Machine Learning on Air

Overview and Tutorial on Open-Source Machine Learning Frameworks for DSP and Radio

Andrej Rode, Laurent Schmalen

01.02.2026

Who am I?

- Started using GNU Radio during my studies in **2015**
- Internship at Ettus Research in **2016**
- Contribute code and manage the CI/CD of the GNU Radio project ∼**2017**
- GNU Radio project infrastructure (website, wiki, conference stuff, . . .) since **2018**
- Finished M.Sc. in EE/IT **2019** at KIT in the Communications Engineering Lab (CEL)
- Two years at the European Space Agency (ESA) working on and learning about satcom
- Since **2021**: PhD student at KIT in the CEL working on machine learning for fiber-optical communications

Overview

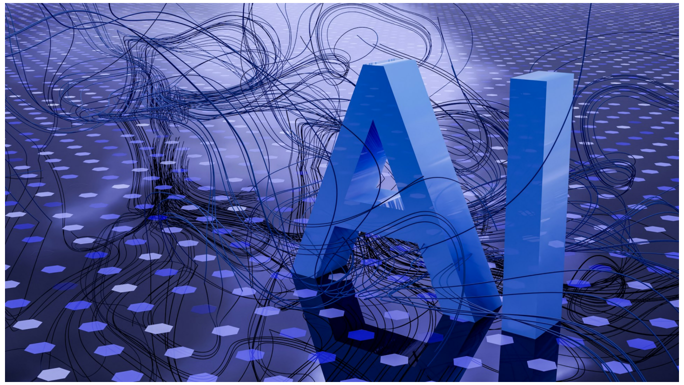
- Introduction to Machine Learning for DSP and Radio

- Free and Open Source ML Toolboxes for the PHY

- (Short) Tutorial with Sionna and MOKka

AI and Machine Learning

- Current hype around AI requires a short disambiguation and definition of what this talk is about



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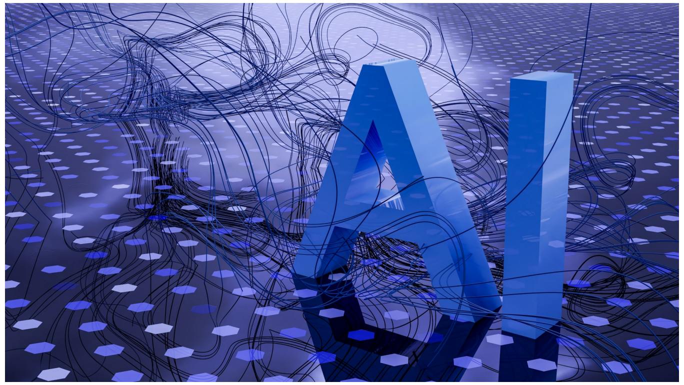

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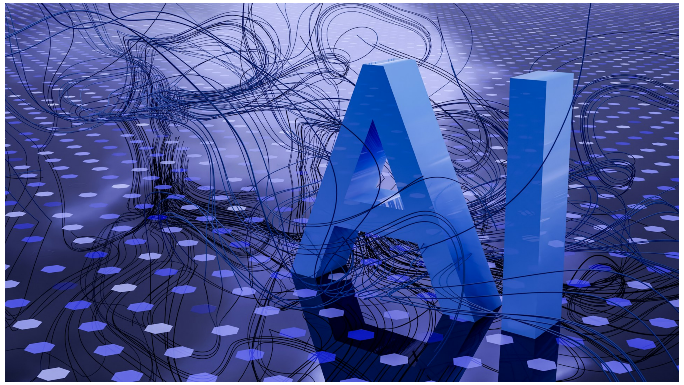

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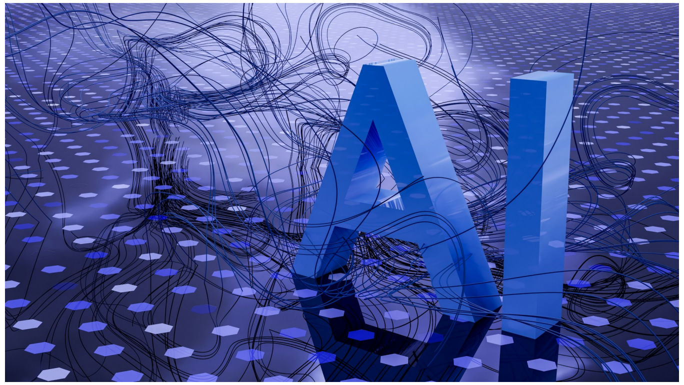

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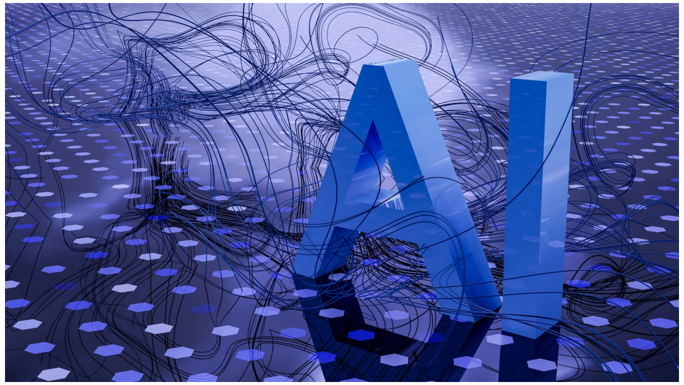

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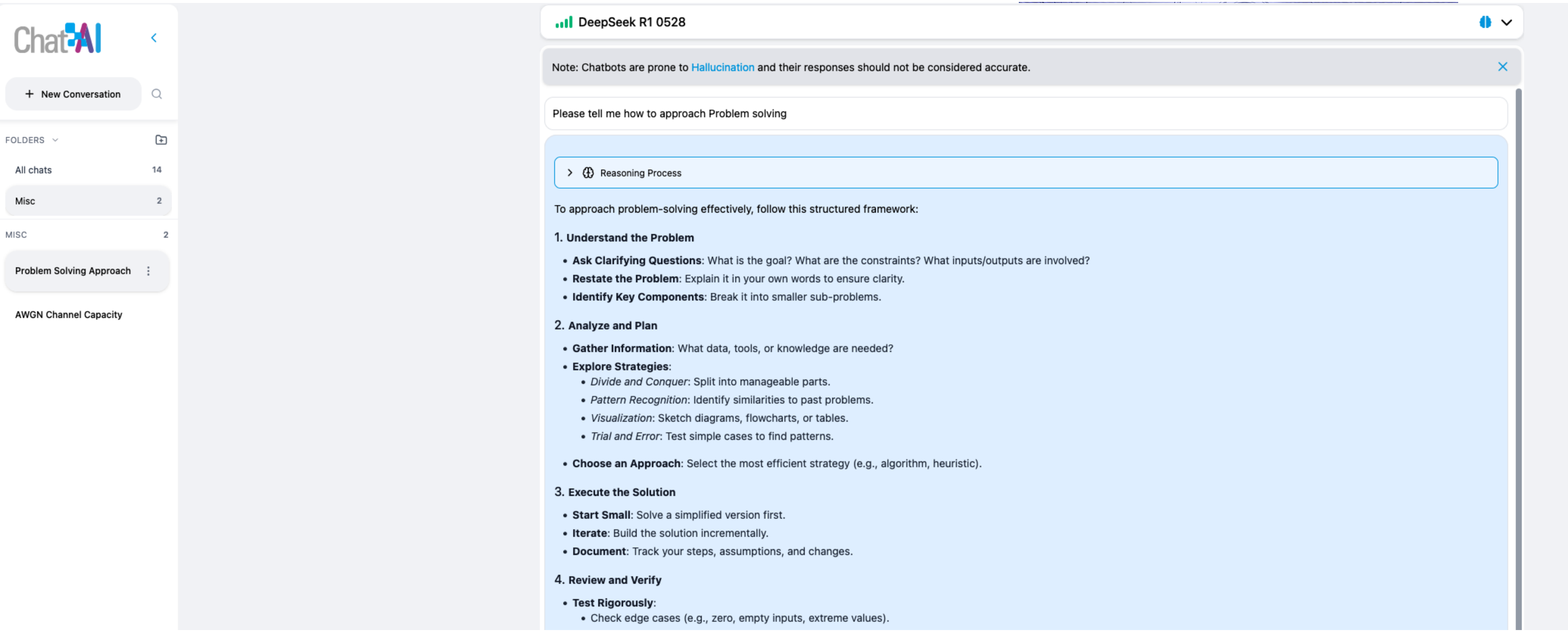

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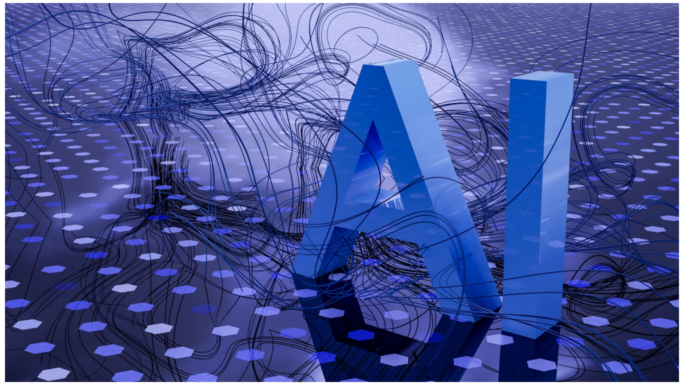
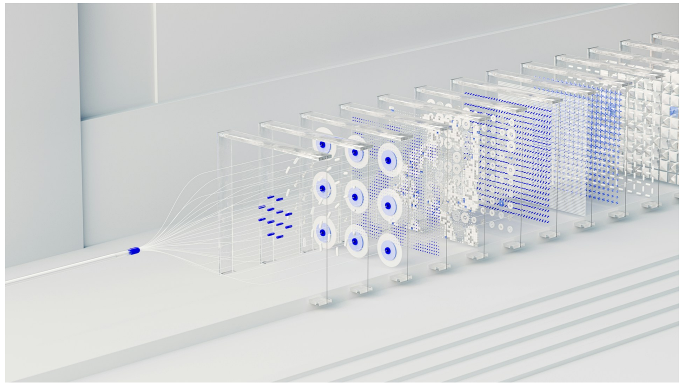
→ We will take look at a communication system and see how we can use open-source tools to apply machine learning





What is Machine Learning?

Machine learning (ML) according to [Mit97]

“A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E.

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$\rightarrow$ **This sounds a lot like we already had machine learning (but not in "modern" data-driven way) in DSP and communications!**

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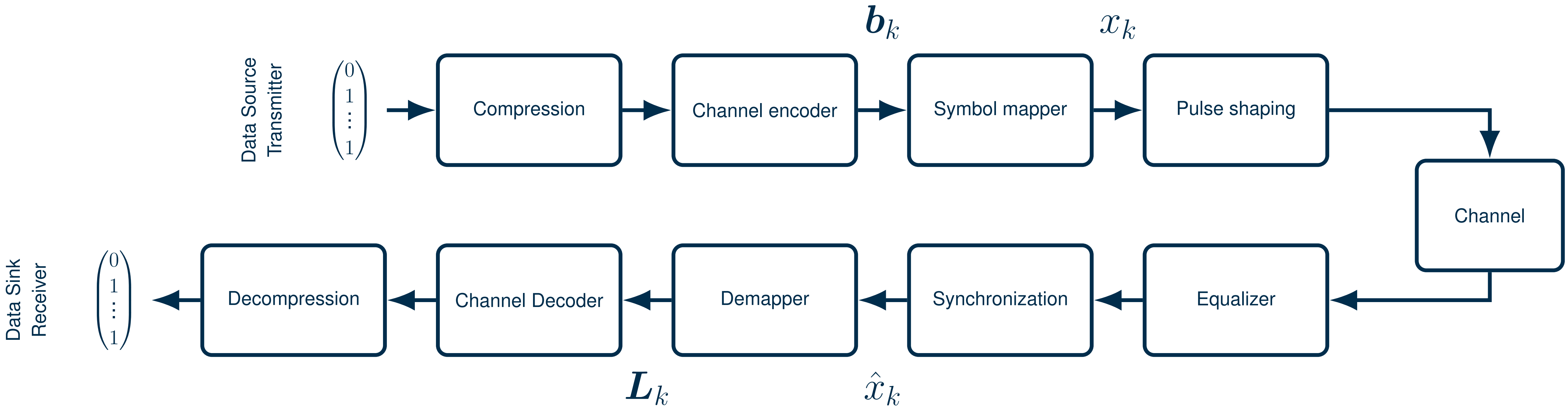
Data-driven End-to-end Offline Optimization in Communications



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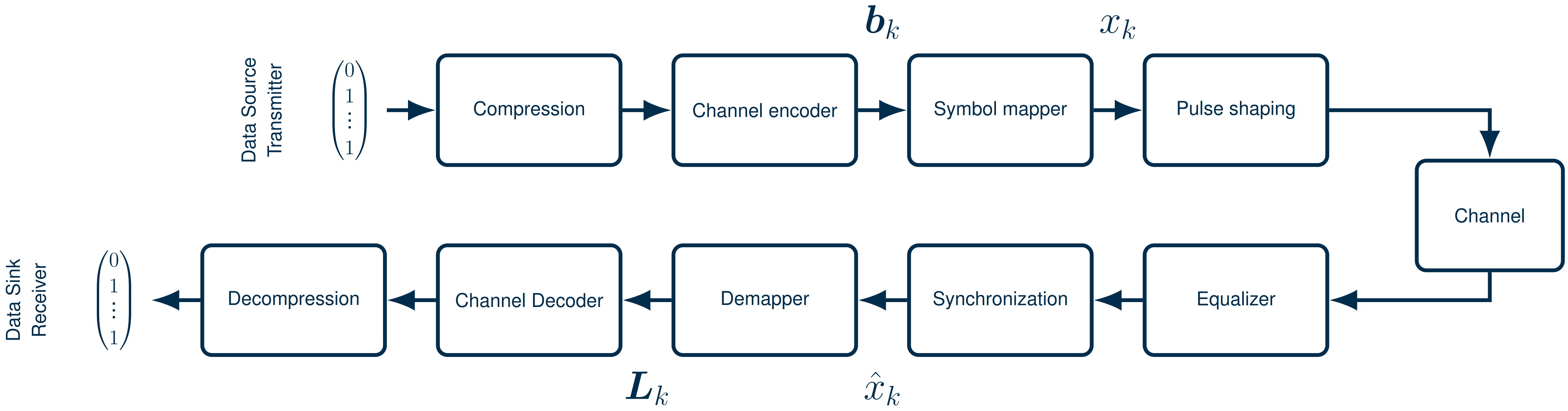

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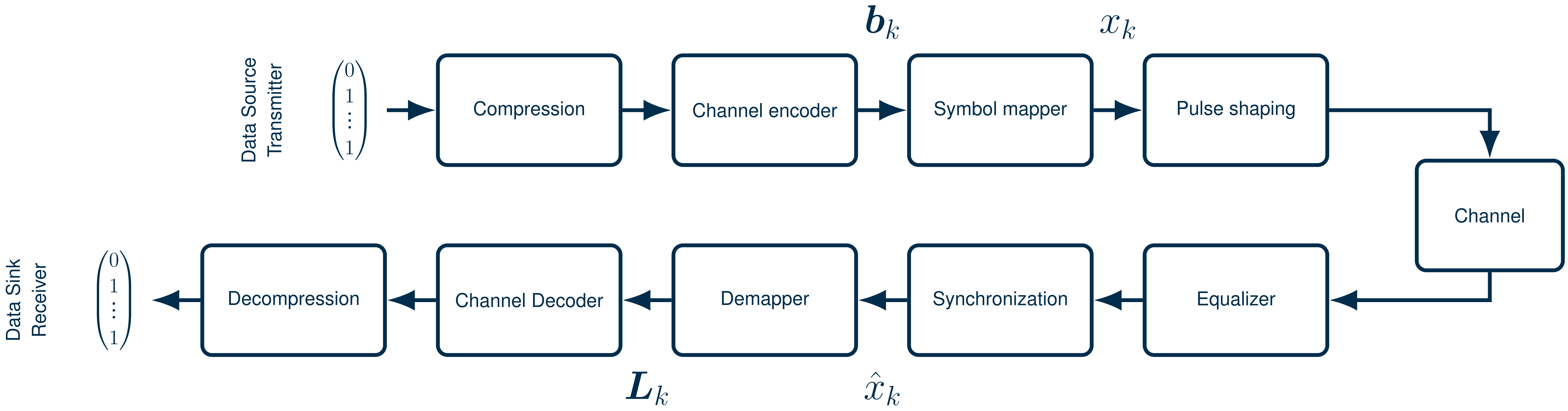

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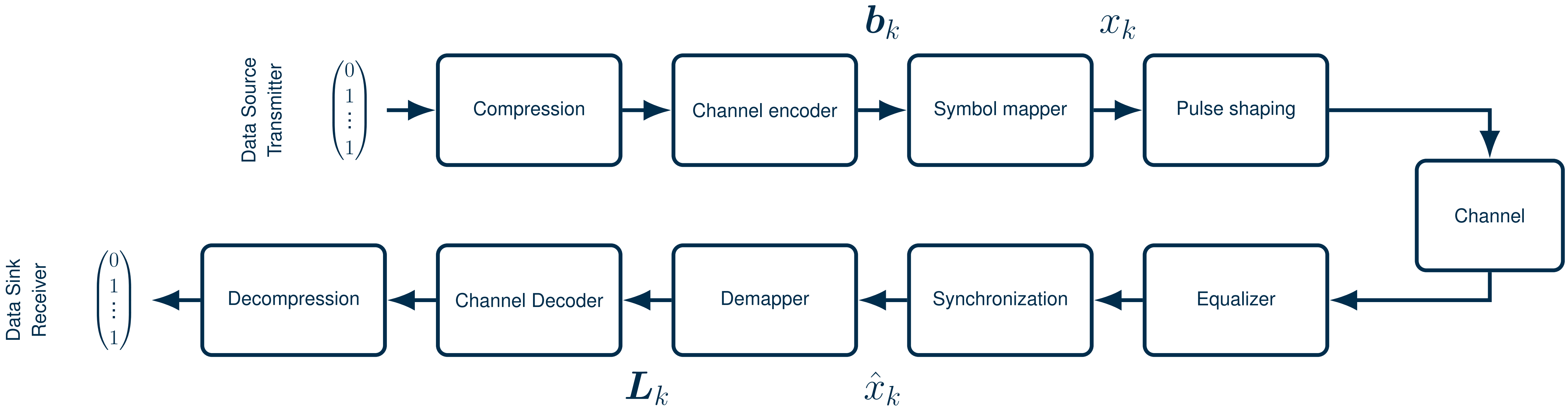

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4. Optimization step $\boldsymbol{\theta}_{t+1} \leftarrow \boldsymbol{\theta}_t - \mu\nabla_{\boldsymbol{\theta}_t}\mathcal{L}$

Performance Measures for Communications

- "Good" objective (commonly: loss) functions

Mean-squared error $\mathcal{L}_{\mathrm{mse}} \approx \frac{1}{K}\sum_{k=0}^{K-1} |\hat{x}_k - x_k|^2$

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mod. binary CE (BCE) $\widetilde{\mathcal{L}}_{\text{BCE}} \approx \frac{1}{K}\sum_{k=1}^{K}\sum_{i=1}^{m}\log_2\left(1 + \mathrm{e}^{(-1)^{b_{k,i}}L_{k,i}}\right) - H(X)$

where

Log-Likelihood Ratio (LLR) $L_{k,i} = \frac{\log(b_{k,i} = 0|y_k)}{\log(b_{k,i} = 1|y_k)}$

Receiver-side Gradient-based Methods in Communications

- Adaptive Equalization with the least mean square (LMS) equalizer introduced in 1960 [WH60]
- System model $\hat{x}_k = \mathbf{f}_k^{\mathsf{T}} \mathbf{y}_k = \mathbf{f}_k^{\mathsf{T}} (\mathbf{H}\mathbf{x}_k + \mathbf{n}_k)$

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- Simple optimization of the equalizer taps $\mathbf{f}_k$ on the (mean) squared error $|\epsilon_k|^2 = |\hat{x}_k - x_k|^2$

$$\min_{\mathbf{f}_k} |\hat{x}_k - x_k|^2 = \min_{\mathbf{f}_k} \big((\hat{x}_k - x_k)(\hat{x}_k - x_k)^* \big)$$

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for a real-valued system

$$\nabla_{\mathbf{f}_k} |\epsilon_k|^2 = \nabla_{\mathbf{f}_k} (\hat{x}_k - x_k)^2 = 2\mathbf{y}_k \epsilon_k$$

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- Update the equalizer taps for the next step

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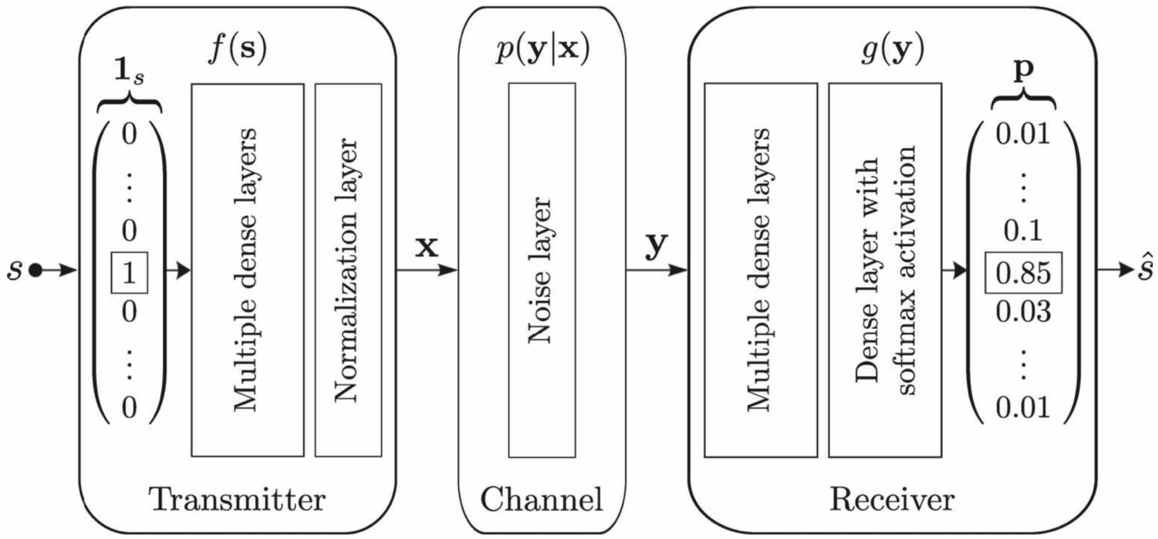
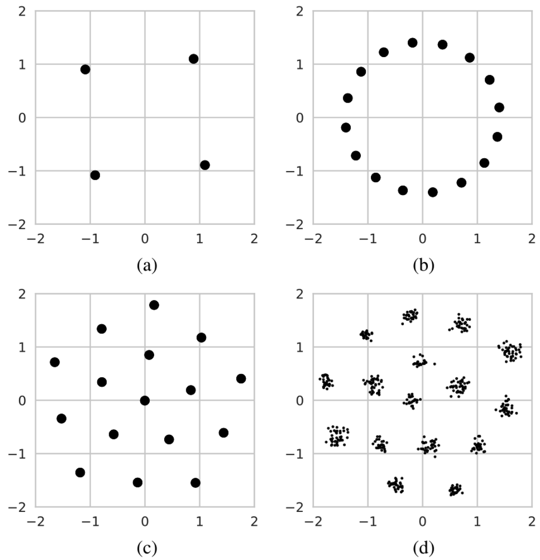
End-to-end Learning for the Physical Layer





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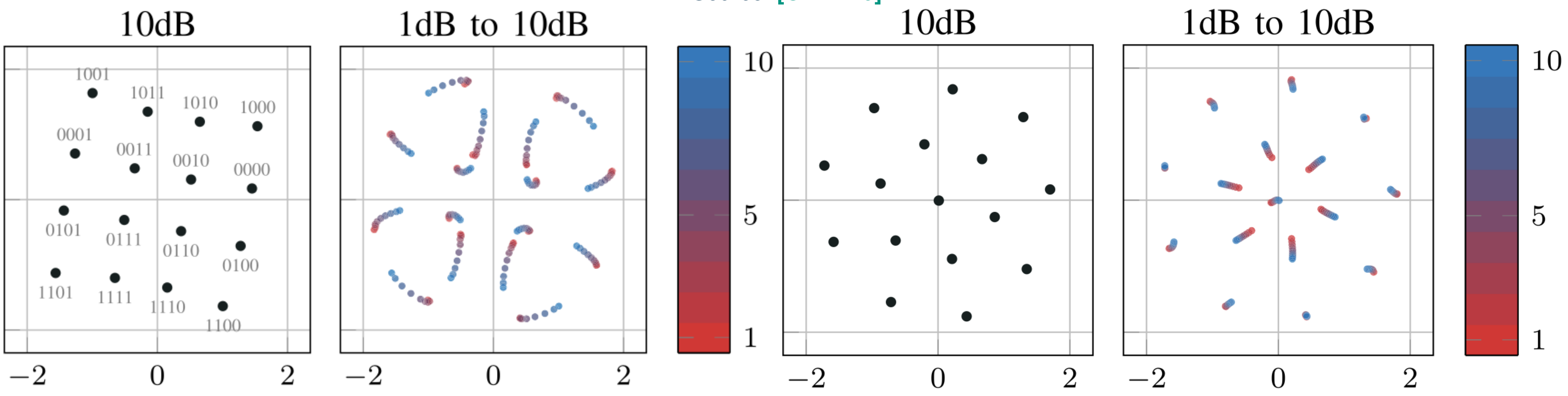

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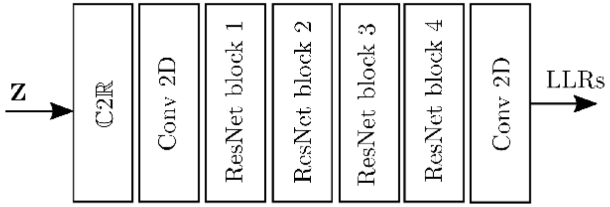
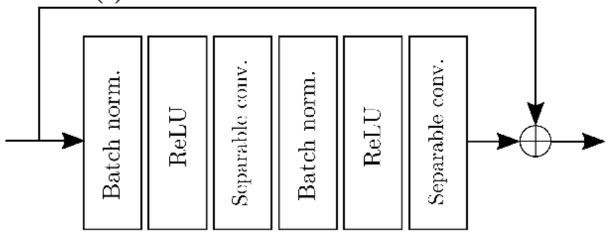
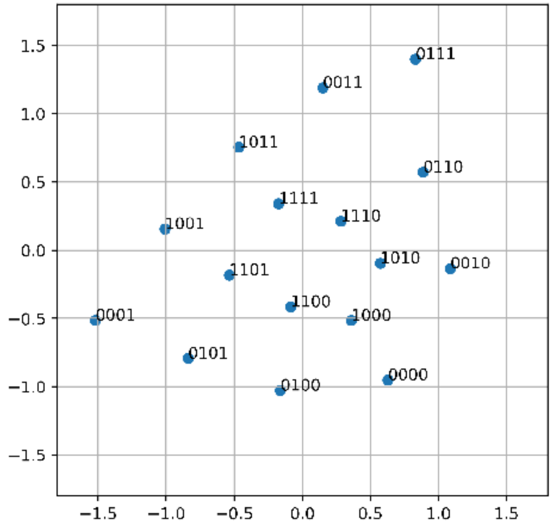


(a) Architecture of the neural receiver.



(b) Architecture of a ResNet block.



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$\rightarrow$ The authors of the research papers of course!

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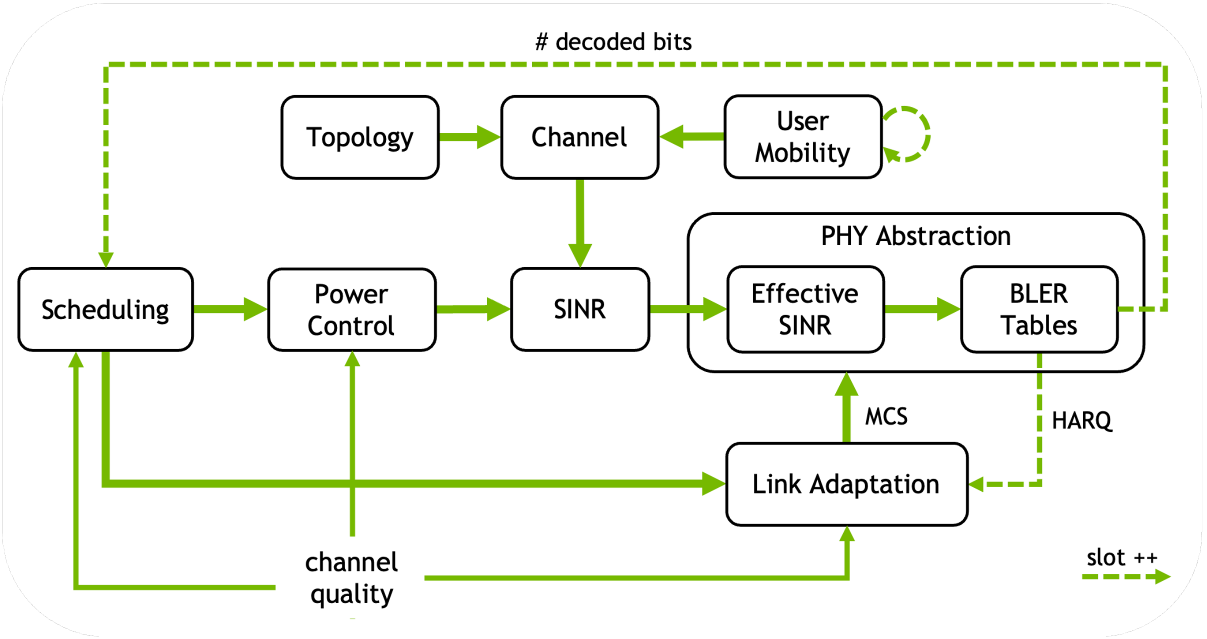

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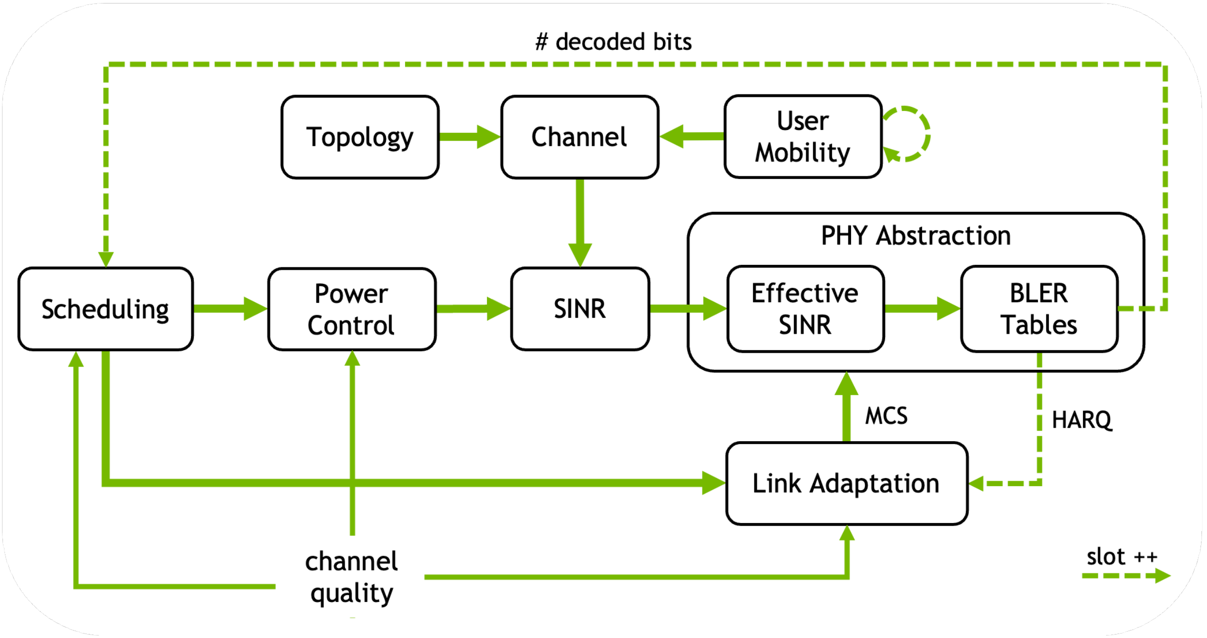
  - Power Control
  - Scheduling



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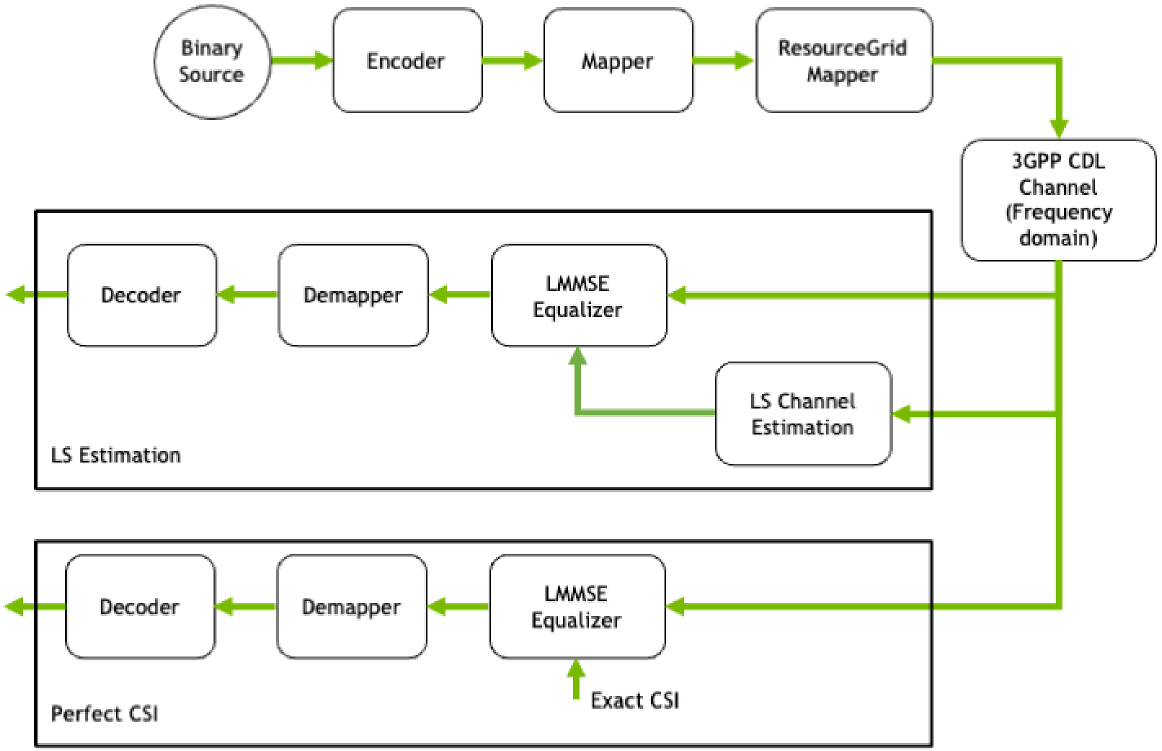

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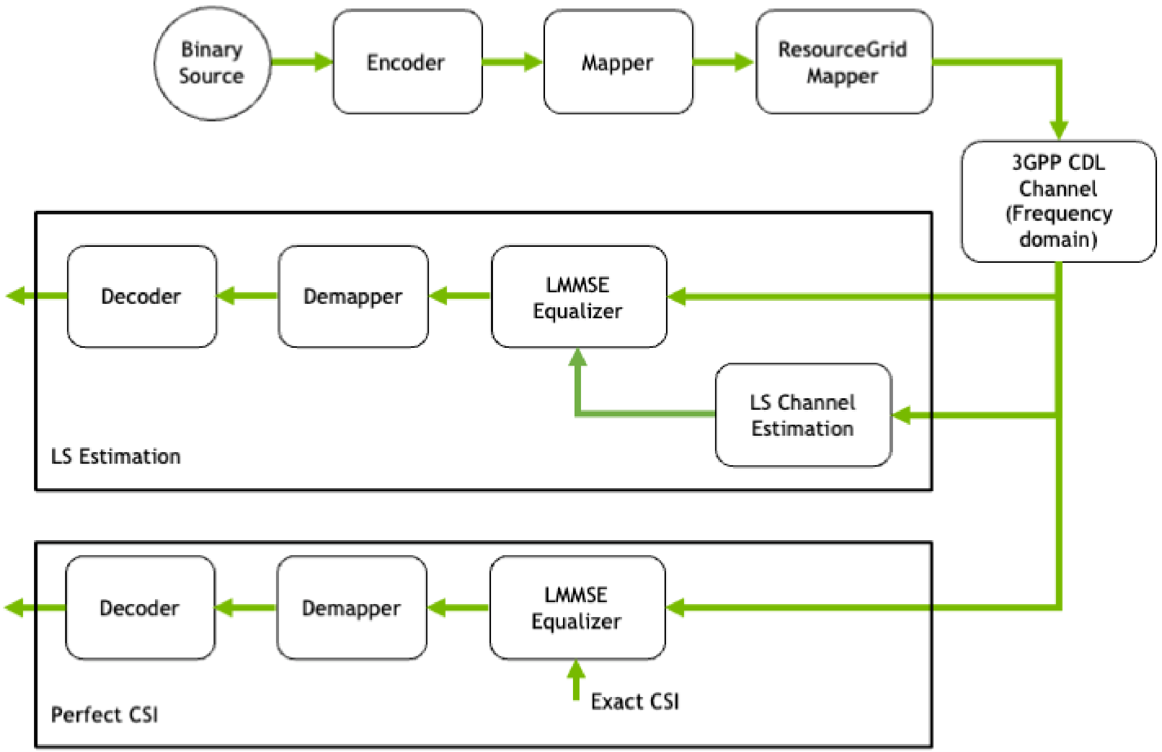
  - Forward Error Correction
  - Mapping
  - Channel Models (Wireless, Optical, Discrete)
  - OFDM & MIMO
  - 5G NR



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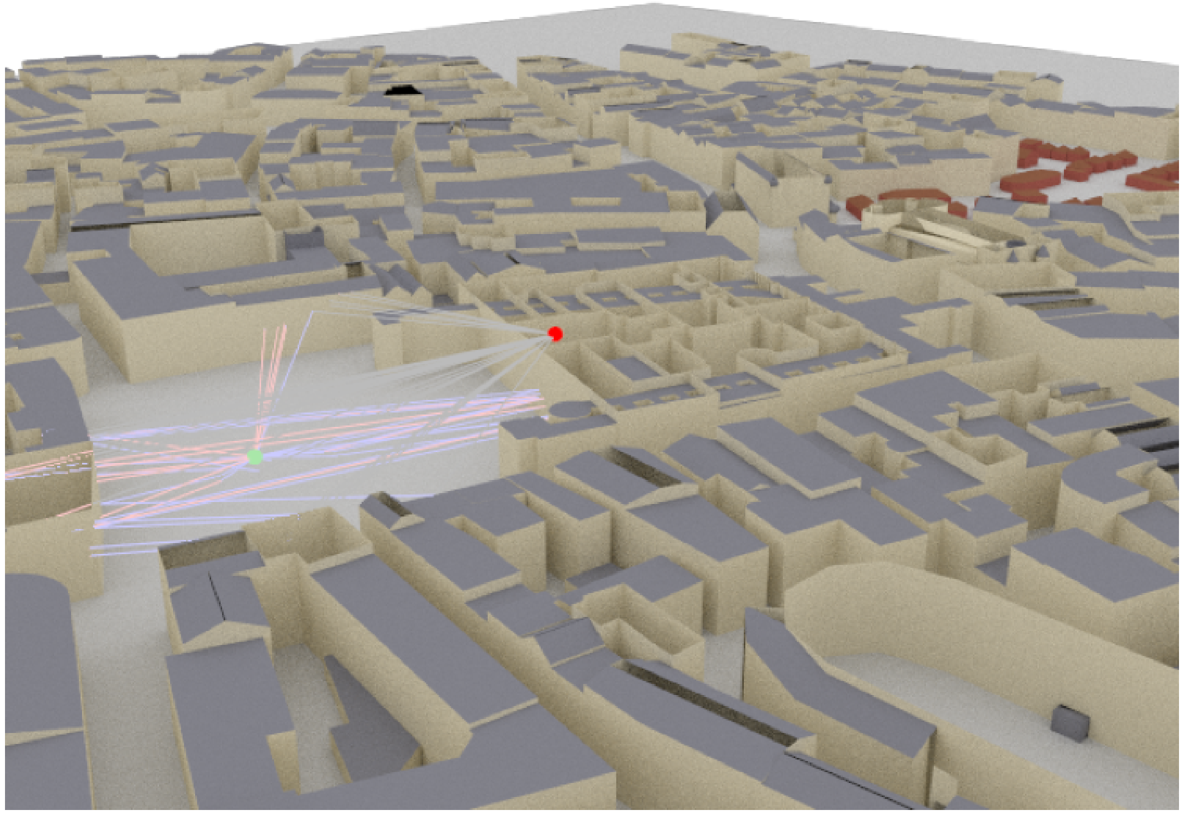

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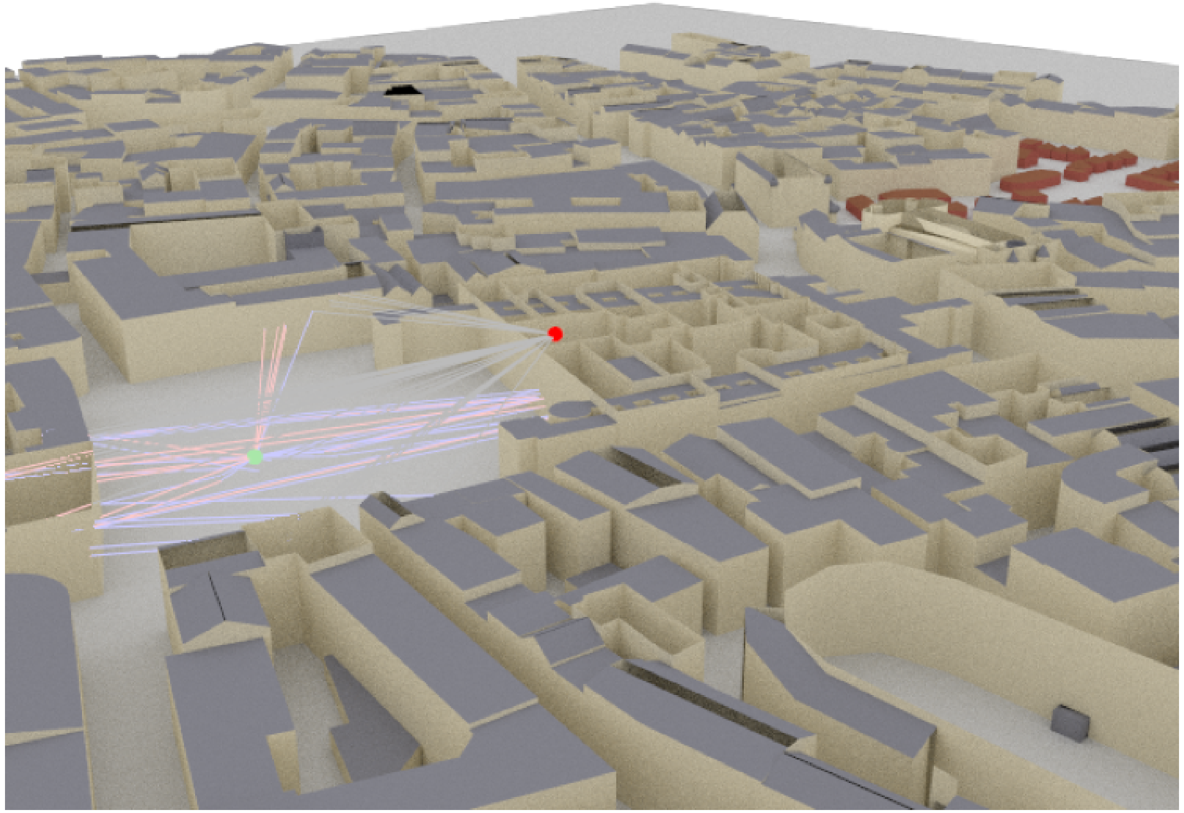
  - Antenna arrays
  - Scenes
  - EM-accurate channel modelling



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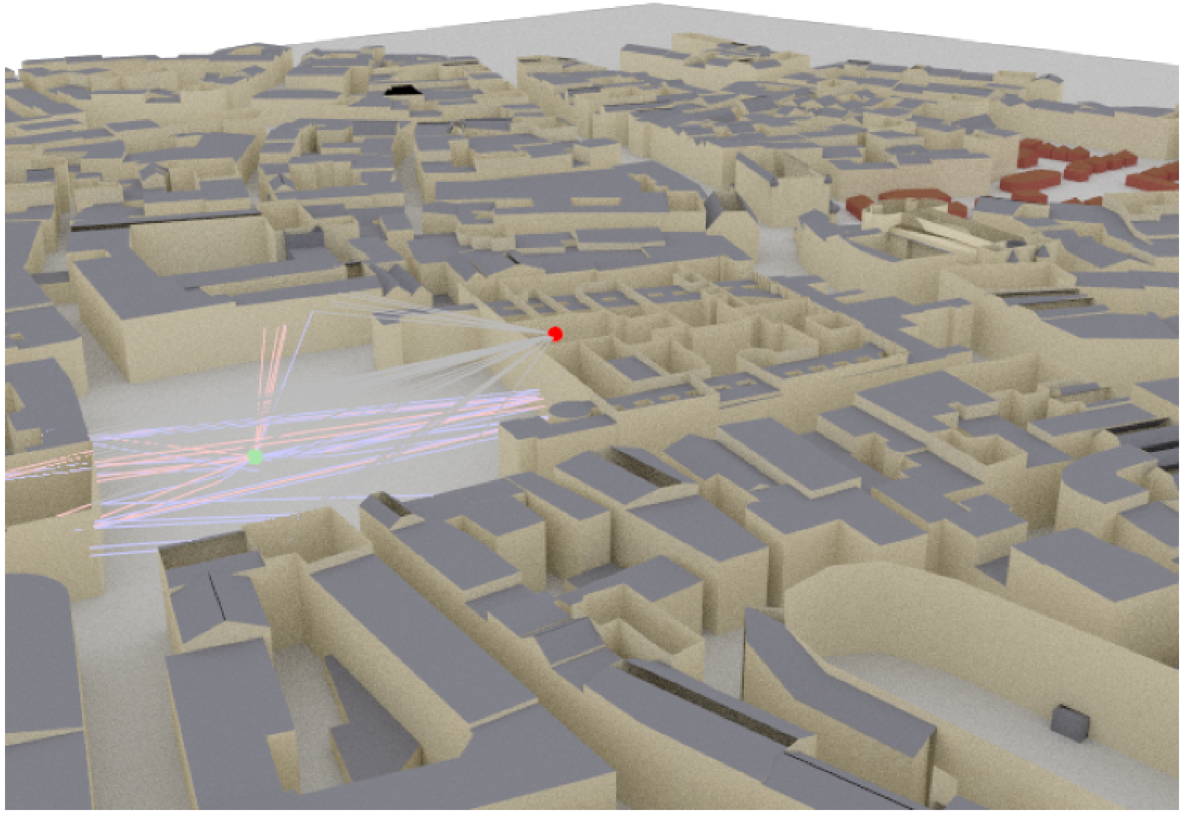

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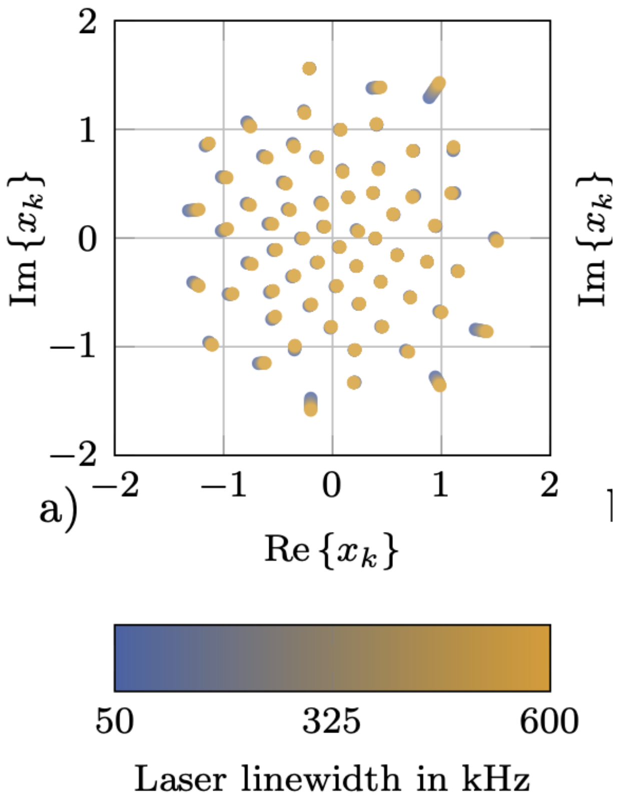

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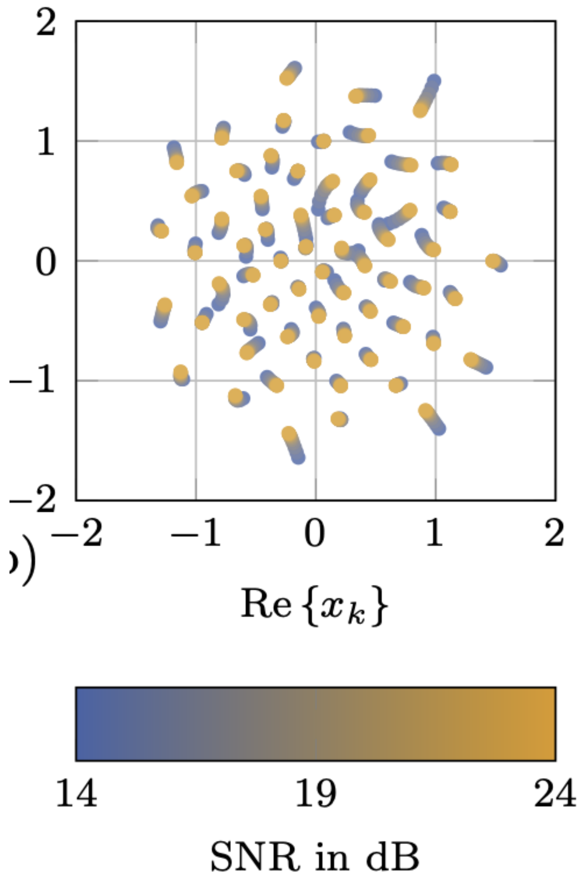

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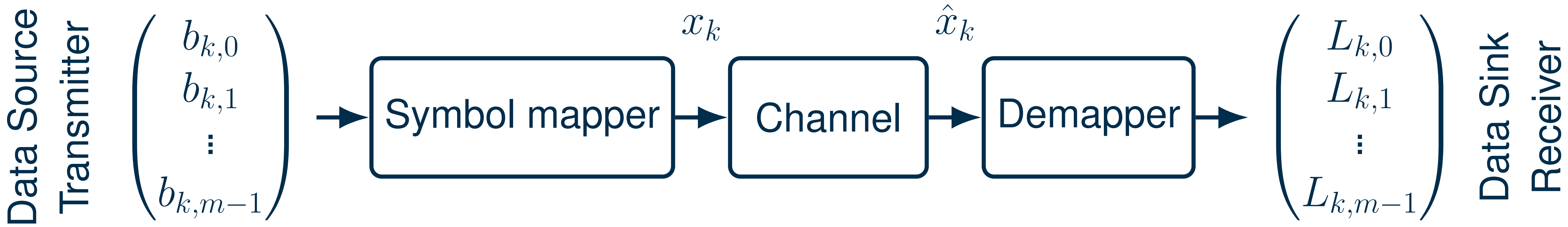
- (Short) Tutorial with Sionna and MOKka

Simulation Setup



- AWGN Channel for demo purposes
- Use aforementioned mod. binary cross entropy (BCE) to compute the loss

Constellation Shaping with Sionna

```python
from sionna.phy.mapping import Mapper, Demapper, Constellation,
    BinarySource
from sionna.phy.channel import AWGN
from sionna.phy.utils import ebnodb2no, log10, expand_to_rank
import tensorflow as tf
from tensorflow.keras.layers import Layer, Dense

num_bits_per_symbol = 4
batch_size = 2000
ebno_db = 10
coderate = 0.5

no = ebnodb2no(ebno_db, num_bits_per_symbol, coderate)
```

Constellation Shaping with Sionna

```
binary_source = BinarySource()
qam_points = Constellation("qam", num_bits_per_symbol).points
constellation = Constellation("custom",
                              num_bits_per_symbol,
                              points=qam_points,
                              normalize=True,
                              center=True)
channel = AWGN()
demapper = NeuralDemapper()
bce = tf.keras.losses.BinaryCrossentropy(from_logits=True)
```

- Create all necessary processing blocks

Constellation Shaping with Sionna

```
# Run a single batch
b = binary_source([batch_size, num_bits_per_symbol])
x = mapper(b)
y = channel(x, no)
llr = demapper(y, no)
loss = bce(c, llr)
```

- Run a single simulation loop
- Loss is related to current transmit constellation and demapper configuration

Constellation Shaping with Sionna

```
with tf.GradientTape() as tape:
    loss, y = model(training_batch_size,  ebno_db)
# Computing and applying gradients
weights = model.trainable_variables
grads = tape.gradient(loss, weights)
optimizer.apply_gradients(zip(grads, weights))
constellation = model._mapper.constellation.points
```

- Wrap the previous processing blocks in a `Model`
- Register optimization parameters

Constellation Shaping with Sionna

https://nvlabs.github.io/sionna/phy/tutorials/Sionna_tutorial_part2.html

https://github.com/noc0lour/fosdem_26_machine_learning _on_air

Constellation Shaping with MOKka

```
# Transmission
SNR = args.snr
m = args.modulation
nsymbols = args.symbols

epochs = args.epochs

config = {
    "n_symbols": symbols,
    "bits_per_symbol": m,
    "epoch": epochs,
    "snr": SNR,
    "learning_rate": 1e-2,
}
N0 = torch.tensor(mokka.utils.N0(config["snr"]), dtype=torch.float32)
```

Constellation Shaping with MOKka

```
    mapper = mokka.mapping.torch.ConstellationMapper(
            config["bits_per_symbol"], initialization="qam"
        )
    demapper = mokka.mapping.torch.ConstellationDemapper(
    config["bits_per_symbol"])
    channel = mokka.channels.torch.ComplexAWGN(N0).to(device)
    optim = torch.optim.Adam(
        (*demapper.parameters(), *mapper.parameters()),
        lr=config["learning_rate"],
    )
```

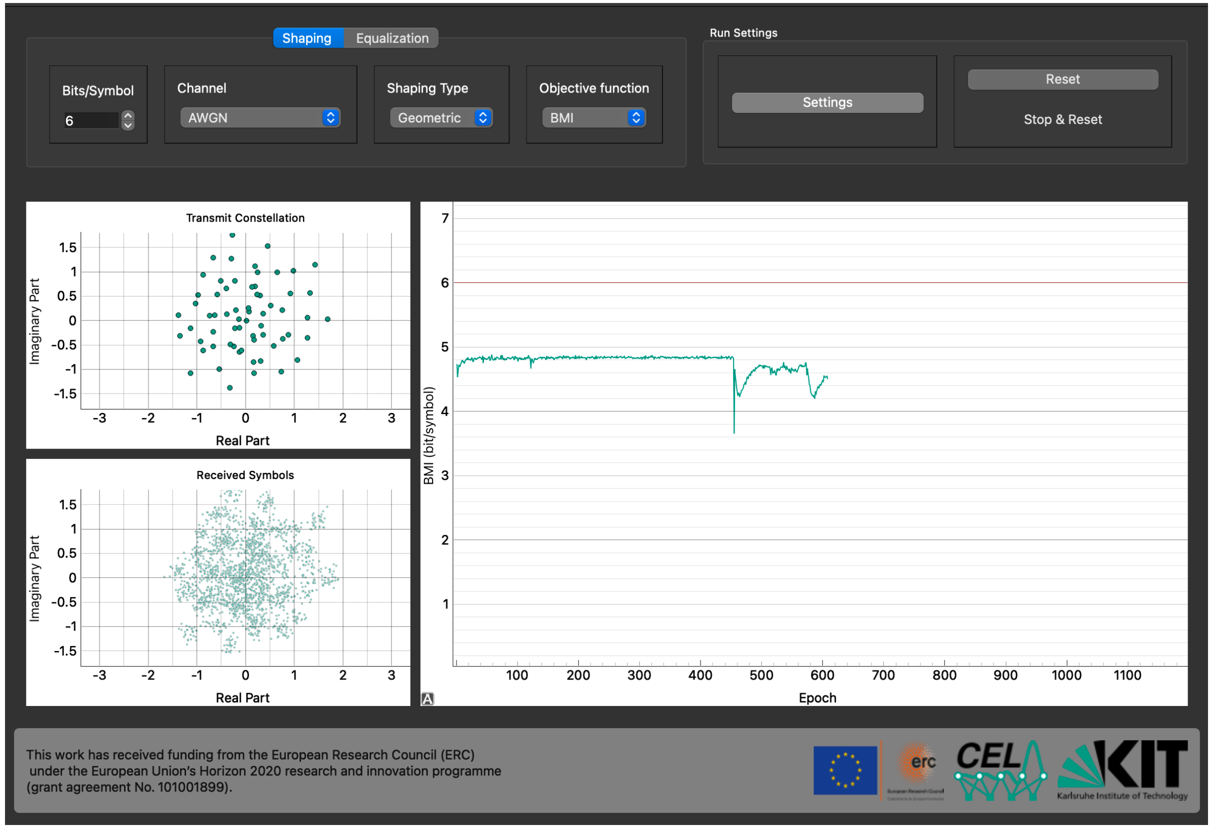
Constellation Shaping with MOKka

```
bits = torch.as_tensortensor(
utils.generators.numpy.generate_bits(
    (config["n_symbols"], config["bits_per_symbol"])
    ))
symbols = mapper(bits).flatten()

tx_signal = symbols
rx_signal = channel.forward(tx_signal)

# Receiver
llrs = demapper(rx_signal.flatten()[:, None])
```

Constellation Shaping with MOKka

```
bmi = mokka.inft.torch.BMI(
    config["bits_per_symbol"],
    config["n_symbols"],
    bits,
    llrs,
    )
loss = config["bits_per_symbol"] - bmi
loss.backward()
optim.step()
optim.zero_grad()
```

Constellation Shaping with MOKka



https://github.com/kit-cel/mokka_demo

FIN

- Download interesting open-source machine learning toolboxes for communications
- Design your own RF waveform with the help of machine learning

rode@kit.edu

Sionna	**MOKka**	**Commplax**
github.com/NVlabs/sionna	github.com/kit-cel/mokka	github.com/remifan/commplax

References I

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