



End-to-end Optimization of Optical Communication Systems using Deep Learning

Laurent Schmalen, Boris Karanov, Vincent Lauinger



- Introduction
- Application 1: Waveform Optimization for Short-Reach Optical Communications
 - Simple Transmitter Using Feed-Forward Neural Networks
 - Improved Transceivers Using Recurrent Neural Networks
- Application 2: In-Situ Optimization of Transmitters
- Application 3: Blind Equalization Using Variational Autoencoders
- Conclusions and Outlook

■ Introduction

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A Few Words About Myself



- Grew up in Luxembourg



- M.Sc. (Dipl.-Ing.) and PhD in electrical engineering and information technology from RWTH Aachen University in multimedia communications over heterogeneous networks



- 8 years of industry work at Bell Labs conducting fundamental research on error correction coding, fiber optical communication and machine learning for communications



- Contributed to transceiver ASICs with throughputs of 100 GBit/s to 600 GBit/s



- As of April 1st 2019, full professor at KIT and head of communications engineering lab

Machine Learning Success: Handwritten Digit Recognition

■ The MNIST database^{1 2}



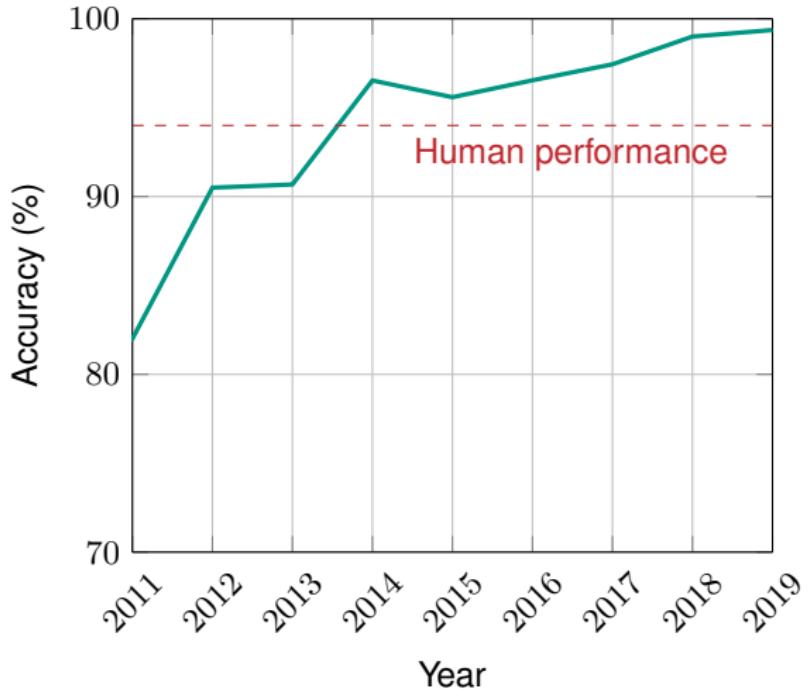
A 10x10 grid of handwritten digits. Each digit is a black outline on a white background. The digits are arranged in rows: Row 1 contains ten '0's; Row 2 contains ten '1's; Row 3 contains ten '2's; Row 4 contains ten '3's; Row 5 contains ten '4's; Row 6 contains ten '5's; Row 7 contains ten '6's; Row 8 contains ten '7's; Row 9 contains ten '8's; and Row 10 contains ten '9's.

■ Error rates of 0.23% can be achieved today

¹ Available online at: <http://yann.lecun.com/exdb/mnist/>

² Image source: <https://upload.wikimedia.org/wikipedia/commons/2/27/MnistExamples.png>

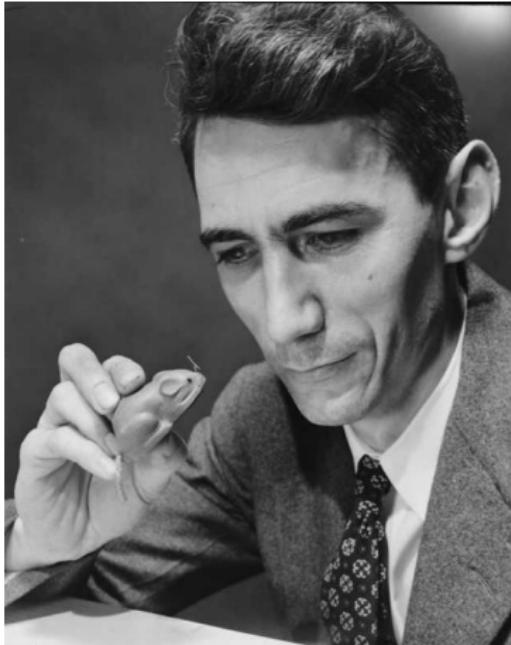
Machine Learning Success: Image Recognition



- Image recognition accuracy on CIFAR-10 dataset³
- In less than 10 years, advances in machine learning and in particular **neural networks** and **deep learning** yield systems that surpass human capabilities
- Almost perfect recognition accuracy

³Accuracy data from <https://benchmarks.ai/cifar-10>

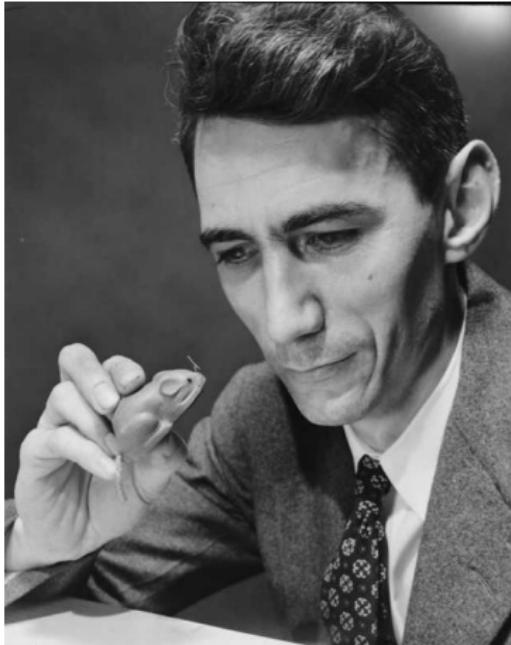
Machine Learning for Communications



- 70 years of communications engineering have brought us close to the Shannon limit⁴ (Shannon capacity)
- **But:** this applies only to a sub-class of all communication problems
- We don't know neither good nor optimal transceivers for many communication systems

⁴Image source: https://commons.wikimedia.org/wiki/File:Claude_Shannon_1776.jpg

Machine Learning for Communications



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- **But:** this applies only to a sub-class of all communication problems
- We don't know neither good nor optimal transceivers for many communication systems
- **Machine learning** can help us identify novel transceivers
- **This talk:**
 - Concept of using neural networks for optimizing of optical communication systems
 - Use of neural networks to learn parameters of the communication system

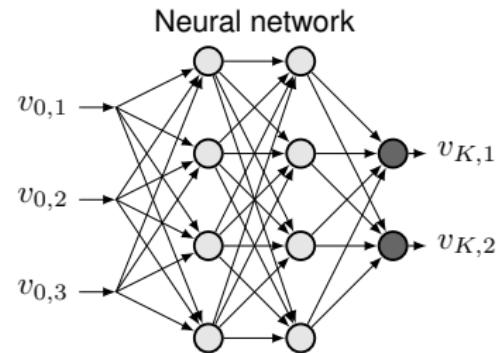
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Neural Networks: A Whirlwind Tour

Feed-Forward Neural Networks (FFNN)

- Maps an input vector $\mathbf{v}_0 = (v_{0,1} \dots v_{0,M})$ to an output vector $\mathbf{v}_K = (v_{K,1} \dots v_{K,n}) = f_{\text{NN}}(\mathbf{v}_0)$
- The neural network (NN) is a composed function consisting of layers, where each layer computes

$$\mathbf{v}_k = g_{\text{NL},k}(\mathbf{W}_k \mathbf{v}_{k-1} + \mathbf{b}_k), \quad k = 1, \dots, K$$



Neural Networks: A Whirlwind Tour

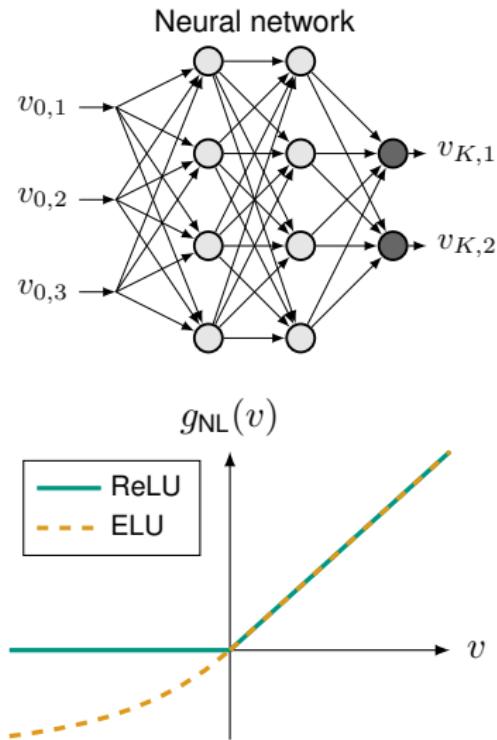
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- Activation function g_{NL} introduces **nonlinear** relation between layers
- A popular choice for g_{NL} is the ReLU activation function (or one of its variants, e.g. the ELU function)

$$\mathbf{x} = g_{\text{NL}}(\mathbf{v}) = g_{\text{ReLU}}(\mathbf{v}) \quad \text{with } x_i = \max(0, v_i)$$



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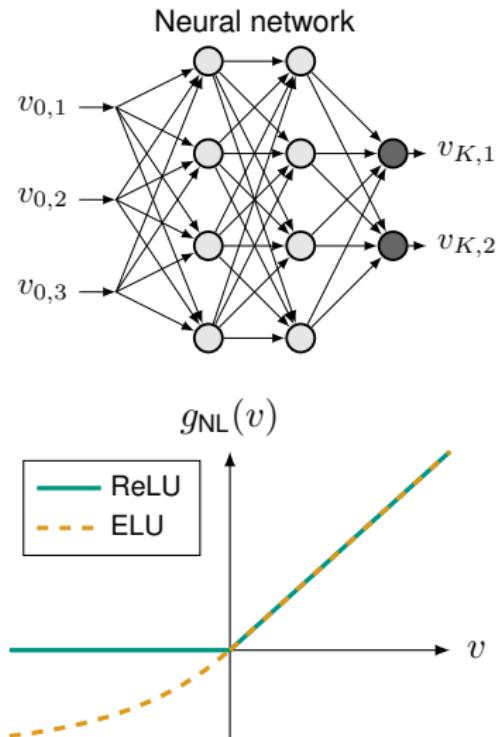
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- Objective of learning:** Find parameters \mathbf{W}_k and \mathbf{b}_k such that $f_{\text{NN}}(\mathbf{v}_0)$ approximates an (unknown) function whose inputs and outputs can be observed and fed to a training algorithm



Neural Networks: Computational Graph

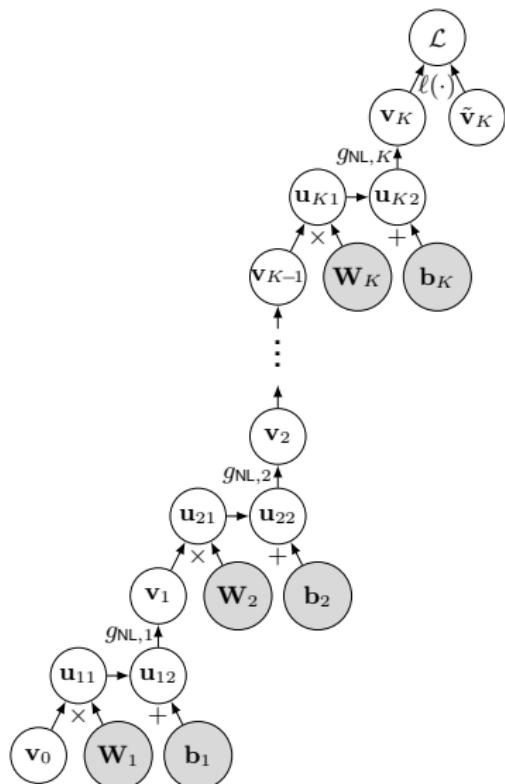
Deep Learning

- Objective is to find NN parameters $\{\mathbf{W}_k, \mathbf{b}_k\}$ that minimize a **loss function**

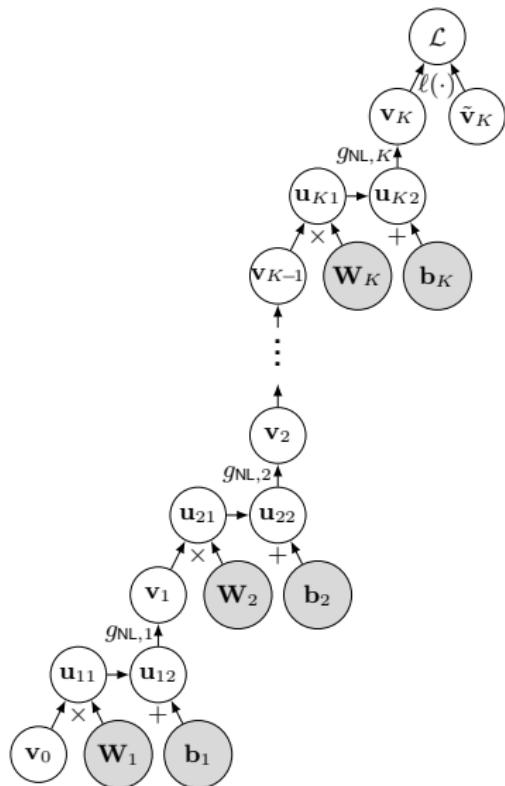
$$\mathcal{L}(\{\mathbf{W}_k, \mathbf{b}_k\}_K) = \frac{1}{|\mathcal{S}|} \sum_{(\mathbf{v}_{0,i}, \tilde{\mathbf{v}}_{K,i}) \in \mathcal{S}} L(f_{\text{NN}}(\mathbf{v}_{0,i}), \tilde{\mathbf{v}}_{K,i})$$

where $(\mathbf{v}_{0,i}, \tilde{\mathbf{v}}_{K,i})$ are **examples** of inputs $(\mathbf{v}_{0,i})$ and observed outputs $(\tilde{\mathbf{v}}_{K,i})$ of the system we like to approximate

- Training data set \mathcal{S} contains these examples



Neural Networks: Computational Graph



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- Training data set \mathcal{S} contains these examples
- Parameters $\{\mathbf{W}_k, \mathbf{b}_k\}$ are optimized using **gradient descent**

$$\mathbf{W}_k \leftarrow \mathbf{W}_k - \epsilon \nabla_{\mathbf{W}_k} \mathcal{L} (\{\mathbf{W}_k, \mathbf{b}_k\}_K)$$

$$\mathbf{b}_k \leftarrow \mathbf{b}_k - \epsilon \nabla_{\mathbf{b}_k} \mathcal{L} (\{\mathbf{W}_k, \mathbf{b}_k\}_K)$$

- Efficient computation of gradient using a **computational graph**

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Application 2: In-Situ Optimization of Transmitters

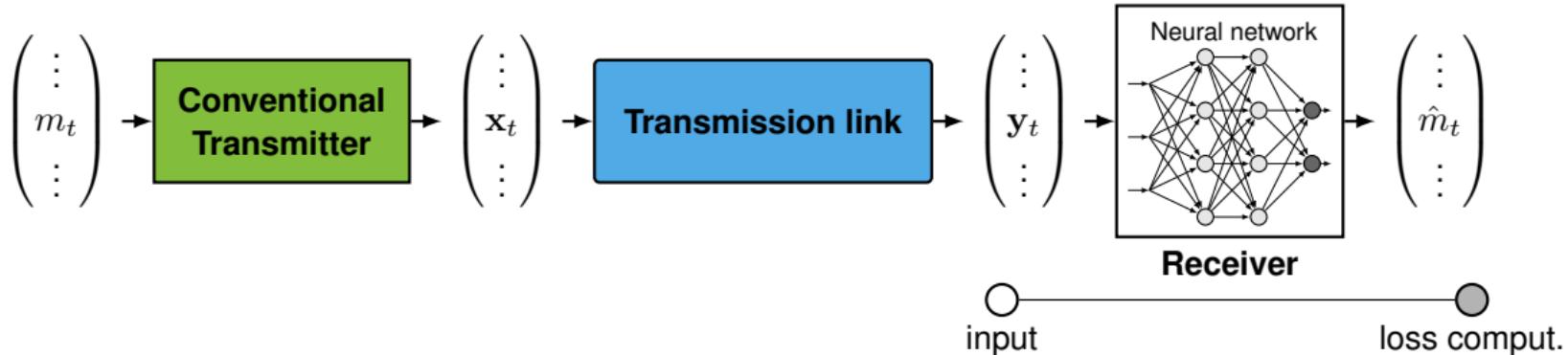


Application 3: Blind Equalization Using Variational Autoencoders



Conclusions and Outlook

Receiver Processing Using Neural Networks

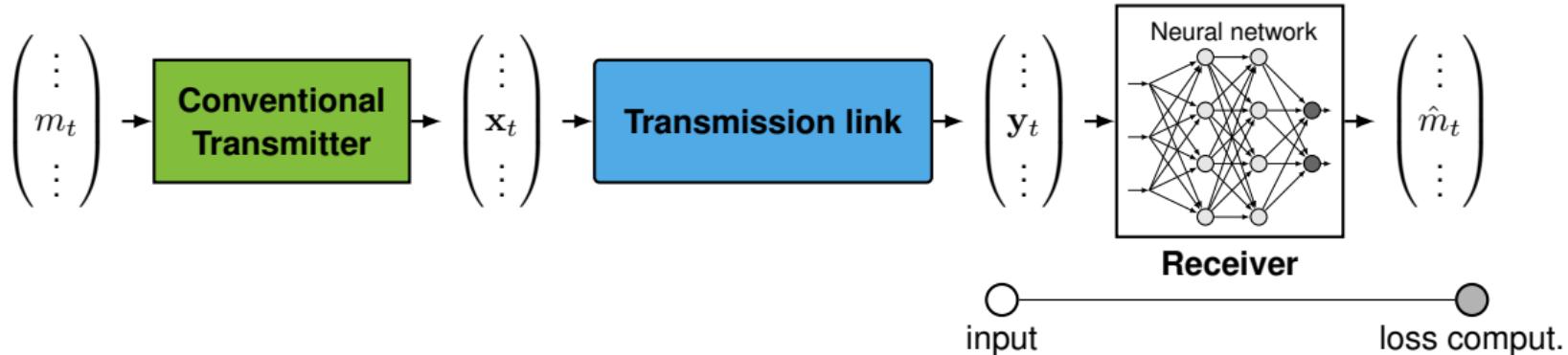


- Transmission of known sequence of messages (e.g., pilot) m_t
- Based on received data (y_t), try to recover m_t as closely as possible
- Training dataset is database of received signals and associated symbols $\mathcal{S} = \{(y_t, m_t) : t = 1, \dots, N\}$
- Proposed for optical communications [Lyu15] and used for example as receivers in PON systems [HCvV19]

[Lyu15] I. Lyubomirsky, "Machine learning equalization techniques for high speed PAM4 fiber optic communication systems," *CS229 Final Project Report*, Stanford University, 2015

[HCvV19] V. Houtsma, E. Chou, and D. van Veen, "92 and 50 Gbps TDM-PON using neural network enabled receiver equalization specialized for PON," in *Proc. Optical Fiber Communications Conference (OFC)*, 2019

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- **Example:** AWGN channel

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Example: Deep NN Detection in AWGN Channel

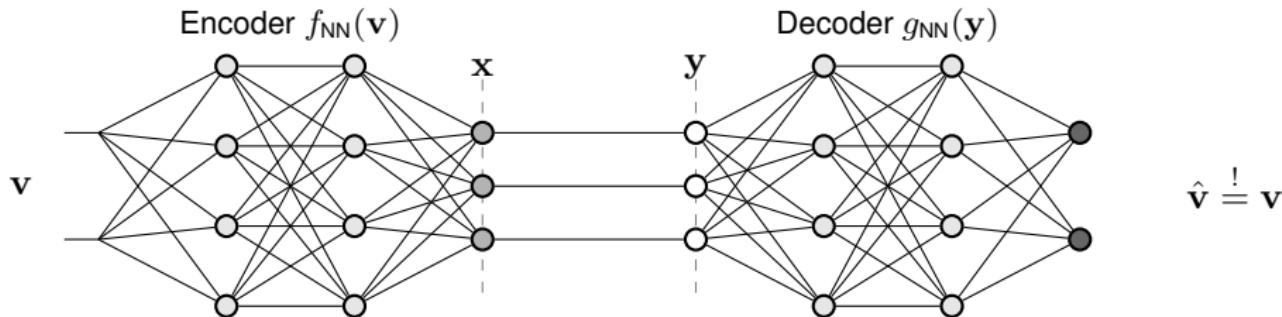
- Implementation using PyTorch^a
- Source code available online^b



^a<http://pytorch.org>

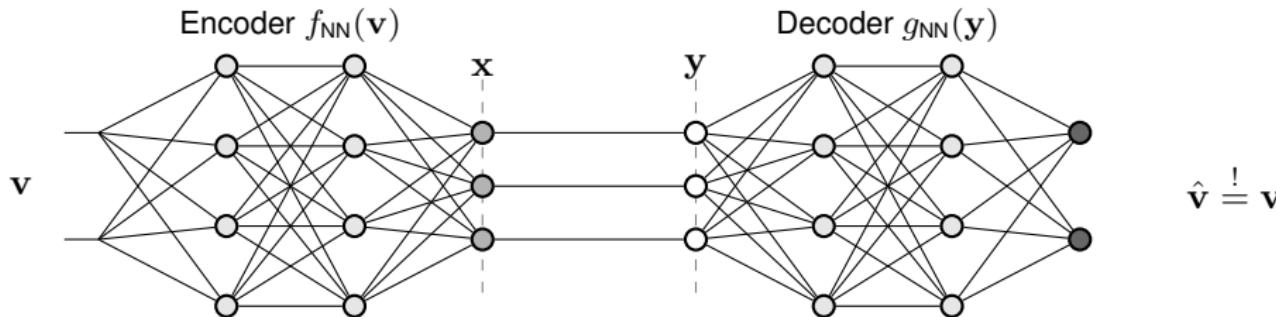
^bhttps://github.com/kit-cel/TUe_Guest_Lecture_Jan2022

Auto-encoders – Basic Concept



- Consists of an **encoder** $f_{NN}(v)$ and a **decoder** $g_{NN}(y)$
- **Goal:** Try to reproduce v by \hat{v} as close as possible

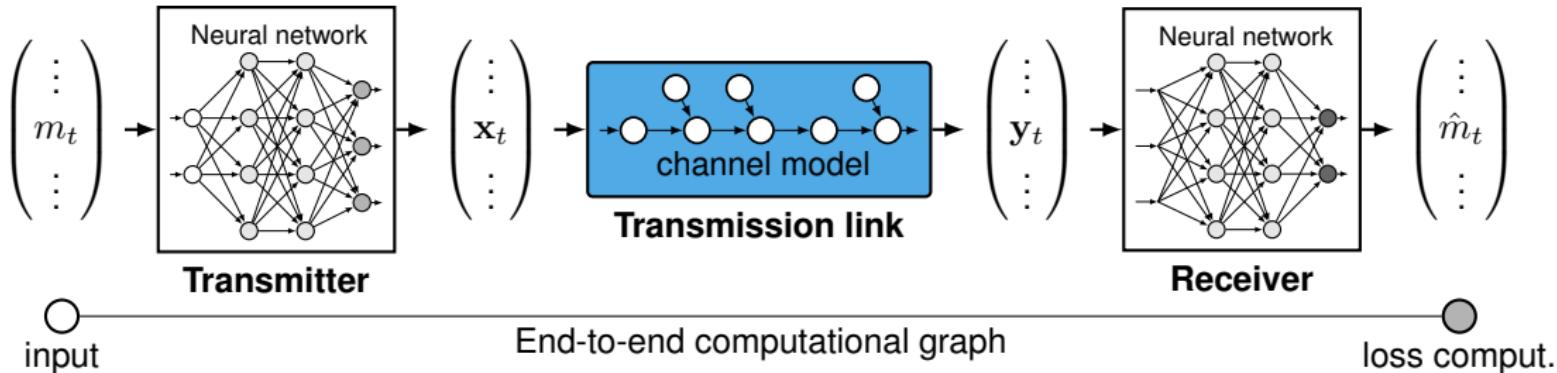
Auto-encoders – Basic Concept



- Consists of an **encoder** $f_{NN}(v)$ and a **decoder** $g_{NN}(y)$
- **Goal:** Try to reproduce v by \hat{v} as close as possible
- Resembles a communication system (Goal: reproduce information as close as possible)
- Can we use auto-encoders to design communication systems? [OKC16], [OH17]

- [OKC16] T. O'Shea, K. Karra and T. C. Clancy, "Learning to Communicate: Channel Auto-encoders, Domain Specific Regularizers, and Attention," *2016 IEEE International Symposium on Signal Processing and Information Technology (ISSPIT)*, 2016
- [OH17] T. O'Shea and J. Hoydis, "An introduction to deep learning for the physical layer," *IEEE Trans. Cogn. Commun. Netw.*, vol. 3, no. 4, pp. 563-575, 2017.
- [CAD⁺20] S. Cammerer, F. Ait Aoudia, S. Dörner, M. Stark, J. Hoydis, S. ten Brink, "Trainable communication systems: Concepts and prototype," *IEEE Trans. on Commun.*, 2020

Communication System as Auto-Encoder



- Replacing (parts of) transmitter by neural network
- Transmission link needs to be modeled by an adequate, **differentiable** channel model that can be part of the computational graph
- **Example:** AWGN channel $y_t = x_t + n_t$ with $\nabla_W y_t = \nabla_W x_t$

Example: Auto-Encoder in AWGN Channel

- Implementation using PyTorch
- Source code available online⁵



⁵https://github.com/kit-cel/TUe_Guest_Lecture_Jan2022

Example: Auto-Encoder in AWGN Channel

- Implementation using PyTorch
- Joint optimization of bit mapping and constellation minimizing bit error rate
- $M = 2^4 = 16$ points, $E_b/N_0 = 5$ dB
- Source code available online⁶



[Sch20] L. S., "Geometric Constellation Shaping for Optical Data Transport," US Patent 10,834,485, filed Oct. 2018, granted Nov. 2020

⁶https://github.com/kit-cel/TUE_Guest_Lecture_Jan2022

Example: Auto-Encoder in AWGN Channel

- Implementation using PyTorch
- Joint optimization of bit mapping and constellation minimizing bit error rate
- $M = 2^5 = 32$ points, $E_b/N_0 = 10$ dB
- Source code available online⁶

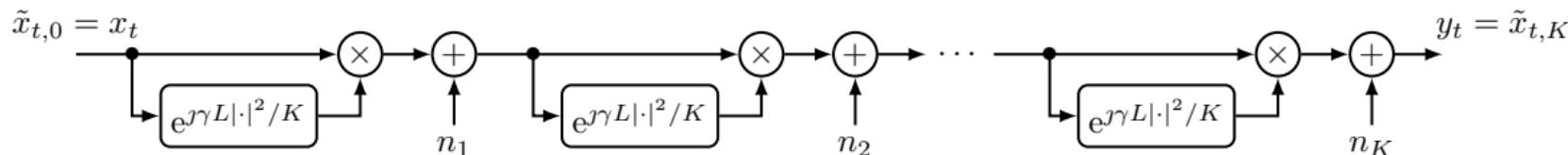


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⁶https://github.com/kit-cel/TUe_Guest_Lecture_Jan2022

Example: Zero-Dispersion Optical Fiber

- A more complicated model is the zero-dispersion optical fiber model used in [LHG⁺18]
- Transmission over an optical fiber of length L having nonlinearity parameter γ and zero dispersion ($\beta_i = 0$)



- Let $\tilde{x}_{x,0} = x_t$ and recursively compute

$$\tilde{x}_{t,i+1} = \tilde{x}_{t,i} \cdot e^{jL\gamma|\tilde{x}_{t,i}|^2/K} + n_{i+1}, \quad 0 \leq i < K$$

where $n_{i+1} \sim \mathcal{CN}(0, P_N/K)$ is complex, circularly symmetric Gaussian noise (assuming ideal distributed amplification) and K the number of steps (ideally, $K \rightarrow \infty$)

- Computation graph is fully **differentiable**

[LHG⁺18] S. Li, C. Häger, N. Garcia, and H. Wymeersch, "Achievable Information Rates for Nonlinear Fiber Communication via End-to-end Autoencoder Learning," *Proc. ECOC*, Rome, Sep. 2018

Example: Zero-Dispersion Optical Fiber

- Implementation using PyTorch
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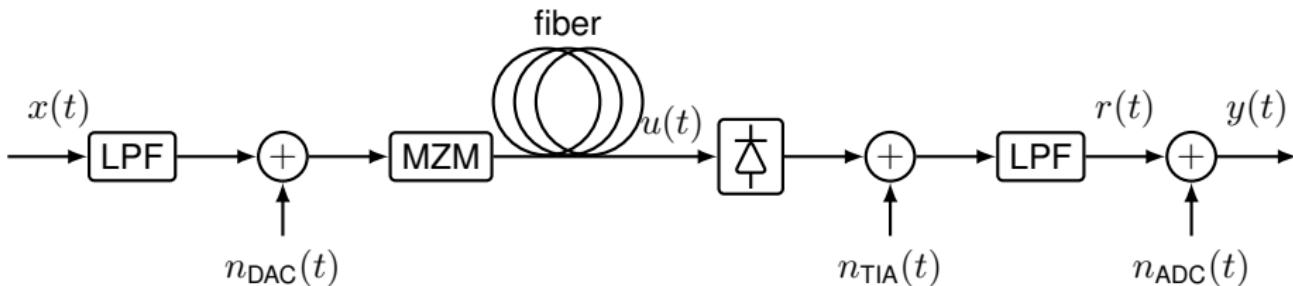
⁷https://github.com/kit-cel/TUE_Guest_Lecture_Jan2022

Auto-Encoders in Optical Communications

- End-to-end learning applied to optimize multidimensional constellations for IM/DD links [KCT⁺18], [CBS18]
- End-to-end learning of transceivers for the nonlinear Fourier transform [GJD⁺20]
- Constellation optimization for the zero-dispersion channel [LHG⁺18]
- Constellation optimization for geometric shaping [JEY⁺18], [JYZ19], [GAC⁺20]
- Differentiable channel models and nonlinearity compensation for coherent systems [HP20]

- [KCT⁺18] B. Karanov, M. Chagnon, F. Thouin, T. A. Eriksson, H. Bülow, D. Lavery, P. Bayvel, and L. Schmalen, "End-to-end deep learning of optical fiber communications," *Journal of Lightwave Technology*, vol. 36, no. 20, pp. 4843–4855, 2018
- [CBS18] M. Chagnon, B. Karanov, and L. Schmalen, "Experimental demonstration of a dispersion tolerant end-to-end deep learning-based IM-DD transmission system," *Proc. European Conference on Optical Communication (ECOC)*, 2018
- [GJD⁺20] S. Gaiarin, R. T. Jones, F. Da Ros, and D. Zibar, "End-to-end optimized nonlinear Fourier transform-based coherent communications," *Proc. CLEO: Science and Innovations*, May 2020
- [LHG⁺18] S. Li, C. Häger, N. Garcia, and H. Wymeersch, "Achievable Information Rates for Nonlinear Fiber Communication via End-to-end Autoencoder Learning," *Proc. European Conference on Optical Communication (ECOC)*, Sep. 2018
- [JEY⁺18] R. T. Jones, T. A. Eriksson, M. P. Yankov, and D. Zibar, "Deep learning of geometric constellation shaping including fiber nonlinearities," *Proc. European Conference on Optical Communication (ECOC)*, 2018
- [JYZ19] R. T. Jones, M. Yankov, and D. Zibar, "End-to-end learning for GMI optimized geometric constellation shape," arXiv:1907.08535, 2019
- [GAC⁺20] K. Gümüş, A. Alvarado, B. Chen, C. Häger, and E. Agrell, "End-to-End Learning of Geometrical Shaping Maximizing Generalized Mutual Information," *Proc. Optical Fiber Communications Conference (OFC)*, Mar. 2020
- [HP20] C. Häger and H. D. Pfister, "Physics-Based Deep Learning for Fiber-Optic Communication Systems," *Journal of Selected Areas in Communications*, 2021

End-to-end Learning for IM/DD

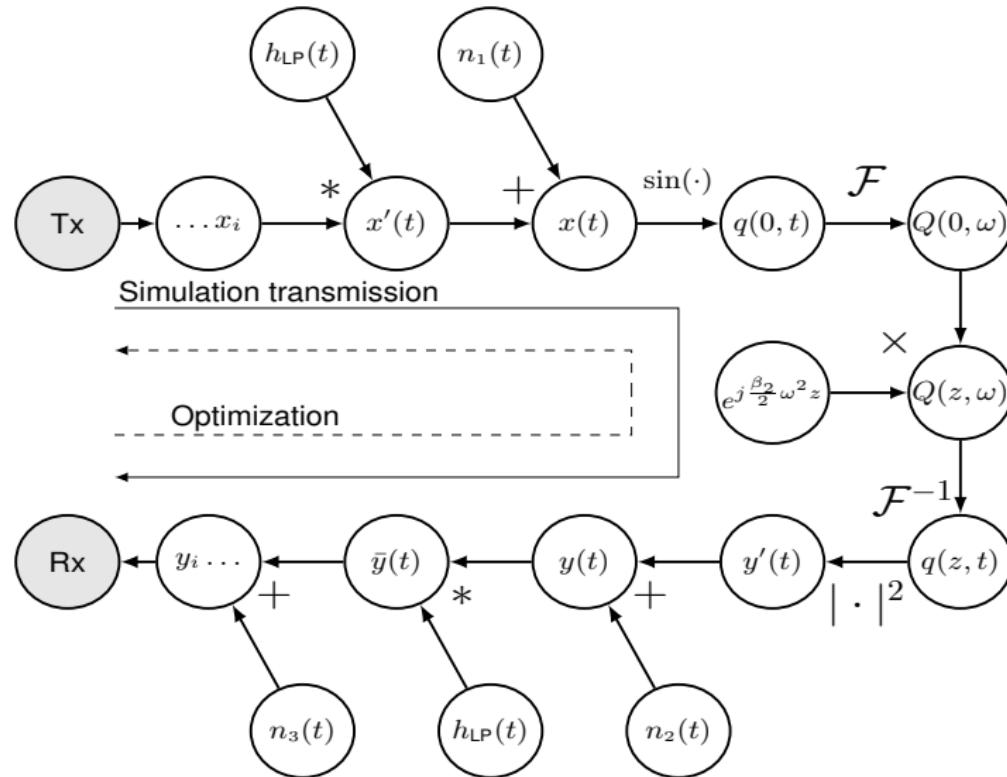


- IM/DD (intensity modul., direct detect.) ubiquitous in access networks and data center interconnects

$$y(t) = \left| \hat{h}_{\text{Fiber}} \left(\hat{h}_{\text{MZM}} (x(t) + n_{\text{DAC}}(t)) \right) \right|^2 + n_{\text{TIA}}(t) + n_{\text{ADC}}(t)$$

- Fiber adds only chromatic dispersion (no nonlinearities) with $H(\omega, z) = \exp \left(j \frac{\beta_2}{2} z \omega^2 \right)$
- Nonlinear channel with memory, *however*, optimal **computationally feasible algorithms absent**
- Model is fully **differentiable**
- Contrary to previous examples, channel input is **waveform**, not modulation symbols
- We need to **learn optimal waveforms**

Computational Graph of Channel Model



- Chromatic dispersion is added in frequency domain
- Fourier transform is linear and differentiable
- Channel model can be directly implemented in machine learning software

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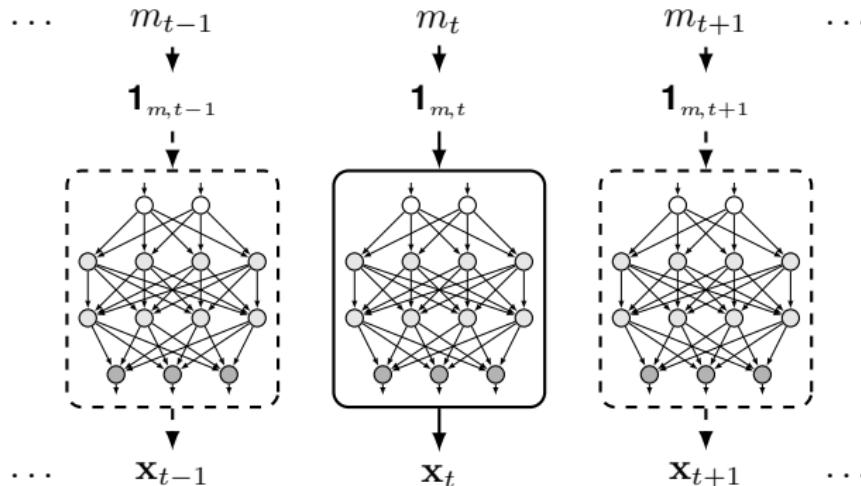
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First Transmitter Attempt Using FFNN

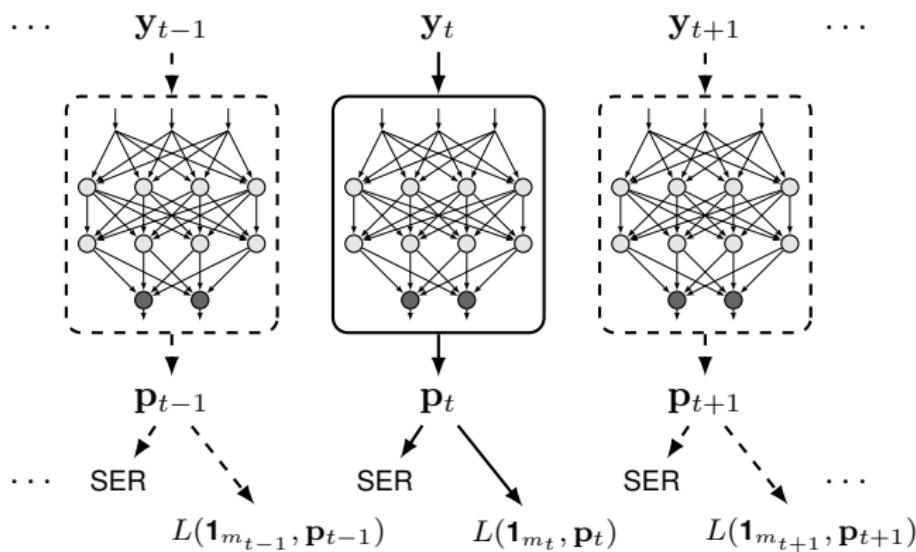


- Transform message m_t (from an alphabet containing M messages (e.g., a modulation alphabet)) into **one-hot⁸vector** $1_{m,t}$
- FNN encodes $1_{m,t}$ into n **oversampled waveform samples** x_t
- Apply low-pass-filter (LPF, part of the channel model) to **smear** the waveforms

[KCT⁺18] B. Karanov, M. Chagnon, F. Thouin, T. Eriksson, H. Bülow, D. Lavery, P. Bayvel, L. S., "End-to-end Deep Learning of Optical Fiber Communications," *Journal of Lightwave Technology*, Oct. 2018

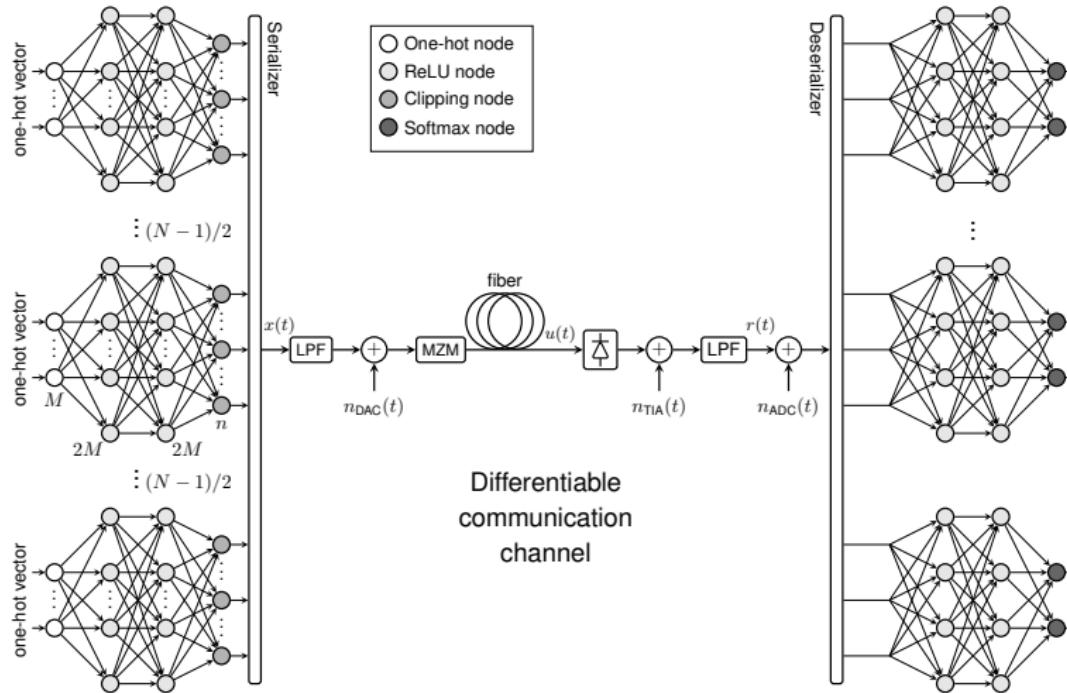
⁸A one-hot vector $1_{m,t}$ of length M contains only zeros except a single "1" at position m_t

First Receiver Attempt Using FFNN



- Receiver input is chopped into blocks y_t of n received **samples**
- Samples are processed by an FFNN with a **softmax** output activation function (“●”)
- Softmax output function generates a probability vector \mathbf{p}_t
- Decision according to most probable symbol
- Training using cross-entropy loss function

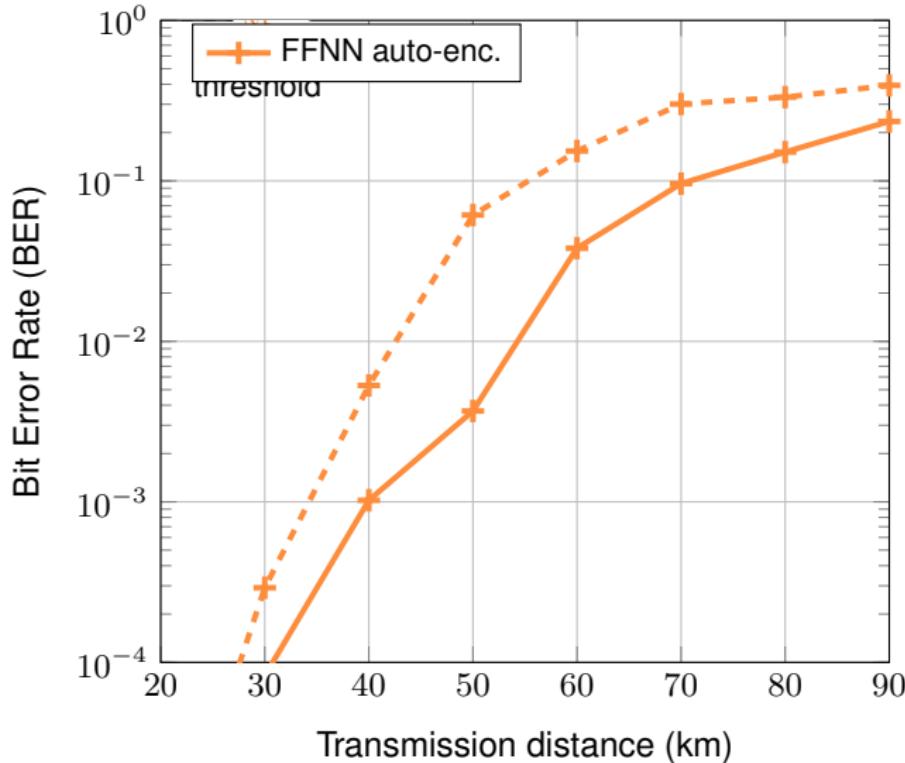
Putting Everything Together



[KCT⁺18]

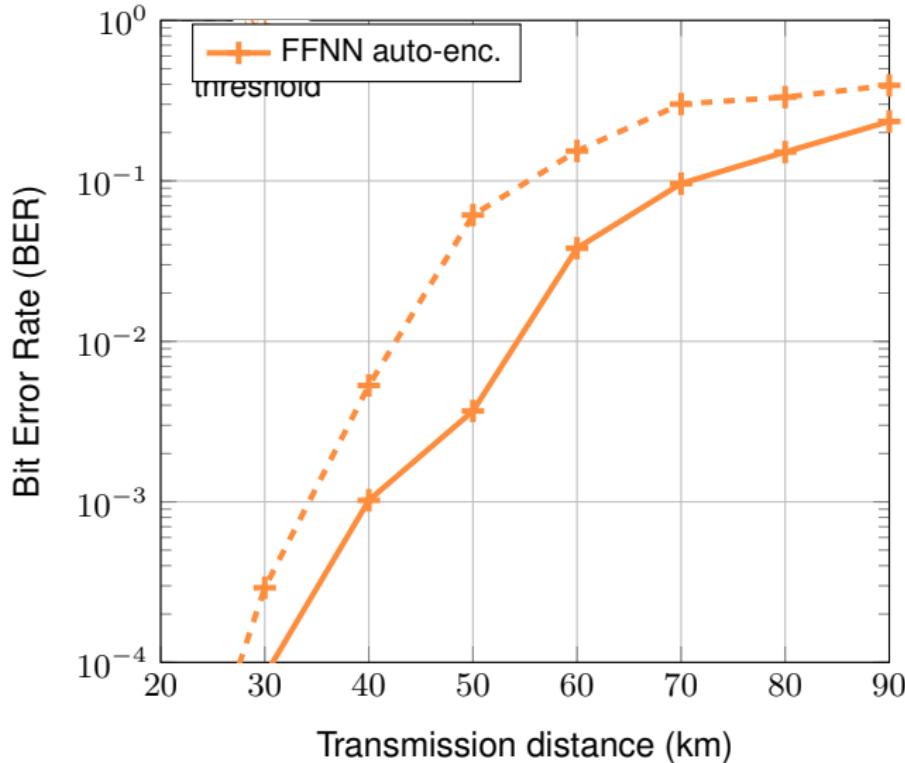
B. Karanov, M. Chagnon, F. Thouin, T. Eriksson, H. Bülow, D. Lavery, P. Bayvel, L. S., "End-to-end Deep Learning of Optical Fiber Communications," *Journal of Lightwave Technology*, Oct. 2018

Simulation Results



- State-of-the-art IM/DD system with 42 Gb/s net rate
- For small alphabets (M small) and neural networks, reach is limited
- Increasing the alphabet and the neural networks enables extra reach (multidimensional constellations) as more dispersion can be compensated for
- Increasing the NN size (i.e., M and thus n) leads to unfeasibly large networks

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- Increasing the NN size (i.e., M and thus n) leads to unfeasibly large networks
- **New approach tailored to dispersive nature of channel needed**



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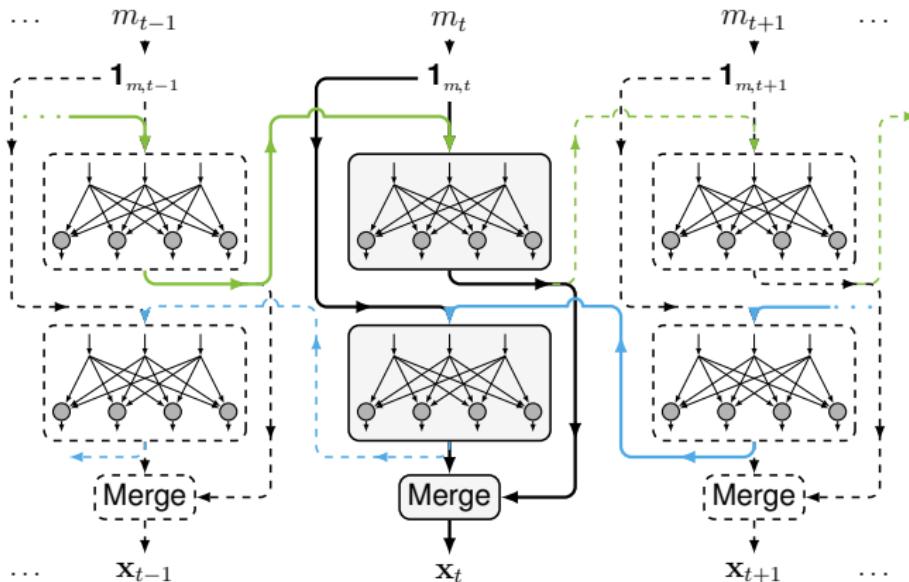
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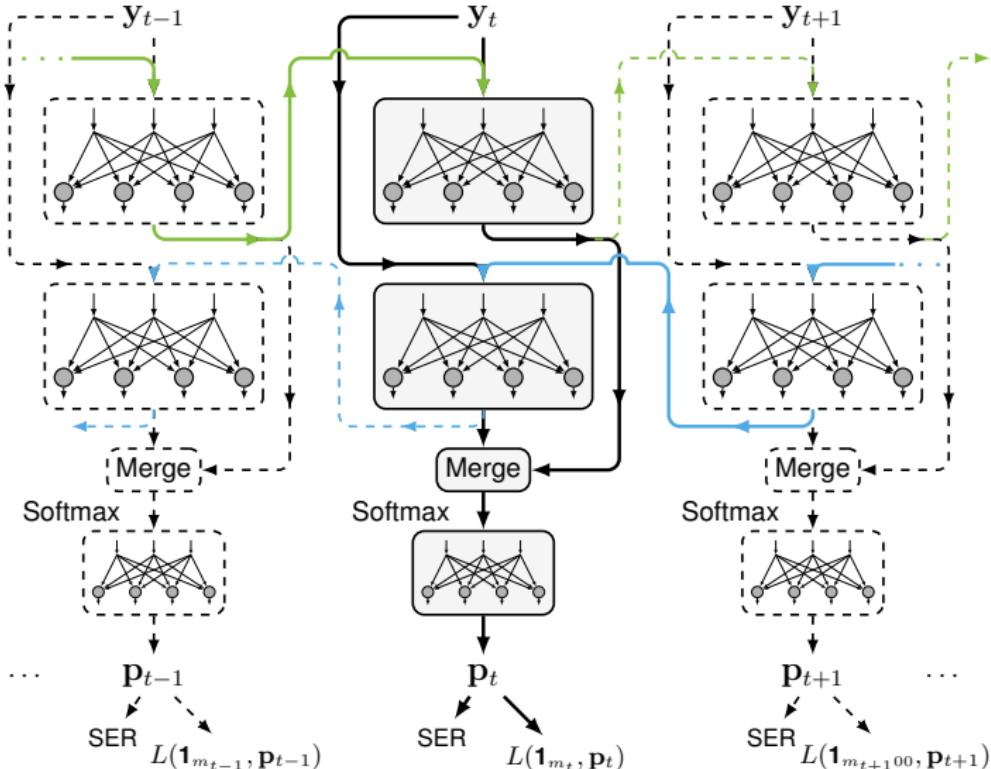
Bidirectional Recurrent NN Based Transmitter



- Transmitter based on **bidirectional recurrent neural networks (BRNN)** [FG18] to account for memory due to chromatic dispersion
- Current message m_t jointly processed with previous and future messages via **bidirectional recurrent neural network (BRNN)**
- Complexity gain using **small** networks inside RNN cells

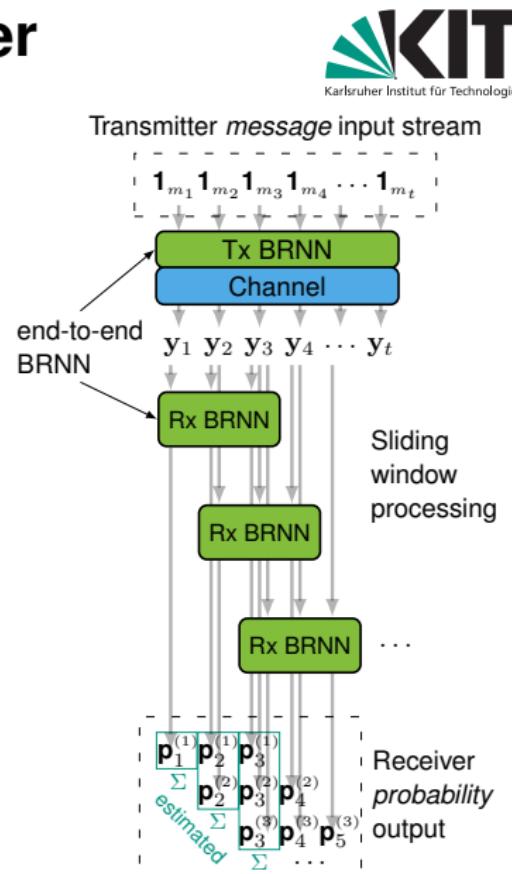
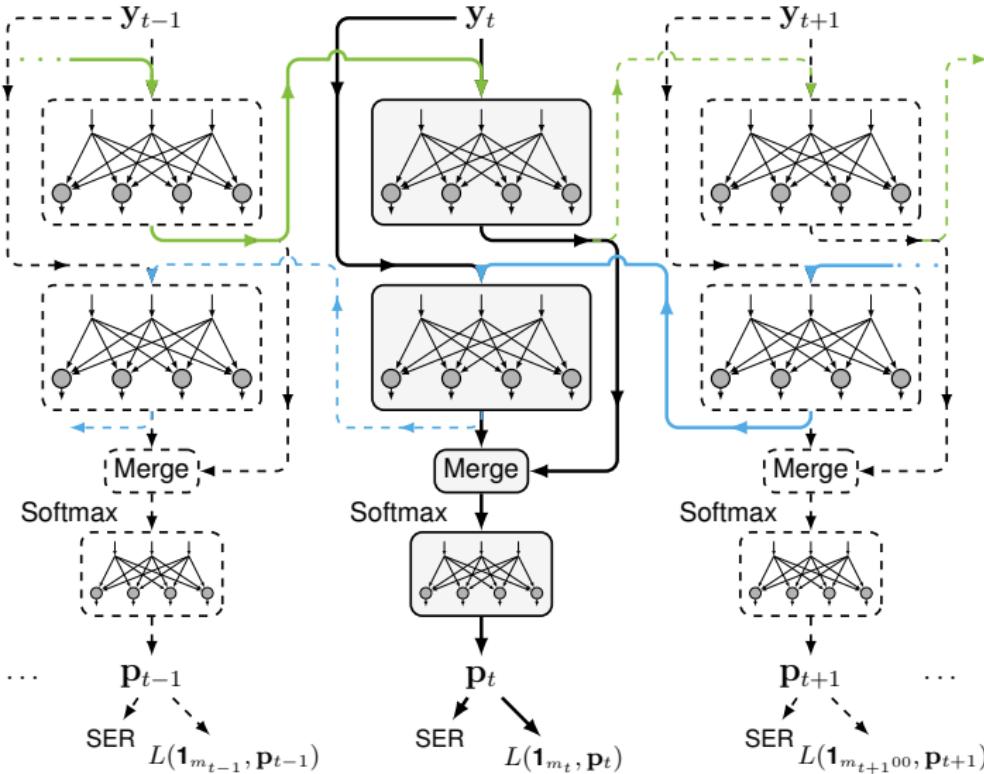
- [KLB⁺19] B. Karanov, D. Lavery, P. Bayvel, L. Schmalen, "End-to-end optimized transmission over dispersive intensity modulated channels using bidirectional recurrent neural networks," *Optics Express*, Jul. 2019
- [FG18] N. Farsad, A. Goldsmith, "Neural network detection of data sequences in communication systems," *IEEE Trans. Signal Process*, 2018

Bidirectional Recurrent NN Based Receiver

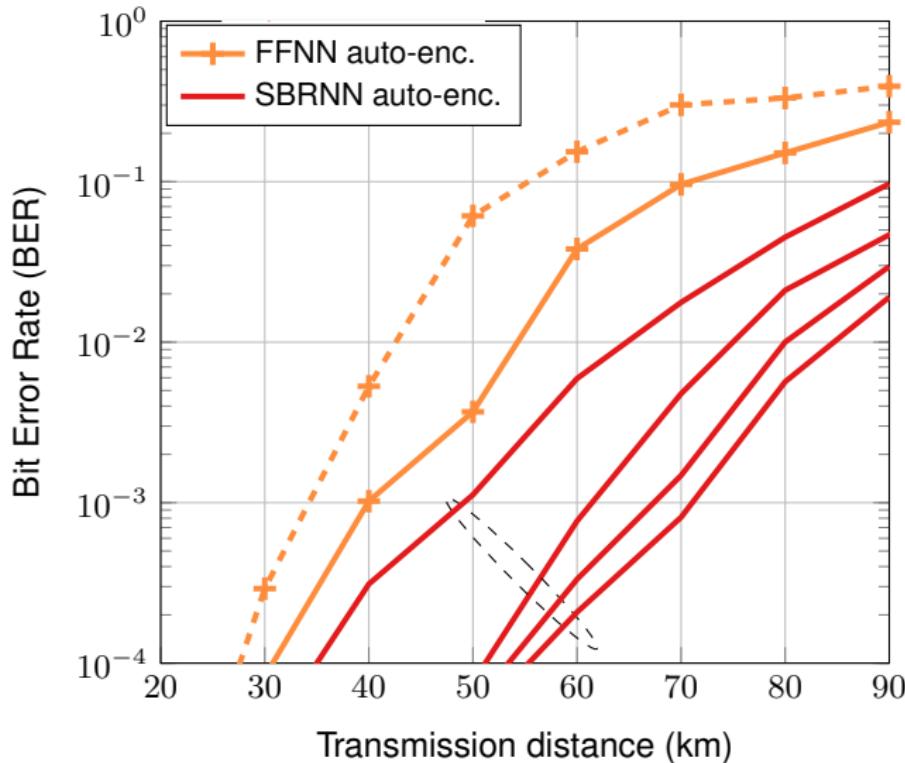


- Receiver structure similar to transmitter
- Additional **softmax** layer to generate probability vectors
- We use **sliding window** processing at the receiver to trade complexity and latency with performance
- A **window** of W stages is jointly processed at the receiver [FG18]

Bidirectional Recurrent NN Based Receiver



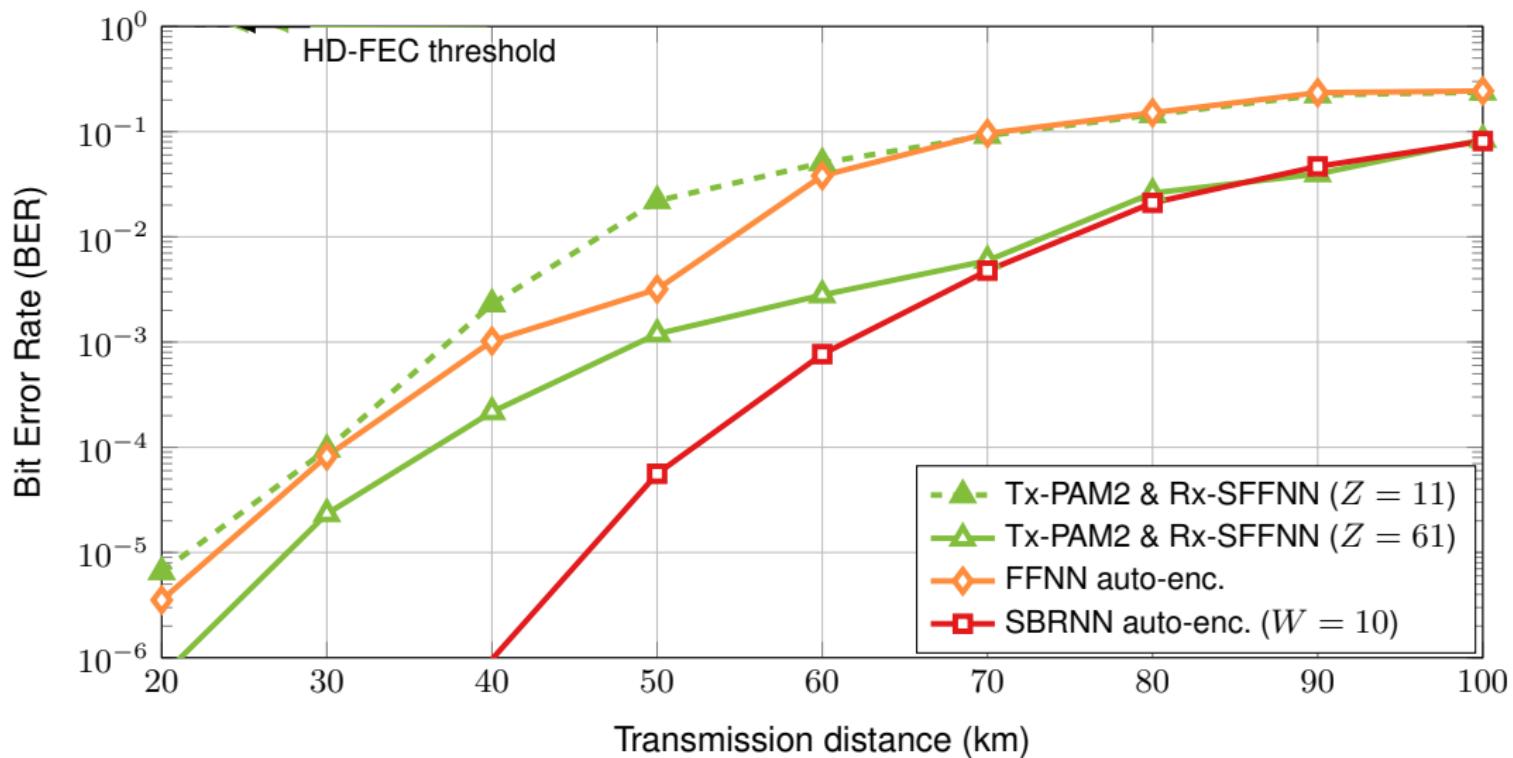
Simulation Results



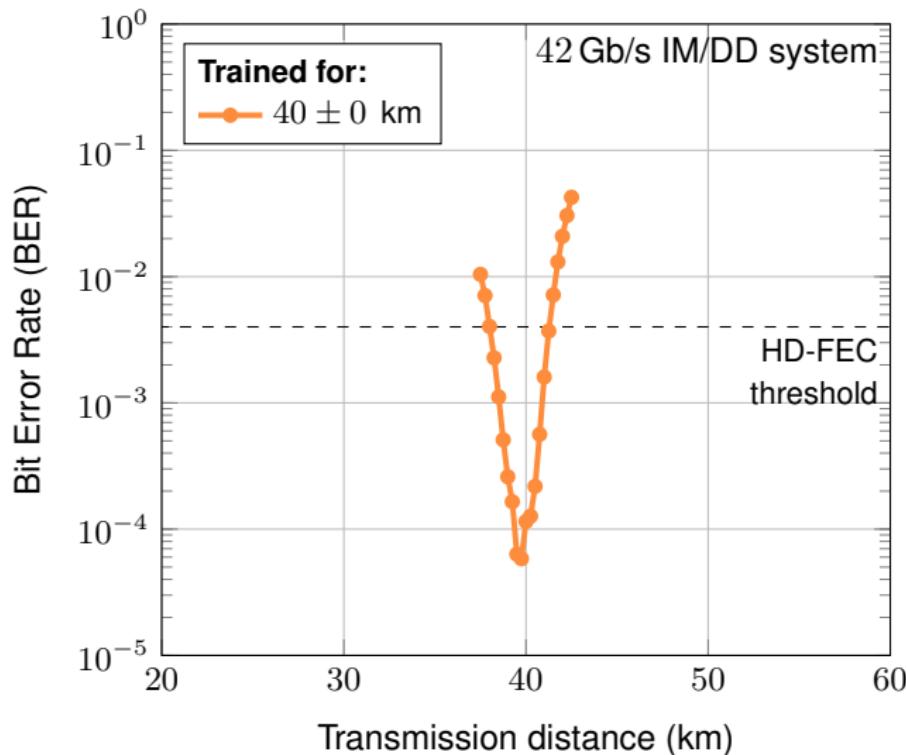
- SBRNN outperforms simple FFNN implementation at significantly **lower complexity**
- 20 km distance gain for $W = 10$
- SBRNN can **outperform** MLSD if complexity is constrained [KLA⁺19]
- Now: Comparison with pure receiver NN processing approximating a Volterra equalizer [Lyu15]

- [KLA⁺19] B. Karanov, G. Liga, V. Aref, D. Lavery, P. Bayvel, and L. Schmalen, "Deep learning for communication over dispersive nonlinear channels: Performance and comparison with classical digital signal processing", *Proc. Allerton Conf. on Commun., Control, and Computing*, 2019
- [Lyu15] I. Lyubomirsky, "Machine learning equalization techniques for high speed PAM4 fiber optic communication systems," *CS229 Final Project Report*, Stanford University, 2015

Simulation Results (2)

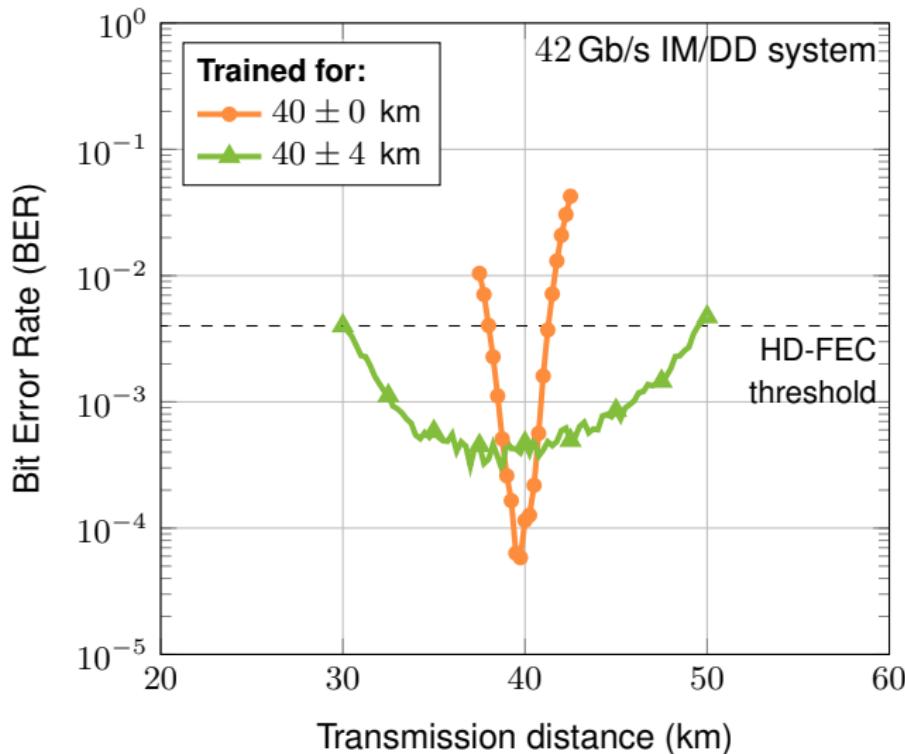


Training Generalization: Simulation Results



- How well does the training generalize?
- If no precautions are taken, not too well

Training Generalization: Simulation Results



- How well does the training generalize?
- If no precautions are taken, not too well
- Multi-task learning enables transceivers that operate on a range of distances **without reconfiguration** [KCT⁺18]
- Big step towards **distance agnostic** transceivers

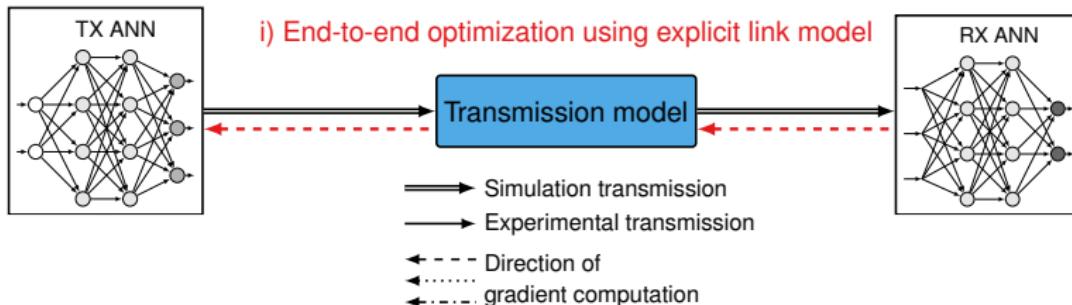
[KCT⁺18]

B. Karanov, M. Chagnon, F. Thouin, T. Eriksson, H. Bülow, D. Lavery, P. Bayvel, L. S., "End-to-end Deep Learning of Optical Fiber Communications," *Journal of Lightwave Technology*, Oct. 2018

Overview

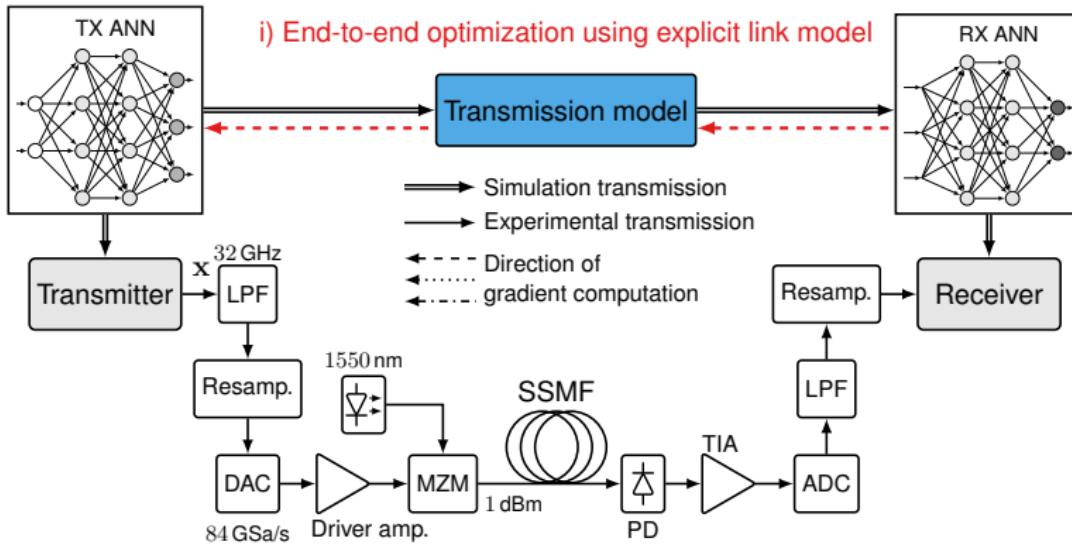
- Introduction
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- Conclusions and Outlook

Experimental Demonstration



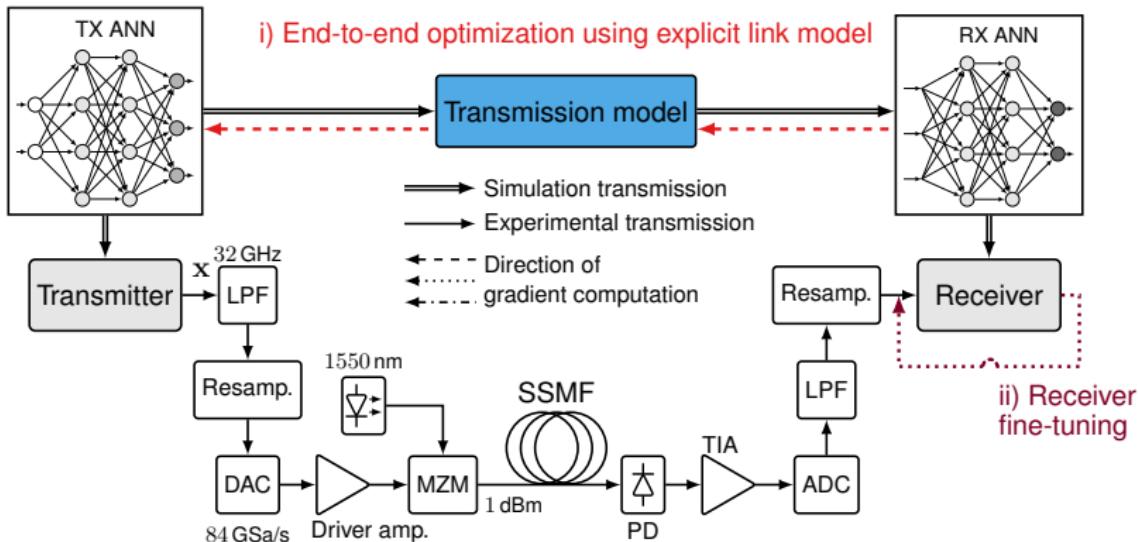
- Optimization of transmitter and receiver using differentiable model

Experimental Demonstration



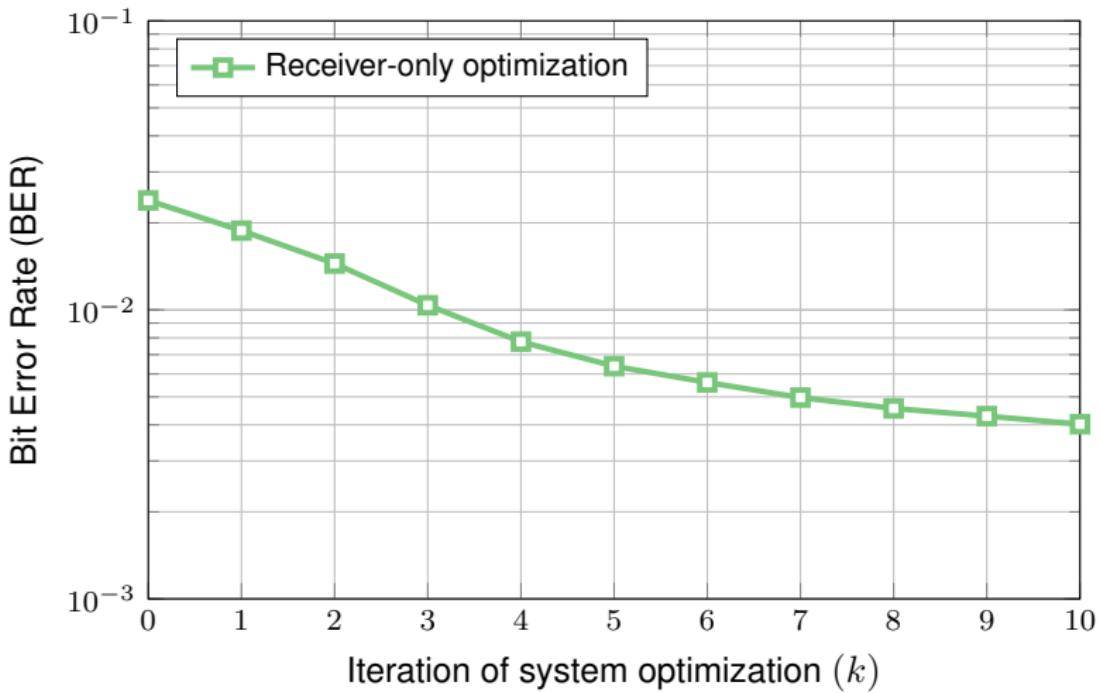
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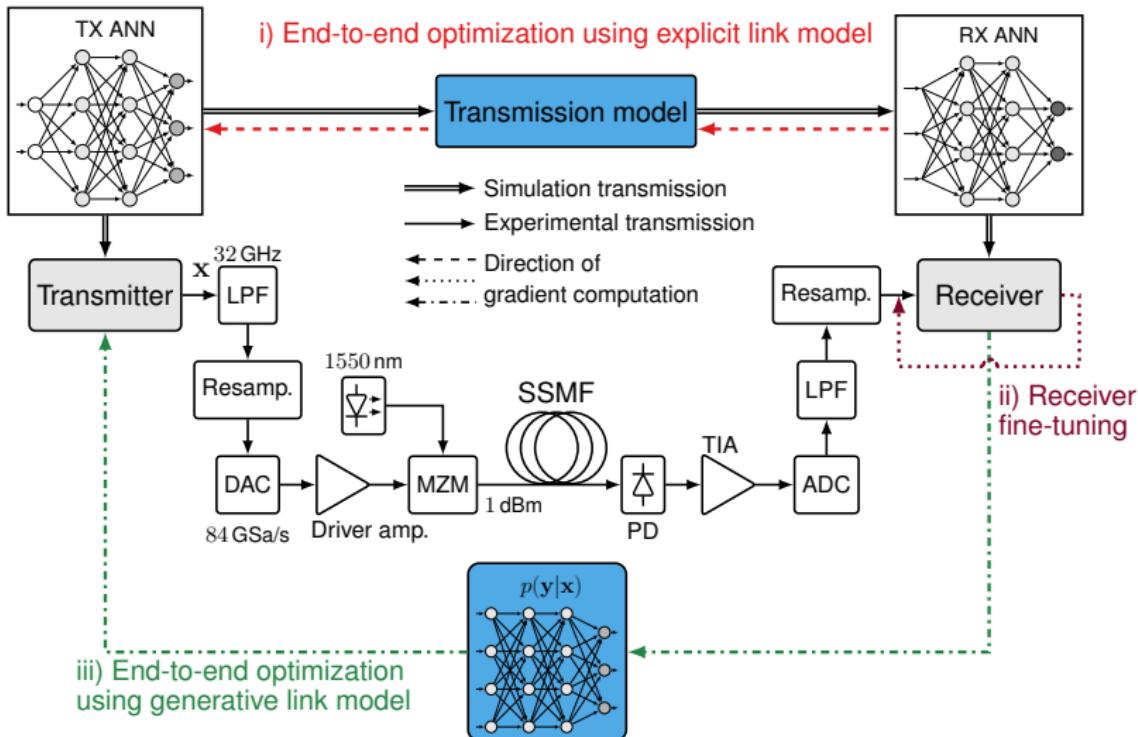
- Optimization of transmitter and receiver using differentiable model
- Mismatch between model and experiment
- Receiver fine-tuning via supervised learning

Experimental Results: Receiver Fine-tuning



- Improvement of symbol and bit error probabilities
- Saturation after a few iterations
- (Had to stop iterating due to unavailability of experimental setup)

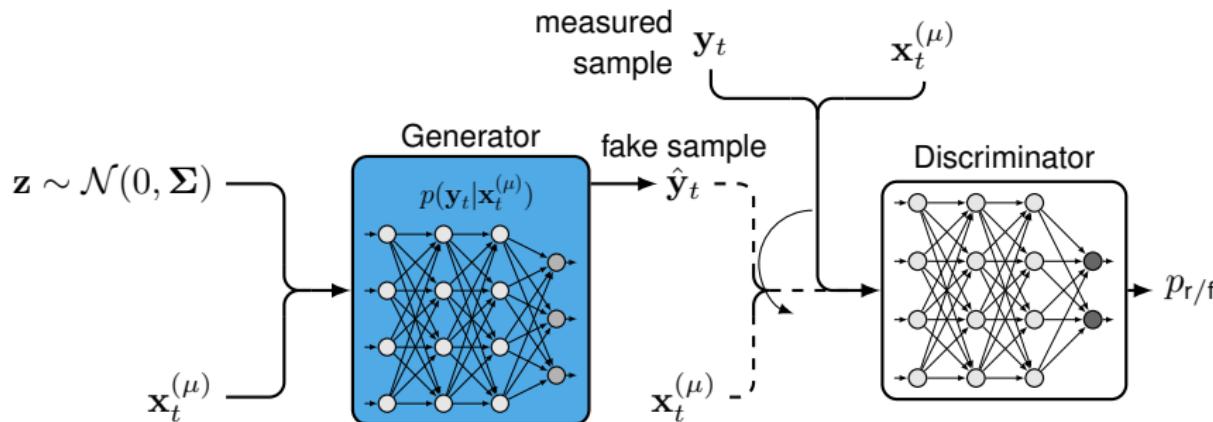
Experimental Demonstration



- Optimazion of transmitter and receiver using differentiable model
- Mismatch between model and experiment
- Receiver fine-tuning via supervised learning
- Transmitter fine-tuning via model of experimental testbed

Channel Modelling Using a Conditional GAN

- Neural network that behaves like a random number generator with the same properties as the channel
- Combining $\mathbf{z} \sim \mathcal{N}(0, \Sigma)$ and the channel input \mathbf{x}_t , the generator generates a channel output distributed according to $p(\mathbf{y}|\vec{\mathbf{x}}_t)$

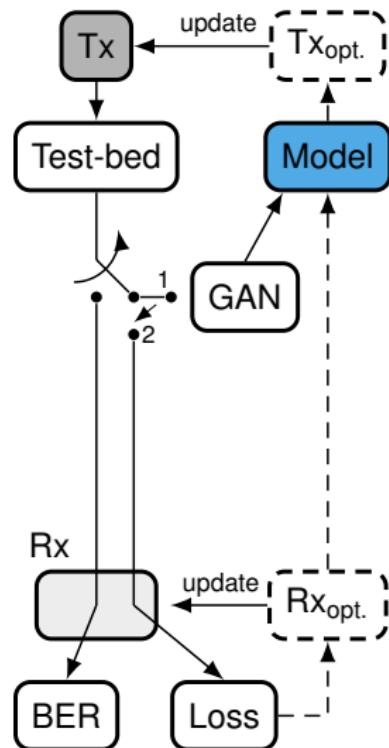


[GPM⁺14]
[KCA⁺20]

I. Goodfellow *et al.*, “Generative adversarial nets,” in *Proc. NeurIPS*, 2014

B. Karanov, M. Chagnon, V. Aref, D. Lavery, P. Bayvel, L. S., “Concept and Experimental Demonstration of Optical IM/DD End-to-End System Optimization using a Generative Model,” *Proc. OFC*, 2020

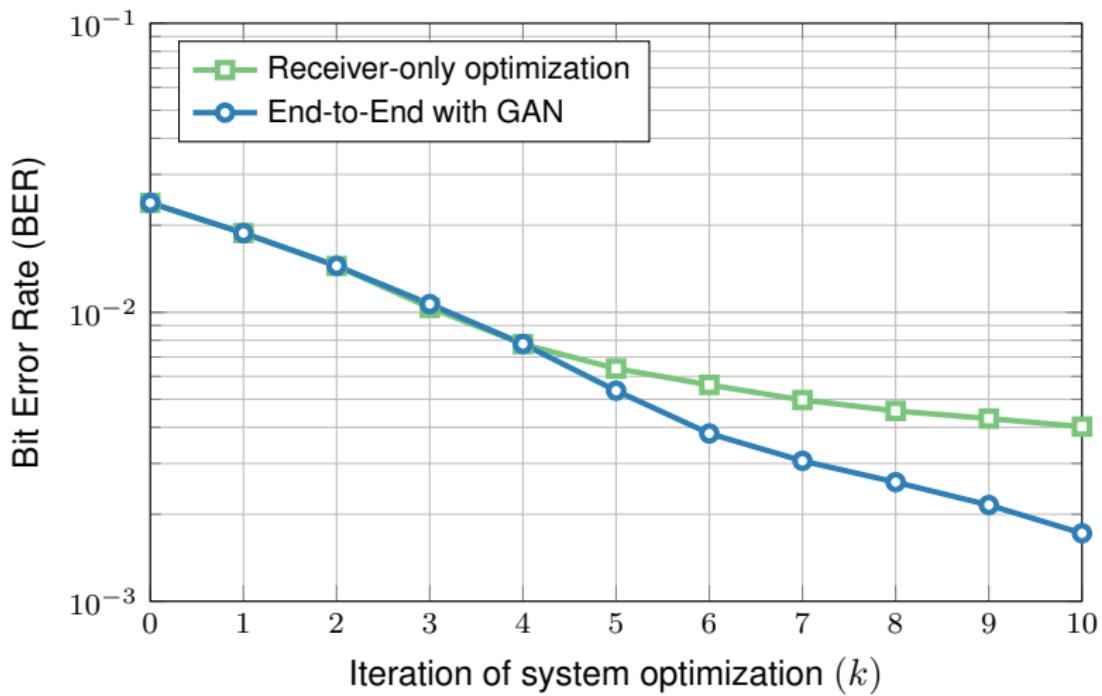
Channel Modelling Using a Conditional GAN



Training procedure:

1. Use testbed to generate input-output samples
2. Apply GAN training to get a channel model
3. Use this model to update and optimize the transmitter
4. With the new transmitter, use the test-bed to get input-output samples and optimize the receiver using supervised learning
5. Evaluate the system and re-iterate if not converged

Experimental Results

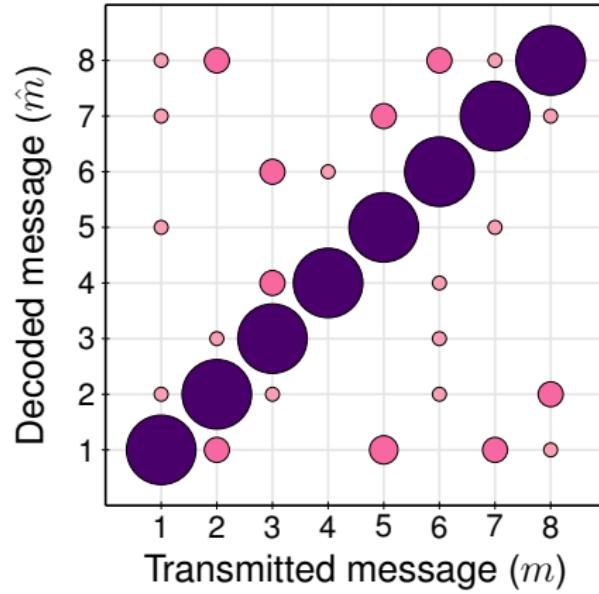
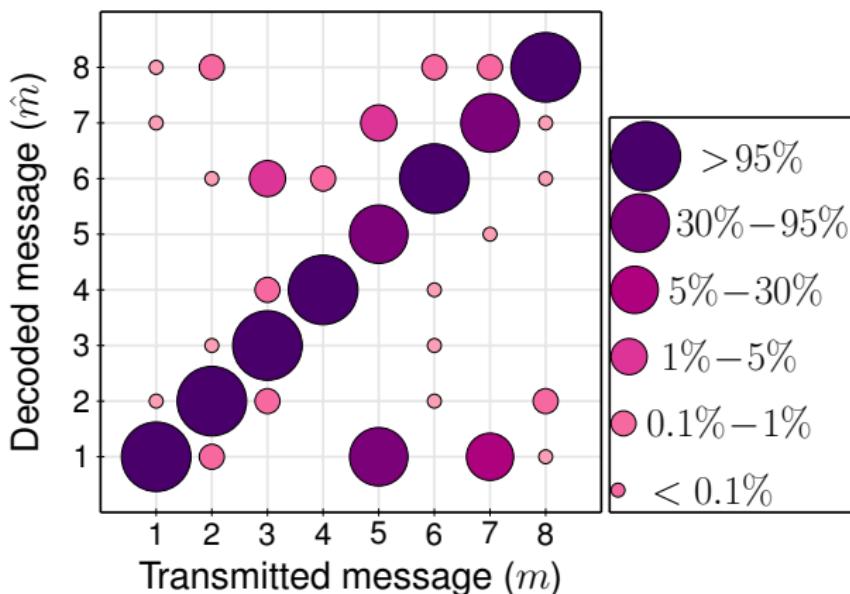


- Improvement of symbol and bit error probabilities
- More iterations will even be more beneficial
- (Had to stop iterating due to unavailability of experimental setup)

Experimental Results (2)

- End-to-end cross-over probabilities
- Initial cross-over probabilities

- After $k = 10$ iterations



In-Situ Transmitter Optimization Approaches

Approach 1: Generative adversarial nets (GANs)

- Demonstrated often ([YLJ+18], [ORW19], [SD19], [KCA⁺20], [DHC⁺20]), however, GAN training tends to be difficult, requiring careful hyperparameter tuning

Approach 2: Policy gradient methods

- Approach from reinforcement learning to estimate gradient [AH19], [GAH19]. Potentially slow convergence and requiring careful hyperparameter tuning

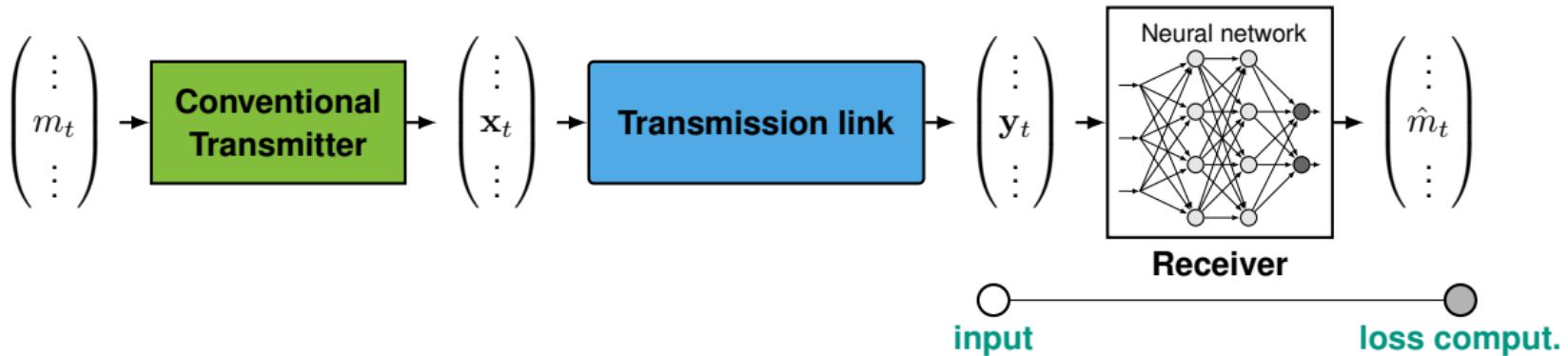
Approach 3: Bayesian filtering

- Recent approach [JYdR⁺], still many open questions

[YLJ+18]	H. Ye, G. Y. Li, B. F. Juang and K. Sivanesan, "Channel agnostic end-to-end learning based communication systems with conditional GAN," in <i>Proc. GLOBECOM</i> , 2018
[ORW19]	T. O'Shea, T. Roy and N. West, "Approximating the void: Learning stochastic channel models from observation with variational generative adversarial networks," in <i>Proc. of 2019 International Conference on Computing, Networking and Communications</i> , 2019
[SD19]	A. Smith and J. Downey, "A communication channel density estimating generative adversarial network," <i>NASA Technical Reports</i> 2019
[KCA ⁺ 20]	B. Karanov, M. Chagnon, V. Aref, D. Lavery, P. Bayvel, L. S., "Concept and Experimental Demonstration of Optical IM/DD End-to-End System Optimization using a Generative Model," <i>Proc. OFC</i> , 2020
[DHC ⁺ 20]	S. Dörner, M. Henninger, S. Cammerer, S. ten Brink, "WGAN-based Autoencoder Training Over-the-air," <i>Proc. SPAWC</i> , 2020
[AH19]	F. Ait Aoudia, J. Hoydis, "Model-free training of end-to-end communication systems," <i>IEEE J. Selected Areas in Communications</i> , 2019
[GAH19]	M. Goutay, F. Ait Aoudia, J. Hoydis, "Deep reinforcement learning autoencoder with noisy feedback," <i>Proc. WiOPT</i> , 2019
[JYdR ⁺]	O. Jovanovic, M. Yankov, F. da Ros, D. Zibar, "Gradient-free training of autoencoders for non-differentiable communication channels," <i>Journal of Lightwave Technology</i> , 2021

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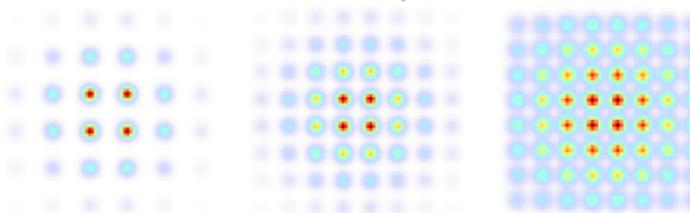
Receiver Processing Using Neural Networks



- So far, we have considered **supervised learning**
- To compute the loss function and update the network parameters, we need to know the transmit sequence, e.g., a **pilot sequence**
- If the transmission link changes rapidly, **large overhead** for transmitting pilots
- Can we find a **blind** scheme that works purely on the received data?

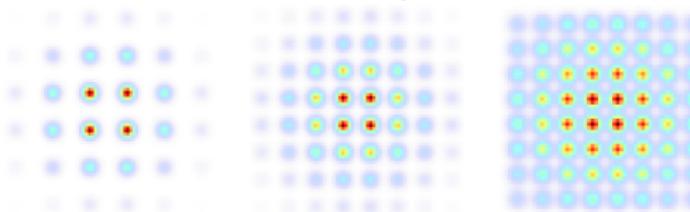
Motivation

- Great demand for **blind** equalizers
 - + saved data rate can increase FEC overhead or data throughput
 - ⚡ have to be flexible and adaptive
 - ⚡ must support higher-order modulation formats and probabilistic constellation shaping (PCS)



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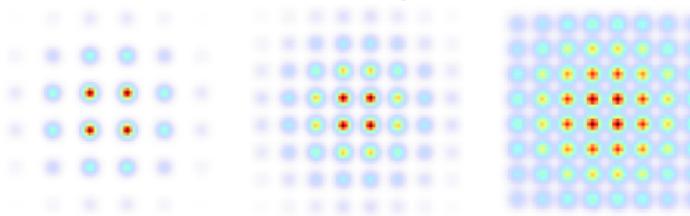


- **State-of-the-art:** Constant modulus algorithm (CMA) / multi modulus algorithm (MMA) [Yan02]
 - CMA: ill-matched for higher-order modulation formats and probabilistic shaping
 - MMA: high implementation complexity and low convergence rate

[Yan02] J. Yang *et al.*, "The multimodulus blind equalization and its generalized algorithms," *IEEE J. Sel. Areas. Commun.* **20**(5), pp. 997ff (2002).
[GW92] M. Ghosh and C. L. Weber, "Maximum-likelihood blind equalization," *Optical Engineering* **31**(6), pp. 1224–1229 (1992).

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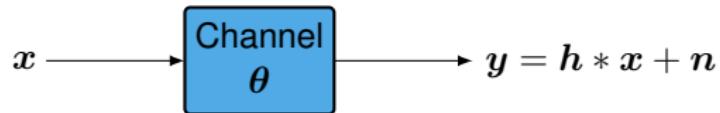
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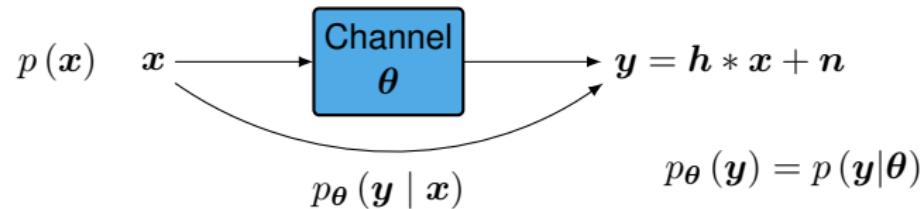
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- **Ideally:** Maximum likelihood detector, e.g. [GW92]

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System and Problem Description

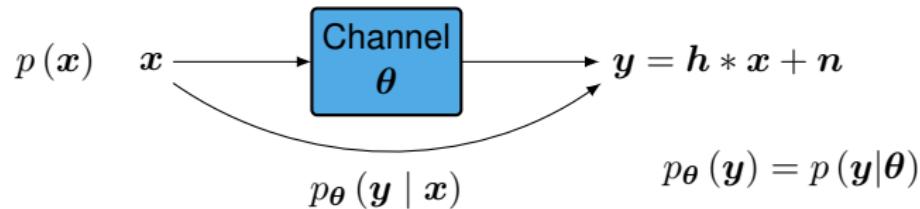


System and Problem Description



Goal: $\hat{\theta}_{\text{ML}} = \arg \max_{\theta} p_{\theta}(y)$

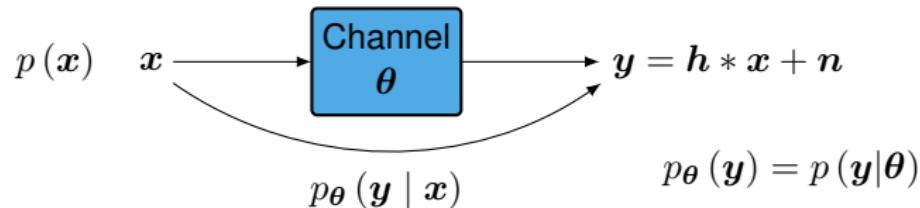
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Given: $p(x)$, $p_{\theta}(y | x) = \mathcal{CN}(\mathbf{h} * \mathbf{x}, \sigma_w^2 \mathbf{I}_N)$

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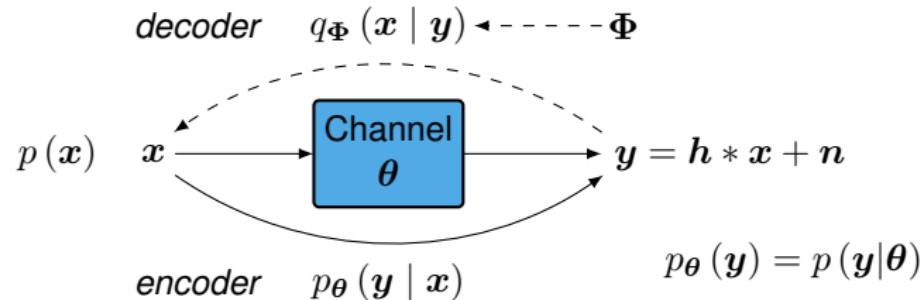


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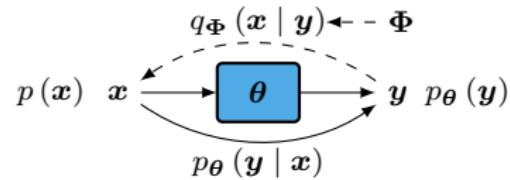
Problem: $p_{\theta}(y) = \sum_x p(x) p_{\theta}(y | x) \rightarrow \text{intractable}$

■ **Idea:** use variational inference to approximate (intractable) ML problem [CB18]

[CB18] A. Caciularu and D. Burshtein, "Blind channel equalization using variational autoencoders," *Proc. IEEE ICC*, Kansas City, USA, 2018.

Variational Inference via VAE Paradigm (1)

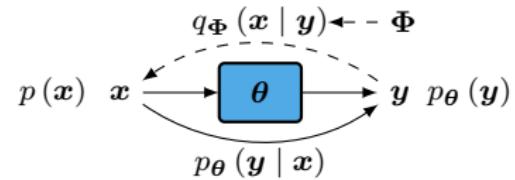
■ ML criterion: $\hat{\theta} = \arg \max_{\theta} p_{\theta}(y) = \arg \max_{\theta} \ln p_{\theta}(y)$



$$\ln p_{\theta}(y) = \dots = \underbrace{\sum_x q_{\Phi}(x | y) \cdot \ln \frac{p_{\theta}(x, y)}{q_{\Phi}(x | y)}}_{=: \mathcal{L}(\theta, \Phi, y)} + \underbrace{\sum_x q_{\Phi}(x | y) \cdot \ln \frac{q_{\Phi}(x | y)}{p_{\theta}(x | y)}}_{=: D_{KL}(q_{\Phi}(x|y) \| p_{\theta}(x|y))}$$

- [KW14] D. P. Kingma and M. Welling, "Auto-encoding variational Bayes," in *Proc. ICLR*, 2014.
[BKM17] D. M. Blei, A. Kucukelbir, and J. D. McAuliffe, "Variational inference: A review for statisticians," *J. Amer. Statist. Assoc.* **112**(518) (2017).

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■ Kullback-Leibler divergence $D_{KL}(q_{\Phi}(x|y) \| p_{\theta}(x|y)) \geq 0$

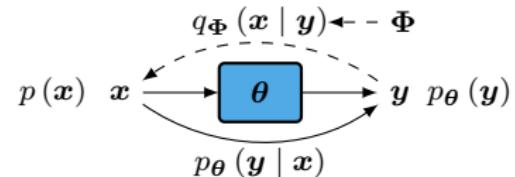
⇒ Evidence lower bound (ELBO): $\mathcal{L}(\theta, \Phi, y)$

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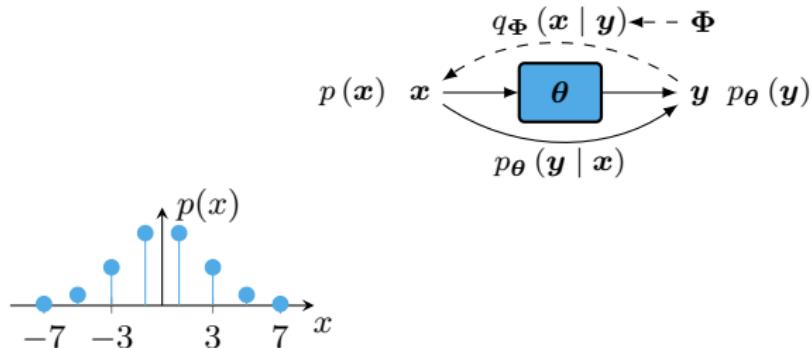
■ **Optimization:** $\mathcal{L}(\theta, \Phi, y) \uparrow \Rightarrow D_{KL}(q_{\Phi}(x|y) \| p_{\theta}(x|y)) \rightarrow 0$

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Variational Inference via VAE Paradigm (2)

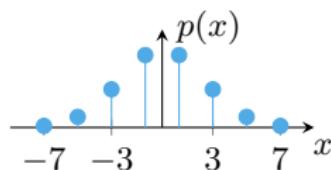
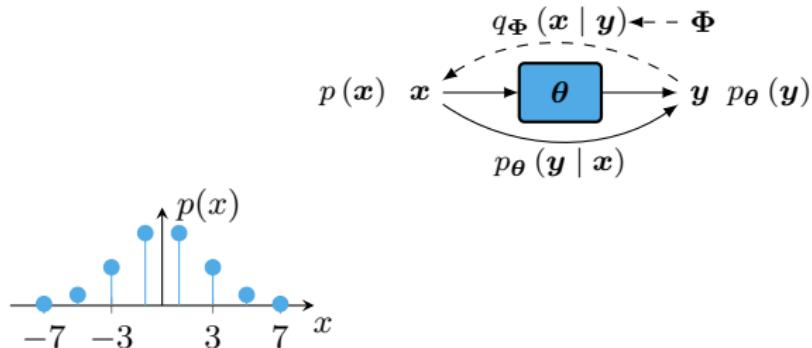
$$\mathcal{L}(\theta, \Phi, y) = B(h, \Phi, y) - A(\Phi, y)$$



- $A(\Phi, y) = D_{KL}(q_\Phi(x | y) \| p(x))$
- Tries to shape $q_\Phi(x | y)$ similar to $p(x)$

Variational Inference via VAE Paradigm (2)

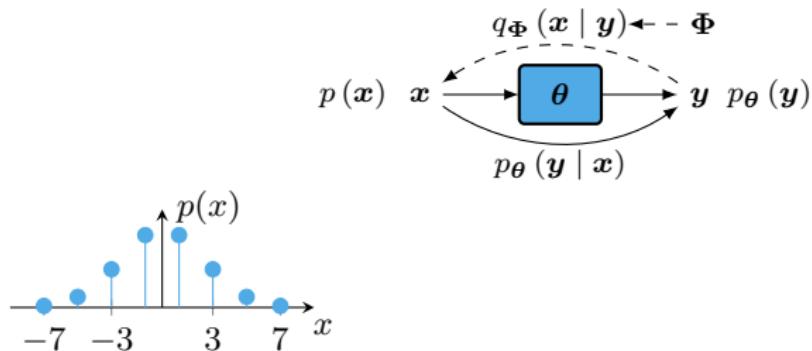
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- $A(\Phi, y) = D_{KL}(q_\Phi(x | y) || p(x))$
 - Tries to shape $q_\Phi(x | y)$ similar to $p(x)$
- $B(h, \Phi, y)$
 - Matches equalizer output to received symbols

Variational Inference via VAE Paradigm (2)

$$\mathcal{L}(\theta, \Phi, y) = B(h, \Phi, y) - A(\Phi, y)$$

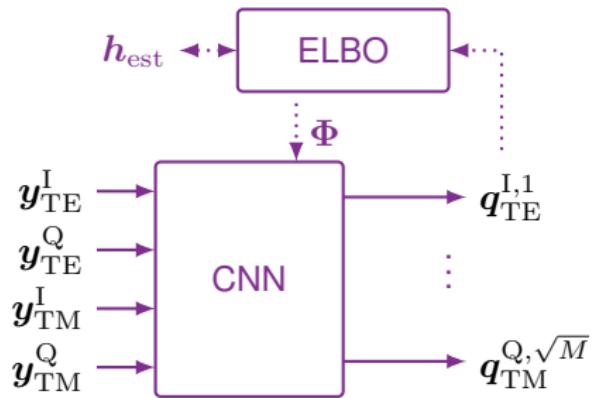


- $A(\Phi, y) = \text{D}_{\text{KL}}(q_{\Phi}(x | y) \| p(x))$
 - Tries to shape $q_{\Phi}(x | y)$ similar to $p(x)$

- $B(h, \Phi, y)$
 - Matches equalizer output to received symbols

- ⇒ **Blind approach:** requires only $p(x)$, not x
- ⇒ $q_{\Phi}(x | y)$ can be used in conjunction with Soft-FEC

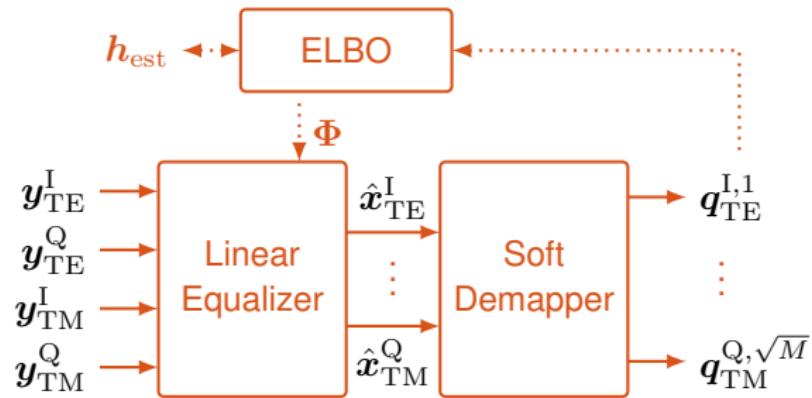
VAE Equalizer – Neural Network (VAE-NN)



- Convolutional Neural Network (CNN) has two tasks: equalization *and* demapping
- Outputs $q_{\Phi}(x | y)$
- Potentially capable of compensating non-linearities

[CB18] A. Caciularu and D. Burshtein, "Blind channel equalization using variational autoencoders," Proc. IEEE ICC, Kansas City, USA (2018).

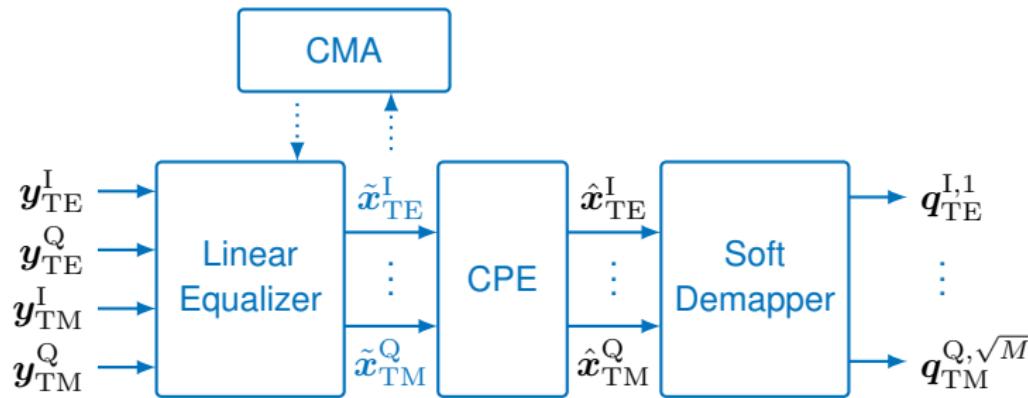
VAE Equalizer – Linear Equalizer (VAE-LE)



- Equalization and demapping are split
- Classical butterfly structure with FIR filters
- Outputs estimated symbols and soft demapper computes $q_{\Phi}(x | y)$
- Targets compensation of linear impairments

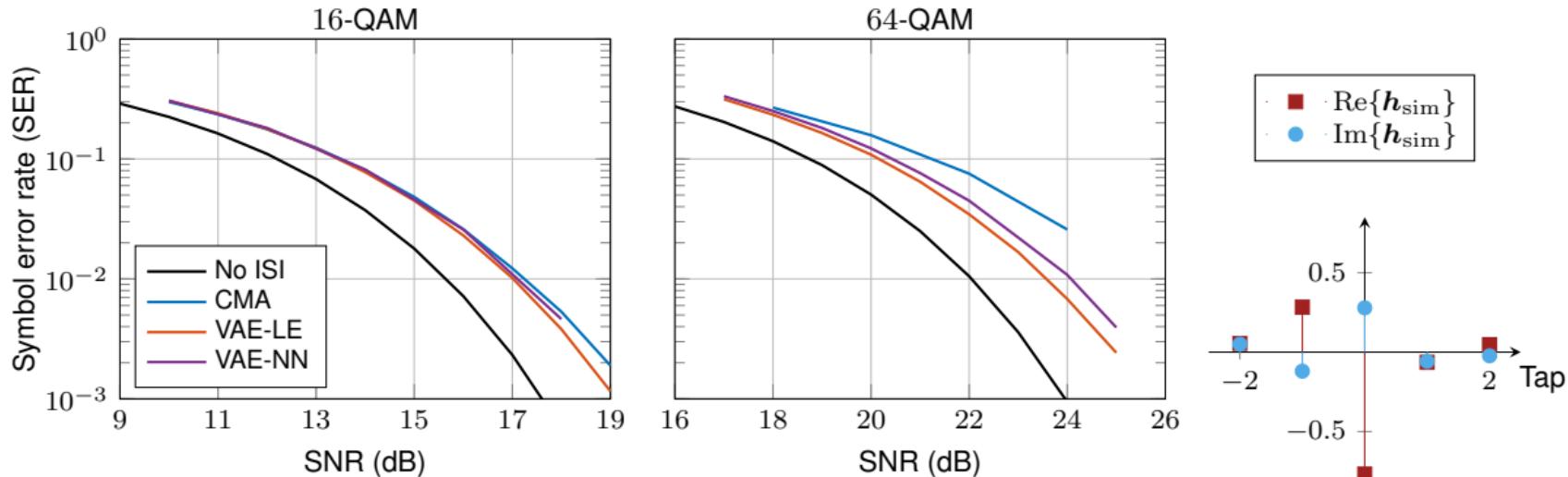
[LBS21] V. Lauinger, F. Buchali, L. S., "Blind equalization for coherent optical communications based on variational inference," *Proc. Adv. Photon. Congr., SPPCOM*, Jul. 2021

Reference: CMA-based Equalizer



- **State-of-the-art** blind adaptive equalizer in optical comm.
- Carrier Phase Estimation (CPE) required (e.g. Viterbi-Viterbi algorithm)
- Targets compensation of linear impairments

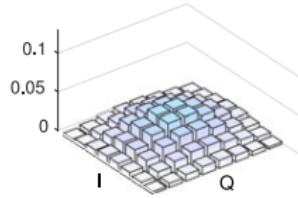
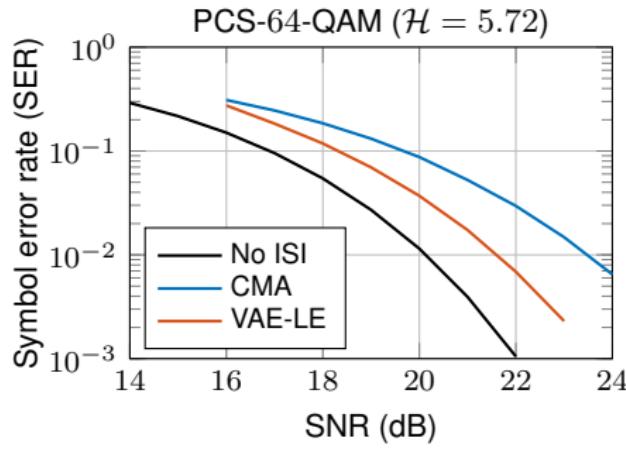
Simulation Results: Conventional QAM



- Single polarization
- 2 samples per symbol
- Batch-wise update with Adam optimizer

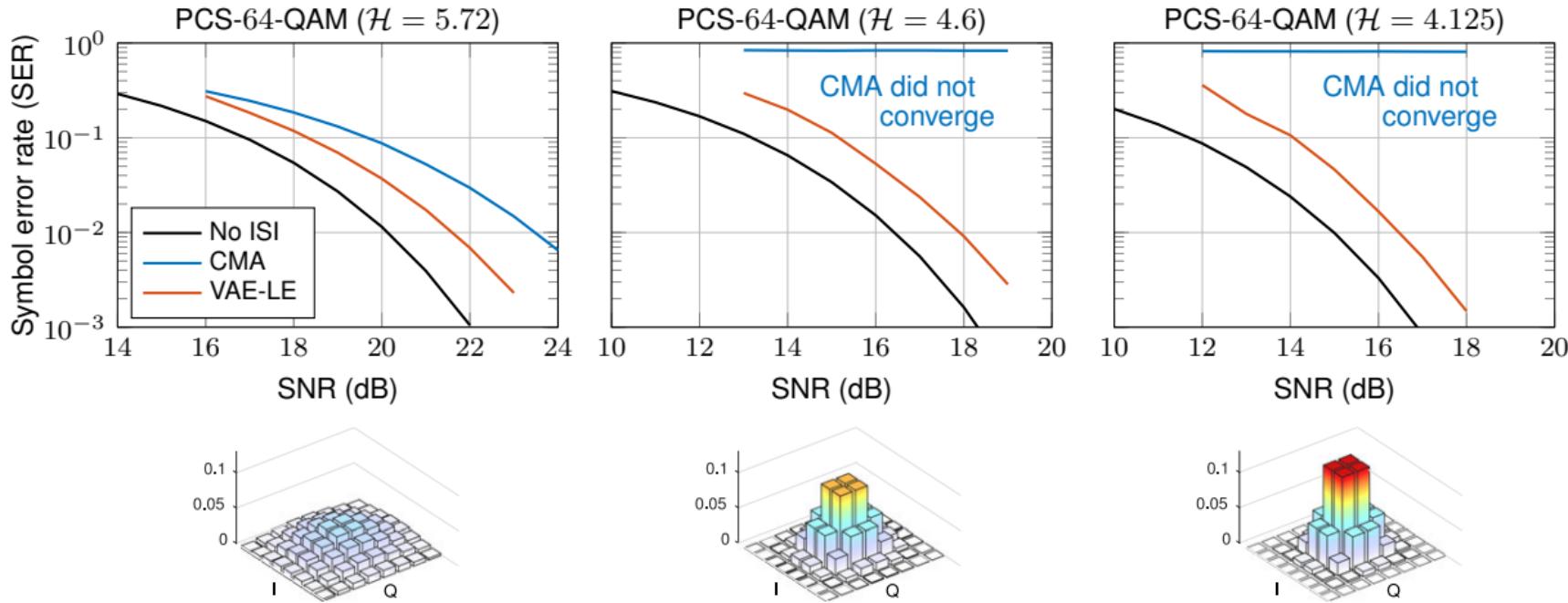
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Simulation Results: PCS-QAM



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Conclusion and Outlook

- Neural networks are and will be **integral part** of optical communication systems
- Machine learning enables design of **novel waveforms and modulation formats**
- Machine learning enables **novel applications** that are difficult with traditional approaches, e.g. distance agnostic transceivers
- Generative networks can be used to **model** (part of) the communication system for model-based optimization
- Powerful tools from the machine learning community can be used to design **novel receiver algorithms**

Questions?



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Bundesministerium
für Bildung
und Forschung

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