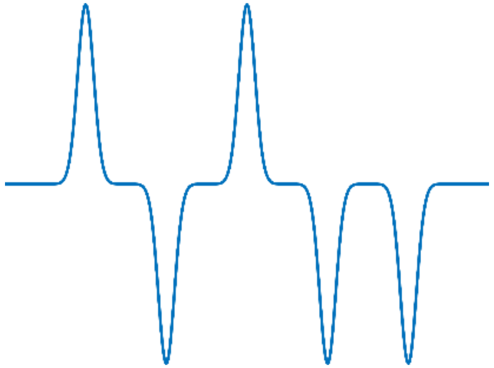
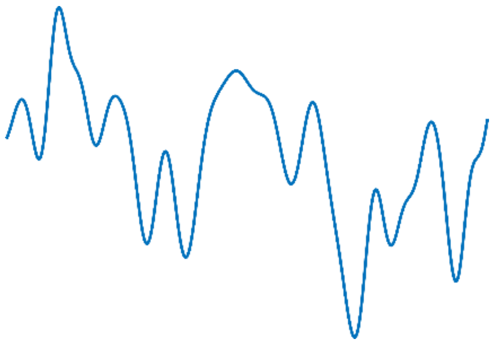
Recovery of signal distorted by nonlinearity in optical communications using deep learning





DL PROJECT 2021

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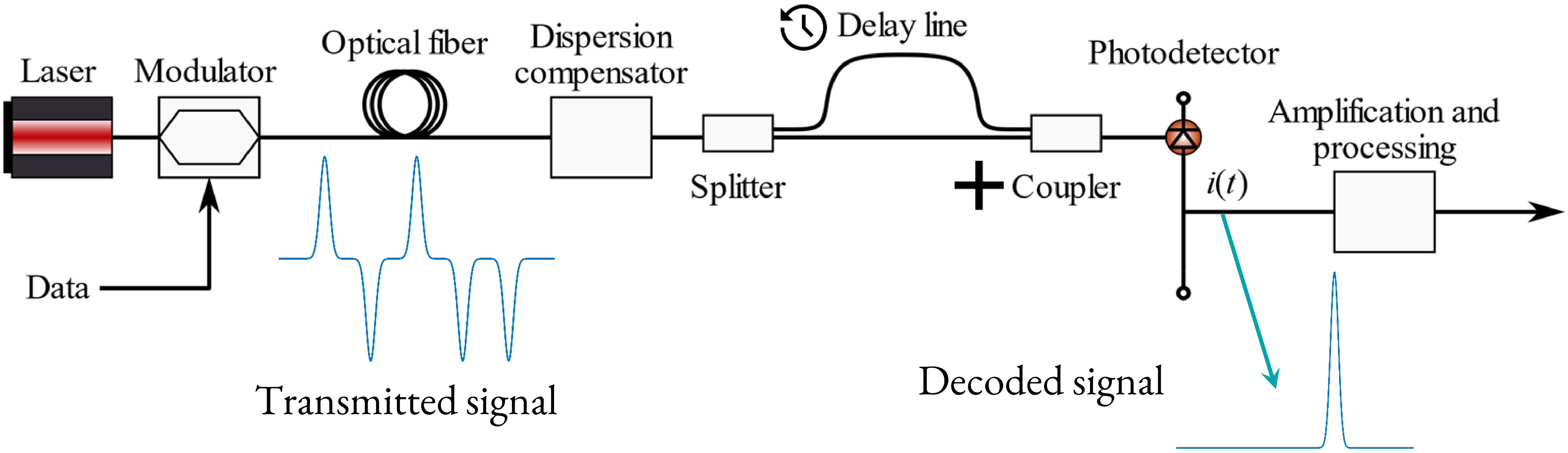
Problem description

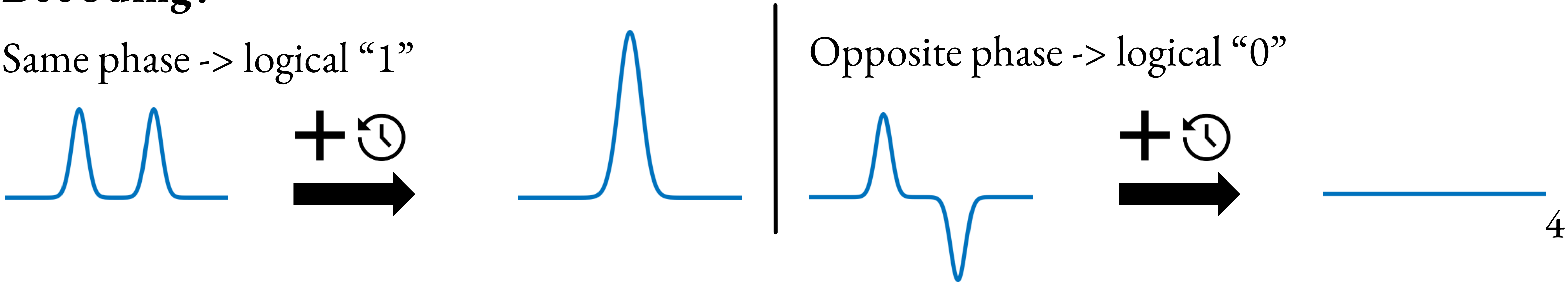
Coherent communications. Ideal case



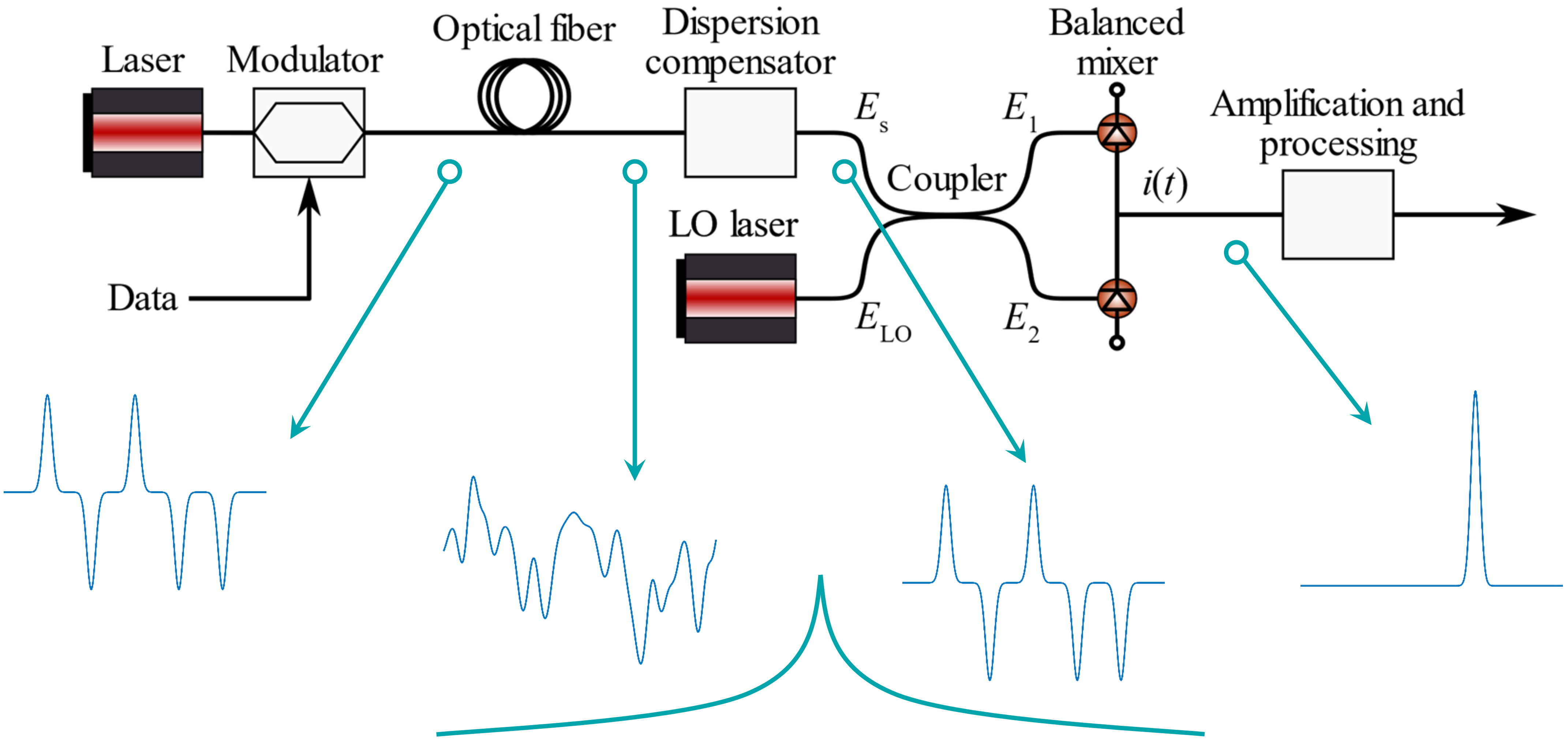
Decoding:

Same phase -> logical "1"

Opposite phase -> logical "0"

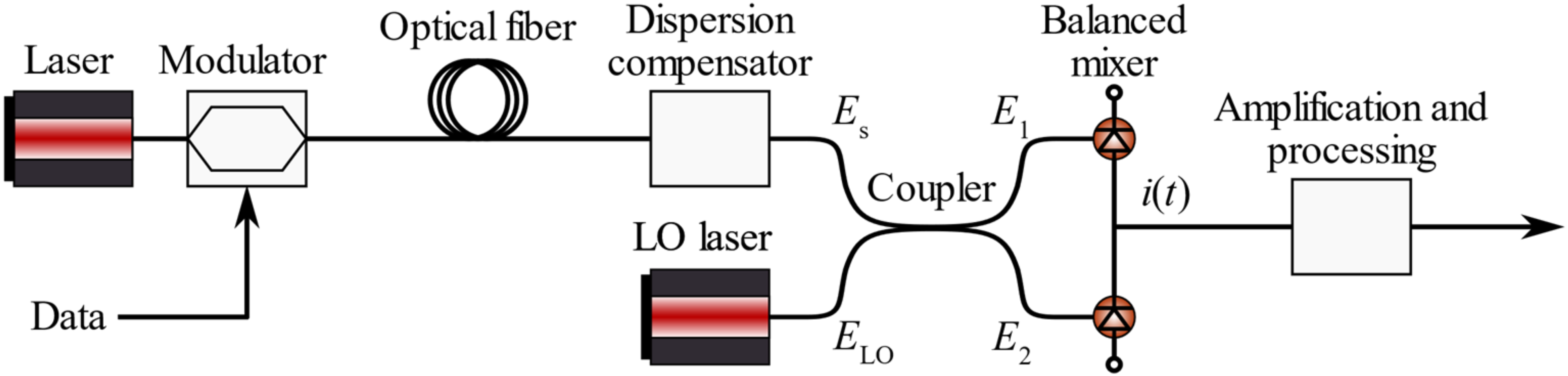


Coherent communications. Real case



Digital back propagation

Main challenges



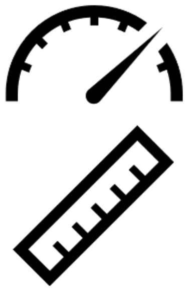
Fiber chromatic dispersion → pulse broadening

Kerr nonlinearity ($n = n_0 + \alpha|E|^2$) → phase distortion ⇒ errors after decoding.

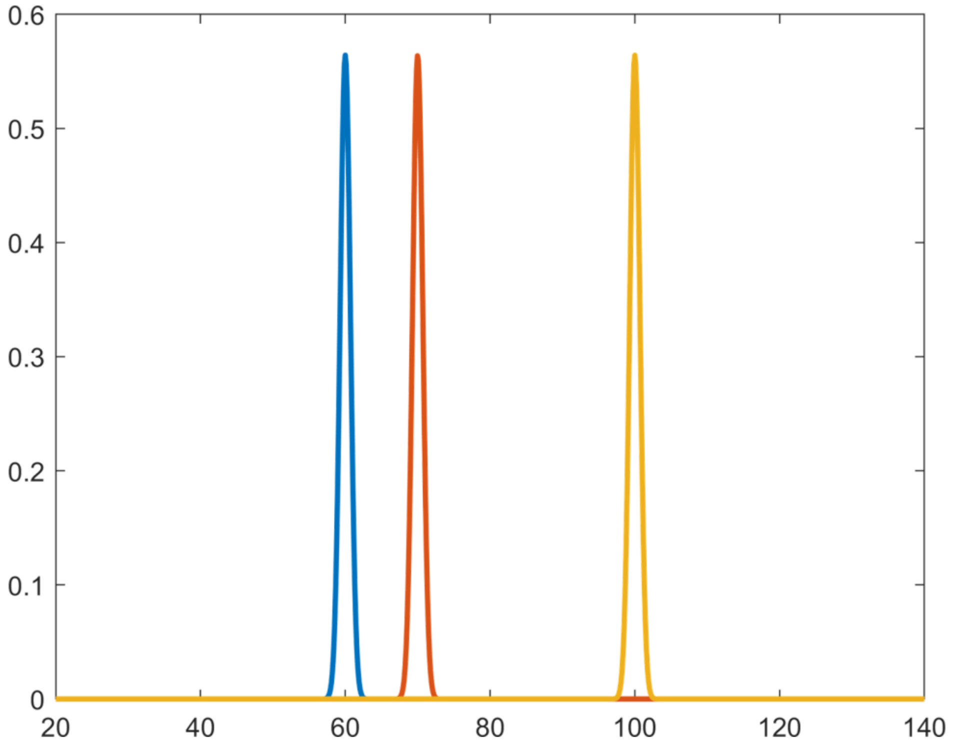
Nonlinearity is limiting system performance:

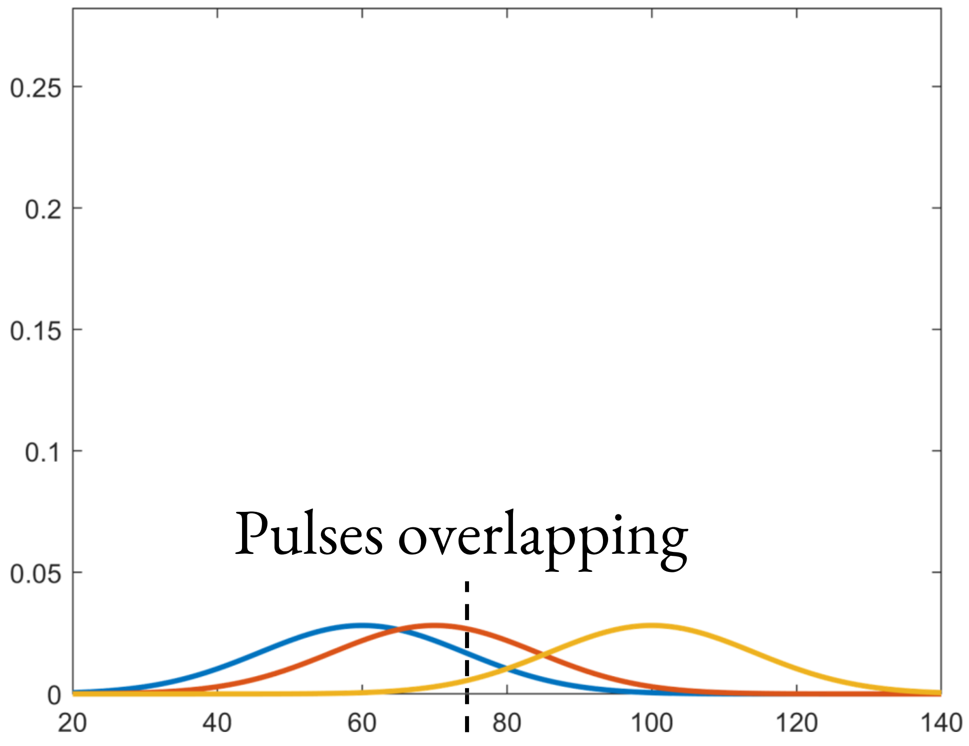
higher bit-rate or longer transmission distance

1. **higher bit-rate**: $\mathcal{E} \approx |E|^2\tau_0 \approx |E|^2/BR \geq \mathcal{E}_{cr} \Longrightarrow |E|^2 \geq \mathcal{E}_{cr}BR$
2. **Length of nonlinearity**: $z_{nl} \approx (\alpha|E|^2)^{-1}$.
   Nonlinearity becoming noticeable when $L \sim z_{nl}$



Mamyshev effect





For wave interaction is a mechanism that create **energy redistribution** along bit pattern which lead to **amplitude jitter** of the output signal – Mamyshev effect

- Has the Gaussian shape
- Collects energy from the triplet surrounding pulses

Data modeling

Modeling equation

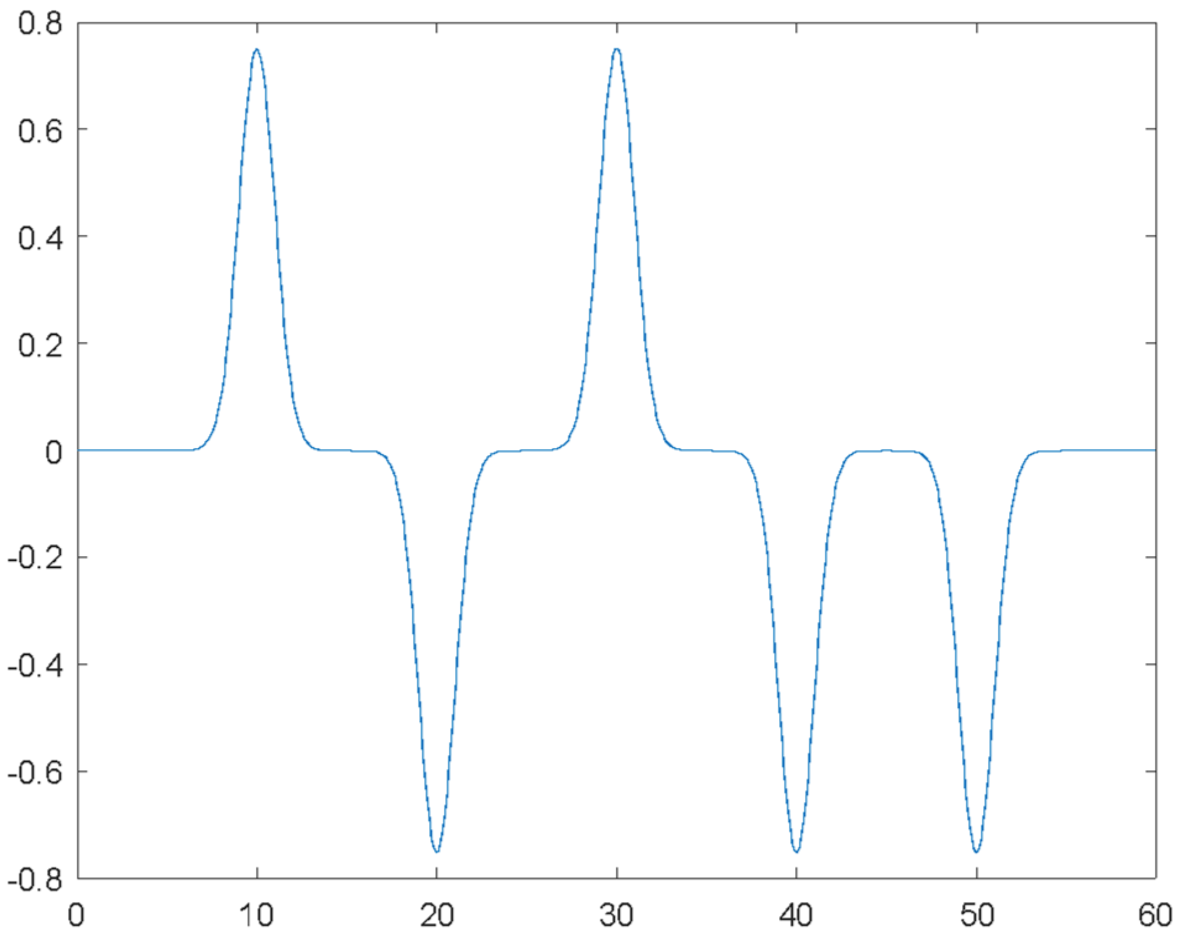
Dimensionless NLS:

$$iE_z + \frac{1}{2}E_{tt} + \varepsilon |E|^2 E = 0 \qquad (7)$$

Bit-sequence launched at the front end of the system is represented by periodic train of **gaussian pulses** with Differential Phase Shift Keying (DPSK)

$$E(t,0) = \sum_{k=1}^{N} a_k \pi^{-1/4} \exp\left[-\frac{1}{2}\left(t - kT^2\right)\right] \qquad (8)$$

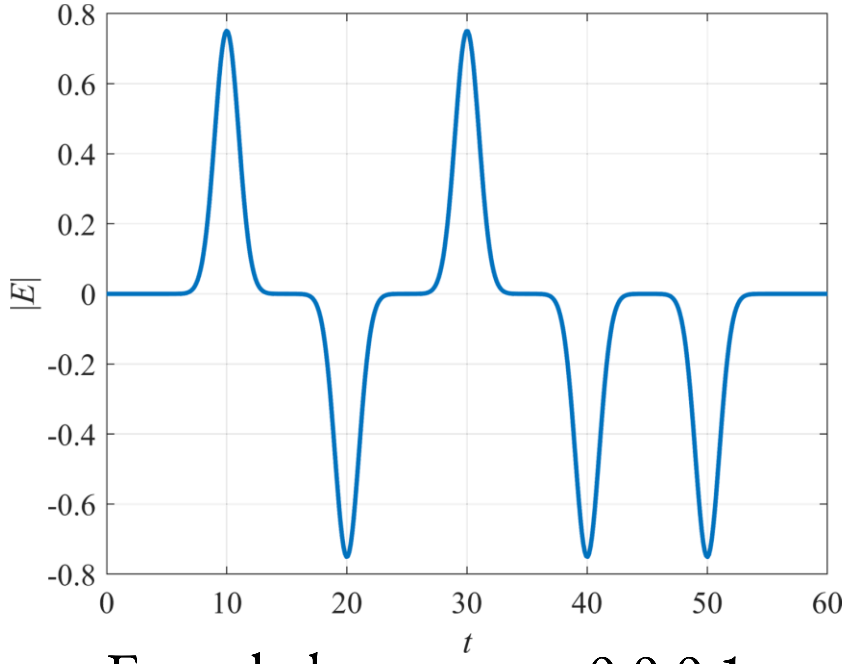
$$\begin{aligned} a_k &= 1 \quad \text{with probability} \quad p_1 = 1/2 \\ a_k &= -1 \quad \text{with probability} \quad p_2 = 1/2 \end{aligned} \qquad (9)$$



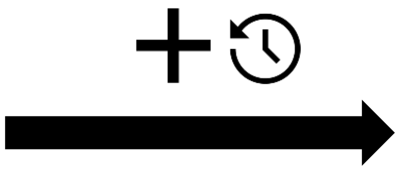
Output data decoding

Decoding. Modeling case

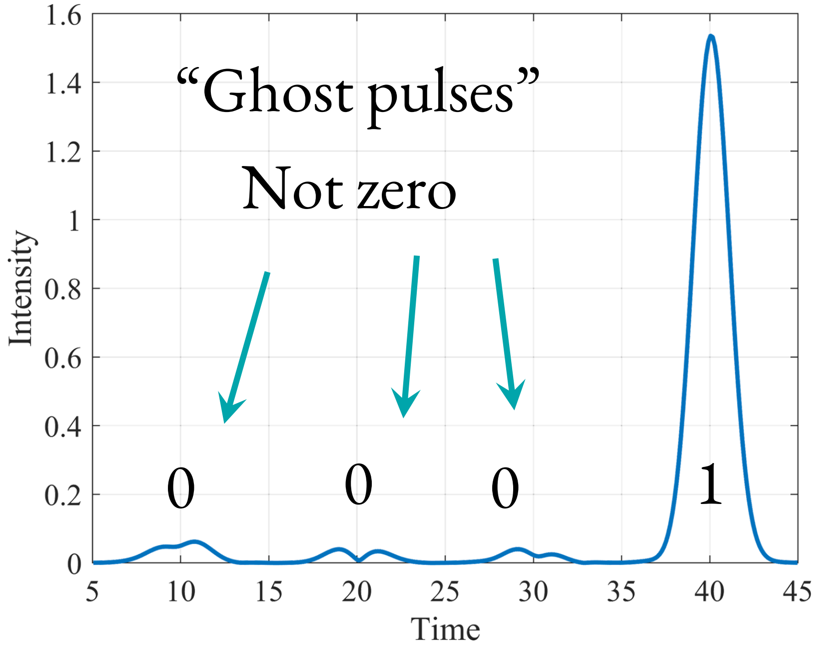
Input signal



Encoded sequence: 0 0 0 1



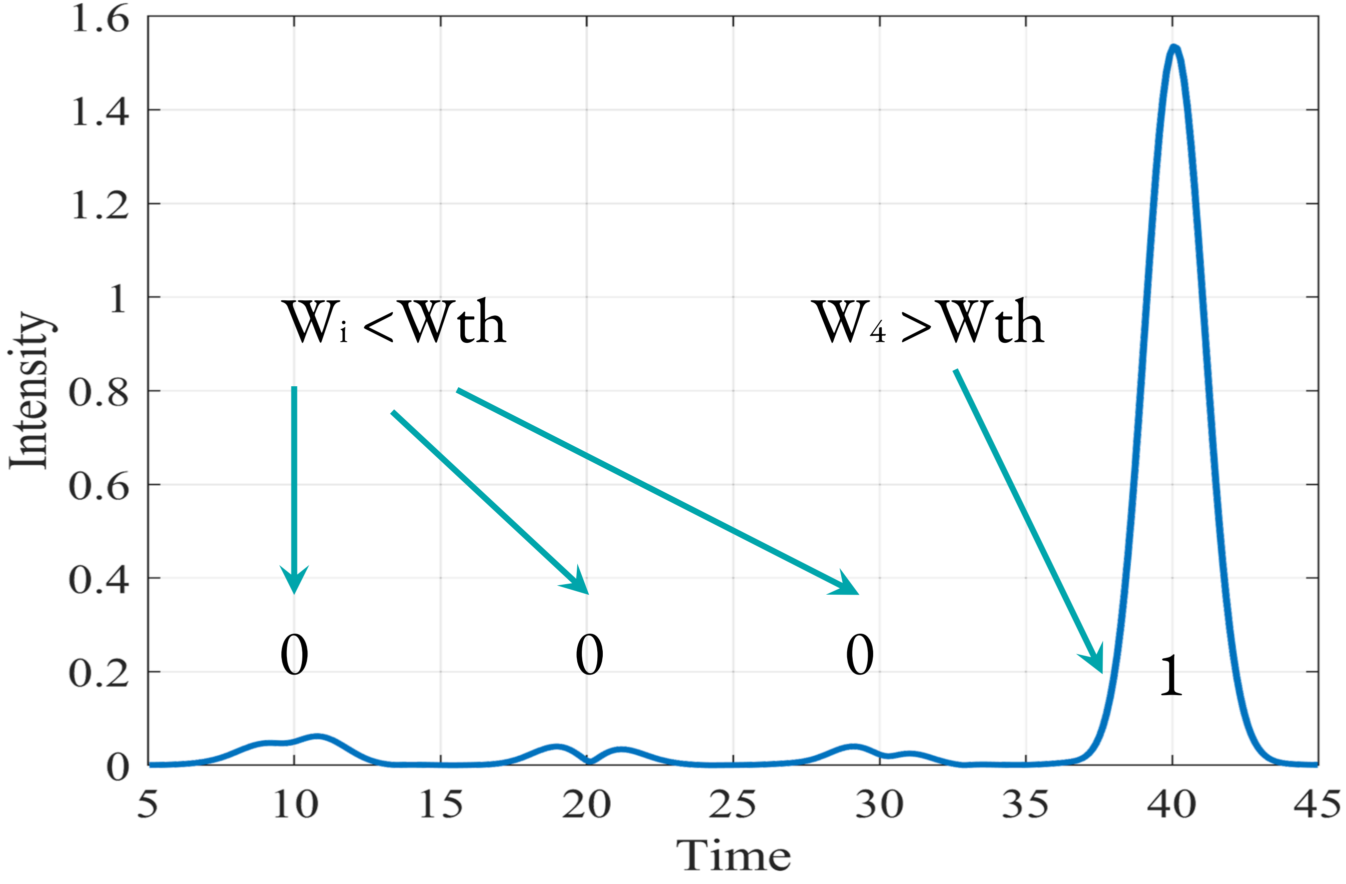
Output decoded signal



$\varepsilon = 0.1$

$L = 20$

Direct decoding. Modeling case



Decoding bit sequence:
0 0 0 1

↓

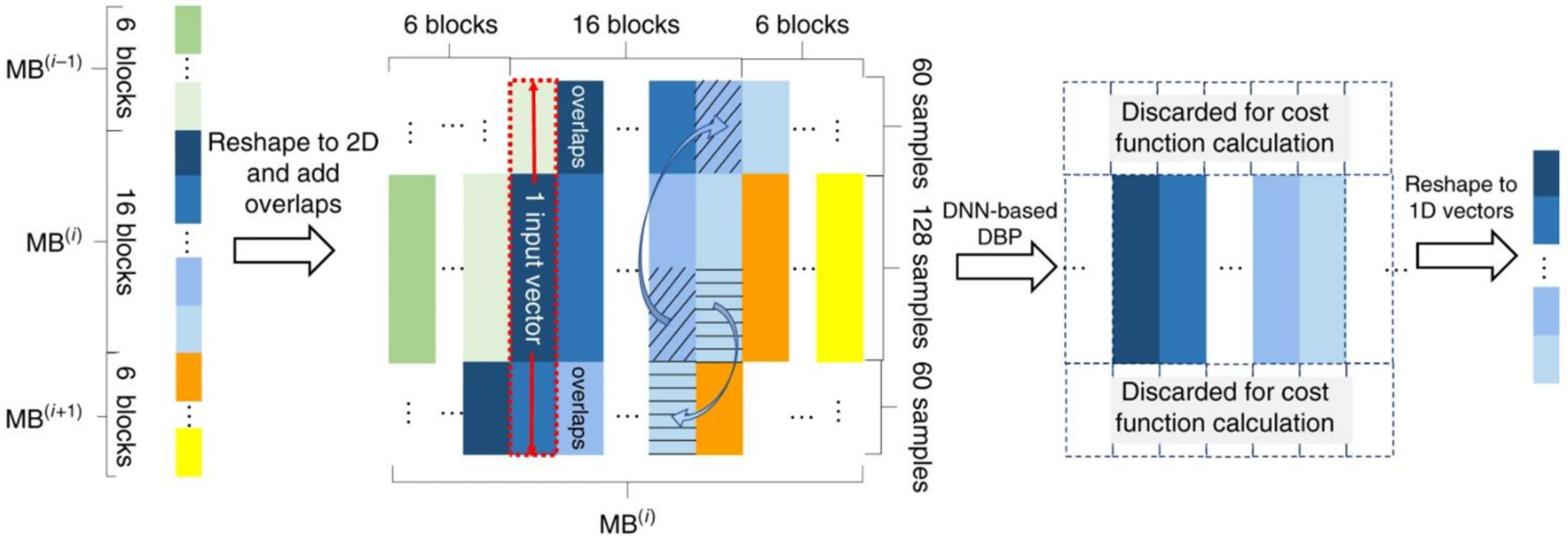
BER - Bit Error Ratio

Wi - energy of ith pulse

Wth = 0.5*W(ligical 1) - threshold

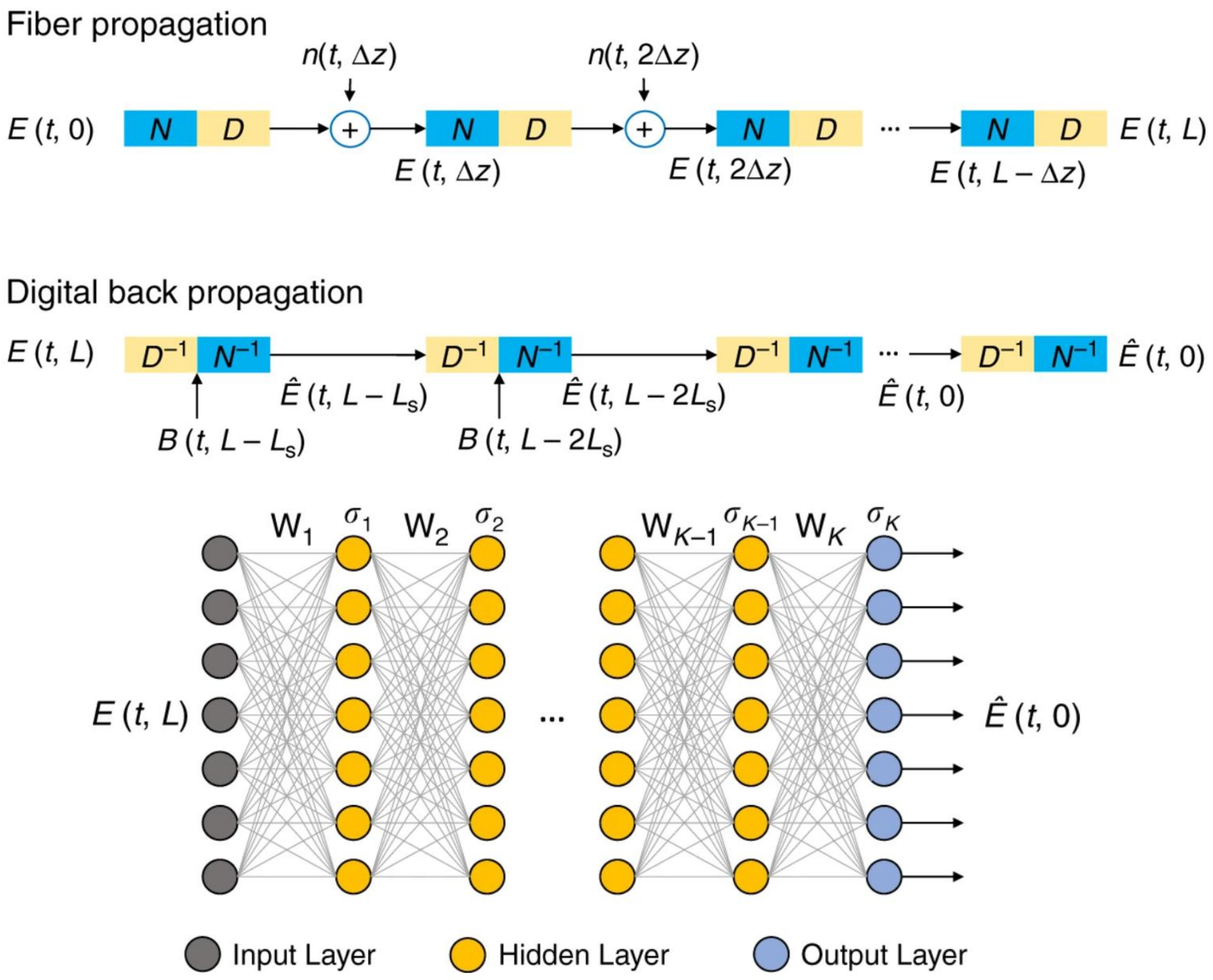
Data preparation

- 1d time data - simple time series
- 2d time data - regrouping time in 2d blocks



Source: https://www.nature.com/articles/s41467-020-17516-7

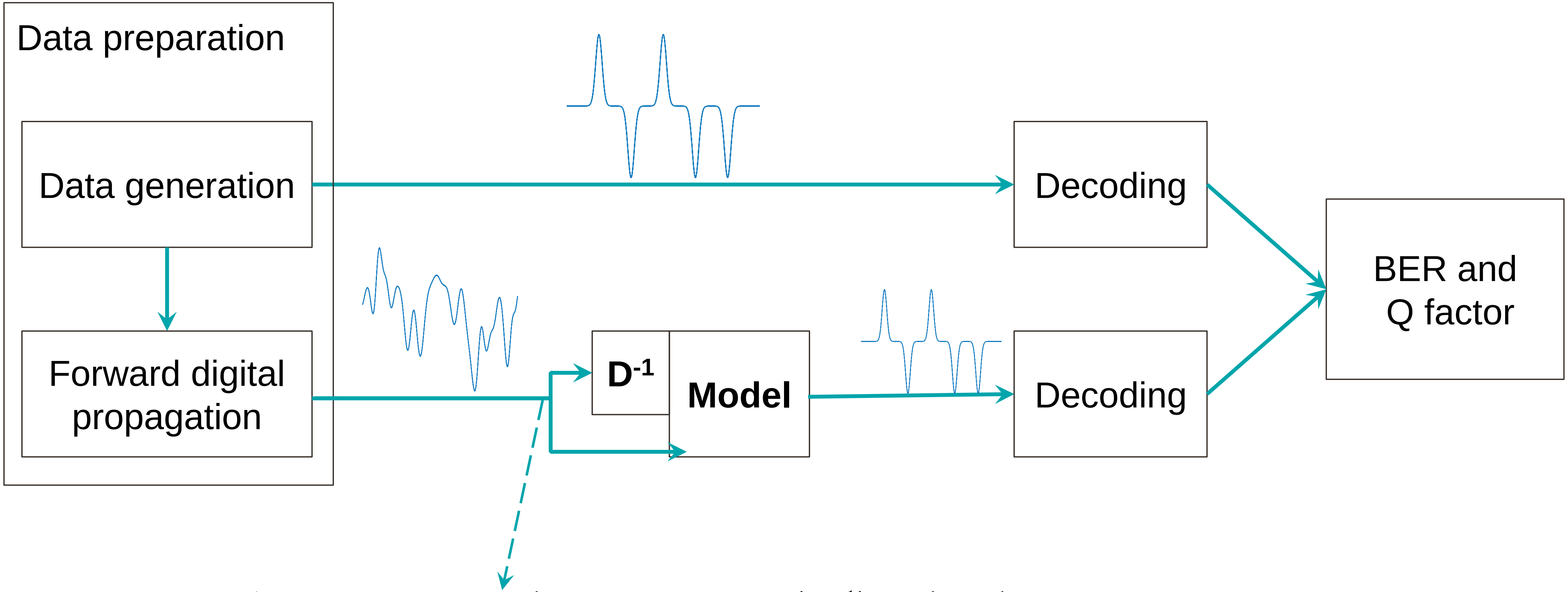
Base work: DNN based DBP



Source: https://www.nature.com/articles/s41467-020-17516-7

Workflow

Workflow



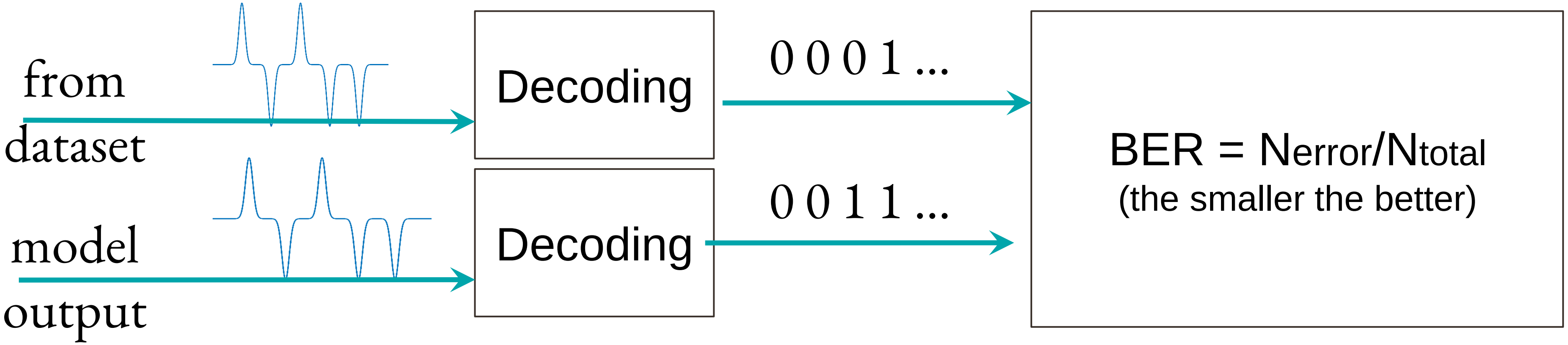
Two variants: with compensation (D^{-1}) and without compensation

Metric estimation

- Loss: Error Vector Magnitude (EVM) and MSE

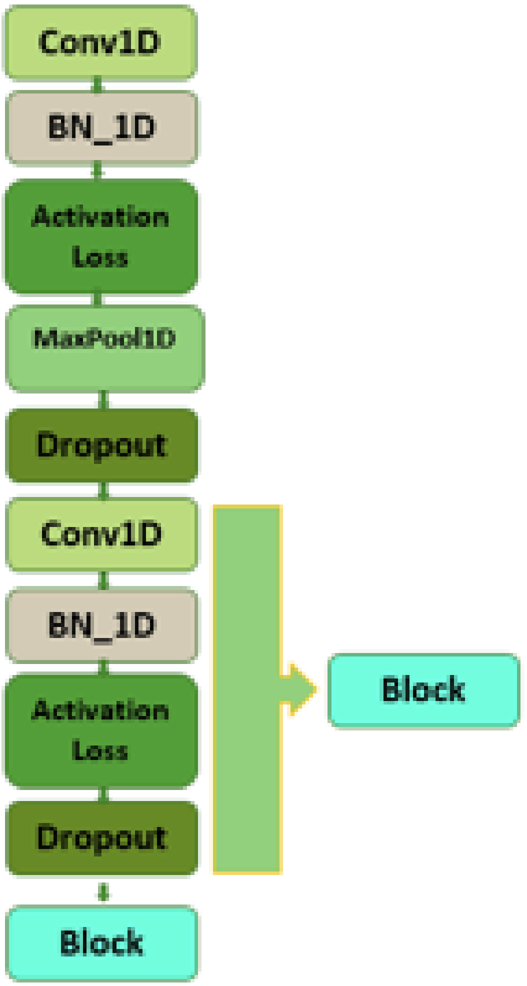
$$\frac{\left|\hat{E}(t,0)-E(t,0)\right|^2}{\left|E(t,0)\right|^2}$$

- Evaluation: BER and Q factor

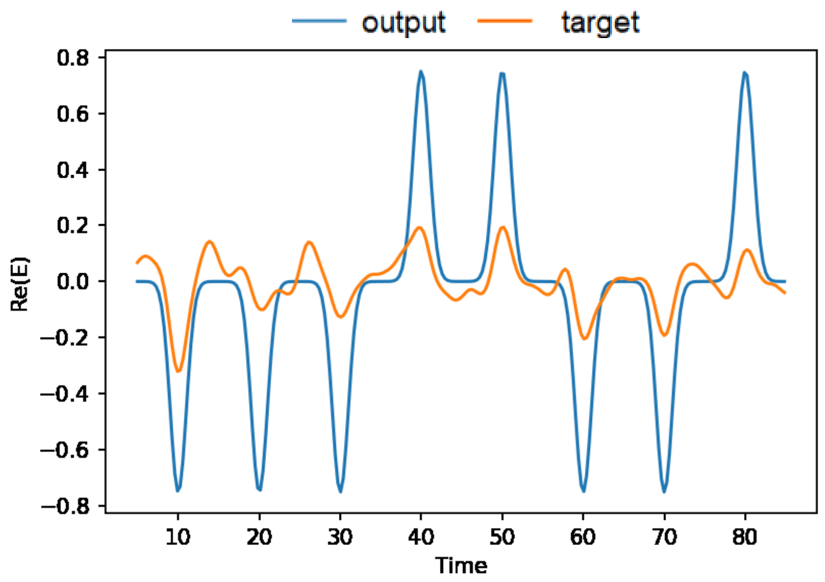


Convnet

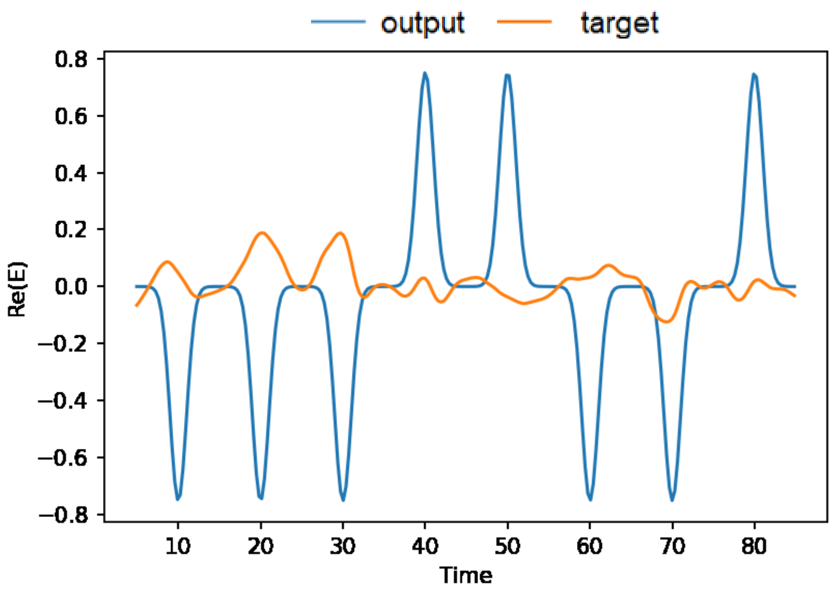
Architecture



Results:



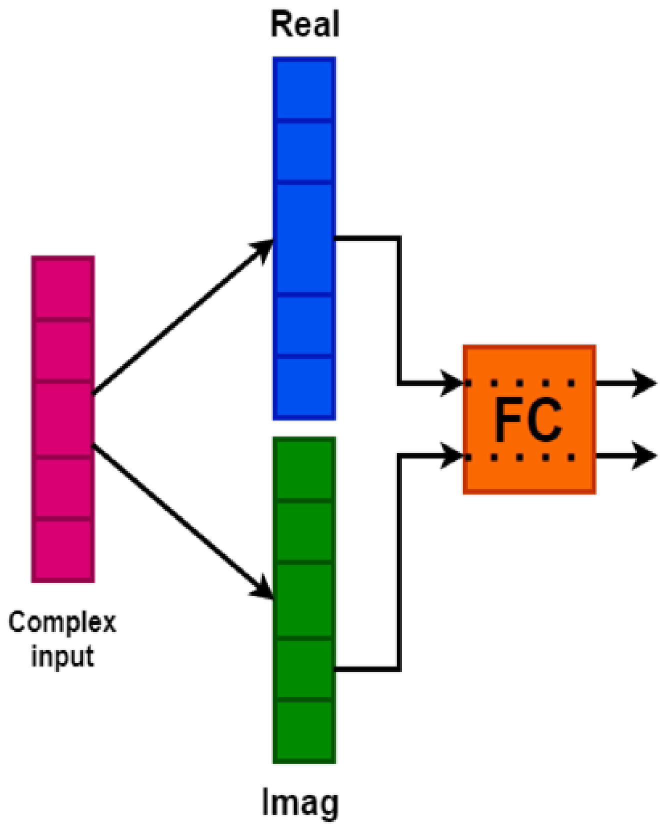
Without compensation



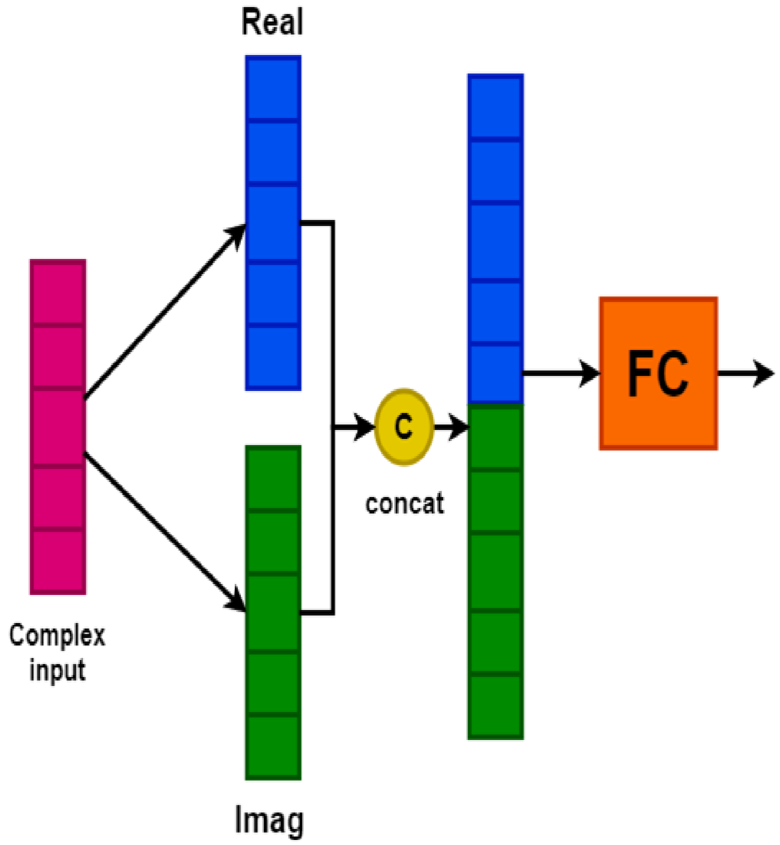
With compensation

FC-models

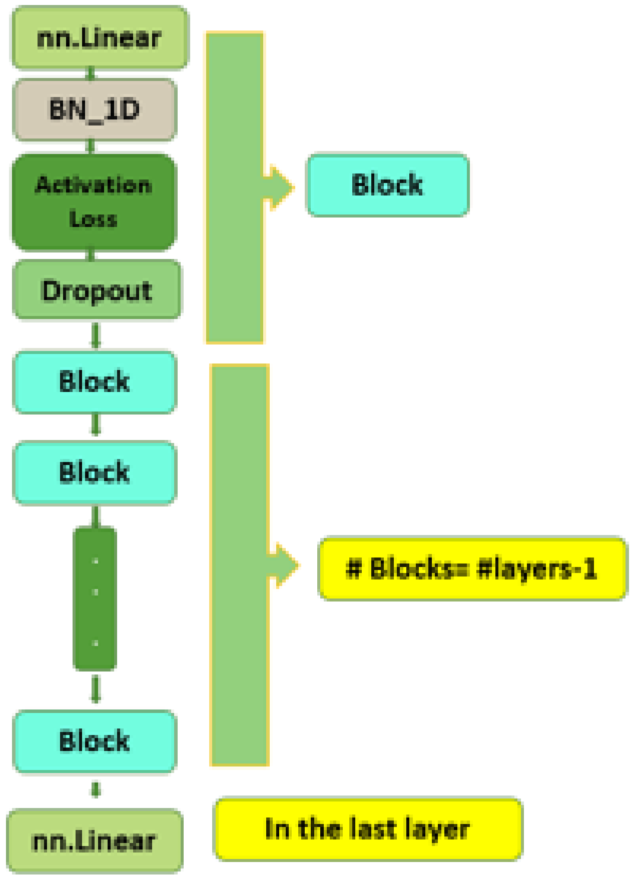
With parallel layers



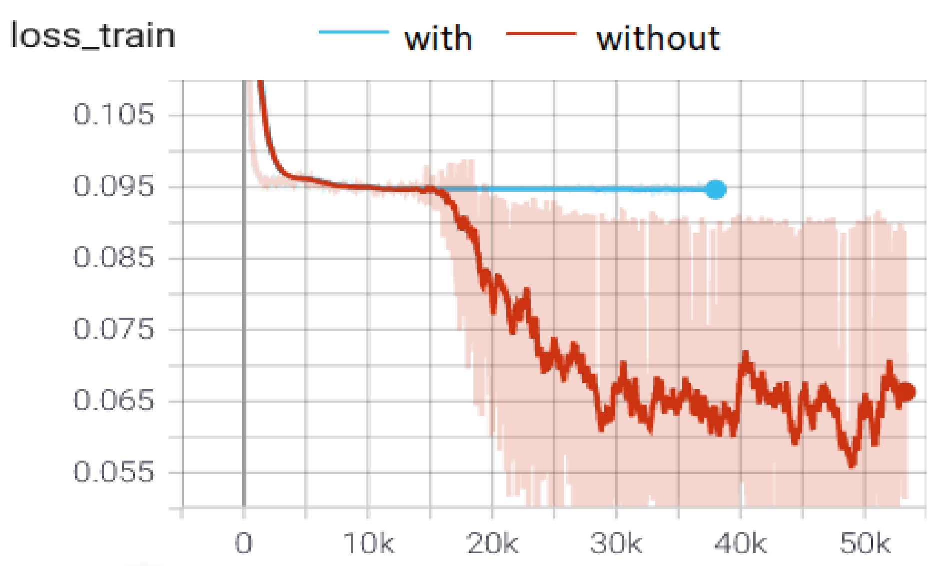
With concatenation

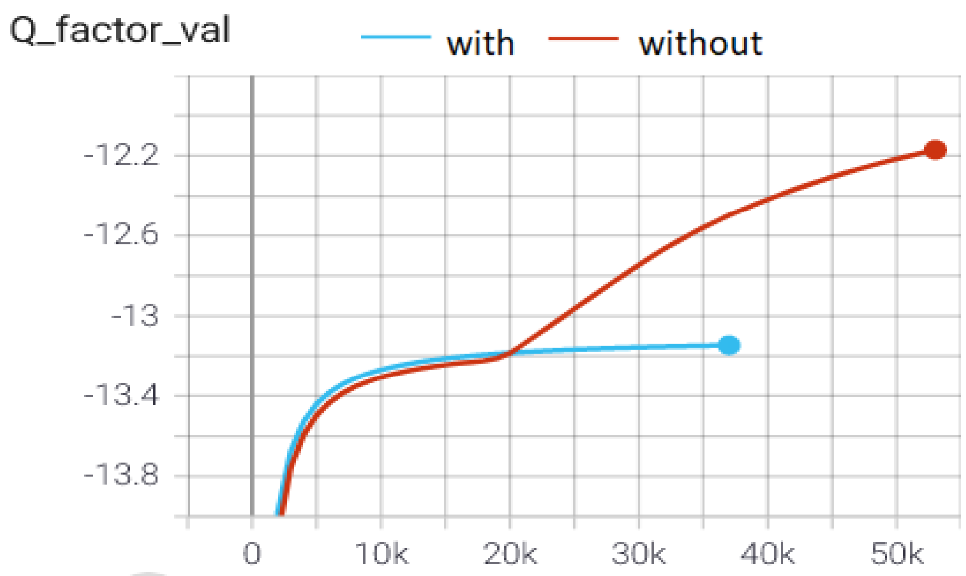


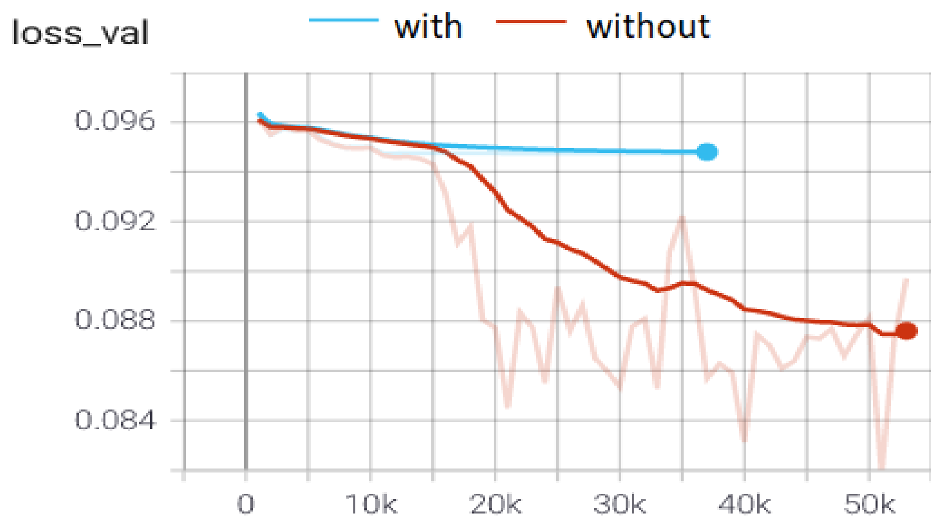
FC architecture

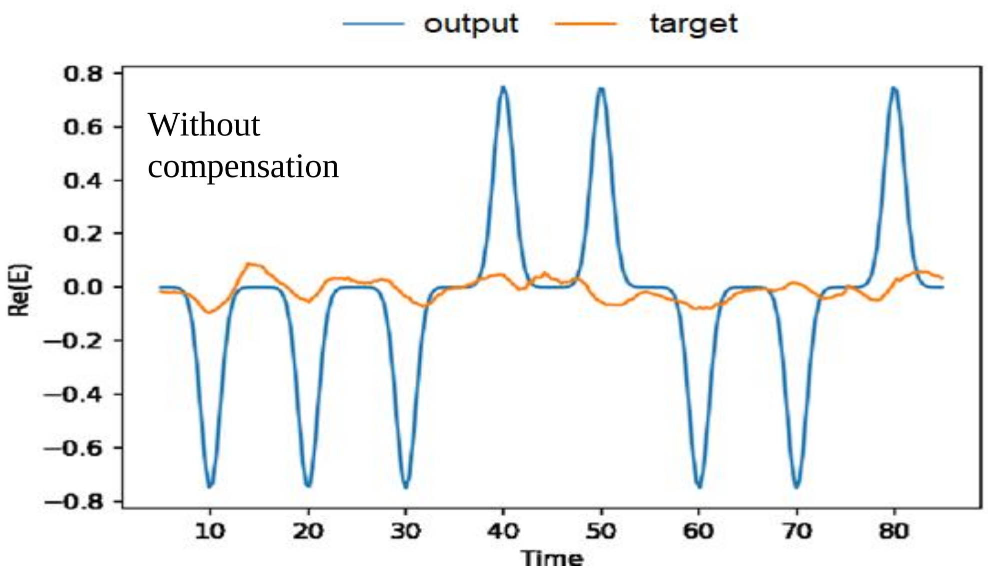


FC-model with parallel layers

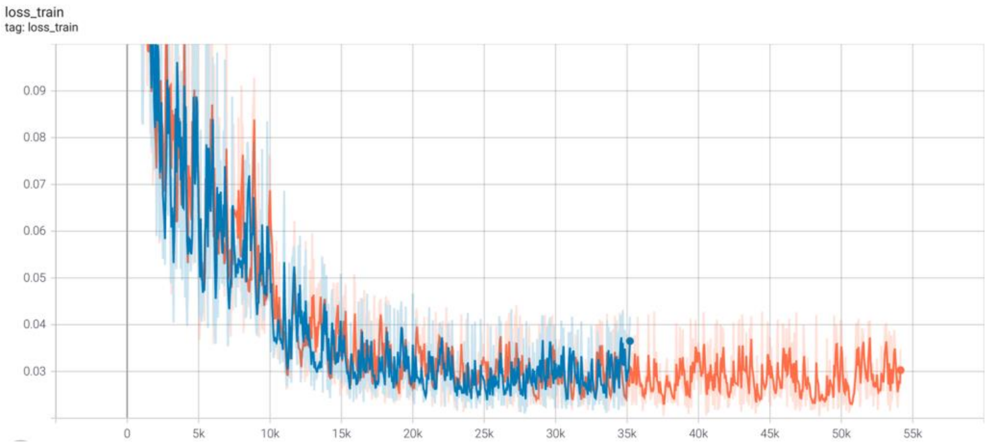


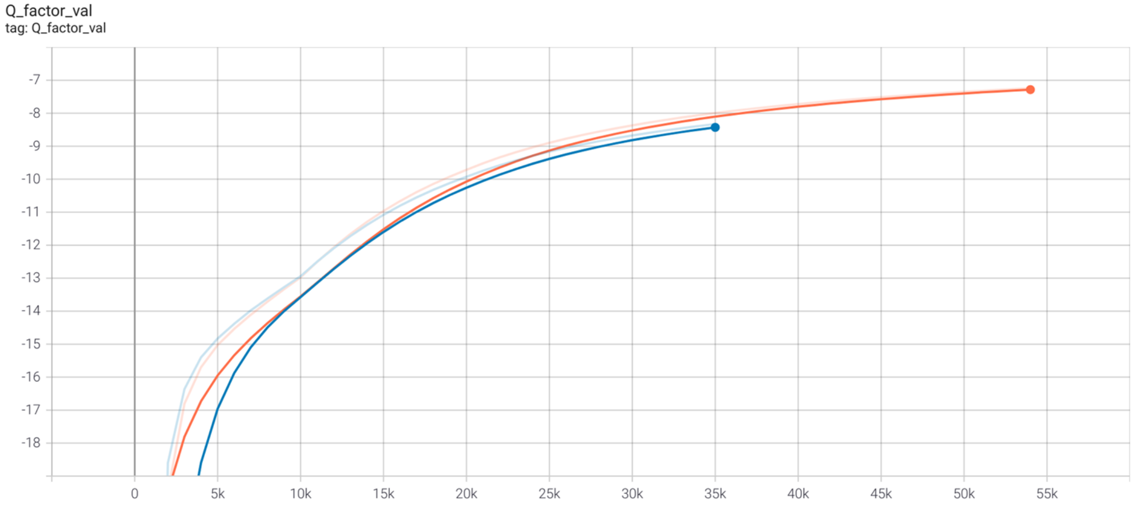


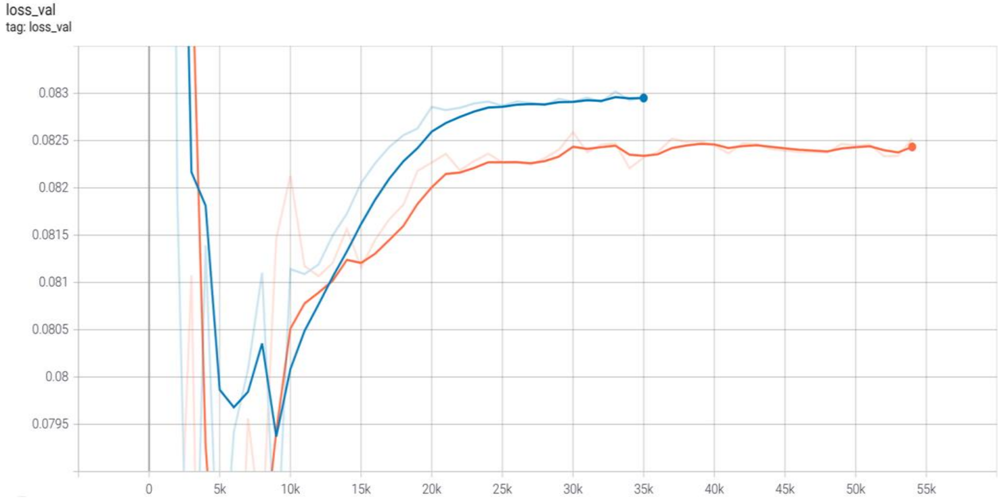




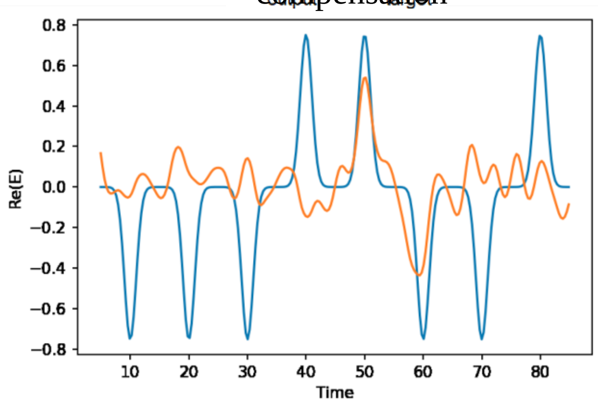
FC-model with concatenation (train)



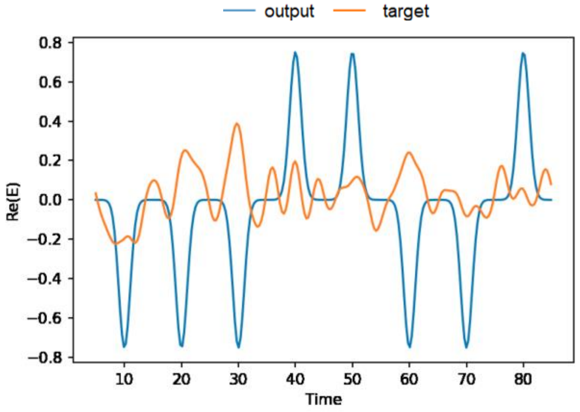




Without compensation



With compensation



Literature

- **Nonlinear optics:** Agrawal, G. P. (2000). Nonlinear fiber optics.
- **Coherent communications:** https://www.osapublishing.org/jlt/abstract.cfm?URI=jlt-34-1-157
- **DNN based DBP:** https://www.nature.com/articles/s41467-020-17516-7

Another Textbooks for Additional Reading:

- B E A Saleh, M C Teich, “Fundamentals of Photonics”, ISBN 978 0 471 35832 9 2007
- G P Agrawal, “Fiber optic communication systems”, ISBN 0 471 21571 6 John Wiley Sons Inc New York, 2002
- Ivan P Kaminow Tingye Li, Alan E Willner “Optical Fiber Telecommunications Systems and Networks”, SIXTH EDITION, ISBN 978 0 12 396960 6

Thank you for attention

Our team:

Ilya Kuk
- Proposing a project idea, holding a seminar with a detailed explanation of the problem, proposing an idea for the implementation of neural network models.
- At all stages, advising team members on the implementation of the code.
- Implementation of the original code for generating data using the split-step method
- Fc-model with concatenation training

Razan Dibo
- Prepare the template of the report.
- Responsible for Introduction, related work, Models architecture figures, references in the report.
- Search for alternative models and propose CNN+biLSTMP: a CNN model using 1D con volutional layers and a biLSTMP layer

Mohammed Deifallah
- Optimization of Data Generation and Transformation.
- Q-Factor (performance metric) implementation.
- Introduction of a new type of baseline models: a CNN model using 1D convolutional layers.

Alexander Blagodarnyi
- Video presentation preparation.
- Both fully connected linear models preparation and testing.
- A part of introduction and literature review preparation

Alexey Larionov
- Creating of GitHub repository, README file, sole review of all the pull requests and the fixes they required.
- Implementation of the whole project structure, training pipeline using PyTorch Lightning, including starting a training from YAML config files, saving of checkpoints, easy Jupyter Notebook for more advanced launch of training (using Google Drive, checkpoints), example models dedicated for team members
- Pregenerating 6 variants of datasets, including datasets with nonconstant nonlinearity
- Training and collecting results of Fully Connected model without concatenation, with tweaking of default parameters

Sergei Gostilovich
- Make the final presentation
- Design code for BER estimation
- Work on Section 3 of report. (Method description mainy on parts: 3.1, 3.2, 3.4)

Stanislav Krikunov
- Video presentation preparation.
- Help with fully connected linear models preparation and testing.
- A part of introduction and literature review preparation.