

NTIRE 2021 Challenge on High Dynamic Range Imaging: Dataset, Methods and Results

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Abstract

This paper reviews the first challenge on high-dynamic range (HDR) imaging that was part of the New Trends in Image Restoration and Enhancement (NTIRE) workshop, held in conjunction with CVPR 2021. This manuscript focuses on the newly introduced dataset, the proposed methods and their results. The challenge aims at estimating a HDR image from one or multiple respective low-dynamic range (LDR) observations, which might suffer from under- or over-exposed regions and different sources of noise. The challenge is composed by two tracks: In Track 1 only a single LDR image is provided as input, whereas in Track 2 three differently-exposed LDR images with inter-frame motion are available. In both tracks, the ultimate goal is to achieve the best objective HDR reconstruction in terms of PSNR with respect to a ground-truth image, evaluated both directly and with a canonical tonemapping operation.

1. Introduction

Current consumer-grade cameras struggle to capture scenes with varying illumination with a single exposure shot due to the inherent limitations of the imaging sensor, which suffers from saturation in high-irradiance regions and from uncertainty in the readings for low-light regions.

In recent years, advances in computational photogra-

phy have enabled single-sensor cameras to acquire images with an extended dynamic range without the need of expensive, bulky and arguably more inconvenient multi-camera rigs, e.g. [11, 23, 35]. Generally, those algorithms exploit multiple LDR frames captured with different exposure values (EV) that are then fused into a single HDR image [8, 24], with some of those methods including frame alignment [15, 29, 38] or pixel rejection strategies [39].

Convolutional Neural Networks (CNNs) have greatly advanced the state-of-the-art for HDR reconstruction, especially for complex dynamic scenes [15, 27, 38, 39]. Additionally, CNNs have opened a new path into single-image HDR imaging thanks to their ability to learn complex and entangled vision tasks seamlessly, e.g. denoising, camera response function estimation, image in-painting, high-frequency and detail hallucination [20]. Despite the ill-posed nature of the single-image HDR reconstruction, most current methods obtain plausible results that, if not as accurate as those reconstructed from multiframe LDR images, can be a good alternative when multiple frames are not available or can not be captured due to time constraints.

The NTIRE 2021 HDR Challenge aims at stimulating research for computational HDR imaging, and better understand the state-of-the-art landscape for both single and multiple frame HDR processing. It is part of a wide spectrum of associated challenges with the NTIRE 2021 workshop: non-homogeneous dehazing [3], defocus deblurring using dual-pixel [2], depth guided image relighting [10], image deblurring [25], multi-modal aerial view imagery classification [19], learning the super-resolution space [22], quality enhancement of heavily compressed videos [40], video super-resolution [32], perceptual image quality assessment [12], burst super-resolution [4], high dynamic

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<https://data.vision.ee.ethz.ch/cvl/ntire21/>

range [26].

2. Challenge

The NTIRE 2021 HDR Challenge is the first edition that addresses the HDR image enhancement task. This challenge aims to gauge and advance the state-of-the-art on HDR imaging. It is focused specially in challenging scenarios for HDR image reconstruction, *i.e.* wide range of scene illumination, accompanied by complex motions in terms of camera, scene and light sources. In this section we present details about the new dataset used for the challenge, as well as how the challenge tracks are designed.

2.1. Dataset

Both training and evaluation of HDR imaging algorithms require high quality annotated datasets. Specially for deep learning methods, the number of training examples and their diversity in terms of *e.g.* scene and camera motion, exposure values, textures, semantic content, is of crucial importance for the model performance and generalization capabilities. Creating a high quality HDR dataset with such features still poses several challenges. Current HDR datasets are generally captured using static image bracketing, with some efforts towards controlling the scene motion so that *stop-motion* dynamic scenes can be assembled: In the work of Kalantari *et al.* [15] a subject is asked to stay still in order to capture three bracketed exposure images on a tripod used to generate ground-truth, and afterwards two additional images are captured while the subject is asked to move, obtaining therefore a input LDR triplet with inter-frame motion and a reference HDR ground-truth image aligned to the central frame. Such capturing approaches are normally limited to small datasets, as this type of capturing is time consuming, and additionally it constrains the motions that can be captured while misalignment might still happen if the subject is not completely still.

For this challenge we introduce a newly curated HDR dataset. This dataset is composed of approximately 1500 training, 60 validation and 201 testing examples. Each example in the dataset is in turn composed of three input LDR images, *i.e.* short, medium and long exposures, and a related ground-truth HDR image aligned with the central medium frame. The images are collected from the work of Froelich *et al.* [11], where they capture an extensive set of HDR videos using a professional two-camera rig with a semitransparent mirror for the purpose of HDR display evaluation. The contents of those videos include naturally challenging HDR scenes: *e.g.* moving light sources, brightness changes over time, high contrast skin tones, specular highlights and bright, saturated colors. As these images lack the necessary LDR input images, similarly to [16], we synthetically generate the respective LDR counterparts by fol-

lowing accurate image formation models that include several noise sources [13].

Image Formation Model: In order to model the HDR to LDR step, we use the following pixel measurement model as described in [13]:

$$I_l = \min \{ \Phi t / g + I_0 + n, I_{max} \}, \quad (1)$$

where I_l is an LDR image, Φ is the scene brightness, t is the exposure time, g is the sensor gain, I_0 is the constant offset current, n is the sensor noise and I_{max} denotes the saturation point. For our data processing, we assume Φ to be well approximated by the ground-truth HDR images, and produce different LDR images by modifying the exposure time t parameter of any three consecutive frames.

Noise Model: In order to realistically reproduce the characteristic of common LDR images, we include a zero-mean signal whose variance comes from three independent sources, *i.e.* photon noise, read noise and analog-to-digital (ADC) gain and quantization noise (for 8-bit LDR images). For pixels under the saturation level, the variance of n reads:

$$\text{Var}(n) = \Phi t / g^2 + \sigma_{read}^2 / g^2 + \sigma_{ADC}^2 \quad (2)$$

Note that first photon-noise term is signal-dependent (normally represented by a Poisson distribution), while the read-noise term is gain-dependent.

We show in Figure 1 some examples of the HDR and the synthetically generated LDR images.

Partitions: We provide training, testing and validation data splits. With our synthetically processed set, we manually discard images to balance the number of frames per scene and to remove undesirable frames, mostly due to *e.g.* dominant presence of lights, lack of inter-frame motion, excessive presence of noise in the HDR image. This leads to roughly 1750 frames within 29 different scenes. The validation and testing splits are obtained randomly from 4 different scenes (*carousel fireworks 02, fireplace 02, fishing longshot, poker travelling slowmotion*) while the other 25 scenes are used for the training set, ensuring that there is no scene overlap between training and testing/validation. This results on a training set short of 1500 examples, and a validation and testing set of 60 and 201 examples respectively.

2.2. Challenge Design and Tracks

This challenge is organized into two different tracks, both of them sharing the same evaluation metrics and ground-truth data. The results from both tracks are thus directly comparable and can explain the performance differences between single and multi-frame HDR imaging.

2.2.1 Track 1: Single Frame

This track evaluates the HDR reconstruction when only a single LDR frame is available. In contrast to the multi-frame approaches, single image HDR methods have only

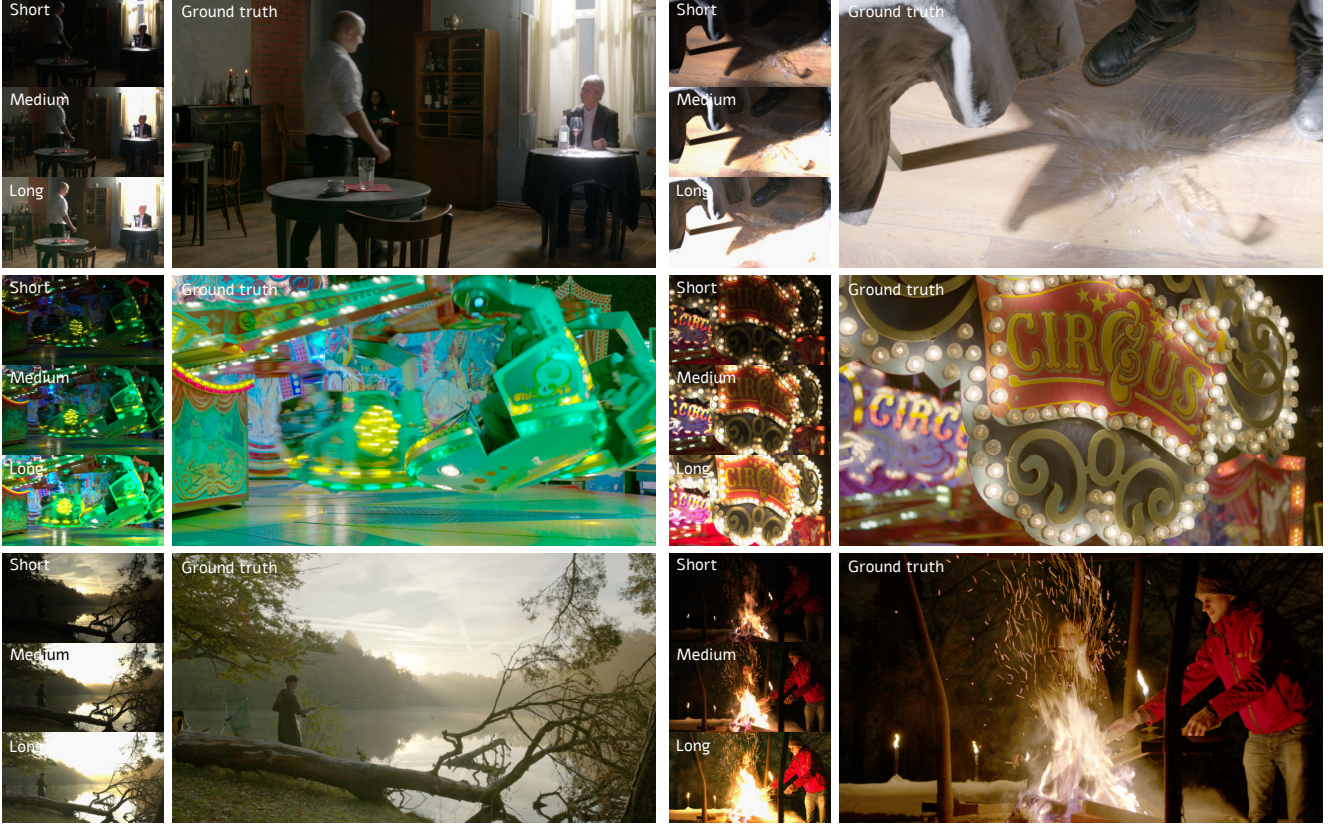


Figure 1. Visualizations of samples included in the newly curated training, validation and testing datasets. Each training example is composed by three input LDR images (short, medium and long) and a related ground-truth image aligned with the medium input LDR. *Note that validation and testing ground-true images were not made available to participants.*

a single exposure (instead of a bracketed set) which is arguably more challenging when recovering under- and over-exposed regions as no information from neighboring frames at different EVs can be leveraged. Similarly, single image denoising poses further challenges than its multiple frame counterpart as noise sources are of zero mean and less observations are available. On the other side, this track does not have to deal with motion related artifacts, *e.g.* ghosting, bleeding edges, which are common in the multiframe set-up.

2.2.2 Track 2: Multiple Frame

This track evaluates the HDR reconstruction for three differently exposed LDR images (*i.e.* short, medium, long) with diverse motion between the respective frames, including camera motion, non-rigid scene motion with an emphasis on complex moving and changing light sources. The bracketed input frames were separated by steps of 2 or 3 EV between them, similarly to other existing datasets [15]. In order to enable direct comparison between both tracks, the medium LDR frame in Track 2 corresponds to the single-frame LDR input on Track 1 and thus both tracks share the

same ground-truth data.

2.3. Evaluation

The evaluation of the challenge submissions is based on the computation of objective metrics between the estimated and the ground-truth HDR images. We use the well-known standard peak signal-to-noise ratio (PSNR) both directly on the estimated HDR image and after applying the μ -law tonemapper, which is a simple and canonical operator used widely for benchmarking in the HDR literature [15, 27, 39]. From within these two metrics, we selected PSNR- μ as the main metric to rank methods in the challenge.

For the PSNR directly computed on the estimated HDR images we normalize the values to be in the range $[0, 1]$ using the peak value of the ground-truth HDR image.

For the PSNR- μ , we apply the following tone-mapping operation $T(H)$:

$$T(H) = \frac{\log(1 + \mu H)}{\log(1 + \mu)} \quad (3)$$

where H is the HDR image, and μ is a parameter that controls the compression, which we fix to $\mu = 5000$ following

common HDR evaluation practises. In order to avoid excessive compression due to peak value normalization, for the PSNR- μ computation we normalize using the 99 percentile of the ground-truth image followed by a tanh function to maintain the $[0, 1]$ range.

3. Results

From 120 registered participants in Track 1, 16 teams participated during the development phase and finally 7 teams entered the final testing phase and submitted results and fact sheets. As for Track 2, from 126 registered participants, 28 teams participated during the development phase and finally 6 teams entered the final testing phase and submitted results and fact sheets. We report the final test phase results in Table 1 and 2 for track 1 and 2 respectively. A visualization of both metrics for each track separately can be found in Figure 2 and 3, and all the results from both tracks are aggregated in Figure 4. The methods and the teams that entered the final phase are described in Section 4, more detailed information about each team and their member’s affiliation can be found in Appendix A.

3.1. Main ideas

In the single frame track, the majority of the proposed architectures consist of several sub-networks which aim to reverse single aspects of the HDR to LDR image pipeline, perhaps inspired by the success of Liu *et al.* [20]. Variants of the Residual Dense Block [43] are the most commonly used backbone although U-Net style architectures are used by a significant minority. In addition to the standard ℓ_1 loss, some methods also use perceptual colour losses.

In the multiple frames track, a major number of solutions are inspired by Yan *et al.* AHDRNet [39], with most submissions using their attention mechanism. Most methods also adopt the Dilated Residual Dense Block, although similarly to Track 1, U-Net style architectures with non-dense residual blocks are also present and achieve competitive performance. Ensemble approaches to improve performance via test time augmentations such as flips/transpose [34] are common among the participants, leading to increases of up to 0.5 dB. Some submissions aim to explicitly align input images instead of just rejecting unaligned regions with attention, including the first-ranked submission which aligns images using deformable convolutions [7, 21].

3.2. Top results

Track 1: The top two methods (NOAHTCV and XPixel) obtain similar PSNR- μ scores, only about 0.07 dB apart, while in terms of PSNR the difference is more noticeable, in the range of 0.6 dB. BOE-IOT-AIBD comes third in terms of PSNR- μ , at around 0.4 dB gap to the first position, however they are ranked first in terms of PSNR by a notice-

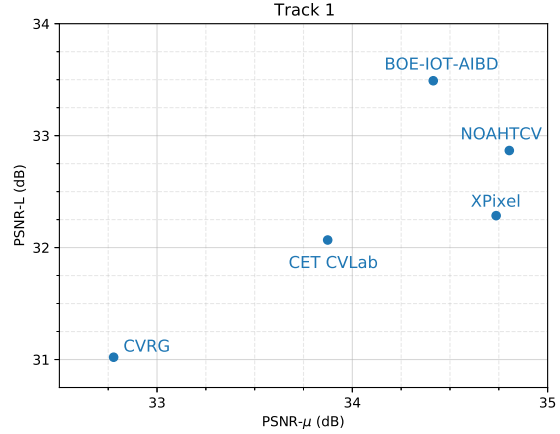


Figure 2. Combined PSNR- μ and PSNR values of methods from the Track 1 (single frame).

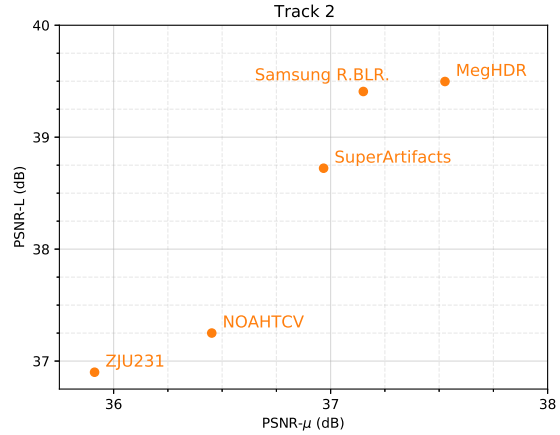


Figure 3. Combined PSNR- μ and PSNR values of methods from the Track 2 (multiple frames).

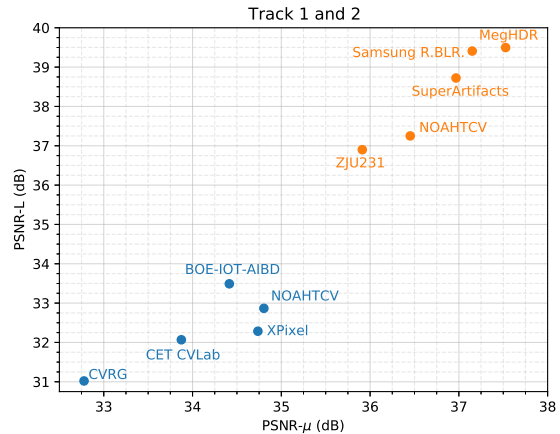


Figure 4. Combined PSNR- μ and PSNR values of methods from the Track 1 (in blue) and Track 2 (in orange).

able margin (0.6 dB) to the second best-performer in that metric (NOAHTCV). The rest of competing teams obtain scores within 2 and 1 dB gaps when compared to the best-performer in terms of PSNR and PSNR- μ respectively.

Track 2: In this track, both metrics behave similarly and exactly the same ranking is obtained with either of them. The MegHDR team obtains the first position, with a lead of 0.56 dB in terms of PSNR- μ and a broader difference of 0.78 in terms of PSNR when compared against the runner-up team in the leaderboard (SuperArtifacts). NOAHTCV follows at roughly 0.5 dB and 0.8 dB performance gap with respect to MegHDR in terms of PSNR- μ and PSNR respectively. The rest of competing teams obtain scores within 1.6 and 2.6 dB gaps when compared to the best-performer in terms of PSNR and PSNR- μ respectively.

4. Team and Methods

4.1. NOAHTCV

NOAHTCV have proposed two methods, one for single frame and one for multi-frame. Both methods are discussed here.

Single Image HDR Reconstruction in a Multi-stage Manner The team propose a multi-stage method which decomposes the problem into two sub-tasks; denoising and hallucination. The input image, I is first passed through a denoising network to get the denoised image D . Both I and D are processed by the hallucination network to obtain H . Finally I , D and H are fused by a refinement network. The general architecture can be seen in Figure 5. MIRNet [42] is employed as the denoising network, while the hallucination network uses masked features as in [28] to reconstruct details in the over-exposed regions. The refinement network is a U-Net equipped with coordinate attention [14].

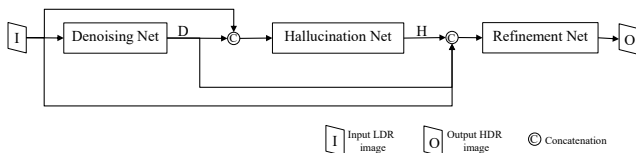


Figure 5. Architecture of Single Image HDR Reconstruction in a Multi-stage Manner, proposed by the NOAHTCV team.

Alignment Augmentation and Multi-Attention Guided HDR Fusion The team propose a three stage method consisting of an Alignment and Augmentation module, an Attention Based Information Extraction module, and an Enhancement and Fusion module. The architecture can be seen in Figure 6. The Alignment and Augmentation module uses a pretrained PWC-Net [33] to warp the short and long input images with a predicted optical flow. Both the original images and warped images are fed into the network. The Attention Based Information Extraction module employs the occluded attention

mechanism from AHDRNet [39] to reduce misalignment distortion. Channel attention is also used on shallow features extracted by a shared convolutional layer to re-weight features generated by different frames. The Enhancement and Fusion module employs the network architecture from AHDRNet [39] with the final sigmoid layer removed.

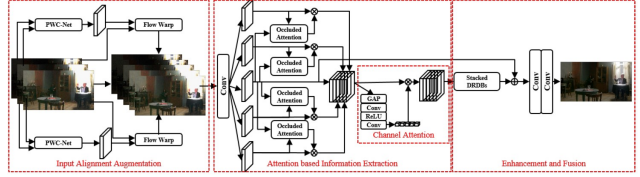


Figure 6. Architecture of Alignment Augmentation and Multi-Attention Guided HDR Fusion, proposed by the NOAHTCV team.

4.2. MegHDR

ADNet: Attention-guided Deformable Convolutional Networks for High Dynamic Range Imaging The team propose ADNet [21], a novel multi-frame imaging pipeline where the LDR images and their corresponding gamma-corrected images are processed separately, instead of being concatenated together. This is motivated by the intuition that images in the LDR domain are helpful for detecting noisy or saturated regions, while images in the HDR domain help to detect misalignment. The PCD align module aligns the gamma corrected images using pyramid, cascading and deformable convolutions based on EDVR [36]. The spatial attention module suppresses undesired saturation and noisy regions in the LDR images while highlighting the regions useful for fusion. The resulting features are concatenated and processed by dilated residual dense blocks (DRDBs) as in AHDRNet [39]. The architecture can be seen in Figure 7.

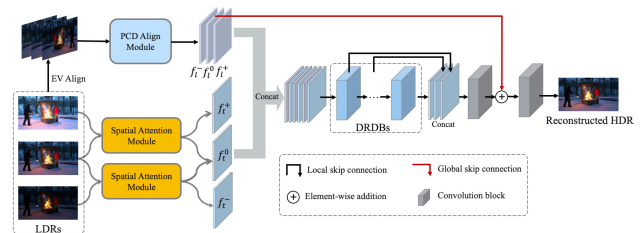


Figure 7. Architecture of ADNet, proposed by the MegHDR team.

4.3. XPixel

HDRUNet: Single Image HDR Reconstruction with Denoising and Dequantization The team propose HDRUNet [6], which consists of three sub-networks: the base network, the condition network and the weighting network. The architecture can be seen in Figure 8. The base network is a U-Net style encoder-decoder model. The condition network and spatial feature transform (SFT) layers [37] are introduced to achieve adaptive modulation

Team	Username	PSNR- μ	PSNR	Runtime (s)	GPU	Ensemble
NOAHTCV	nohtcv	34.804 ⁽¹⁾	32.867 ⁽²⁾	61.52 ⁽⁵⁾	Tesla P100	flips, transpose
XPixel	Xy_Chen	34.736 ⁽²⁾	32.285 ⁽³⁾	0.53 ⁽²⁾	RTX 2080 Ti	-
BOE-IOT-AIBD	chenguannan1981	34.414 ⁽³⁾	33.490 ⁽¹⁾	5.00 ⁽⁴⁾	Tesla V100	-
CET CVLab	akhilkashok	33.874 ⁽⁴⁾	32.068 ⁽⁴⁾	0.20 ⁽¹⁾	Tesla P100	flips, rotation
CVRG	sharif_apu	32.778 ⁽⁵⁾	31.021 ⁽⁵⁾	1.10 ⁽³⁾	GTX 1060	-
<i>no processing</i>	-	25.266 ⁽⁶⁾	27.408 ⁽⁶⁾	-	-	-

Table 1. Results and rankings of methods submitted to the *Track 1: Single frame HDR*. Please note that running times are self-reported.

Team	Username	PSNR- μ	PSNR	Runtime (s)	GPU	Ensemble
MegHDR	liuzhen	37.527 ⁽¹⁾	39.497 ⁽¹⁾	1.35 ⁽³⁾	RTX 2080 Ti	flips, transpose
SuperArtifacts	evelynchee	36.968 ⁽²⁾	38.723 ⁽²⁾	3.80 ⁽⁴⁾	RTX 2080 Ti	-
NOAHTCV	nohtcv	36.452 ⁽³⁾	37.250 ⁽³⁾	1.26 ⁽²⁾	Tesla V100	-
ZJU231	ZJU231	35.912 ⁽⁴⁾	36.900 ⁽⁴⁾	0.37 ⁽¹⁾	RTX 2080 Ti	flips, rotation, $\times 4$ models
Samsung Research Bangalore*	AnointedKnight	37.151	39.408	15.77	Tesla P40	flips, transpose
<i>no processing</i>	-	25.266 ⁽⁵⁾	27.408 ⁽⁵⁾	-	-	-

Table 2. Results and rankings of methods submitted to the *Track 2: Multiple frames HDR*. Please note that running times are self-reported.

based on the features being processed. Besides, inspired by [9], a mask is calculated for the global residual, as adding it directly is sub-optimal. Finally, a $\tanh \ell_1$ loss function is adopted to balance the impact of over-exposed values and well-exposed values on the network learning.

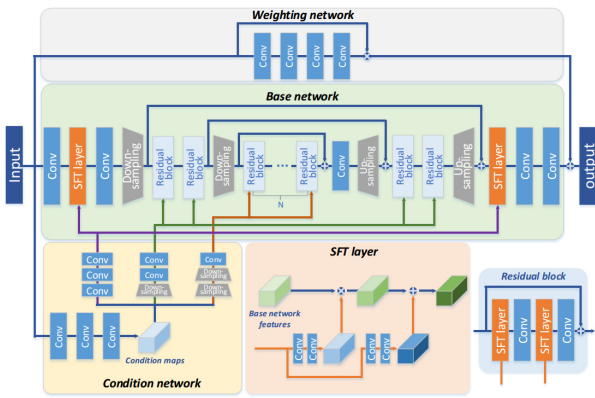


Figure 8. Architecture of HDRUNet: Single Image HDR Reconstruction with Denoising and Dequantization, proposed by the XPixel team.

* Incomplete submission (no reproducibility) thus not in the challenge ranking.

4.4. BOE-IOT-AIBD

Task-specific Network based on Channel Adaptive RDN The team propose a method [5] which consists of three sub-networks which each perform a different task: Image Reconstruction (IR), Detail Restoration (DR) and Local Contrast Enhancement (LCE) [17]. The IR network reconstructs the coarse HDR image from the input LDR image. The DR network can further refine the image details by adding its output to the coarse HDR output of IR. Finally the LCE network predicts a luminance equalization mask which is multiplied by the refined HDR image for contrast adjustment. The total architecture can be seen in Figure 9. All three sub-networks use the same backbone, named the Channel Adaptive RDN. This consists of the standard Residual Dense Network [43] with the Gate Channel Transformation layer [41] added to each RDB block.

4.5. SuperArtifacts

Multi-Level Attention on Multi-Exposure Frames for HDR Reconstruction The team propose a multi-level architecture which processes and merges features at three different resolutions. On top of the architecture of AHDR-Net [39], the model encodes the frames into three levels, with each feature being half the resolution of the previous level. This increases the receptive field and helps to bet-

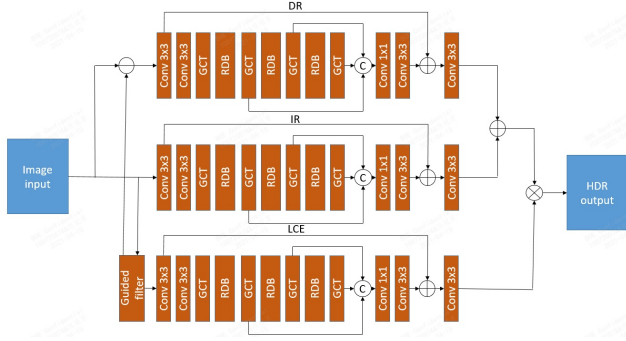


Figure 9. Architecture of Task-specific Network based on Channel Adaptive RDN, proposed by the BOE-IOT-AIBD team.

ter handle large foreground motion. At each level, the attention mechanism is used to identify which regions to use from the long and short exposure frames. The features at each level are merged independently first before being up-sampled back to the original resolution. The features from all three levels are then merged together using some fusion blocks to generate the final HDR image. The architecture can be seen in Figure 10.

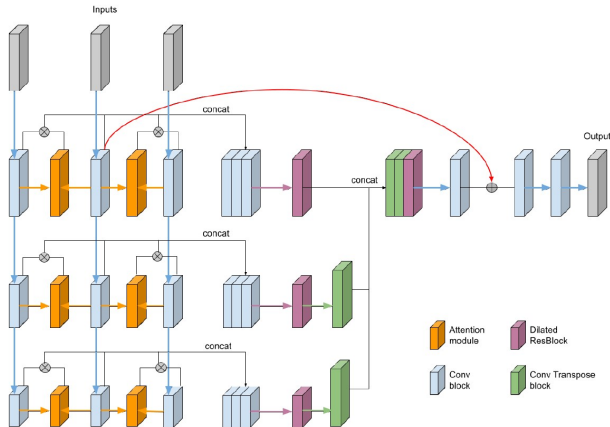


Figure 10. Architecture of Multi-Level Attention on Multi-Exposure Frames for HDR Reconstruction, proposed by the SuperArtifacts team.

4.6. CET-CVLAB

Single Image HDR Synthesis with Densely Connected Dilated ConvNet The team propose an architecture which consists of a densely connected stack of dilated residual dense blocks (DRDBs) [1]. The dilation rate of convolutional layers used within the proposed DRDB progressively grows from 1 to 3 and then progressively decreases from 3 to 1. The DRDBs themselves are also connected as shown in Figure 11 to improve the representation capability of the network.

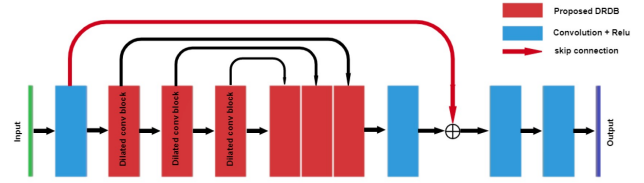


Figure 11. Architecture of Single Image HDR Synthesis with Densely Connected Dilated ConvNet, proposed by the CET-CVLAB team.

4.7. CVRG

Deep Single-Shot LDR to HDR The team propose a two stage method [31]: Stage I (inspired by [30]) performs denoising and recovers the 8-bit HDR image from the single LDR input; Stage II tonemaps the image into the linear domain and recovers the 16-bit HDR image. The architecture can be seen in Figure 12. The team proposes the Residual Dense Attention Block (RDAB) as the building block of the model. The RDAB, which combines the residual dense block and the spatial attention module, can be seen in Figure 13.

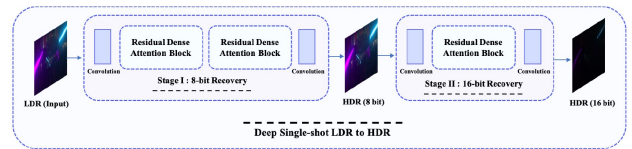


Figure 12. Architecture of Deep Single-Shot LDR to HDR, proposed by the CVRG team.

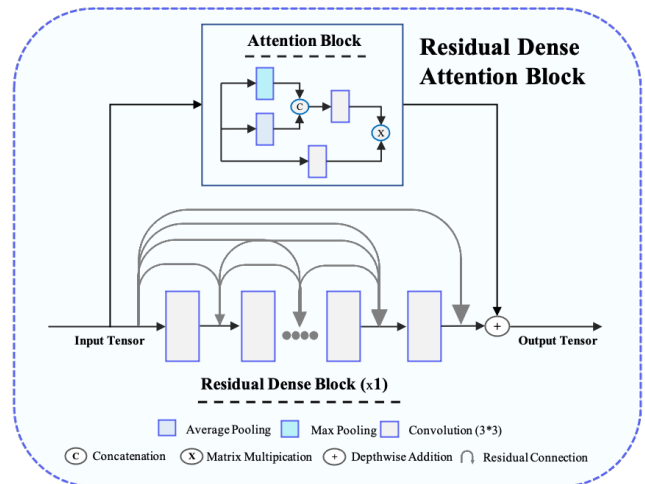


Figure 13. Residual Dense Attention Block, proposed by the CVRG team.

4.8. ZJU231

Reference-Guided Multi-Exposure Fusion Network for HDR Imaging The team propose a two-stage architecture which consists of the ghost reduction sub-network and the multi-exposure information fusion sub-network. Inspired by AHDRNet [39], the ghost reduction sub-network uses the reference image to generate an attention map for the short and long exposure images. The extracted features are guided via element-wise multiplication with the attention maps. The guided features are concatenated and merged by the fusion sub-network, which consists of five DRDBs followed by three convolutions, as shown in Figure 14.

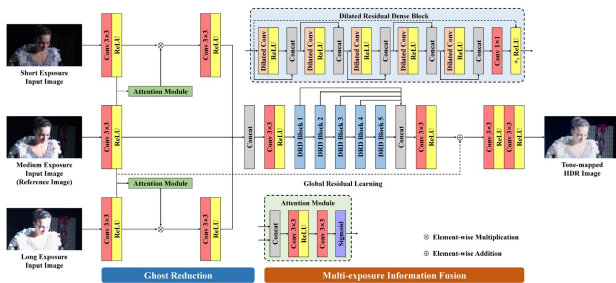


Figure 14. Architecture of Reference-Guided Multi-Exposure Fusion Network for HDR Imaging, proposed by the ZJU231 team.

4.9. Samsung Research Bangalore

HDR Merging using Multi Branch Residual Networks The team propose a multi-branch U-Net architecture inspired by [38] and [18] which consists of an encoder, a residual body and a decoder as seen in Figure 15. The building blocks of the network are Double Convolutional Residual Blocks (DCRB). This consists of two convolutions with prelu activations and the input is skipped to the output using a 1x1 convolution.

Each input image is processed with separate branches. The encoder consists of three blocks which successively downsample the input image. The features are then concatenated and processed using six residual blocks, followed by three decoder blocks which upsample the image back to full resolution. There are skip connections between all three of the encoder and decoder blocks. Self-ensembling strategy by averaging 8 ensembles created using flip and transpose operations are used to further improve the results.

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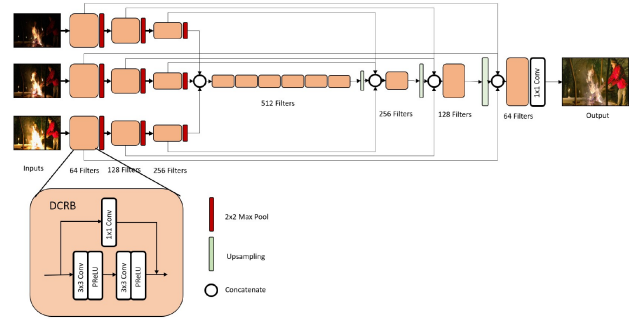


Figure 15. Architecture of HDR Merging using Multi Branch Residual Networks, proposed by the Samsung Research Bangalore team

A. Teams and Affiliations

NOAHTCV

Title: Single Image HDR Reconstruction in a Multi-stage Manner / Alignment Augmentation and Multi-Attention Guided HDR Fusion

Members: Xian Wang¹ (wangxian10@huawei.com), Yong Li¹, Tao Wang¹ and Fenglong Song¹

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MegHDR

Title: ADNet: Attention-guided Deformable Convolutional Networks for High Dynamic Range Imaging

Members: Zhen Liu¹ (liuzhen03@megvii.com) Wenjie Lin¹, Xinpeng Li¹, Qing Rao¹, Ting Jiang¹, Mingyan Han¹, Haoqiang Fan¹, Jian Sun¹ and Shuaicheng Liu¹

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XPixel

Title: HDRUNet: Single Image HDR Reconstruction with Denoising and Dequantization

Members: Xiangyu Chen¹ (chxy95@gmail.com), Yihao Liu¹, Zhengwen Zhang¹, Yu Qiao¹, Chao Dong¹

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SuperArtifacts

Title: Multi-Level Attention on Multi-Exposure Frames for HDR Reconstruction

Members: Evelyn Yi Lyn Chee¹ (evelyn.chee@bst.ai), Shanlan Shen¹, Yubo Duan¹

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BOE-IOT-AIBD

Title: Task-specific Network based on Channel Adaptive RDN

Members: Guannan Chen¹ (chenguanan@boe.com.cn), Mengdi Sun¹, Yan Gao¹, Lijie Zhang¹

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CET-CVLAB

Title: Single Image HDR Synthesis with Densely Connected Dilated ConvNet

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ZJU231

Title: Reference-Guided Multi-Exposure Fusion Network for HDR Imaging

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Title: Deep Single-Shot LDR to HDR

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Title: HDR Merging using Multi Branch Residual Networks

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