# Image Classification in the Dark using Quanta Image Sensors

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## Results from experiments

The complete results from the synthetic experiments can be found in Table 1. The complete results from the real experiments can be found in Table 2. More visualizations of the real data are provided in Figure 1.

| Sensor | Avg. ppp | Vanilla | Restor. Net | Dir. Pix. Shallow | Dir. Pix. Deep | Ours Shallow | Ours Deep |
|---|---|---|---|---|---|---|---|
| | | | | **Dogs** | | | |
| QIS | **0.25** | 17.9% | 35.6% | 42.1% | 43.9% | **48.6%** | **52.1%** |
| | **0.5** | 24.7% | 40.3% | 48.3% | 52.2% | **56.5%** | **58.5%** |
| | **1.0** | 28.9% | 42.9% | 53.9% | 56.5% | **62.7%** | **63.4%** |
| | **2.0** | 38.0% | 44.9% | 59.1% | 63.6% | **68.4%** | **69.3%** |
| | **4.0** | 43.3% | 50.9% | 61.5% | 66.1% | **72.7%** | **72.9%** |
| CIS | **0.25** | 12.1% | 26.3% | 17.4% | **28.6%** | 23.3% | **29.0%** |
| | **0.5** | 14.8% | 30.4% | 22.9% | **34.5%** | 33.9% | **36.7%** |
| | **1.0** | 16.4% | 34.3% | 30.1% | 46.6% | **48.6%** | **50.1%** |
| | **2.0** | 25.3% | 40.4% | 48.4% | 53.5% | **59.5%** | **59.8%** |
| | **4.0** | 33.8% | 44.6% | 58.2% | 62.3% | **69.7%** | **69.8%** |
| No. of parameters in denoiser | | 7.7M | 7.7M | 3,235 | 7.7M | 3,235 | 7.7M |
| | | | | **Animals** | | | |
| QIS | **0.25** | 33.4% | 43.7% | 63.0% | 68.0% | **68.2%** | **68.5%** |
| | **0.5** | 43.8% | 48.8% | 68.5% | **74.5%** | 74.4% | **74.5%** |
| | **1.0** | 51.3% | 56.4% | 77.4% | 78.5% | **81.9%** | **82.3%** |
| | **2.0** | 60.1% | 62.3% | 83.5% | 84.9% | **86.0%** | **86.8%** |
| | **4.0** | 66.9% | 67.5% | 87.4% | 88.7% | **89.4%** | **89.8%** |
| CIS | **0.25** | 17.3% | 27.8% | 28.6% | **41.2%** | 33.1% | **41.6%** |
| | **0.5** | 20.8% | 38.2% | 43.4% | **53.4%** | 45.8% | **53.9%** |
| | **1.0** | 28.0% | 41.1% | 57.8% | **62.6%** | 61.2% | **63.0%** |
| | **2.0** | 42.4% | 49.7% | 69.7% | 73.1% | **73.3%** | **73.4%** |
| | **4.0** | 59.7% | 62.3% | 81.2% | 83.2% | **83.5%** | **83.5%** |
| No. of parameters in denoiser | | 7.7M | 7.7M | 3,235 | 7.7M | 3,235 | 7.7M |

**Table 1. Comparison with state of the art.**

| Photon Level | Dirty Pixels | | Ours | |
|---|---|---|---|---|
| | QIS | CIS | QIS | CIS |
| 0.25 | 15 / 30 | 6 / 30 | **17 / 30** | 6 / 30 |
| 0.5 | 17 / 30 | 8 / 30 | **19 / 30** | 9 / 30 |
| 1.0 | 19 / 30 | 11 / 30 | **22 / 30** | 13 / 30 |
| 2.0 | 22 / 30 | 16 / 30 | **24 / 30** | 18 / 30 |
| 4.0 | 25 / 30 | 21 / 30 | **25 / 30** | 21 / 30 |

**Table 2. Real data** using the Animal Dataset. The reported numbers are number of images correctly classified among the 30 images considered. The networks are trained using the synthetic data.

## Implementation

The proposed network is pre-trained with ImageNet dataset, with fine-tuning using the synthetic datasets simulated from ImageNet. All networks are implemented using Keras [3] with TensorFlow [1] backend. All the networks are learnt using the RMSProp [4] with initial learning rate of $10^{-5}$ and the the learning rate is decayed by a factor of 0.98 at each epoch. The networks are trained for 400 epochs. For a training set containing 9000 training samples, the typical training time is 10 hours.

## References

1. Abadi, M., Agarwal, A., Barham, P., et al.: TensorFlow: Large-scale machine learning on heterogeneous systems (2015), https://www.tensorflow.org/, software available from tensorflow.org
2. Chen, C., Chen, Q., Xu, J., Koltun, V.: Learning to see in the dark. In: CVPR (2018)
3. Chollet, F., et al.: Keras. https://keras.io (2015)
4. Tieleman, T., Hinton, G.: Lecture 6.5-rmsprop: Divide the gradient by a running average of its recent magnitude. COURSERA: Neural networks for machine learning **4**(2), 26–31 (2012)

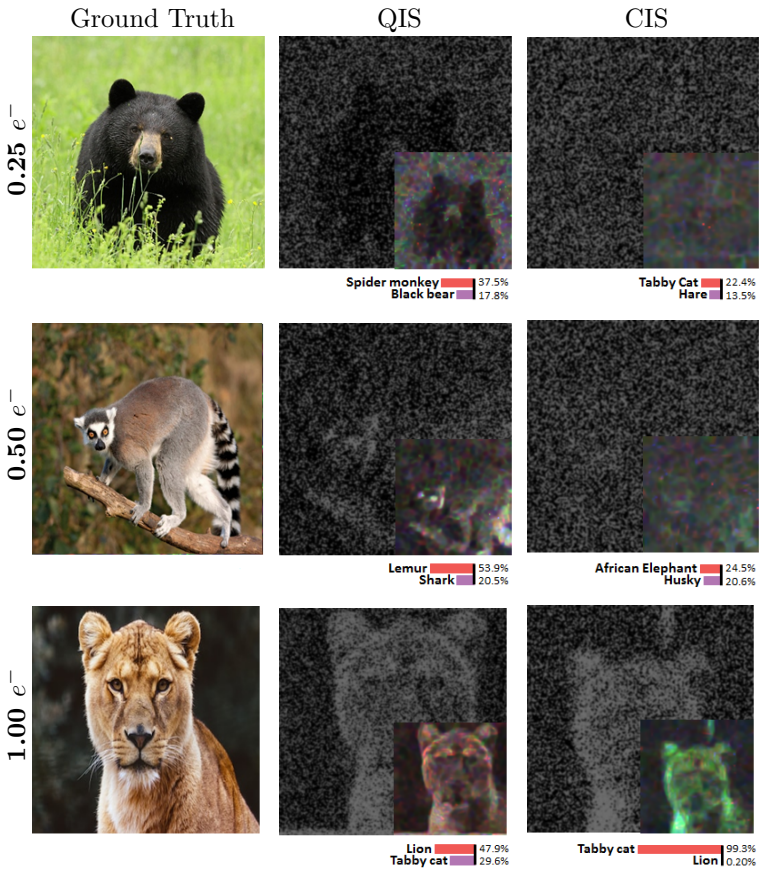


**Fig. 1. More Real Image Results**. This figure shows raw Bayer data obtained from QIS and CIS, and how they are classified using our proposed classifier. The inset images show the denoised images (by [2]) for visualization. Notice the heavy noise at 0.25 and 0.5 ppp, only QIS plus our proposed classification method can produce the correct prediction.