Short-reach Optical Communications

A Real-world Task for Neuromorphic Hardware

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Neuromorphic Benchmarks

- Development of neuromorphic hardware and algorithms are driven by benchmarks
- Typical benchmarks
  - Lack a real-world application (e.g., Yin-Yang, N-MNIST)
  - Lack intrinsic temporal structure (e.g., CIFAR10-DVS)
  - Require network topologies too big for prototype chips (e.g., DVS128 Gesture)

Image source: Rose, G. (2005). Fiber Optic Illuminated [Photograph]. Wikimedia Commons. Retrieved from https://commons.wikimedia.org/wiki/File:Fiber_optic_illuminated.jpg.

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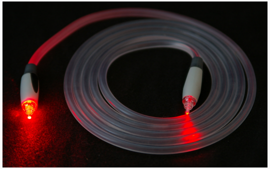
Our contribution

- Optical data transmission task for small-scale SNNs
    - real-world temporal unlimited data
    - predefined communication system requirements
- Interesting for
    - evaluation of resource efficiency of model / hardware
    - Prototyping algorithms utilizing temporal structure
    - Developing hardware with an actual application in mind



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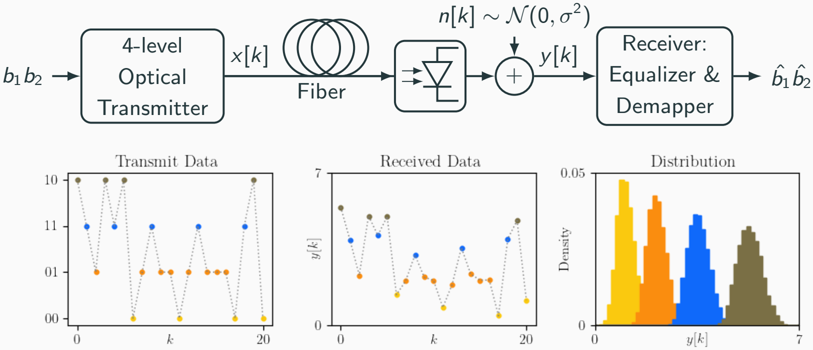
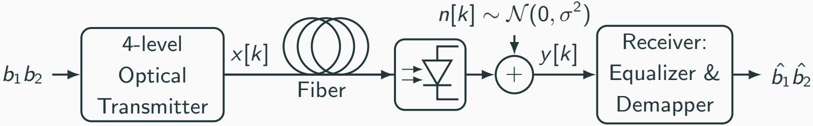
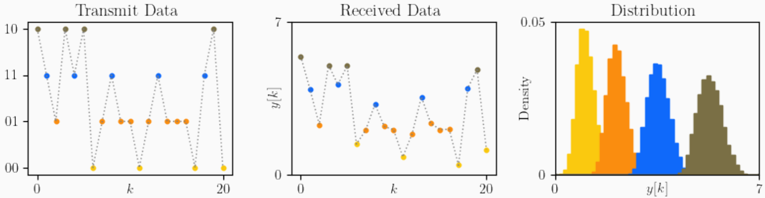


- 4-level intensity modulation (IM) of light source, e.g., laser
- Direct detection (DD) using photo diode

Short-reach optical communications: The IM/DD link





- 4-level intensity modulation (IM) of light source, e.g., laser
- Direct detection (DD) using photo diode
- Link impairments due to:
    - Chromatic dispersion (CD) in fiber
    - Non-linear detection of photo diode
    - Additive white Gaussian noise with power σ^2
- Receiver: Eliminates impairments (equalization) and estimates transmit bits (demapping)

IM/DD task

- Link model $f(\cdot)$:

$$y[k] = f\left(x\left[k - \left\lfloor \frac{n_{\text{taps}}}{2} \right\rfloor\right], \dots, x[k], \dots, x\left[k + \left\lfloor \frac{n_{\text{taps}}}{2} \right\rfloor\right]\right) + n[k]$$

  - CD: overlap of n_{taps} consecutive symbols
  - $f(\cdot)$: linear combination and non-linear distortion

[a] L. Schmalen, *et al.*, "Recent advances on machine learning-aided DSP for short-reach and long-haul optical communications," Proc. Opt. Fiber Commun. Conf. (OFC), San Francisco, CA, USA, Mar. 2025.

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- Receiver $g(\cdot)$:

$$\hat{\boldsymbol{b}}[k] = g\left(y\left[k - \left\lfloor \frac{n_{\text{taps}}}{2} \right\rfloor\right], \ldots, y[k], \ldots, y\left[k + \left\lfloor \frac{n_{\text{taps}}}{2} \right\rfloor\right]\right)$$

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- **Objective 1:** Find $g(\cdot)$ to minimize bit error rate (BER) $\Rightarrow$ Machine learning[a]
- **Objective 2:** Implement energy-efficient receiver $\Rightarrow$ Neuromorphic hardware

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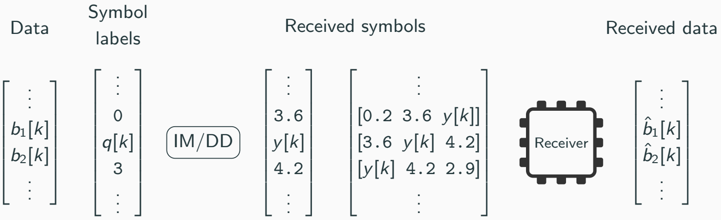
Dataset

```python
from torch.utils.data import DataLoader
from IMDD import LCDDataset
# Dataset
dataset = LCDDataset(bit_wise=False)
# Data loader
dataloader = DataLoader(dataset, batch_size, shuffle=True)
for (y_chunk, q) in dataloader:
    ... # train
```



Parameter Sets

Task I: Low chromatic dispersion (LCD)[b]

Parameter	Value
`wavelength`	1270 nm
`dispersion_parameter`	$-5\,\mathrm{ps\,nm^{-1}\,km^{-1}}$
`n_taps`	7
`N`	10 000
`alphabet`	$[-3, -1, 1, 3]$
`oversampling_factor`	3
`baudrate`	112 GBd
`fiber_length`	4 km
`noise_power_db`	−20 dB
`roll_off`	0.2
`bias`	2.25

Task II: Standard single mode fiber (SSMF)[c]

Parameter	Value
`wavelength`	1550 nm
`dispersion_parameter`	$-17\,\mathrm{ps\,nm^{-1}\,km^{-1}}$
`n_taps`	21
`N`	10 000
`alphabet`	$\left[0, 1, \sqrt{2}, \sqrt{3}\right]$
`oversampling_factor`	3
`baudrate`	50 GBd
`fiber_length`	5 km
`noise_power_db`	−20 dB
`roll_off`	0.2
`bias`	0.25

[b] E. Arnold, *et al.*, "Spiking neural network nonlinear demapping on neuromorphic hardware for IM/DD optical communication," J. Light. Technol., vol. 41, no. 11, 2023. DOI: 10.1109/JLT.2023. 3252819.

[c] A. von Bank, *et al.*, "Spiking neural network decision feedback equalization for IM/DD systems," in Proc. SPPCom, Busan, South Korea, Jul. 2023.

Benchmark: LCD task

- Objective 1: Minimize BER
- Objective 2: Minimize spike rate

- SNN-based receiver[b] implemented using norse[d]

[d] C. Pehle and J. E. Pedersen, *Norse - A deep learning library for spiking neural networks*, Version 0.0.7, Documentation: `https://norse.ai/docs/`, Jan. 2021. DOI: https://doi.org/10.5281/zenodo.4422025.

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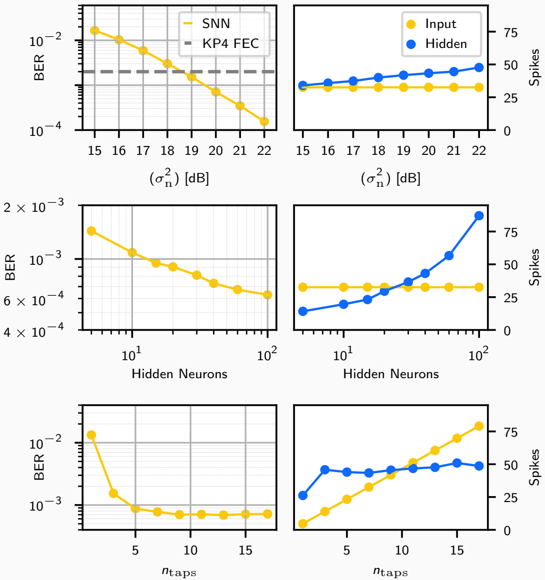

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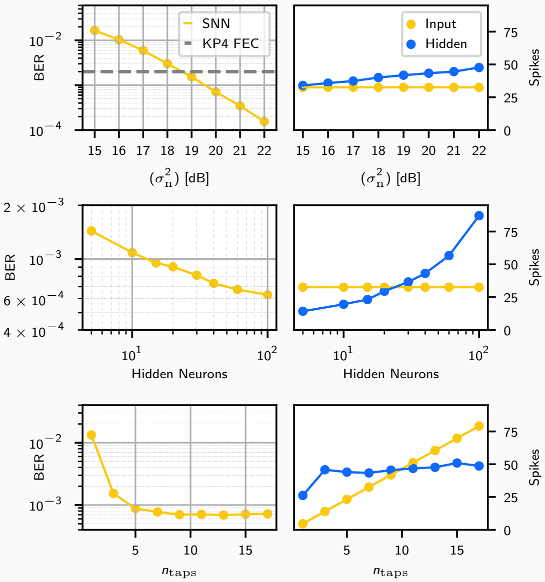
- SSMF-task: SNN-based receiver[c] implemented using norse[d]



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Questions?

This work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No. 101001899).