64       0.8178         Bicubic       20.38       0.4690       22.83       0.4841       22.39       0.5120       23.33       0.5977         RCAN [16]       19.23       0.3515       21.47       0.3686       21.05       0.3960       21.77       0.4689         IKC [6]       x4       23.35       0.6665       25.21       0.6238       25.58       0.6712       27.32       0.7867         DASR [12]       x4       23.48       0.6742       25.25       0.6283       25.75       0.6663       27.32       0.7842         DAN [9]       23.48       0.6742       25.25       0.6283       25.78       0.6792       27.66       0.7977         KXNet(ours)       23.67       0.6844       25.30       0.6296       25.78       0.6792       27.66       0.7977	IKC [6]	2	24.21	0.7019	25.93	0.6564	26.42	0.7018	28.61	0.8135	15
DAN [9]       24.17       0.7013       25.93       0.6551       26.46       0.7014       28.52       0.8130         KXNet(ours)       24.42       0.7135       25.99       0.6585       26.56       0.7063       28.64       0.8178         Bicubic       20.38       0.4690       22.83       0.4841       22.39       0.5120       23.33       0.5977         RCAN [16]       19.23       0.3515       21.47       0.3686       21.05       0.3900       21.77       0.4689         IKC [6]       x4       23.35       0.6662       25.21       0.6238       25.55       0.6712       27.45       0.7867         DAN [9]       23.48       0.6742       25.25       0.6283       25.72       0.6760       27.55       0.7938         KXNet(ours)       23.67       0.6844       25.30       0.6296       25.78       0.6792       27.66       0.7977	DASR [12]	хэ	23.93	0.6890	25.82	0.6484	26.27	0.6940	28.27	0.8047	19
KXNet(ours)         24.42         0.7135         25.99         0.6585         26.56         0.7063         28.64         0.8178           Bicubic         20.38         0.4690         22.83         0.4841         22.39         0.5120         23.33         0.5977           RCAN [16]         19.23         0.3515         21.47         0.3686         21.05         0.3900         21.77         0.4689           IKC [6]         23.35         0.6665         25.21         0.6238         25.55         0.6712         27.45         0.7842           DASR [12]         x4         23.48         0.6742         25.25         0.6238         25.75         0.6780         27.55         0.7938           KXNet(ours)         23.67         0.6844         25.30         0.6296         25.78         0.6792         27.66         0.7977	DAN [9]		24.17	0.7013	25.93	0.6551	26.46	0.7014	28.52	0.8130	
$ \begin{array}{c c c c c c c c c c c c c c c c c c c $	KXNet(ours)		24.42	0.7135	25.99	0.6585	26.56	0.7063	28.64	0.8178	
RCAN [16]         19.23         0.3515         21.47         0.3686         21.05         0.3960         21.77         0.4689           IKC [6]         23.35         0.6665         25.21         0.6238         25.58         0.6712         27.45         0.7867           DASR [12]         x4         23.26         0.6620         25.20         0.6233         25.75         0.6663         27.32         0.7842           DAN [9]         23.48         0.6742         25.25         0.6286         25.72         0.6760         27.55         0.7938           KXNet(ours)         23.67         0.6844         25.30         0.6296         25.78         0.6792         27.66         0.7977	Bicubic		20.38	0.4690	22.83	0.4841	22.39	0.5120	23.33	0.5977	-
IKC [6]       23.35       0.6665       25.21       0.6238       25.58       0.6712       27.45       0.7867         DASR [12]       x4       23.26       0.6620       25.20       0.6223       25.55       0.6683       27.32       0.7842         DAN [9]       23.48       0.6742       25.25       0.6283       25.72       0.6760       27.55       0.7938         KXNet(ours)       23.67       0.6844       25.30       0.6296       25.78       0.6792       27.66       0.7977	RCAN [16]		19.23	0.3515	21.47	0.3686	21.05	0.3960	21.77	0.4689	
DASR [12]       x4       23.26       0.6620       25.20       0.6223       25.55       0.6683       27.32       0.7842         DAN [9]       23.48       0.6742       25.25       0.6283       25.72       0.6760       27.55       0.7938         KXNet(ours)       23.67       0.6844       25.30       0.6296       25.78       0.6792       27.66       0.7977	IKC [6]		23.35	0.6665	25.21	0.6238	25.58	0.6712	27.45	0.7867	
DAN [9]         23.48         0.6742         25.25         0.6283         25.72         0.6760         27.55         0.7938           KXNet(ours)         23.67         0.6844         25.30         0.6296         25.78         0.6792         27.66         0.7977	DASR [12]	x4	23.26	0.6620	25.20	0.6223	25.55	0.6683	27.32	0.7842	
KXNet(ours) 23.67 0.6844 25.30 0.6296 25.78 0.6792 27.66 0.7977	DAN [9]		23.48	0.6742	25.25	0.6283	25.72	0.6760	27.55	0.7938	
	KXNet (ours)		23.67	0.6844	25.30	0.6296	25.78	0.6792	27.66	0.7977	

Table 4. Average PSNR/SSIM of all the comparing methods (Setting 2).

## 6 More Experimental Results

In this section, we provide more numerical results of KXNet on Setting2 in the main text, as shown in Table 4.



KXNet: A Model-Driven Deep Neural Network for Blind Super-Resolution

**Fig. 3.** Blur kernel estimation and performance comparison on  $img \ 11$  and  $img \ 14$  in Set14 [14]. The scale factor is 2 and the noise level is 0. The blur kernel estimated by DIP-FKP shifts to the upper left due to the underlying assumption.

Table 5. Quantitative comparison with the unsupervised SOTA methods.

Noise	Mathad (22)	Set14 [14]			
Level	Method (x2)	PSNR	SSIM		
	KernelGAN $[2] + ZSSR [11]$	24.88	0.7532		
0	DIP-FKP [8]	25.81	0.7210		
	DIP-FKP [8] + USRNet [15]	22.58	0.7317		
	KXNet(ours)	32.10	0.8979		

#### 7 Blur Kernel Estimation

In this section, we demonstrate more experimental results about blur kernel estimation. Currently, there are some unsupervised blind super-resolution methods that have achieved remarkable performance in estimating blur kernel, such as KernelGAN [2] and DIP-FKP [8]. We can combine the estimated blur kernels by these methods and the competing non-blind SR methods, such as ZZSR and USRNet, to accomplish the blind SR task. As shown in Fig. 3 and Table 5, due to the single image learning strategy, these unsupervised methods cannot learn rich image priors underlying data and the SR performance is inferior. Besides, by comparing DIP-FKP and DIP-FKP+USRNet, we can easily find that the inaccuracy of the estimated blur kernel by DIP-FKP tends to adversely affect the SR performance of the non-blind SR method–USRNet. In contrast, under different blur kernel degradation settings, the proposed method can consistently achieve better kernel estimation and obtain better SR performance, which significantly outperforms the KernelGAN+ZSSR and DIP-FKP+USRNet. This finely sub8 Jiahong Fu et al.

stantiates the superiority of our unfolding network which fully and reasonably embeds the inherent relationship between blur kernel and HR image. It is the joint estimation of blur kernel and HR image which guides the network to learn in the right direction.

#### References

- Beck, A., Teboulle, M.: A fast iterative shrinkage-thresholding algorithm for linear inverse problems. SIAM journal on imaging sciences 2(1), 183–202 (2009)
- Bell-Kligler, S., Shocher, A., Irani, M.: Blind super-resolution kernel estimation using an internal-gan. arXiv preprint arXiv:1909.06581 (2019)
- 3. Bevilacqua, M., Roumy, A., Guillemot, C., Alberi-Morel, M.L.: Low-complexity single-image super-resolution based on nonnegative neighbor embedding (2012)
- Donoho, D.L.: De-noising by soft-thresholding. IEEE transactions on information theory 41(3), 613–627 (1995)
- 5. Fang, F., Li, J., Zeng, T.: Soft-edge assisted network for single image superresolution. IEEE Transactions on Image Processing **29**, 4656–4668 (2020)
- Gu, J., Lu, H., Zuo, W., Dong, C.: Blind super-resolution with iterative kernel correction. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. pp. 1604–1613 (2019)
- Huang, J.B., Singh, A., Ahuja, N.: Single image super-resolution from transformed self-exemplars. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 5197–5206 (2015)
- Liang, J., Zhang, K., Gu, S., Van Gool, L., Timofte, R.: Flow-based kernel prior with application to blind super-resolution. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. pp. 10601–10610 (2021)
- Luo, Z., Huang, Y., Li, S., Wang, L., Tan, T.: Unfolding the alternating optimization for blind super resolution. arXiv preprint arXiv:2010.02631 (2020)
- Martin, D., Fowlkes, C., Tal, D., Malik, J.: A database of human segmented natural images and its application to evaluating segmentation algorithms and measuring ecological statistics. In: Proceedings Eighth IEEE International Conference on Computer Vision. ICCV 2001. vol. 2, pp. 416–423. IEEE (2001)
- Shocher, A., Cohen, N., Irani, M.: "zero-shot" super-resolution using deep internal learning. In: Proceedings of the IEEE conference on computer vision and pattern recognition. pp. 3118–3126 (2018)
- Wang, L., Wang, Y., Dong, X., Xu, Q., Yang, J., An, W., Guo, Y.: Unsupervised degradation representation learning for blind super-resolution. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. pp. 10581–10590 (2021)
- 13. Xia, B., Hang, Y., Tian, Y., Yang, W., Liao, Q., Zhou, J.: Efficient non-local contrastive attention for image super-resolution (2022)
- Zeyde, R., Elad, M., Protter, M.: On single image scale-up using sparserepresentations. In: International conference on curves and surfaces. pp. 711–730. Springer (2010)
- Zhang, K., Gool, L.V., Timofte, R.: Deep unfolding network for image superresolution. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition. pp. 3217–3226 (2020)
- Zhang, Y., Li, K., Li, K., Wang, L., Zhong, B., Fu, Y.: Image super-resolution using very deep residual channel attention networks. In: Proceedings of the European conference on computer vision (ECCV). pp. 286–301 (2018)