Fast Probabilistic Shaping Implementation for Long-Haul Fiber-Optic Communication Systems

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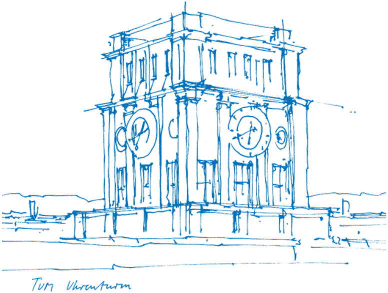
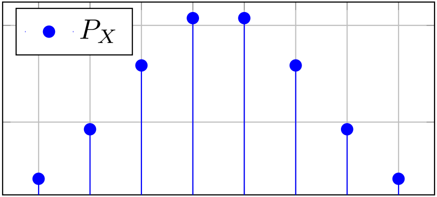


PDM 64-QAM for Transoceanic Transmission

- A. Ghazisaeidi, I. F. de Jauregui Ruiz, R. Rios-Muller, *et al.*, “65Tb/s transoceanic transmission using probabilistically-shaped PDM-64QAM”, in *Proc. Eur. Conf. Optical Commun. (ECOC)*, Post Deadline, Düsseldorf, Germany, Sep. 2016

⇒ Measurement for shaped and FEC encoded sequence with empirical distribution P_X in in-phase and quadrature components of 64-QAM:



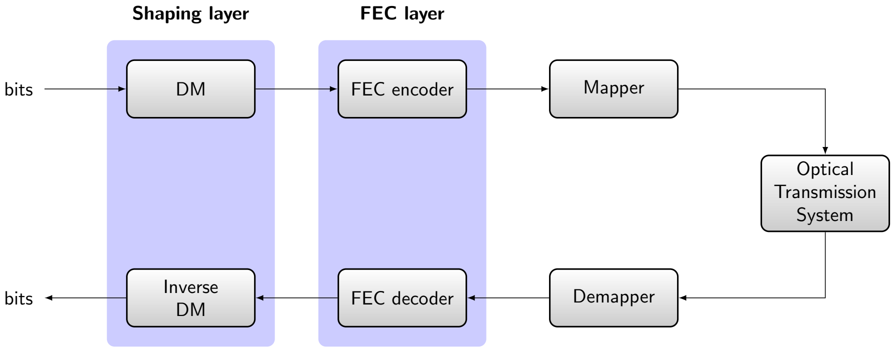
Outline

Implementing it [2]:

- Probabilistic Amplitude Shaping
- Distribution Matching Algorithms

Probabilistic Amplitude Shaping

Probabilistic Amplitude Shaping (PAS)

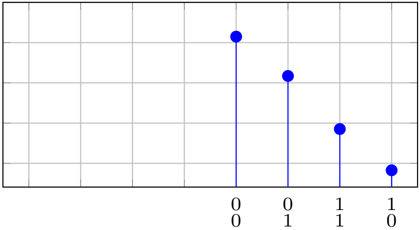


G. Böcherer, F. Steiner, and P. Schulte, “Bandwidth efficient and rate-matched low-density parity-check coded modulation”, *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4651–4665, Dec. 2015

Probabilistic Amplitude Shaping (PAS)

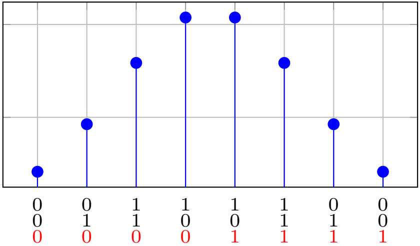
Amplitude DM

k bits → DM → $2n$ amplitude bits



Bit-mapper

amplitude bits 1
amplitude bits 2
unshaped data bits | FEC parity bits



PAS Achievable Rate

- Constellation label bits $\boldsymbol{B}$.
- Ideal DM rate $R_{\mathsf{dm}} = \mathrm{H}(\boldsymbol{B}) - 1$ and bit-metric decoding (BMD):

$$\left[\mathrm{H}(\boldsymbol{B}) - \sum_{i=1}^{m} \mathrm{H}(B_i|Y)\right]^+ .$$

- With practical DM:

$$\left[R_{\mathsf{dm}} + 1 - \sum_{i=1}^{m} \mathrm{H}(B_i|Y)\right]^+ .$$

G. Böcherer, "Achievable rates for probabilistic shaping", *arXiv preprint*, 2017. [Online]. Available: `https://arxiv.org/abs/1707.01134`

Distribution Matching Algorithms

DM Characterization

- DM input and output at instance i:

$$D_1 D_2 \dots D_{k_i} \text{ bits} \rightarrow \boxed{\text{DM}} \rightarrow A_1 A_2 \dots A_{n_i} \text{ amplitudes}$$

- Empirical output distribution P_A.
- Average rate R_{dm}.
- Rate loss

$$R_{\text{loss}} = \mathrm{H}(P_A) - R_{\text{dm}}.$$

- Instantaneous offset

$$\omega_i = n_i R_{\text{dm}} - k_i$$

Parallelization Factor

- FEC:
  - Spatially coupled LDPC code with window decoding.
  - 6000 decoded bits per step

$\Rightarrow$ for assessing DM parallelization potential, we define

Parallelization factor
$=$ *number of DMs that can run in parallel to process 6000 bits.*

Fixed Length

Adaptive arithmetic coding:

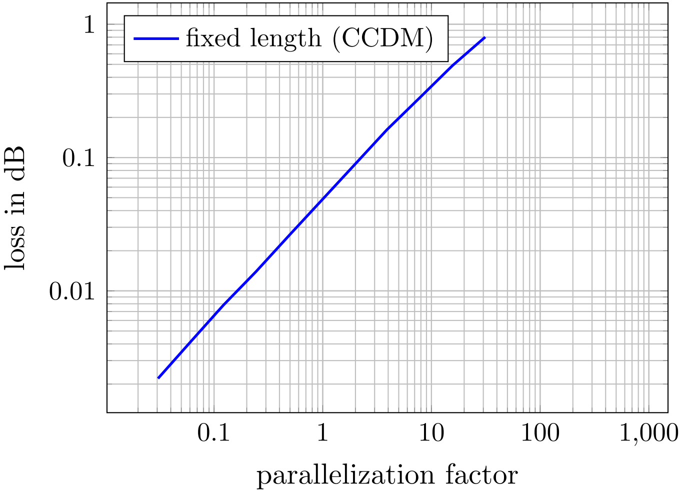
- P. Schulte and G. Böcherer, "Constant composition distribution matching", *IEEE Trans. Inf. Theory*, vol. 62, no. 1, pp. 430–434, Jan. 2016
- P. Schulte, F. Steiner, and G. Böcherer, *shapecomm WebDM: Online constant composition distribution matcher*, `http://dm.shapecomm.de`, Jul. 2017

Pro: Zero offset.

Contra:

$$R_{\text{loss}}(n) \propto \frac{\log n}{n} \Rightarrow \text{Parallelization difficult.}$$

Rate loss–Parallelization Trade-Off



Variable Length

- Prefix-free coding by **Geometric Huffman coding (GHC)**:
  - G. Böcherer and R. Mathar, “Matching dyadic distributions to channels”, in *Proc. Data Compression Conf. (DCC)*, 2011, pp. 23–32

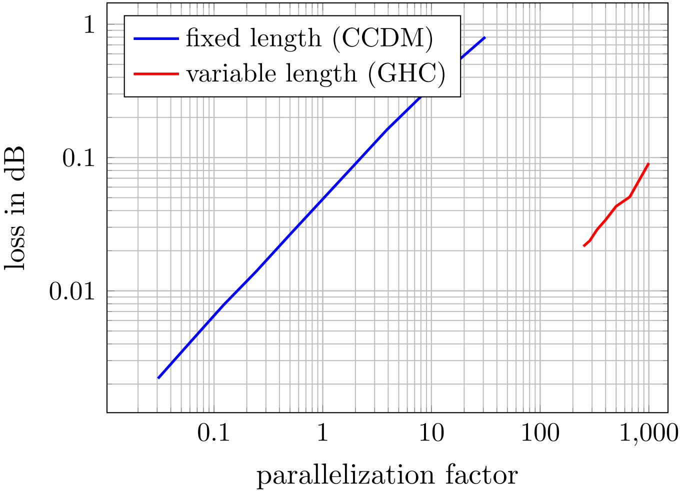
Pro: no multiplication.

Pro:

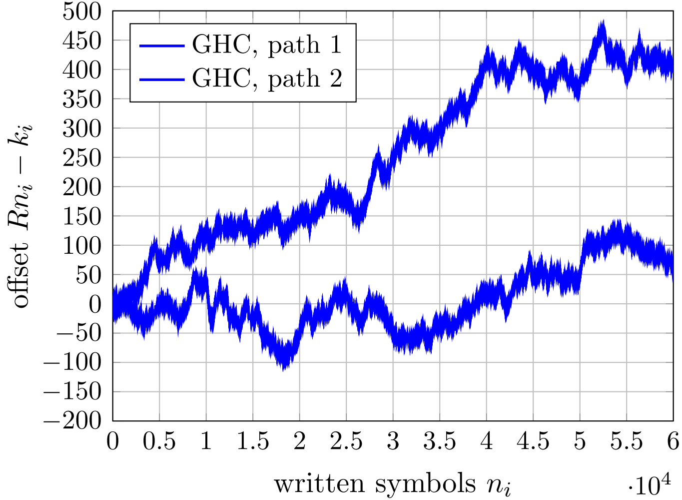
$$R_{\text{loss}}(n) \propto \frac{1}{n} \Rightarrow \text{Parallelization easy.}$$

Contra: Variable rate $\Rightarrow$ unbounded offset.

Rate loss–Parallelization Trade-Off



GHC: Offset Diffusion



Neither Variable Nor Fixed Length: Bounded Offset

Streaming distribution matching (SDM):

Pro: Bounded offset.

Pro: Parallelization possible.

Streaming Distribution Matching (SDM): Key Idea

- Use **two short variable length codes**:
  - Plus code with rate

$$R^+ > R_{\mathsf{dm}}.$$

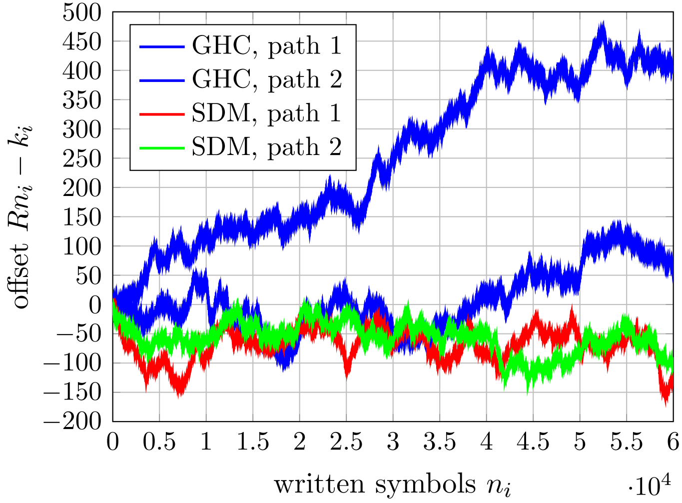
  - Minus code with

$$R^- < R_{\mathsf{dm}}.$$

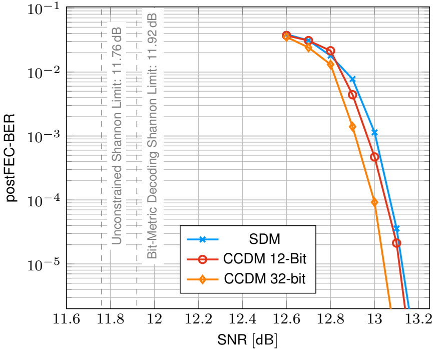
- Choose code based on offset

$$n_i R_{\mathsf{dm}} - k_i.$$

SDM: Bounded Offset



Distribution Matcher Comparison



- 8-ASK constellation.
- DM rate 1.8 bits per amplitude.
- Length 180 000 bit spatially coupled LDPC code.
- Window decoding.
- 6000 decoded bits per step.

DM	Intel i5 single core CPU	SNR@postFEC-BER=1e-5	parallelization factor
32-bit CCDM	0.02 Mbit/s	13.02 dB	0.033
12-bit CCDM	0.1 Mbit/s	13.11 dB	1
SDM	10.0 Mbit/s	13.12 dB	$\gg 1$

Conclusions

Streaming distribution matching (SDM) trades

- Rate loss
- Parallelization factor
- Offset/buffer size

$\Rightarrow$ great potential to meet hardware requirements.

References I

[1] A. Ghazisaeidi, I. F. de Jauregui Ruiz, R. Rios-Muller, L. Schmalen, P. Tran, P. Brindel, A. C. Meseguer, Q. Hu, F. Buchali, G. Charlet, *et al.*, "65Tb/s transoceanic transmission using probabilistically-shaped PDM-64QAM", in *Proc. Eur. Conf. Optical Commun. (ECOC)*, Post Deadline, Düsseldorf, Germany, Sep. 2016.

[2] G. Böcherer, F. Steiner, and P. Schulte, "Fast probabilistic shaping implementation for long-haul fiber-optic communication systems", in *Proc. Eur. Conf. Optical Commun. (ECOC)*, Paper Tu.2.D.3, Gothenburg, Sweden, Sep. 2017.

[3] G. Böcherer, F. Steiner, and P. Schulte, "Bandwidth efficient and rate-matched low-density parity-check coded modulation", *IEEE Trans. Commun.*, vol. 63, no. 12, pp. 4651–4665, Dec. 2015.

[4] G. Böcherer, "Achievable rates for probabilistic shaping", *arXiv preprint*, 2017. [Online]. Available: `https://arxiv.org/abs/1707.01134`.

References II

[5] P. Schulte and G. Böcherer, “Constant composition distribution matching”, *IEEE Trans. Inf. Theory*, vol. 62, no. 1, pp. 430–434, Jan. 2016.

[6] P. Schulte, F. Steiner, and G. Böcherer, *shapecomm WebDM: Online constant composition distribution matcher*, `http://dm.shapecomm.de`, Jul. 2017.

[7] G. Böcherer and R. Mathar, “Matching dyadic distributions to channels”, in *Proc. Data Compression Conf. (DCC)*, 2011, pp. 23–32.