Experimental and Numerical Evaluation of CAZAC-type Training Sequences for MxM SDM-MIMO Channel Estimation

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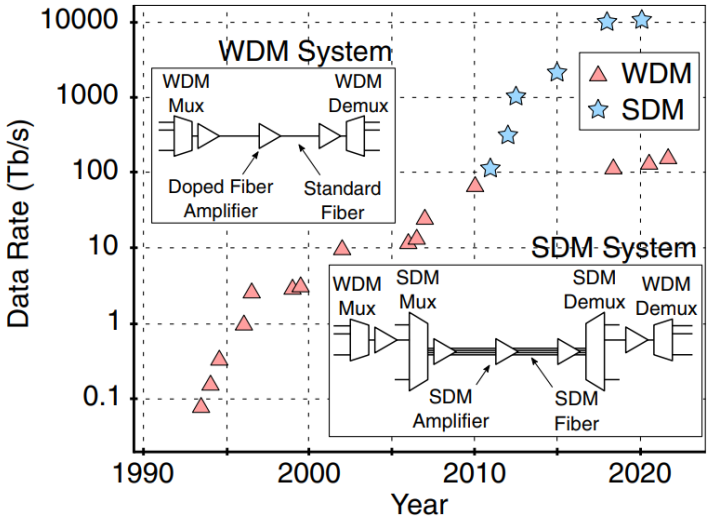
Outline

- Introduction
  - SDM systems become commercial reality
  - High-speed SDM transmission testbed at Fraunhofer HHI
- Experimental set-up
- Results
  - Numerical investigations: MSE of channel estimate
  - Experimental validation: BER of equalized signal
- Summary

Introduction

SDM systems are becoming commercial reality

- SDM increases cable capacity cost-effectively
  - Higher data rates, new networking & integration
- **Commercial deployment is starting**
  - Submarine transmission links
    - 2- and 4-core fibers with **uncoupled cores**
    - “Parallel SMF” in standard cables
  - Field deployed research testbed in L’Aquila
    - Various coupled & uncoupled fibers
- Next step:
  Coupled core SDM transmission → require
  “commercial-grade” robust and efficient **MIMO DSP**



Puttnam, Benjamin J. et al. “Space-Division Multiplexing for Optical Fiber Communications.” (2021)

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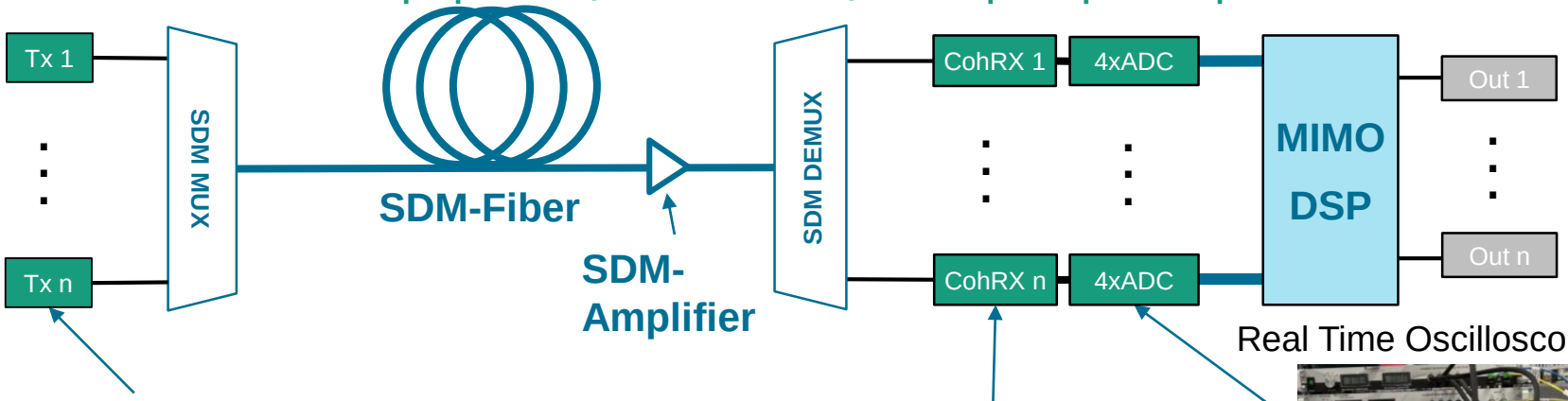
High-Speed SDM Transmission Testbed at Fraunhofer HHI

Coherent terminal equipment, multi band, multiple spatial paths



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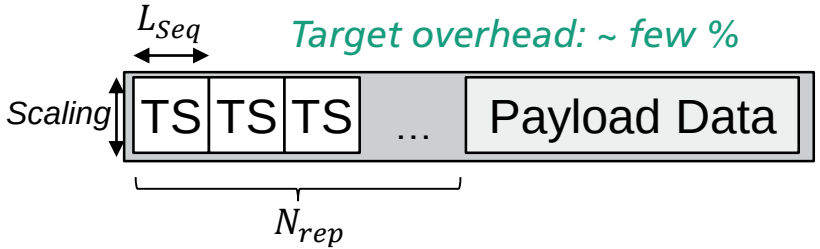
DSP for SDM Systems

Same stability requirements as for SMF systems

- Many commercial systems rely on training-based DSP for **2x2 polarization MIMO**
  - Fast and precise convergence, reliability, low complexity
  - High impairment robustness, stability at soft-FEC threshold
- Coupled core SDM transmission requires **MxM MIMO**
- **This work: CAZAC type training sequences (TS) for MxM MIMO Equalization**
- Investigated degrees of freedom:
  - Sequence length L_{Seq}
  - Number of repetitions N_{Rep}
  - Amplitude Scaling (w.r.t. payload)



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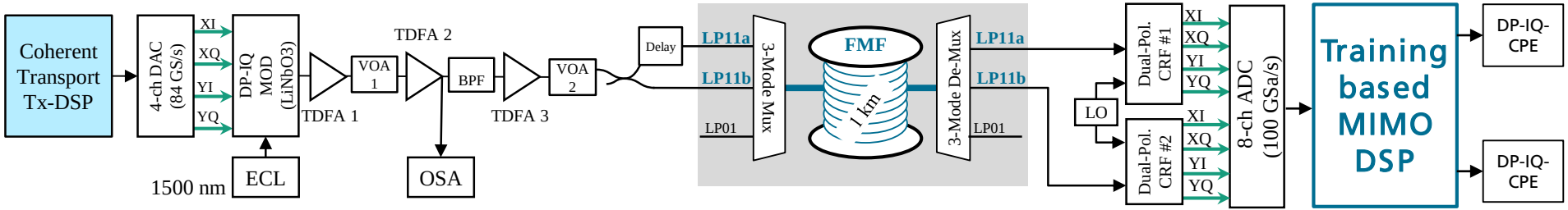
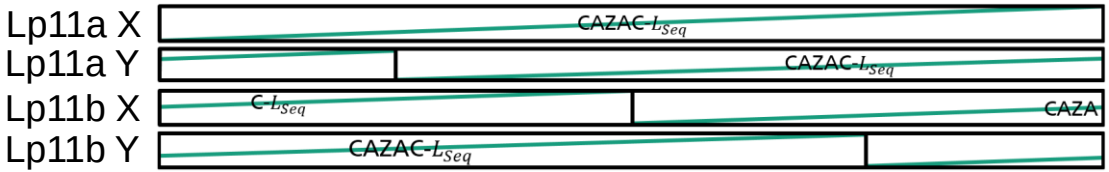
Experimental Setup

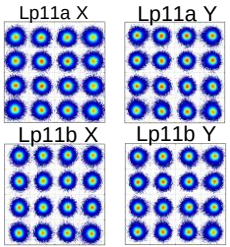
4x4 MIMO Coupled-mode SDM Transmission over 1-km Few-Mode Fiber

- 2 x 32 Gbd PDM-16-QAM signals at 1500 nm (i.e. 2x 200 Gb/s net data rate)
- SDM-Fiber: Standard 3-mode few-mode fiber (FMF)



Training sequence (TS) generation by cyclically shifting





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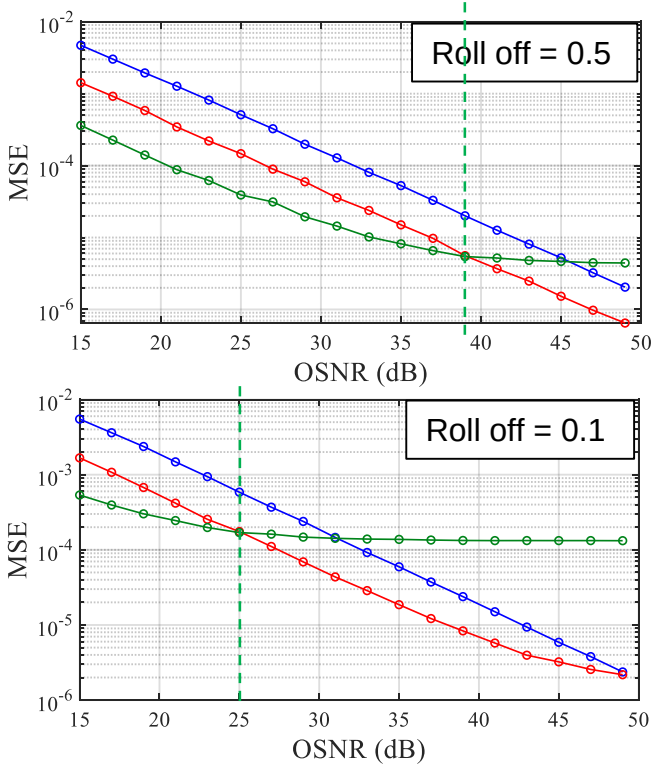
Tradeoff: Repetitions vs. Sequence Length

Repetitions improve estimation quality through noise averaging

- **Imposed constraint: Constant overhead**
  - ==> *Sequence length x repetitions =! const.*
- 1024 Symbols, 2 repetitions
  - Largest MSE (= poorest estimation)
- 64 Symbols, 28 repetitions
  - Lowest MSE (= best estimation) for low OSNR
  - Saturation for higher OSNR
- 256 Symbols, 7 repetitions
  - In between; saturation at even higher OSNR
- MSE saturation level and on-set depend on pulse shape, i.e. on length of channel impulse response (CIR)

Numerical simulations



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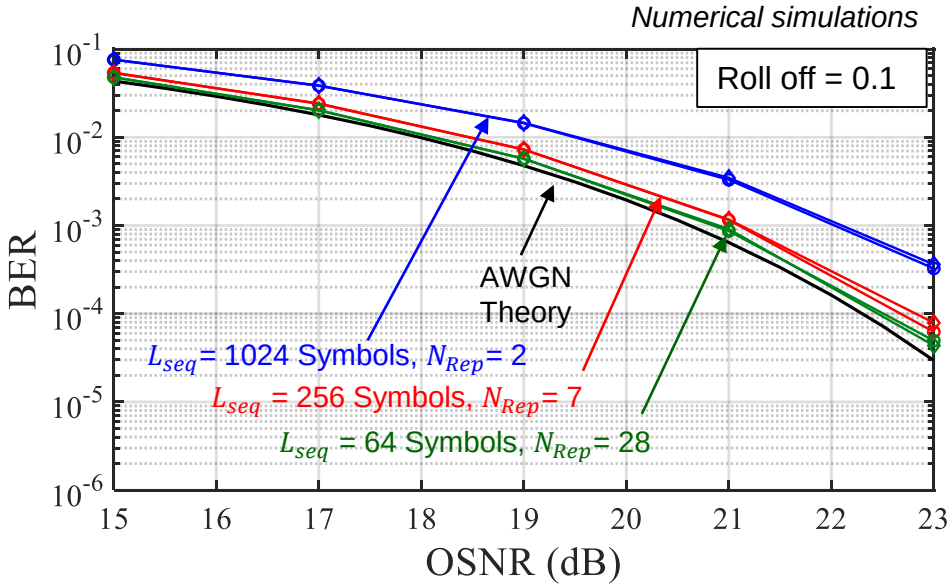
Tradeoff: Repetitions vs. Sequence Length

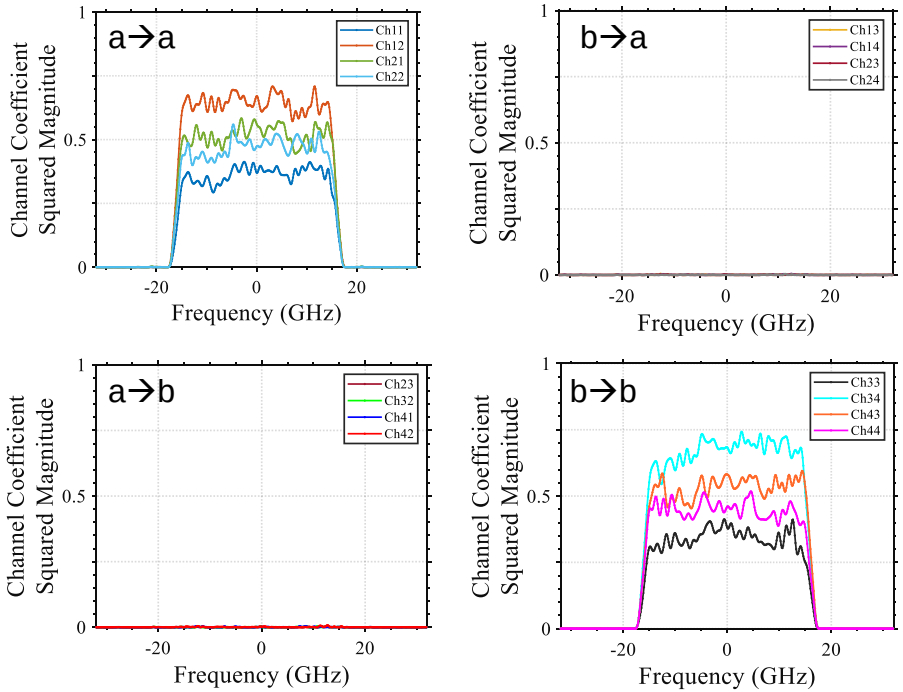
Repetitions improve BER

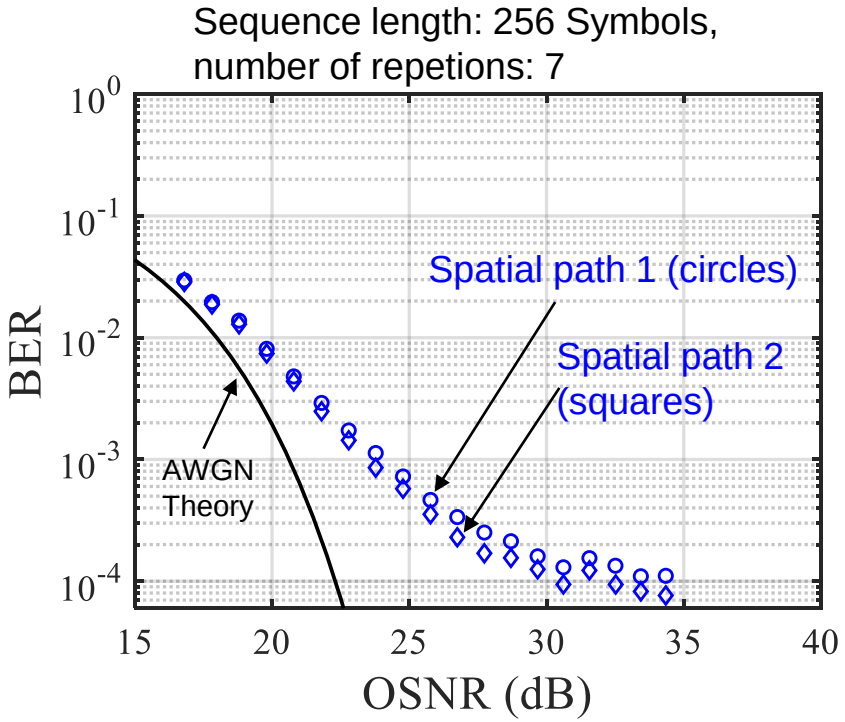
- **1024 Symbols, 2 repetitions**
  - Performs worst
- **256 Symbols, 7 repetitions**
  - Small penalty
- **64 Symbols, 28 repetitions**
  - Performs best
  - closest approach to theoretical curve (black) uncoded PDM-16 QAM
  - **MSE saturation levels not relevant for typical BER levels**



Experimental Validation

Back-to-back scenario (= reference without SDM fiber)





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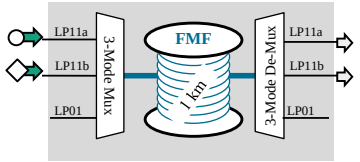
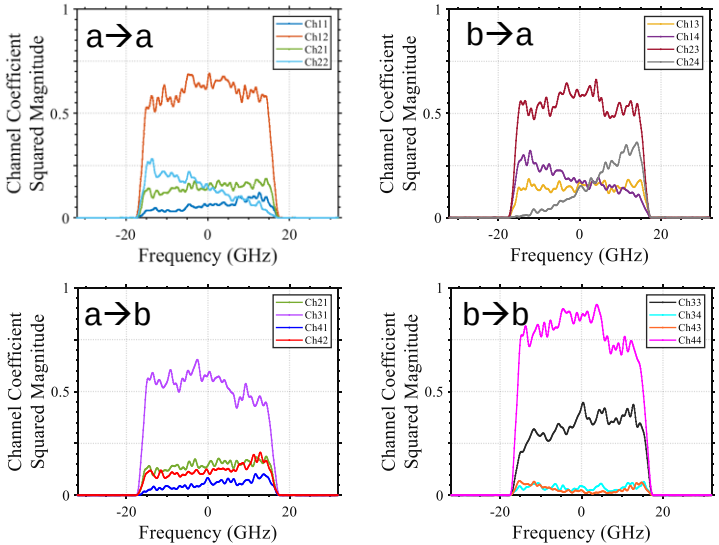
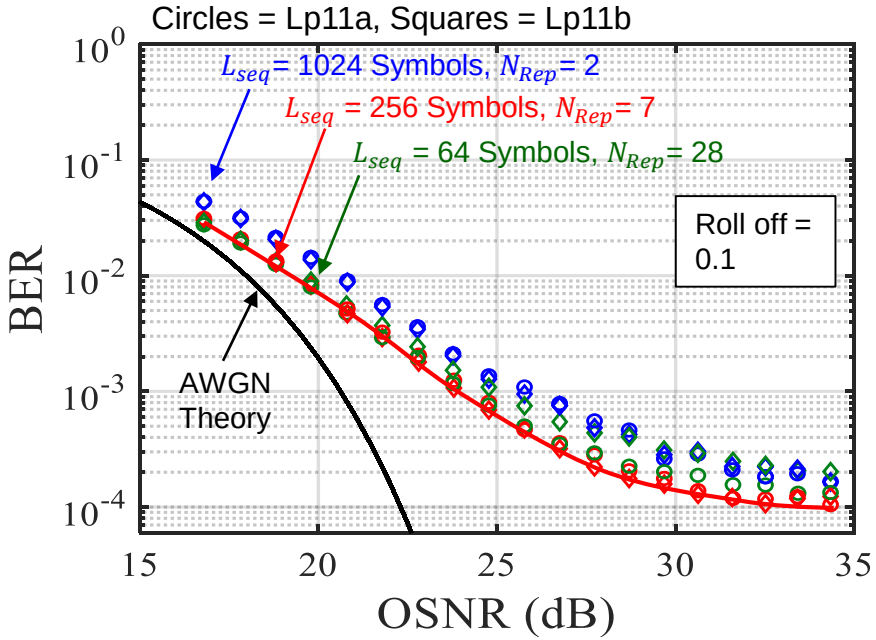
Experimental Validation

Transmission over two degenerated modes of 3-mode FMF







- Transfer functions indicate presence of Differential Mode Group Delay (DMGD)

  → Increased impulse response length requires longer TS

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Summary

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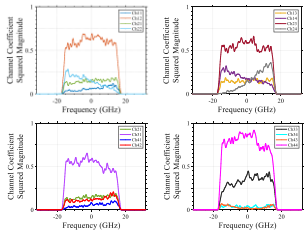
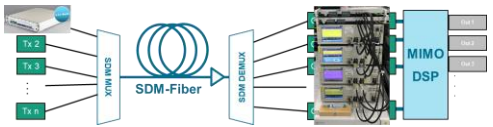
- **SDM systems are becoming commercialy reality, e.g. in submarine systems**
- Next step: **Advanced SDM** systems using **M coupled cores**
  - Advantage: Larger spatial density, shorter overall impulse response
  - Pre-requisite: robust and efficient MxM MIMO-DSP
- Investigated approach: **M-fold cyclic-shifted CAZAC training sequences**
  - Few-% overhead enables channel estimation & equalization in 4x4 SDM
  - Scalability to larger mode count is subject to further studies
- **SDM transmission testbed at Fraunhofer HHI** well suited to develop and validate DSP (and subsystems) for next generation SDM deployments
- **Thank you for your attention**





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Thank you for your attention

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