Reservoir computing for short-reach optical communication

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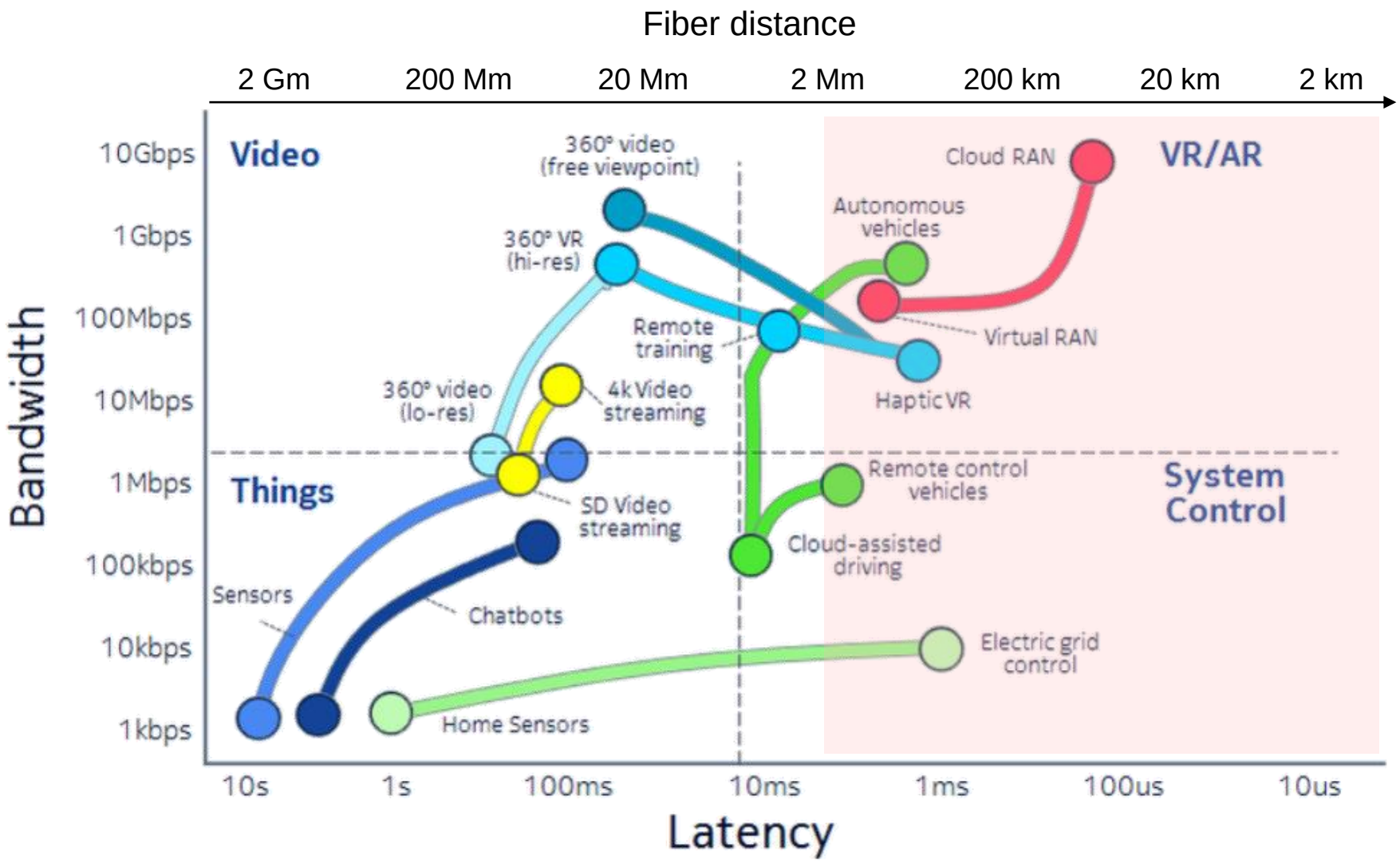
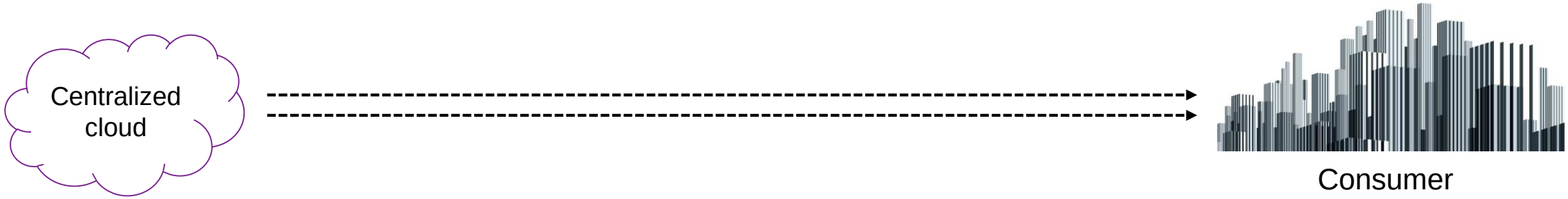
Optical networks and latency

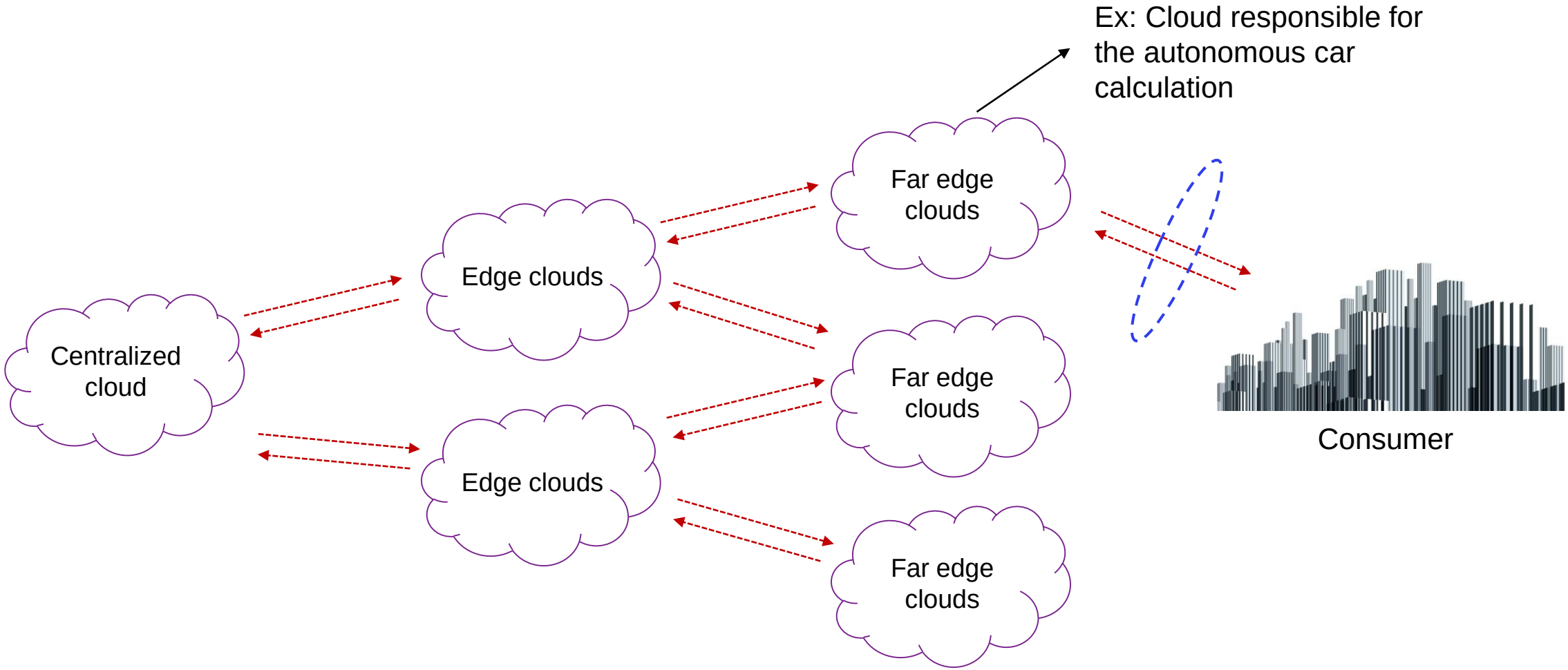


https://www.bell-labs.com/institute/blog/rational-exuberance-5G/

Decrease latency in optical networks



Decrease latency in optical networks



Increased number of short/low-latency interconnections.

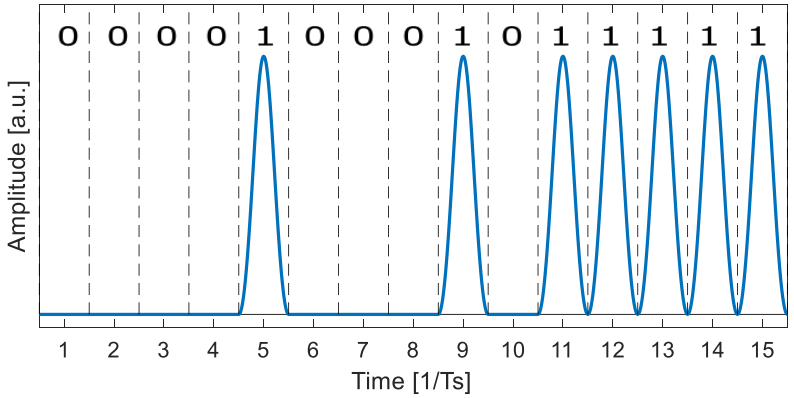
Short-reach optical communication

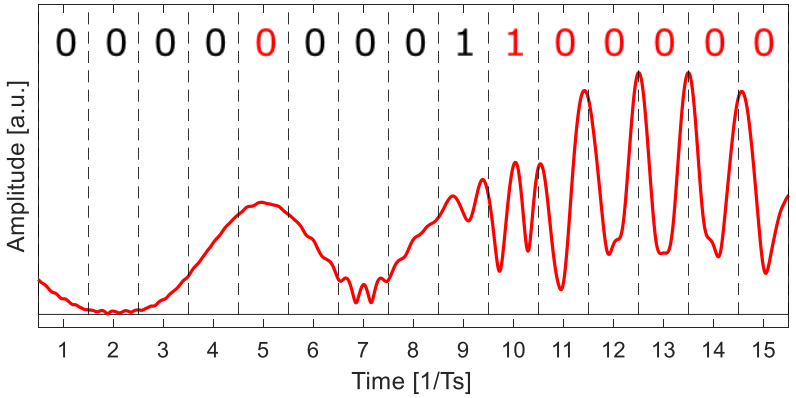
…000010001011111

Laser
(Transmitter)

Optical fiber
(Channel)

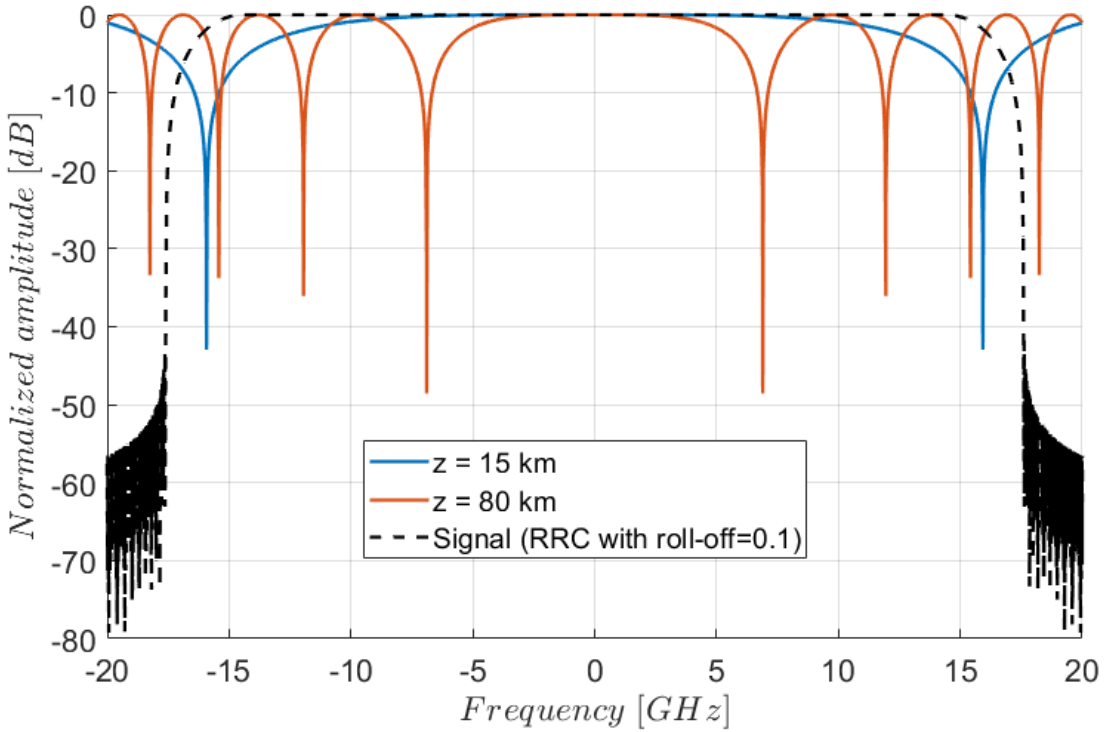
Photodetector
(Receptor)

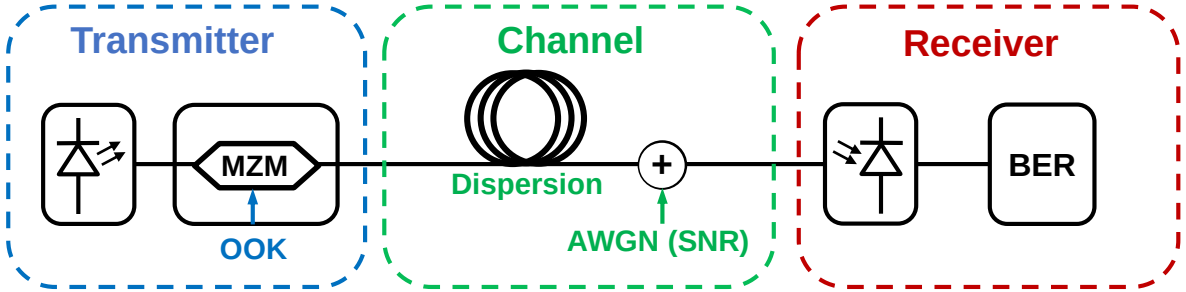




Fiber dispersion + direct-detection = inter-symbol interference

Power-fading



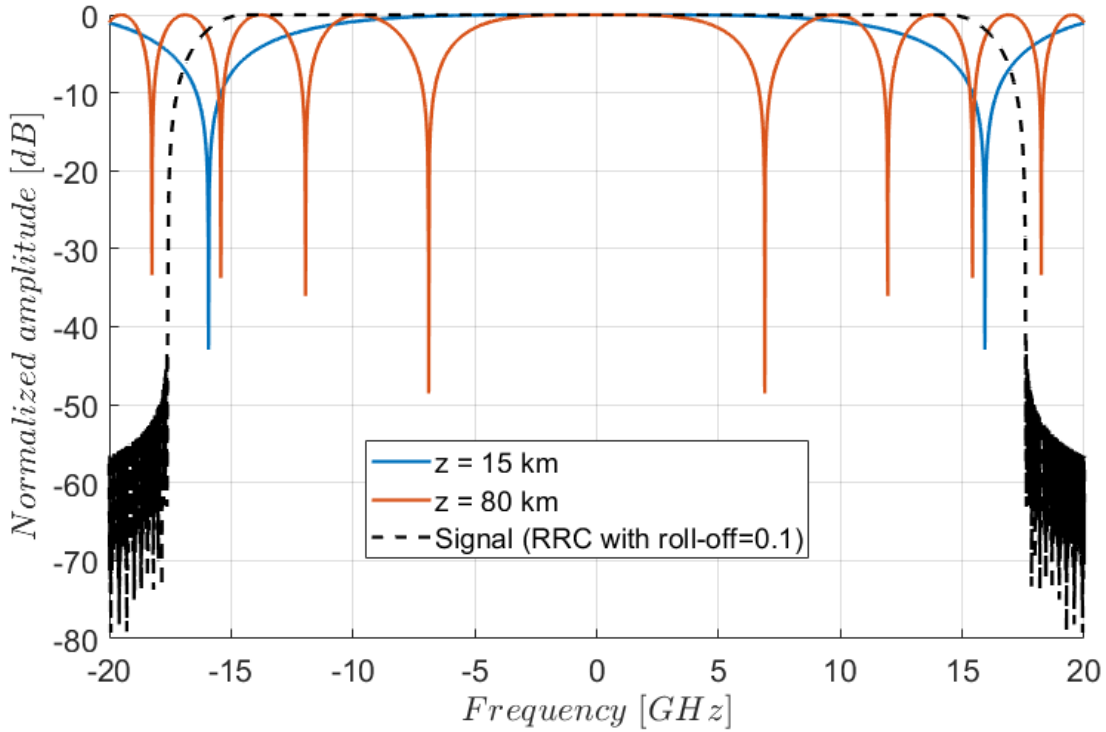


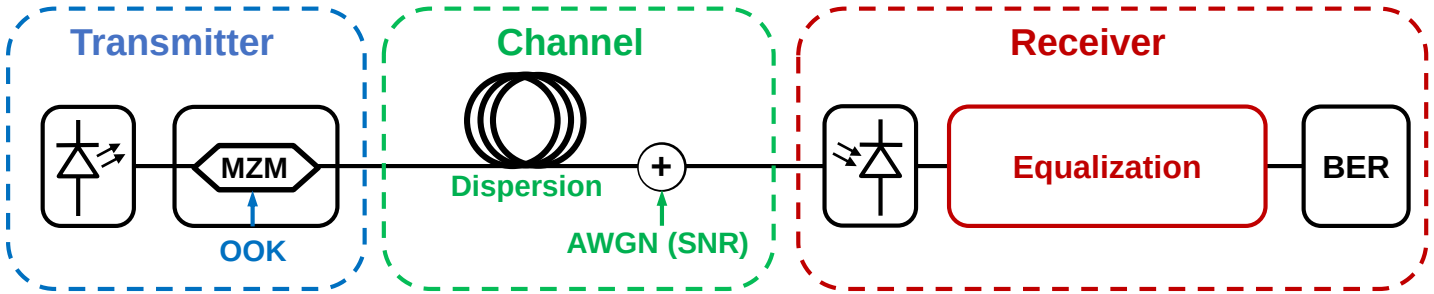
Outline

Combating power-fading effects in short-reach communication

- Digital compensation
  – Nonlinear equalizer with memory
- All-optical compensation
  – Quantized GVD compensation
- Hybrid compensation
  – Physic-inspired receiver architecture + digital equalization
- Conclusions

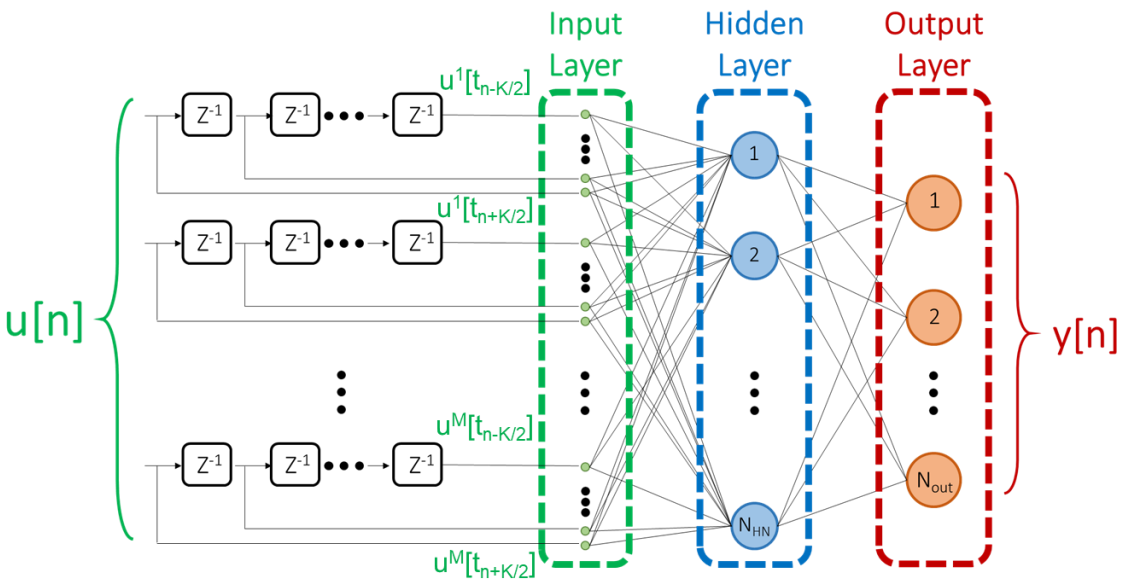
Power-fading and equalization



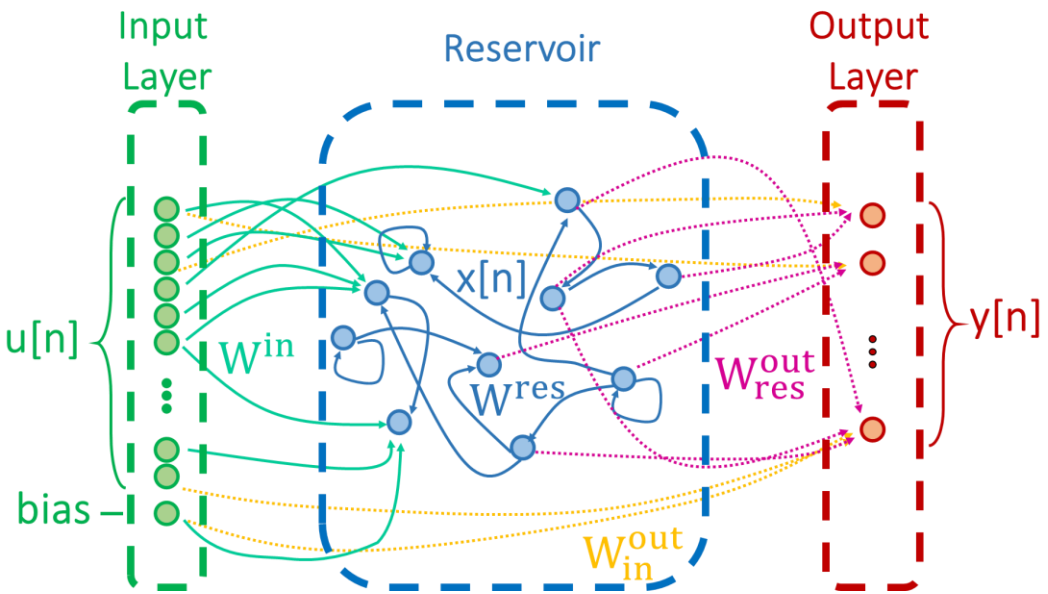


Equalizers with memory

Time-delay feed-forward neural network



Reservoir computing

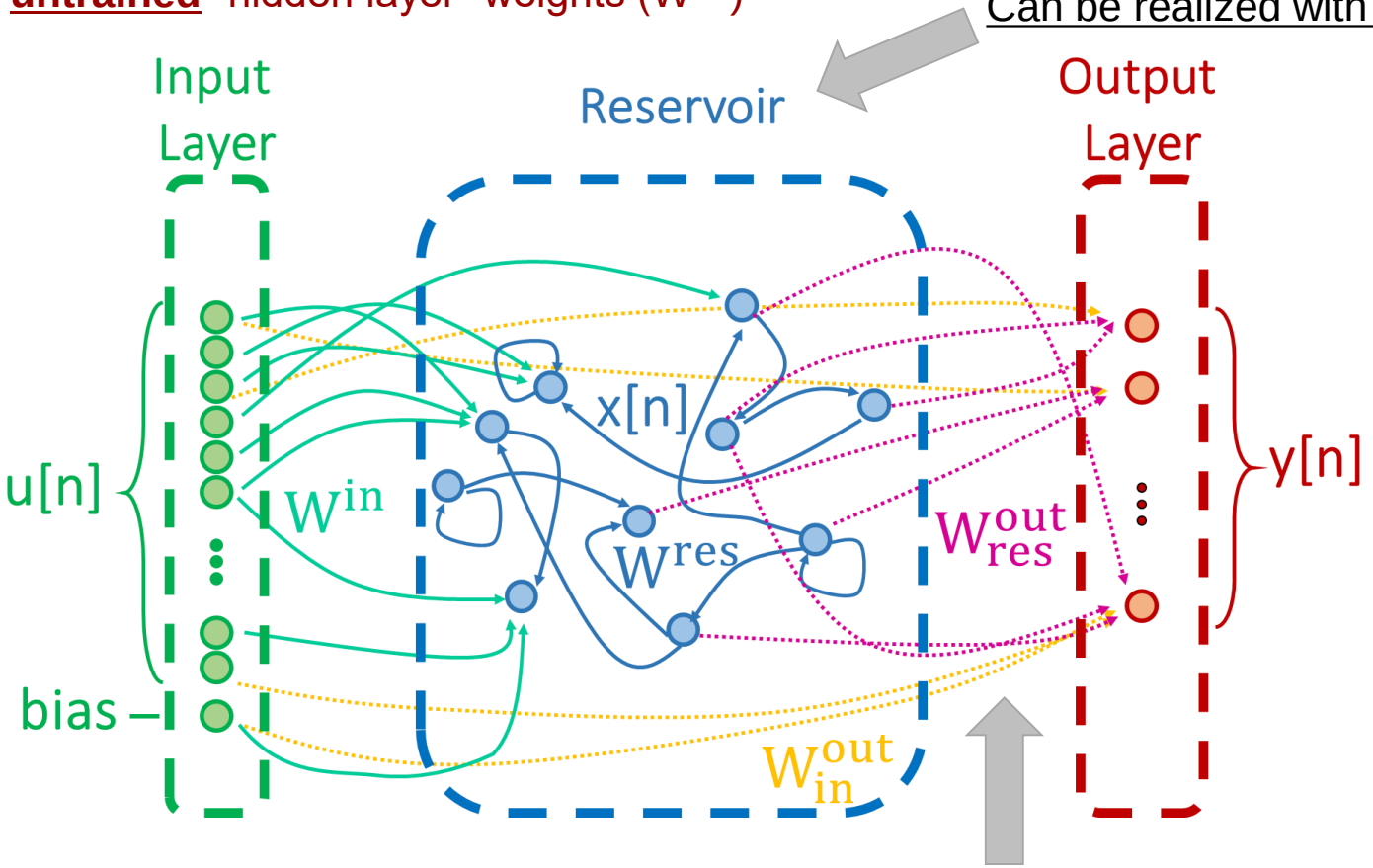


F. Da Ros, Photonics West 2021

Reservoir computing

Highly redundant RNN with **untrained** “hidden layer” weights (W^{res})

Can be realized with an analogue physical system



Training only the connections to the output layer

Jaeger, Technical Report GMD 148, 2001 Maass, et al. Neural Computation, 2002 Schrauwen, et al., Proc. ESANN 2007

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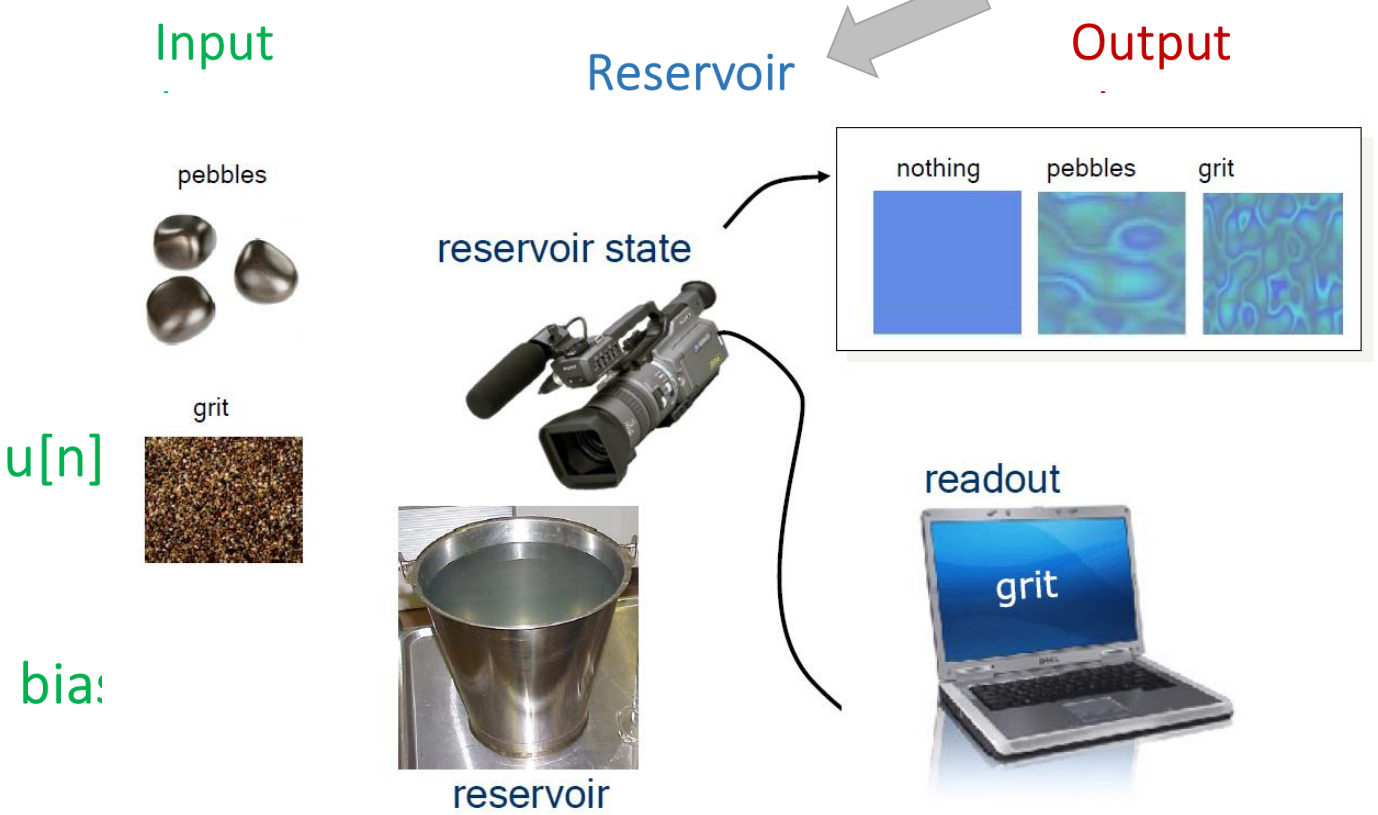

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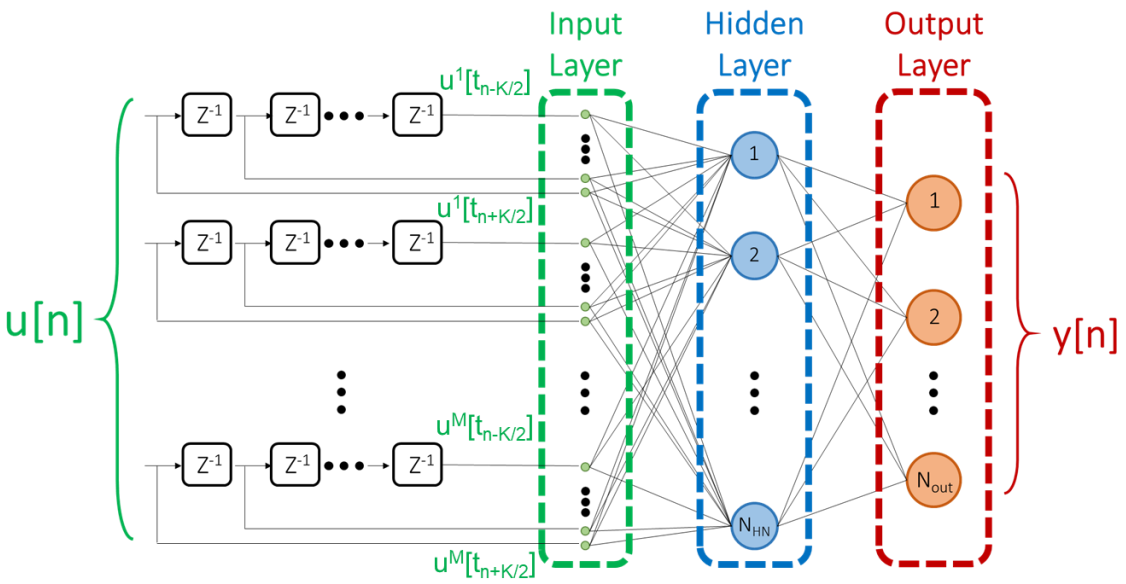
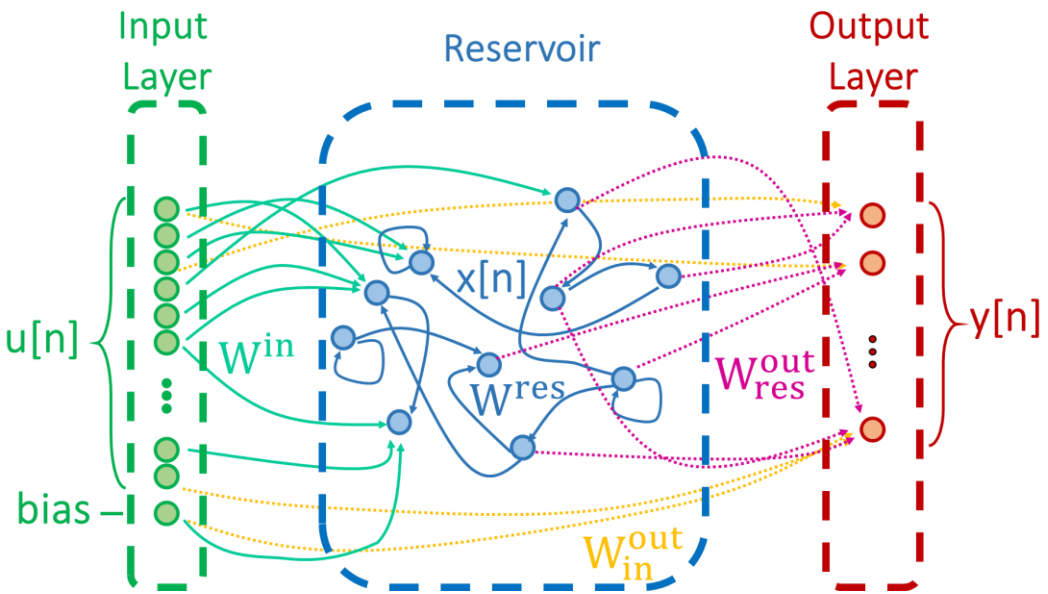
Memory properties

Time-delay feed-forward neural network



Reservoir computing



F. Da Ros, Photonics West 2021

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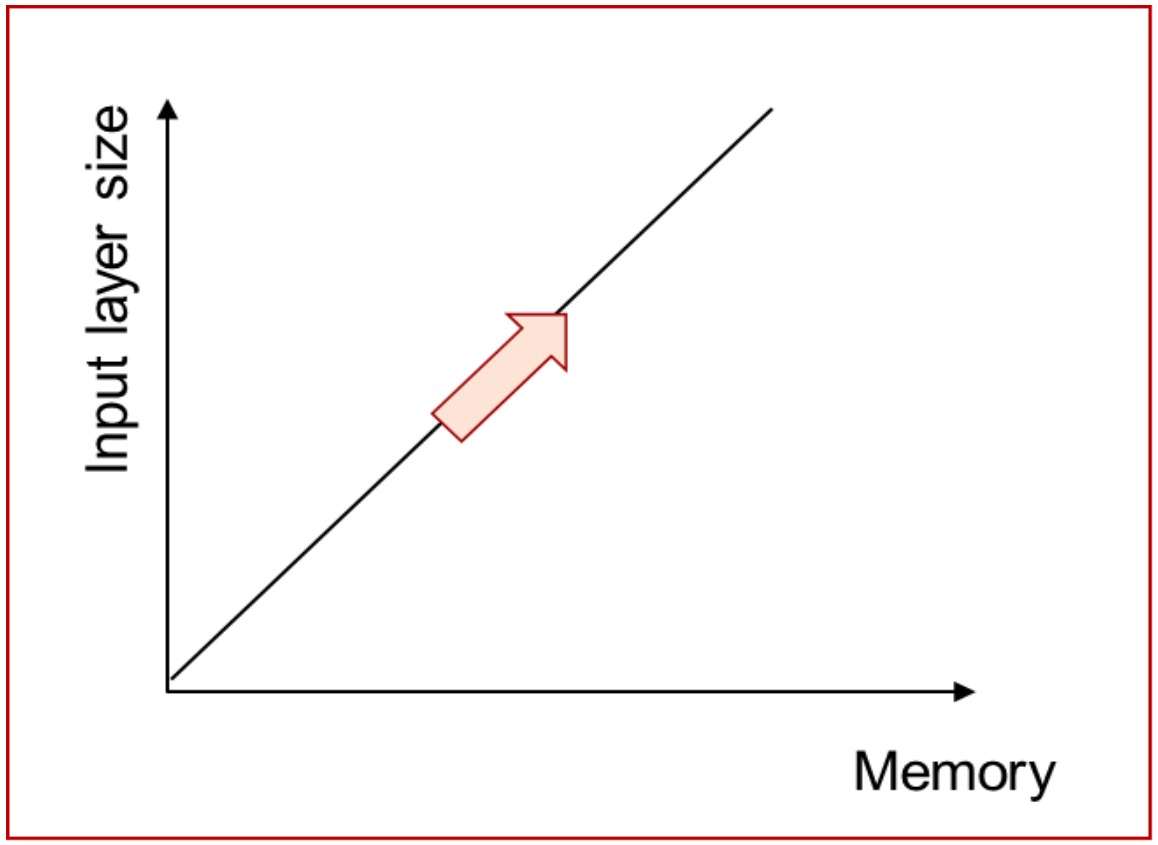
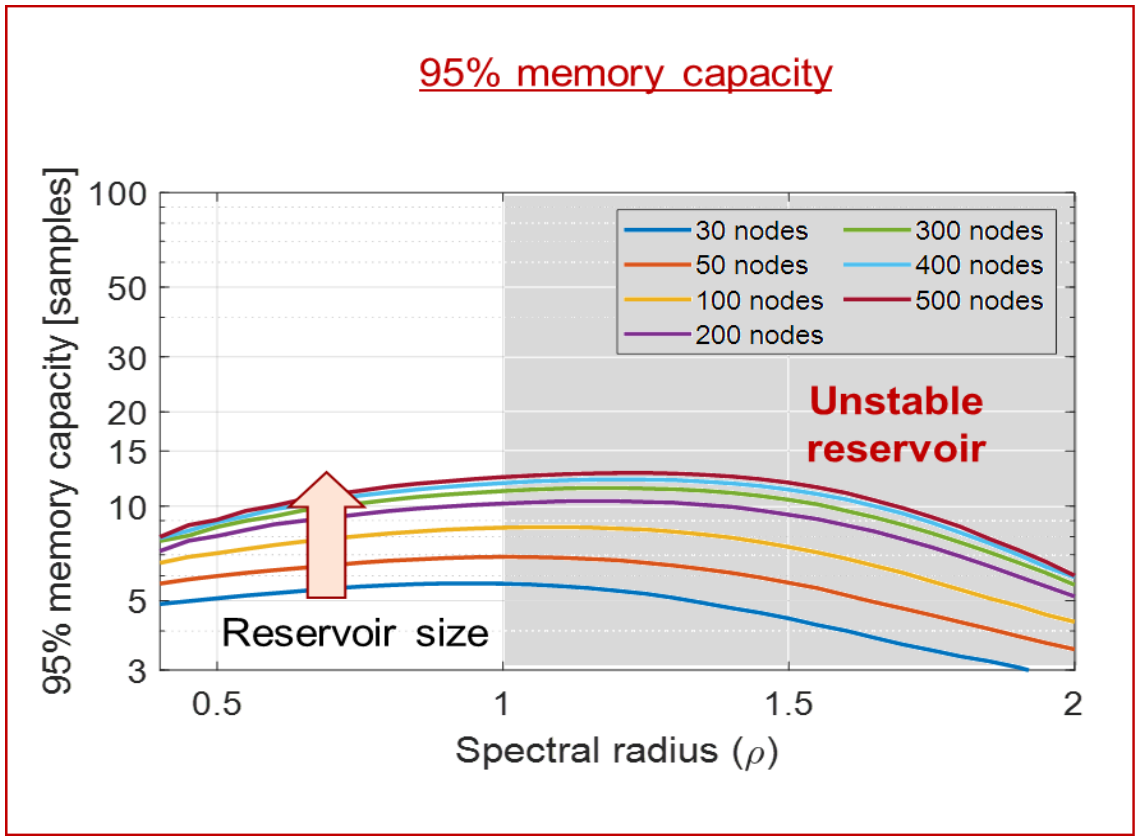
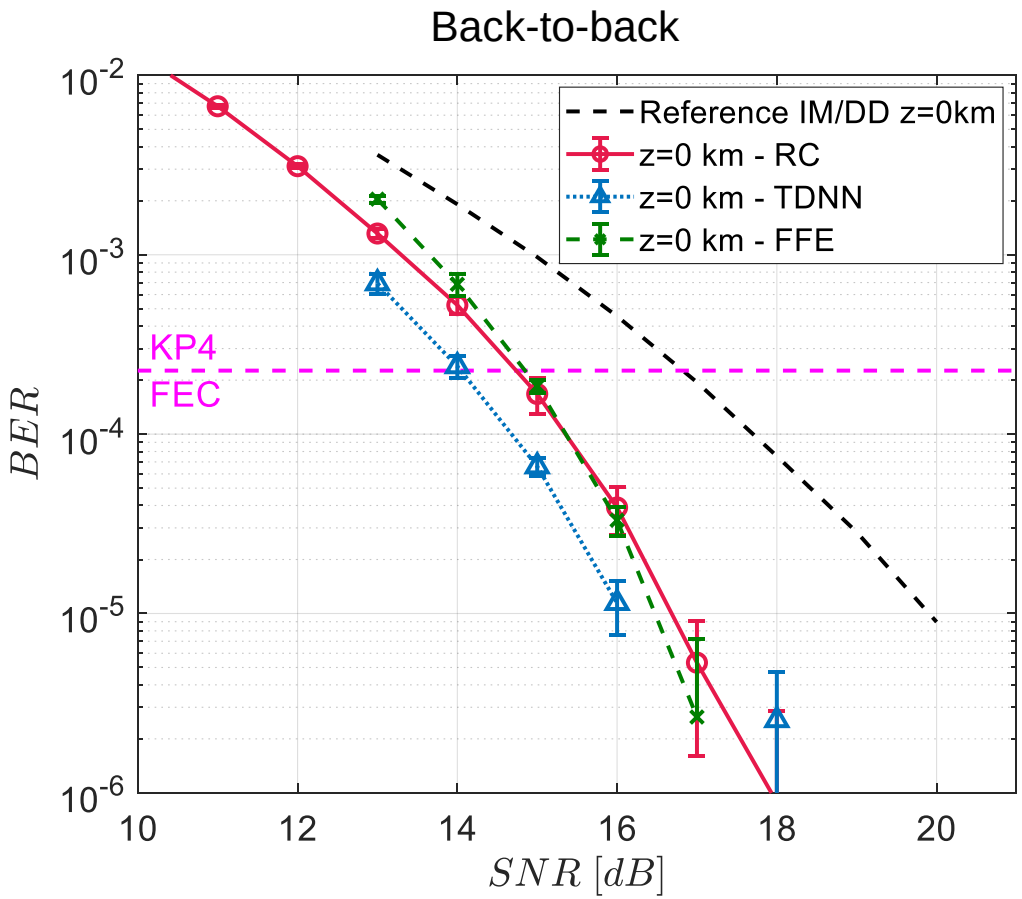


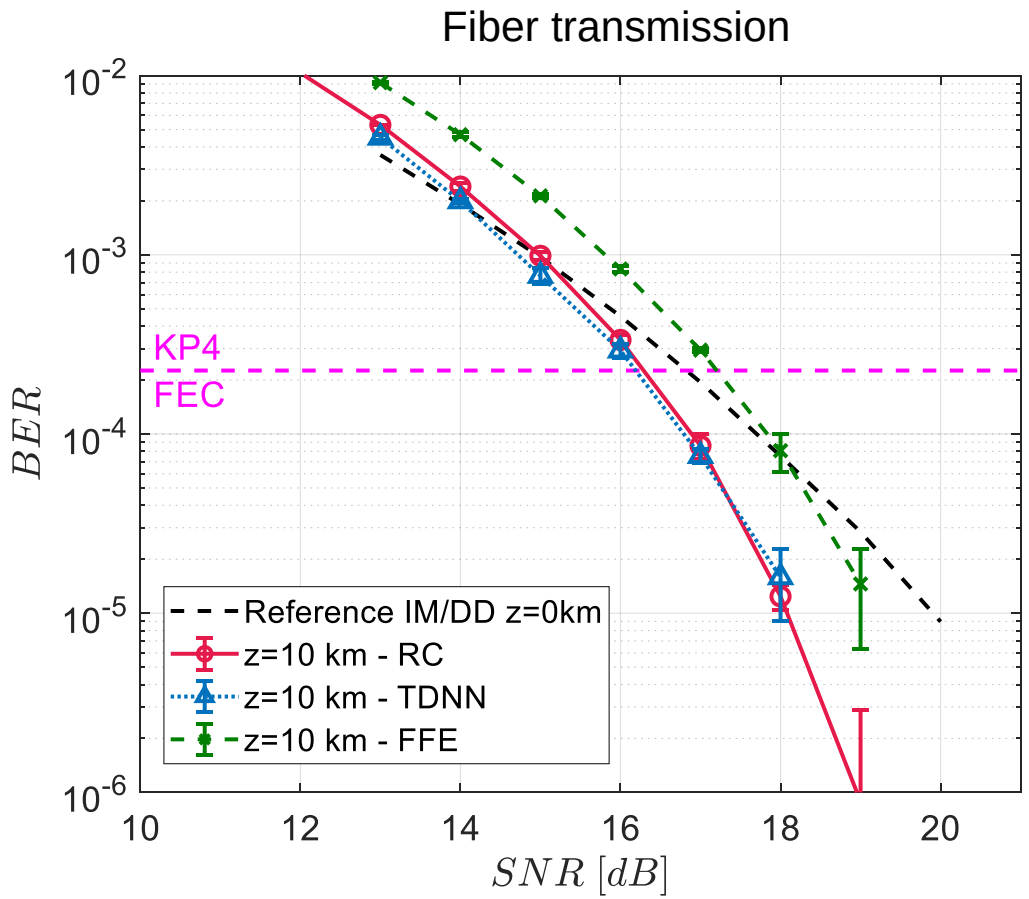
Reservoir computing



F. Da Ros, Photonics West 2021

Numerical comparison

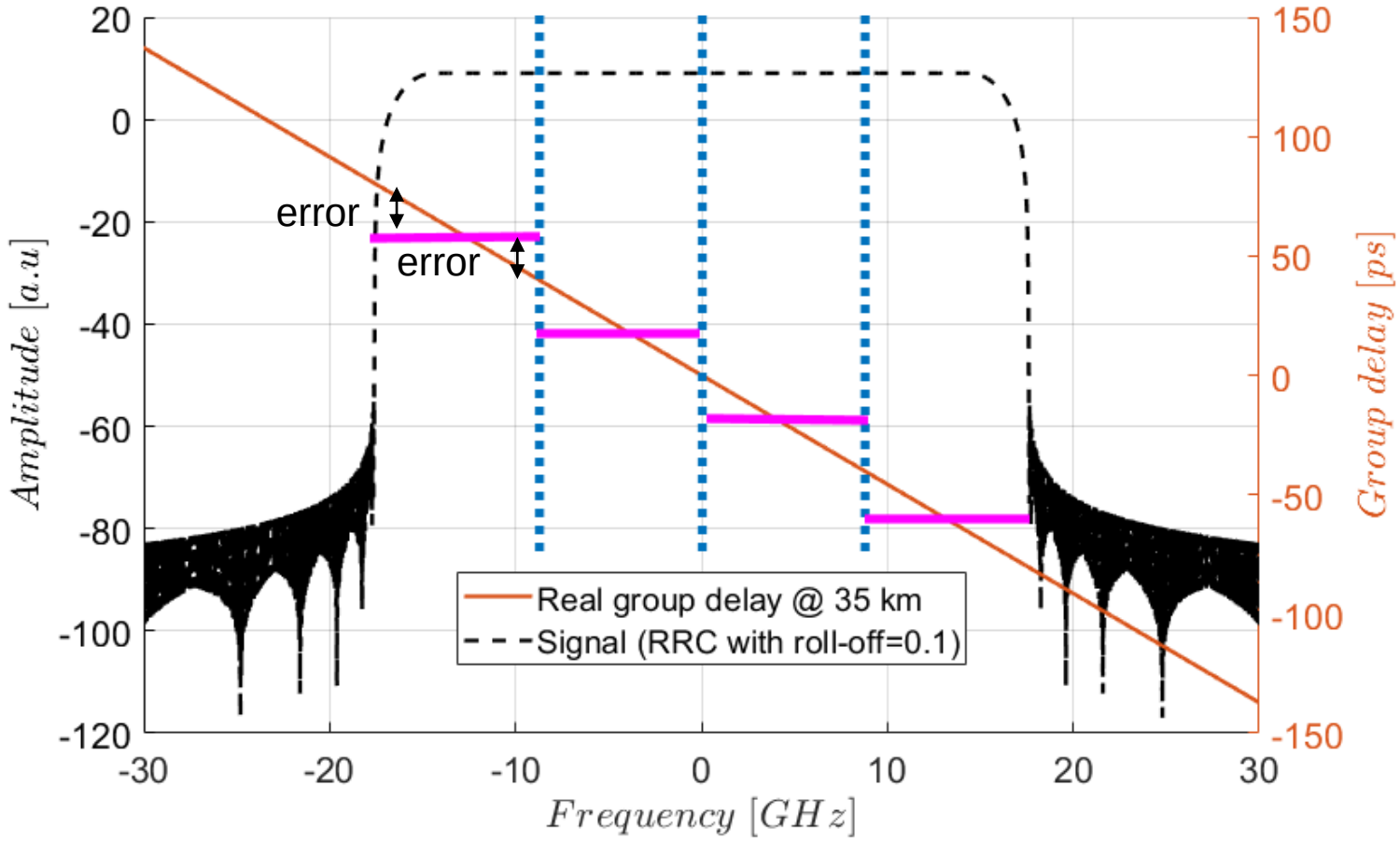




Nonlinear equalizers with memory provide “some” improvement.

S. Ranzini, Appl. Science 2019

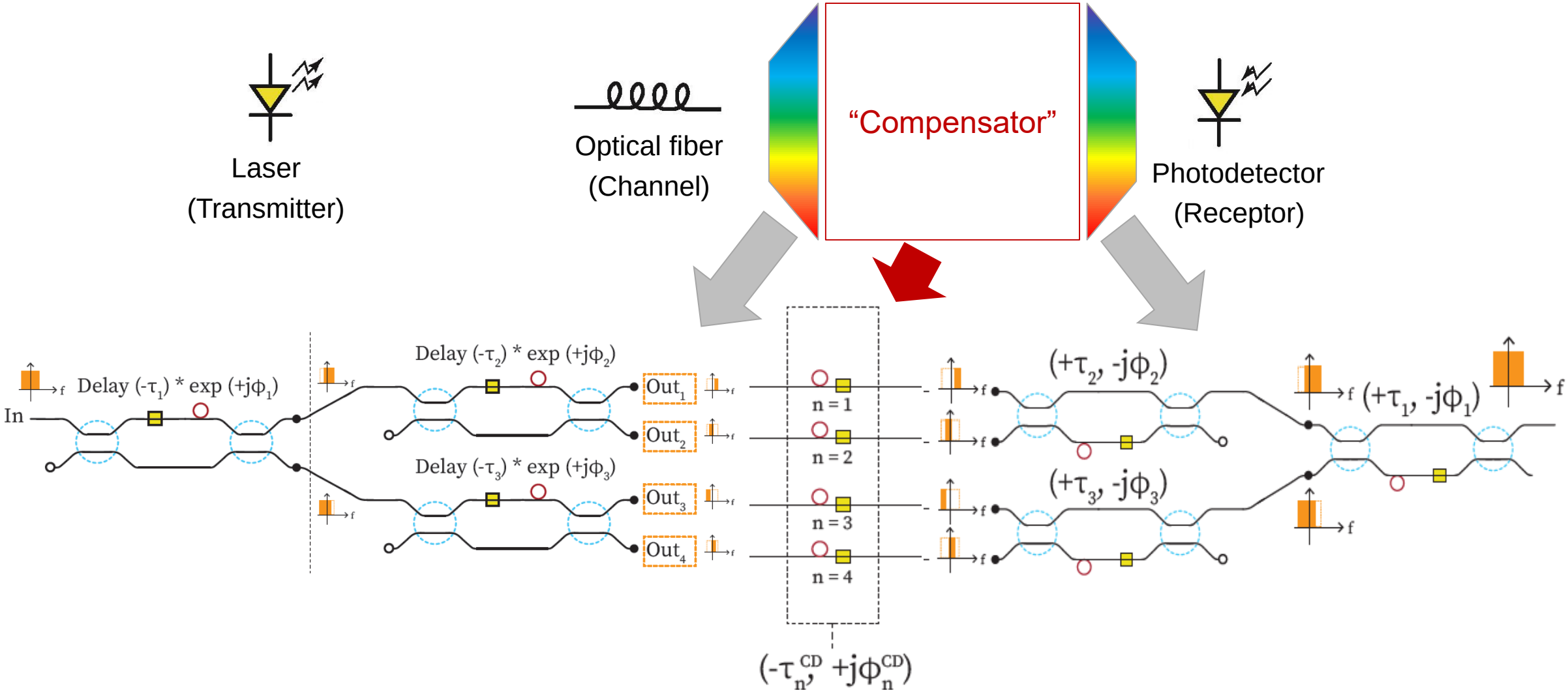
Back to the physics



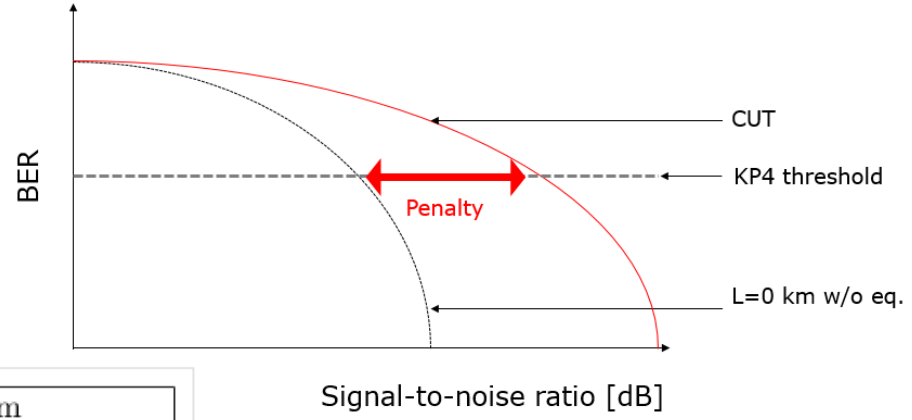
Can the group delay be compensated in a “quantized” way?

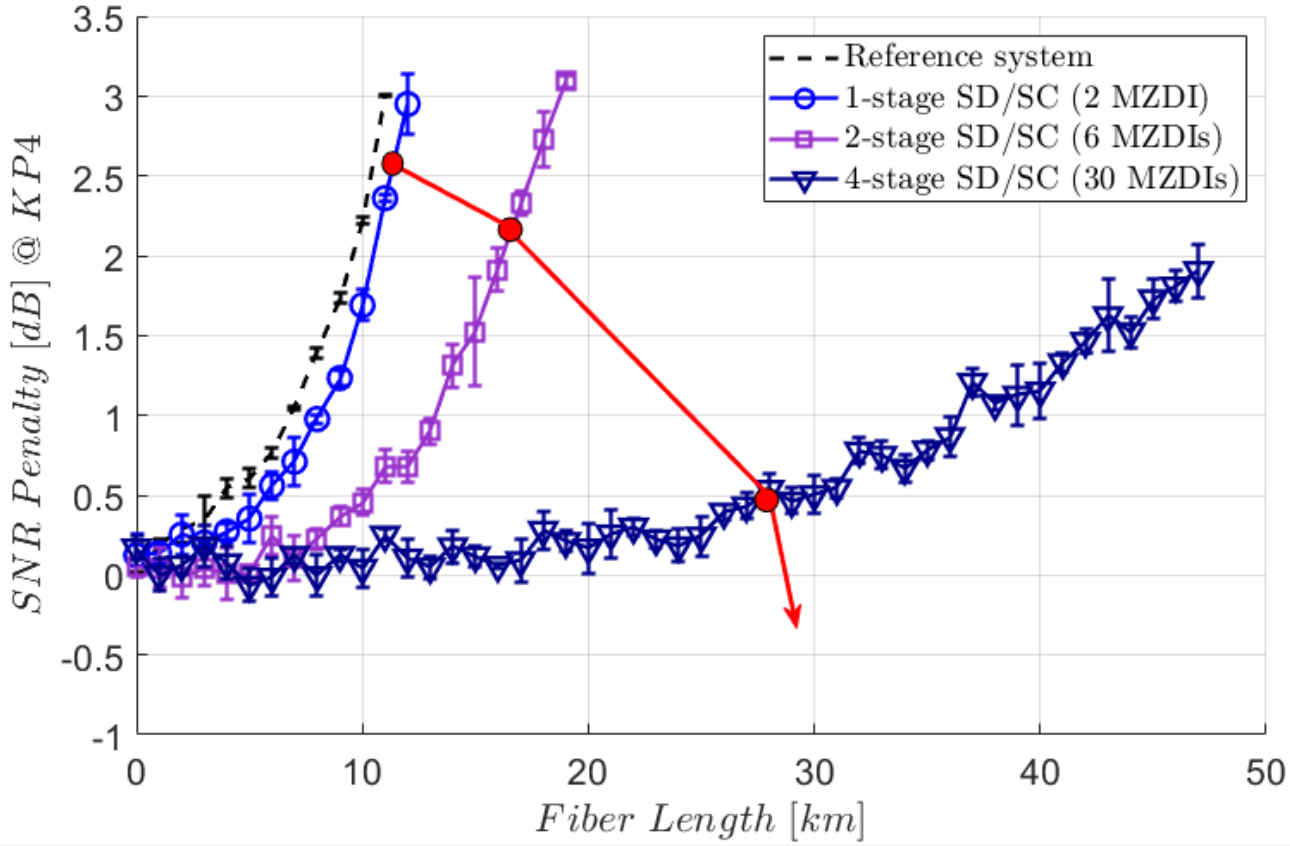
S. Ranzini, Appl. Science 2019

Optical compensation



Optical compensation



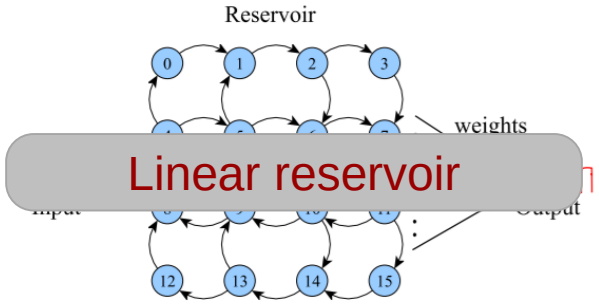


Transmission distance increases with stages → scalability?

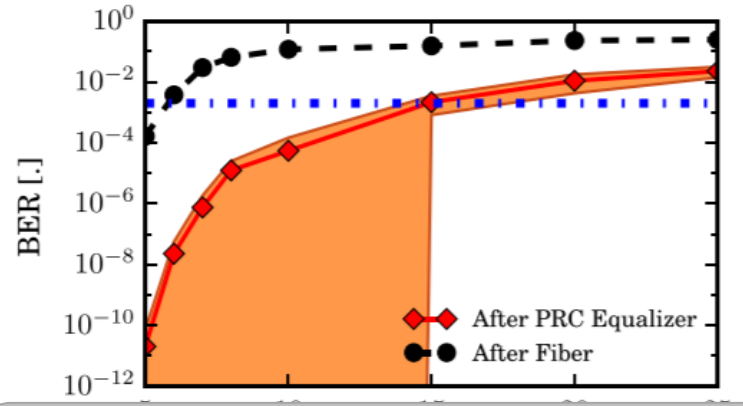
S. Ranzini, Appl. Science 2019

Optoelectronic reservoir computing

Silicon-photonic reservoir with optoelectronic output layer

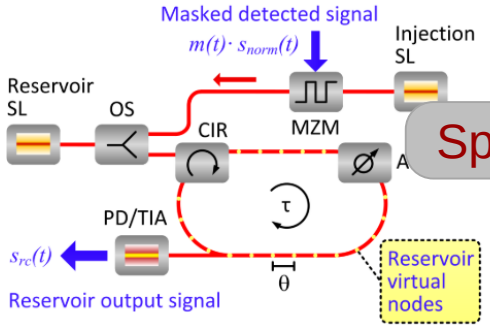


Linear reservoir

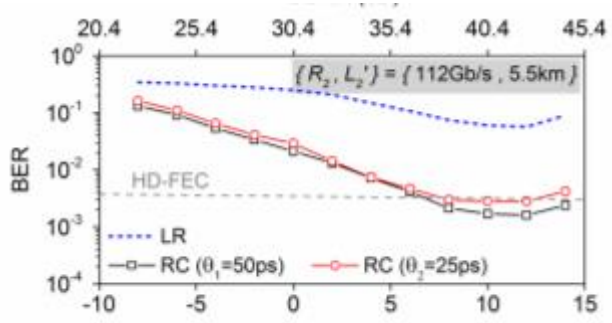


Katumba, et al., JLT 2019

Laser-based reservoir for time-delayed RC

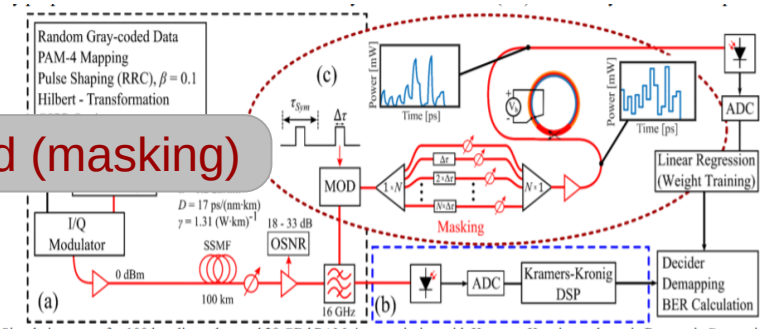


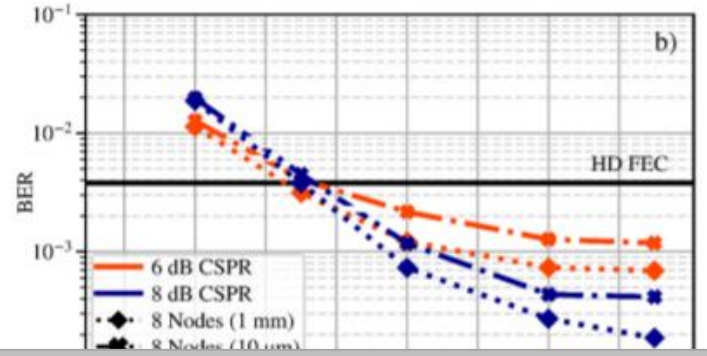
Speed limited (masking)



Argyris, et al, IEEE Access 2019

Micro-ring resonator based reservoir

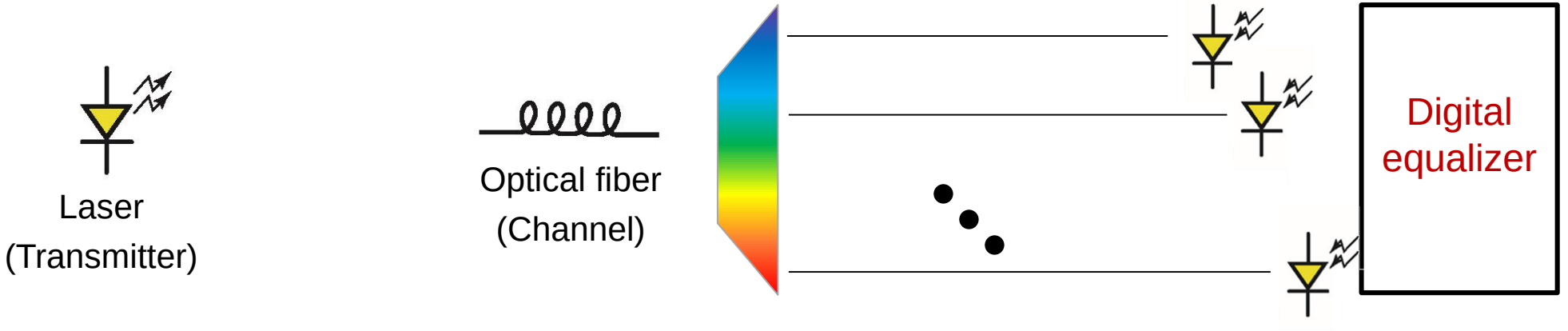


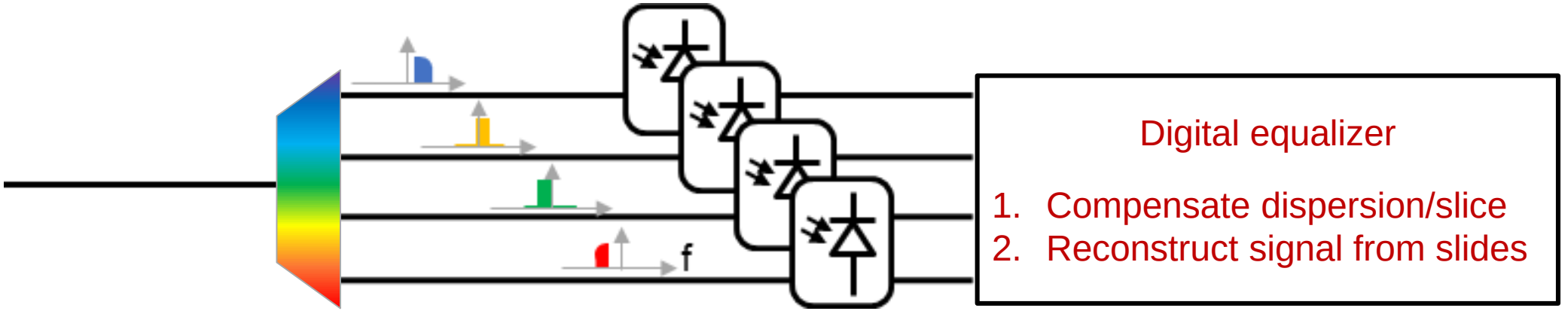


Li, et al., CLEO 2020

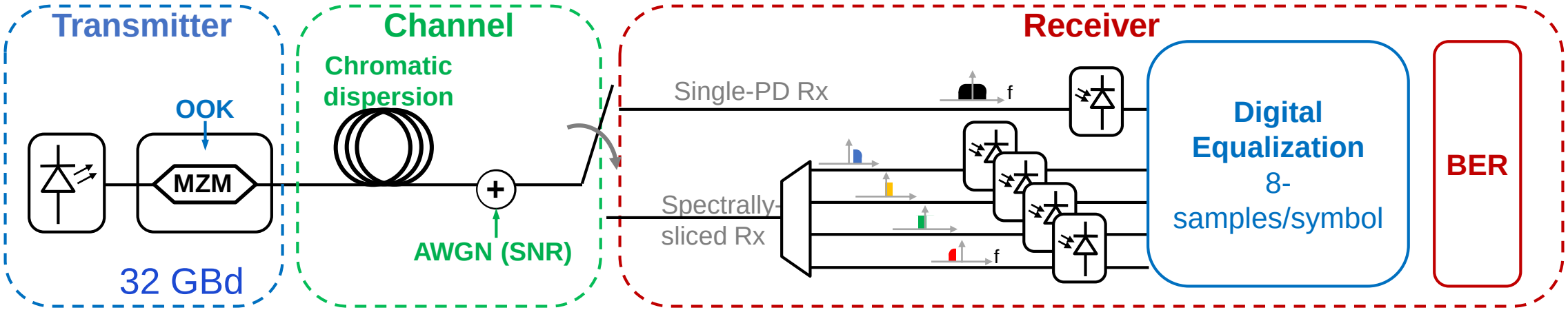
Interesting research topic but quite a few open challenges.

Optoelectronic receiver with digital equalizers

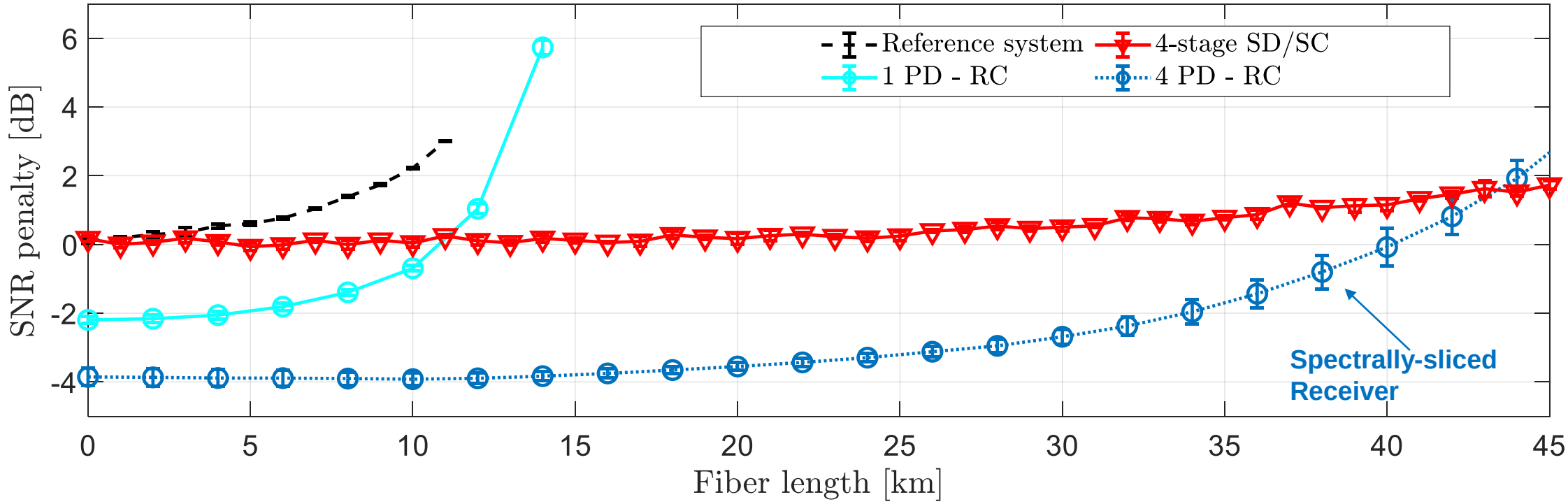




Transmission setup



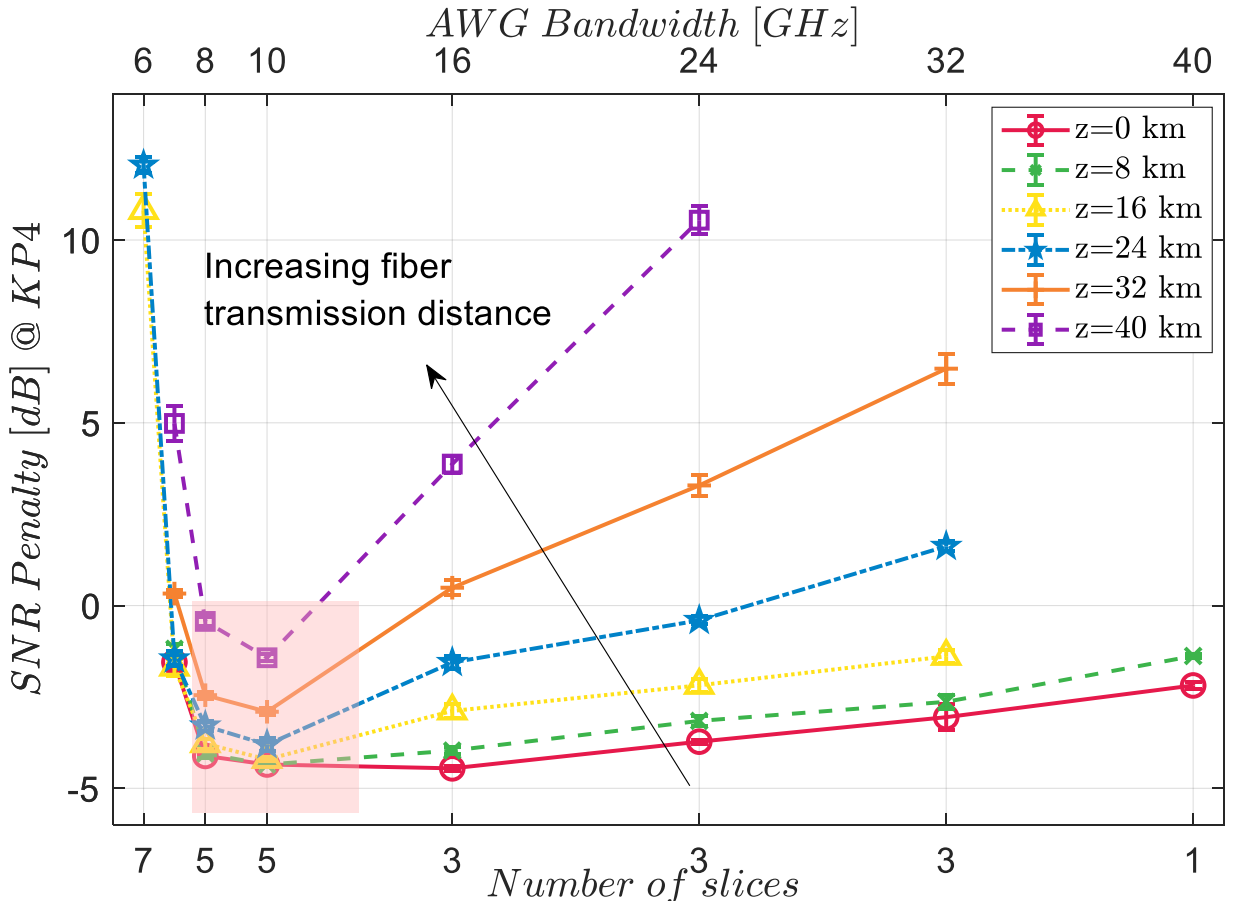
Numerical results

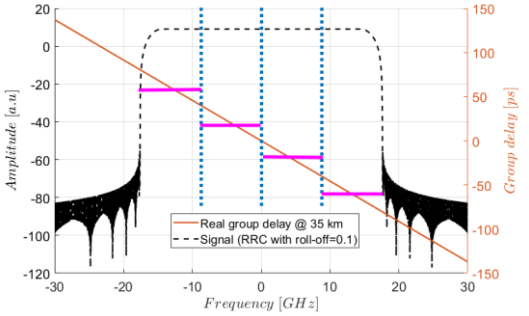


Significant increase in transmission distance, comparable with 4-stages SD/SC.

F. Da Ros, JSTQE 2020 S. Ranzini, Appl. Science 2019

Impact of filtering bandwidth



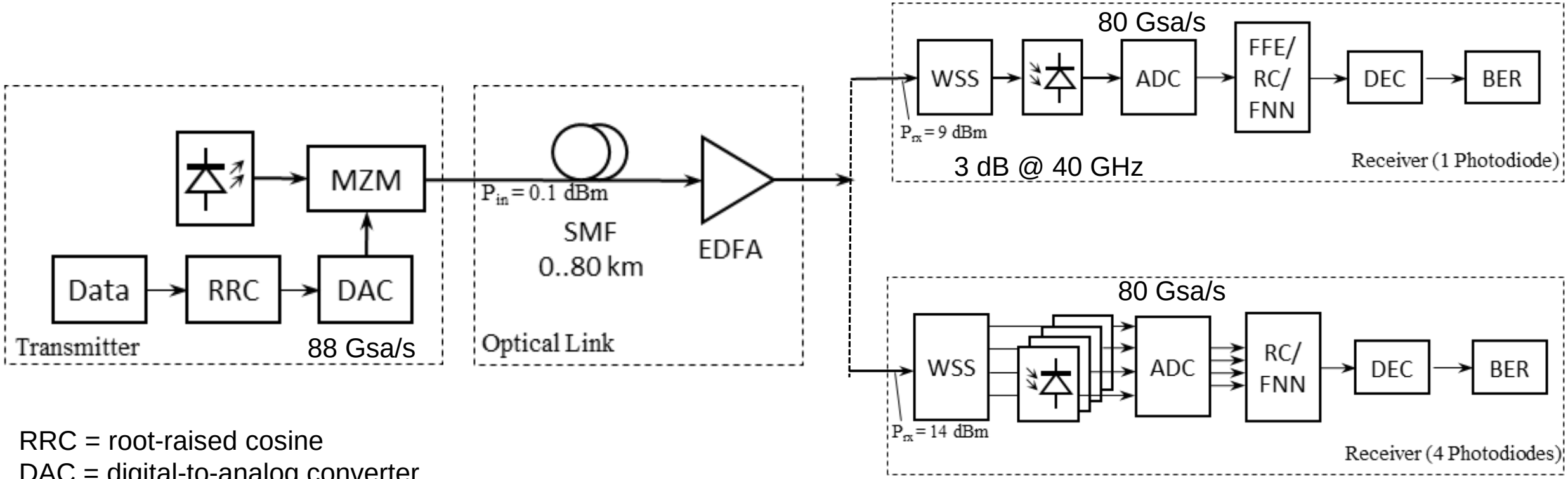


Trade-off between slice-wise GVD approximation and reconstruction/noise.

F. Da Ros, JSTQE 2020

Experimental validation

WSS = wavelength selective switch
FFE = feedforward equalizer
RC = reservoir computing
FNN = feedforward neural network



RRC = root-raised cosine
DAC = digital-to-analog converter
MZM = Mach-Zehnder modulator

Experimental validation

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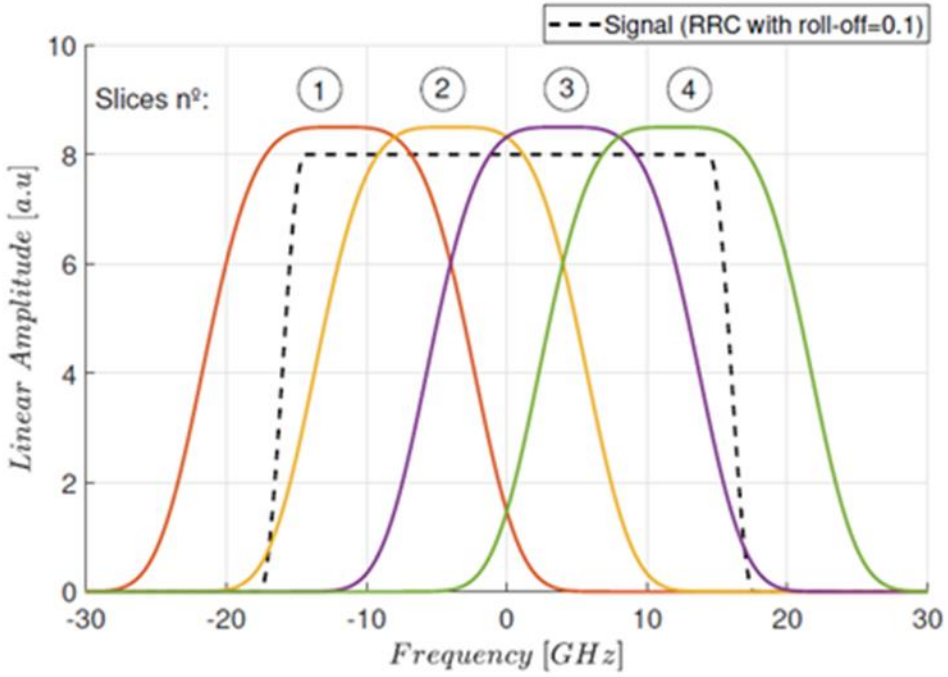
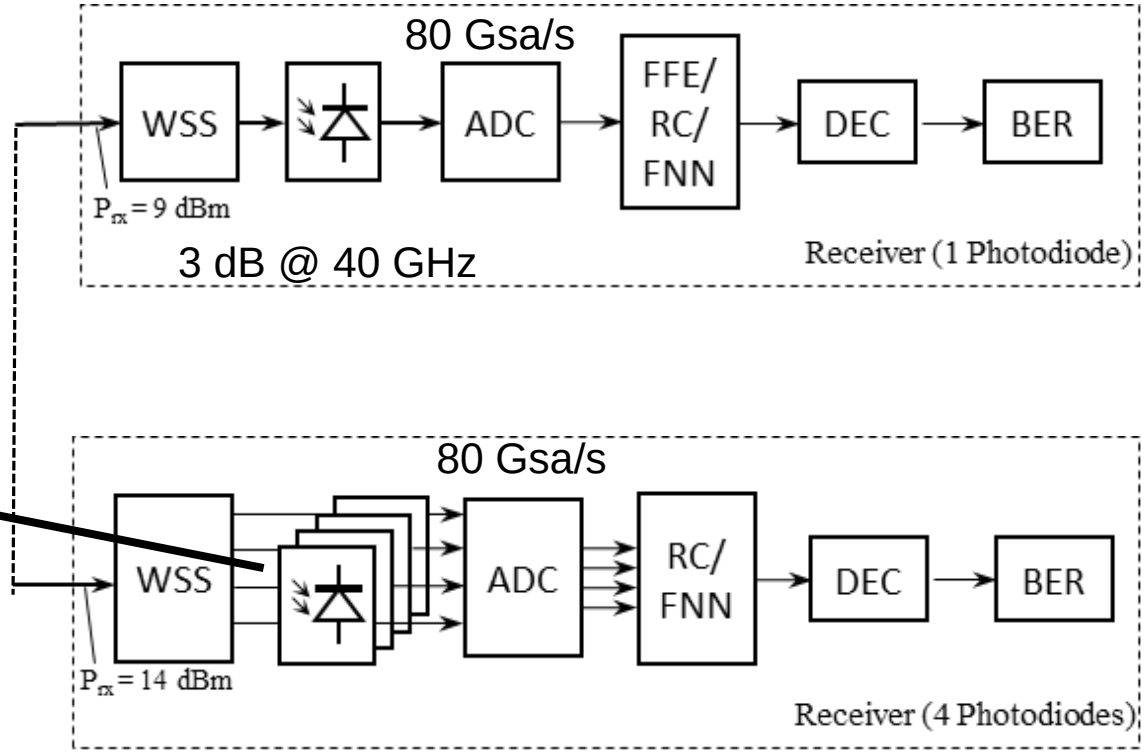
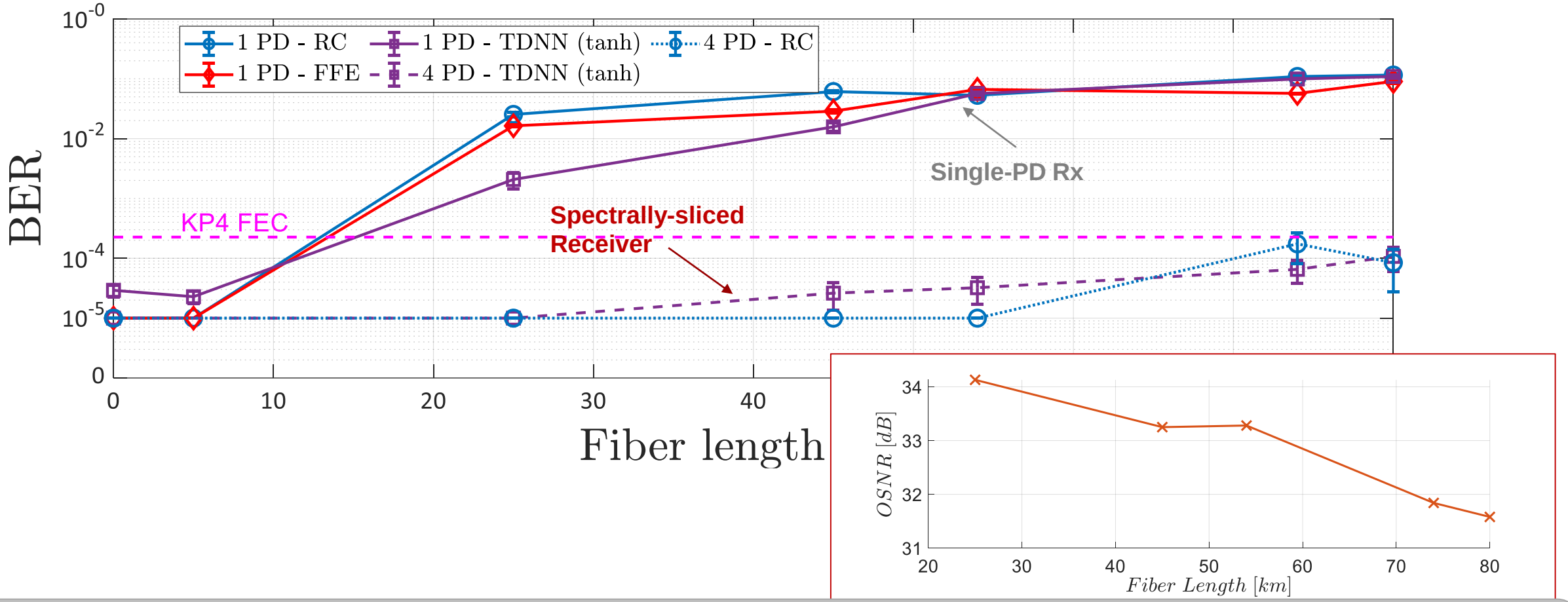




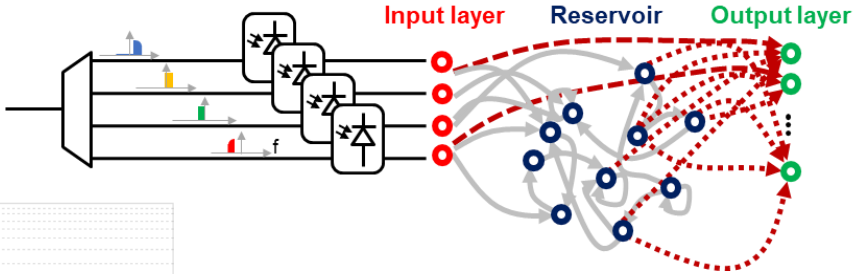
Transmission results

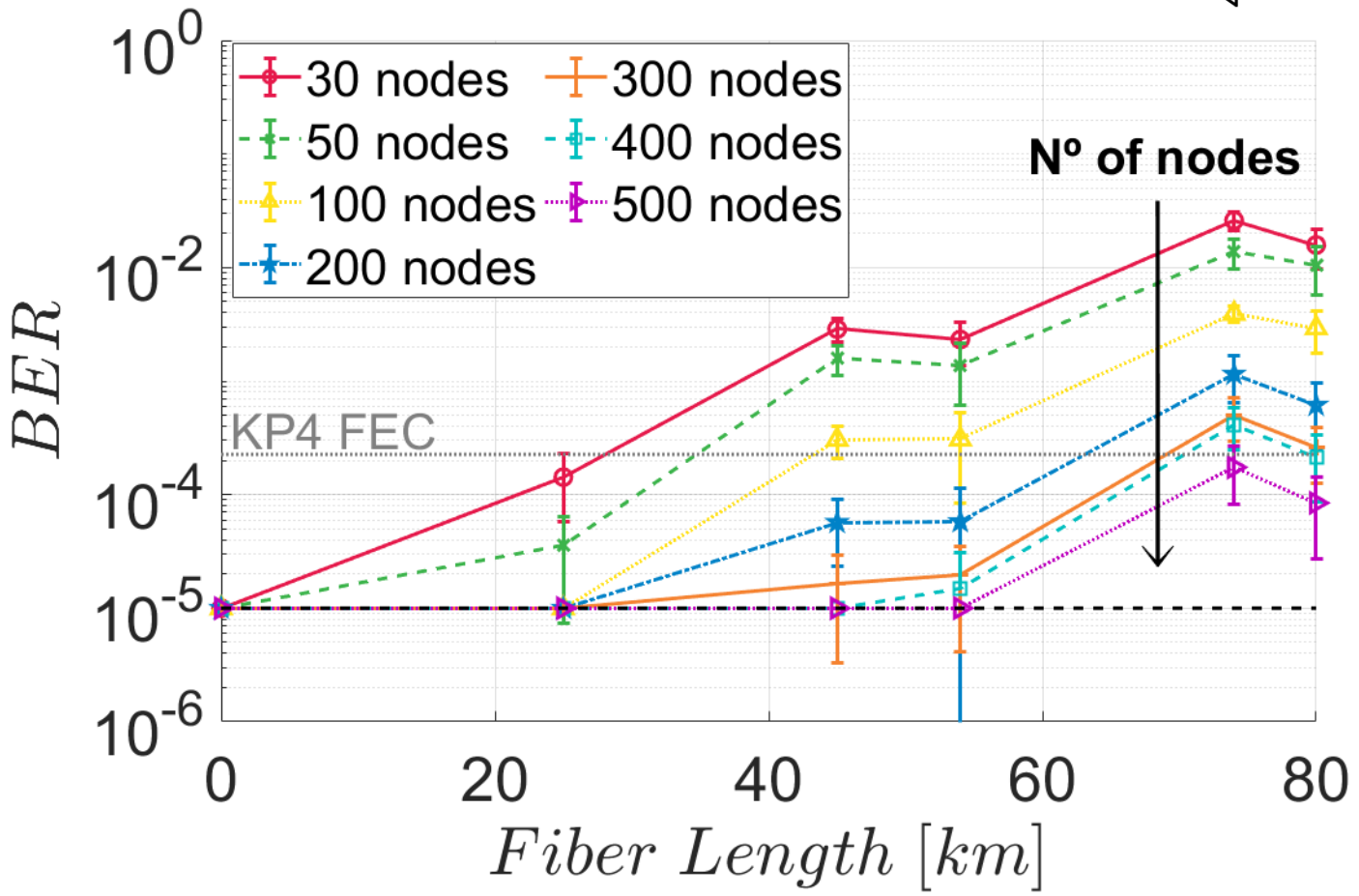


Spectral-slicing + equalization significantly enhances the transmission reach.

F. Da Ros, JSTQE 2020 S. Ranzini, JLT 2021 S. Ranzini, ECOC 2021

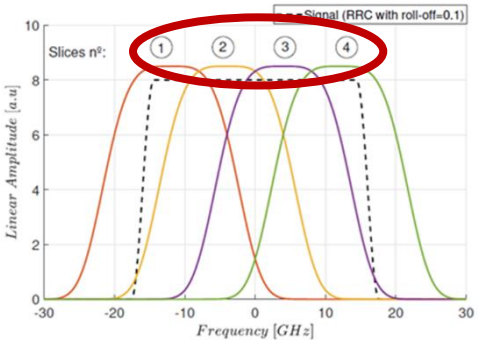
Impact of reservoir memory

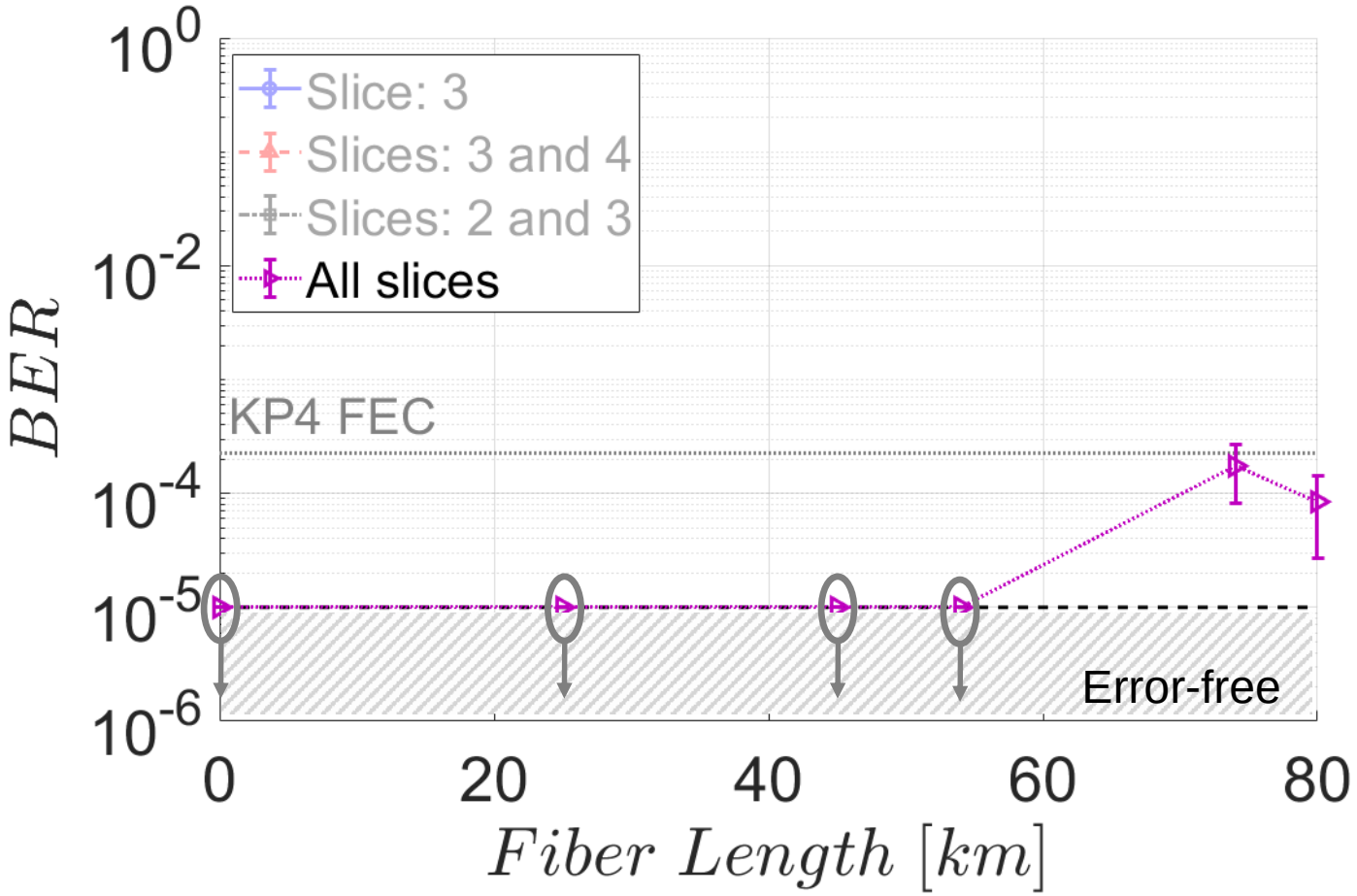




The equalizer memory needs to be adjusted for the specific transmission distance.

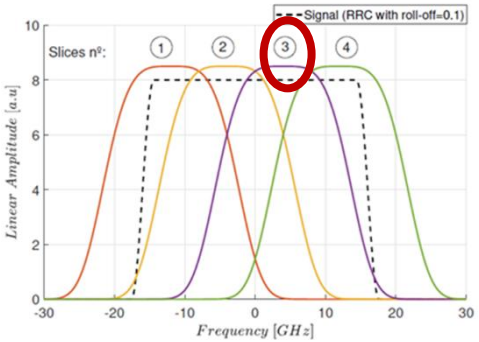
Complexity-performance trade-off

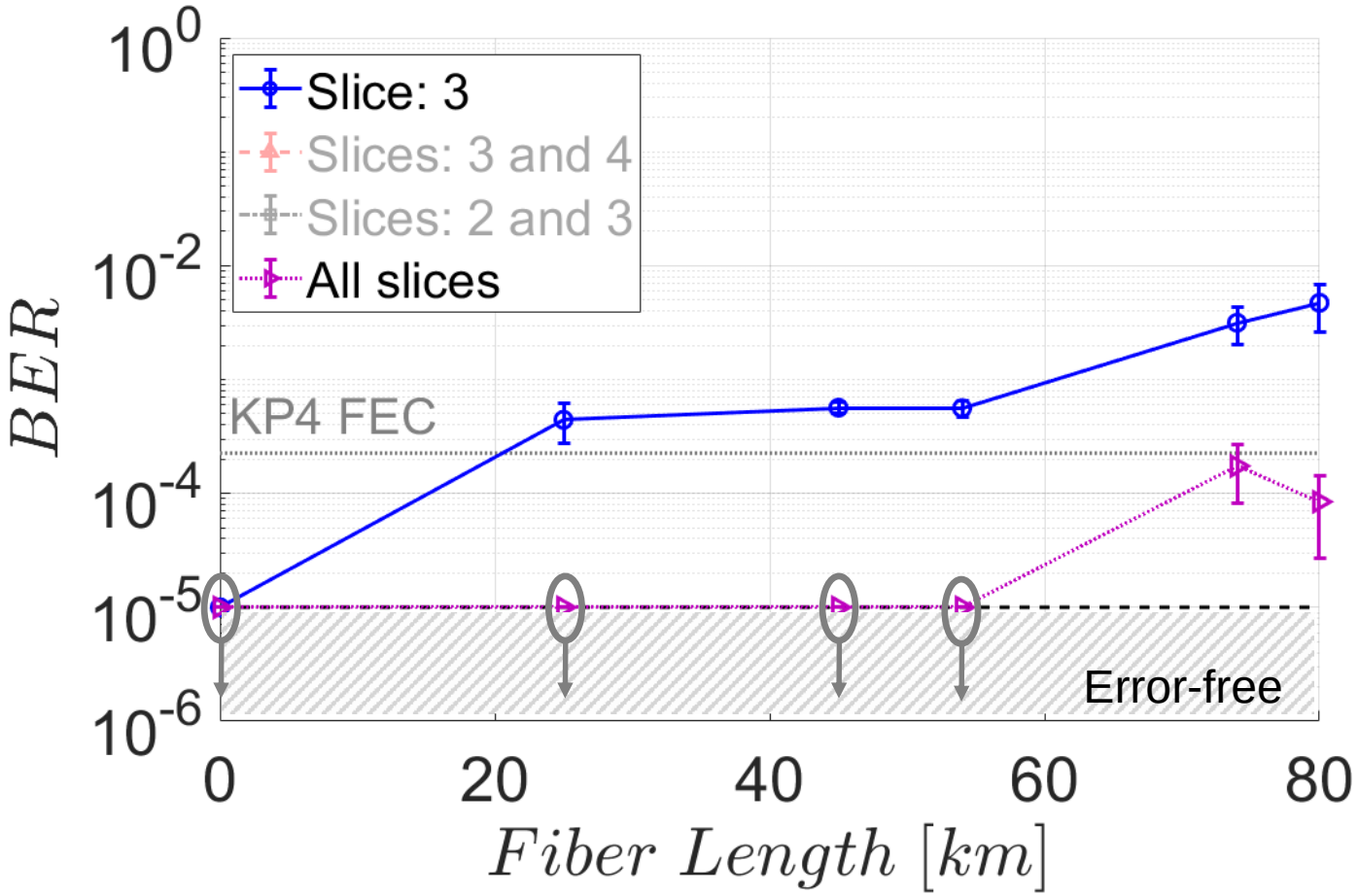




S. Ranzini, JLT 2021

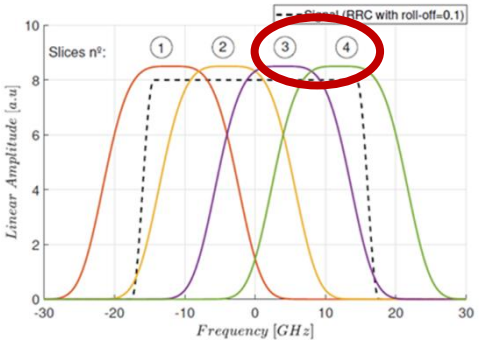
Complexity-performance trade-off

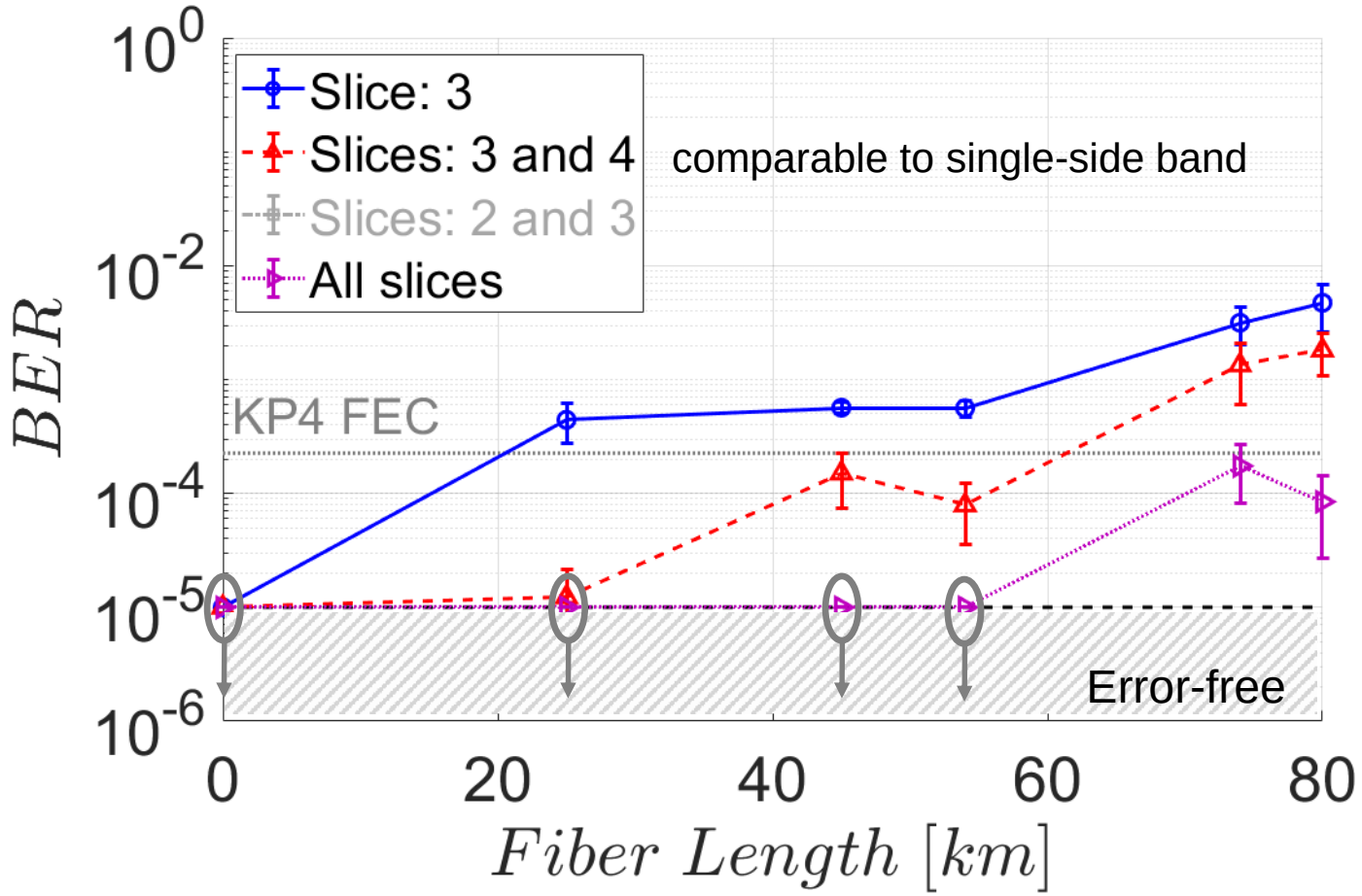




S. Ranzini, JLT 2021

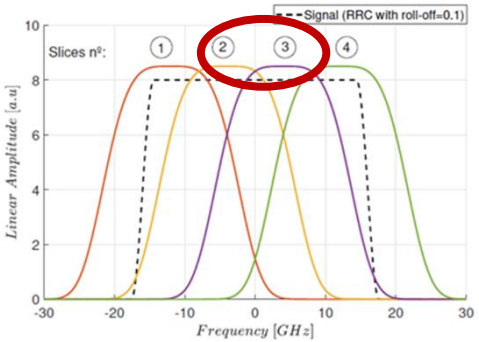
Complexity-performance trade-off

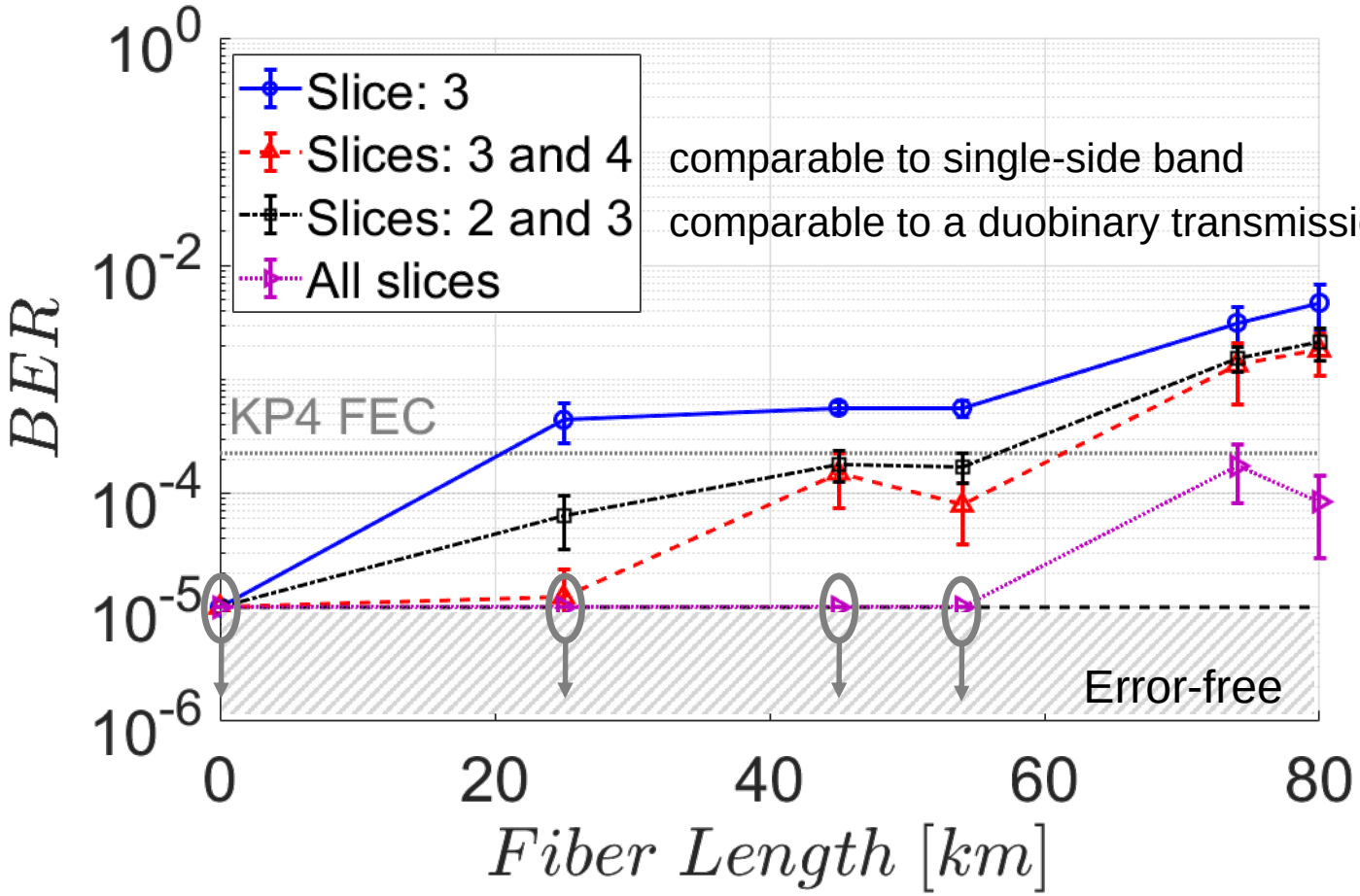




S. Ranzini, JLT 2021

Complexity-performance trade-off



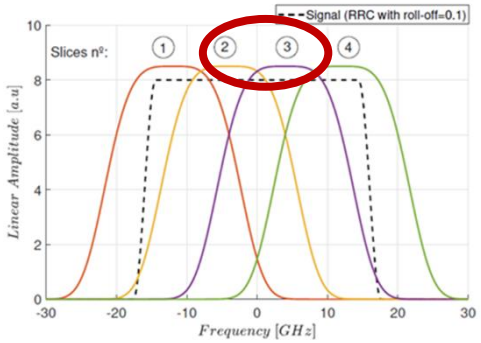


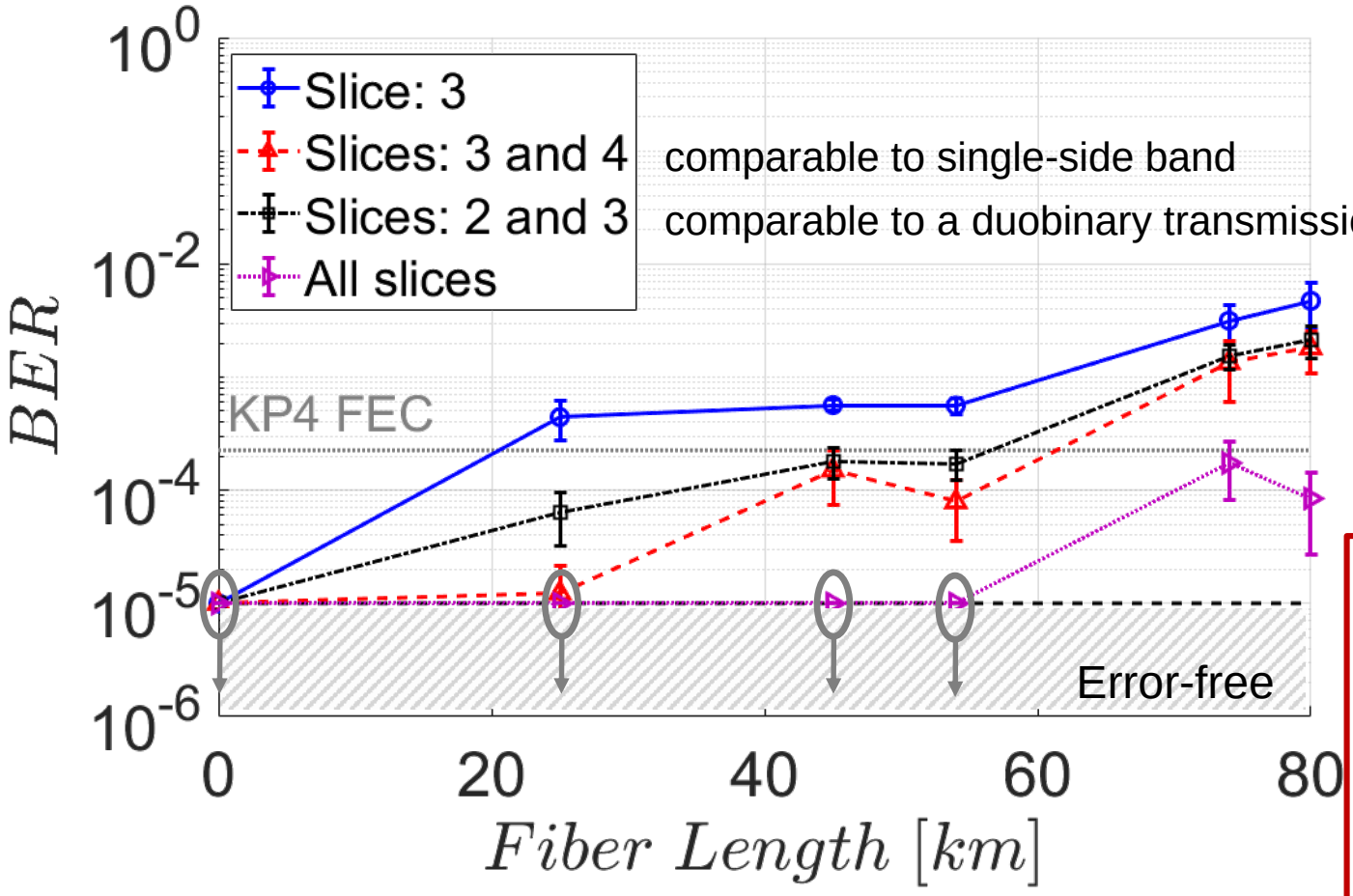
comparable to single-side band

comparable to a duobinary transmission with strong BW limit.

S. Ranzini, JLT 2021

Complexity-performance trade-off





comparable to single-side band

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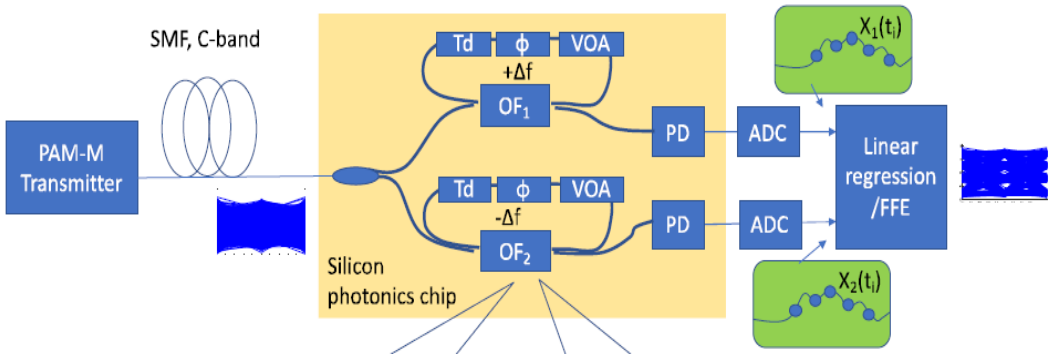
S. Ranzini, JLT 2021

Recurrent filters

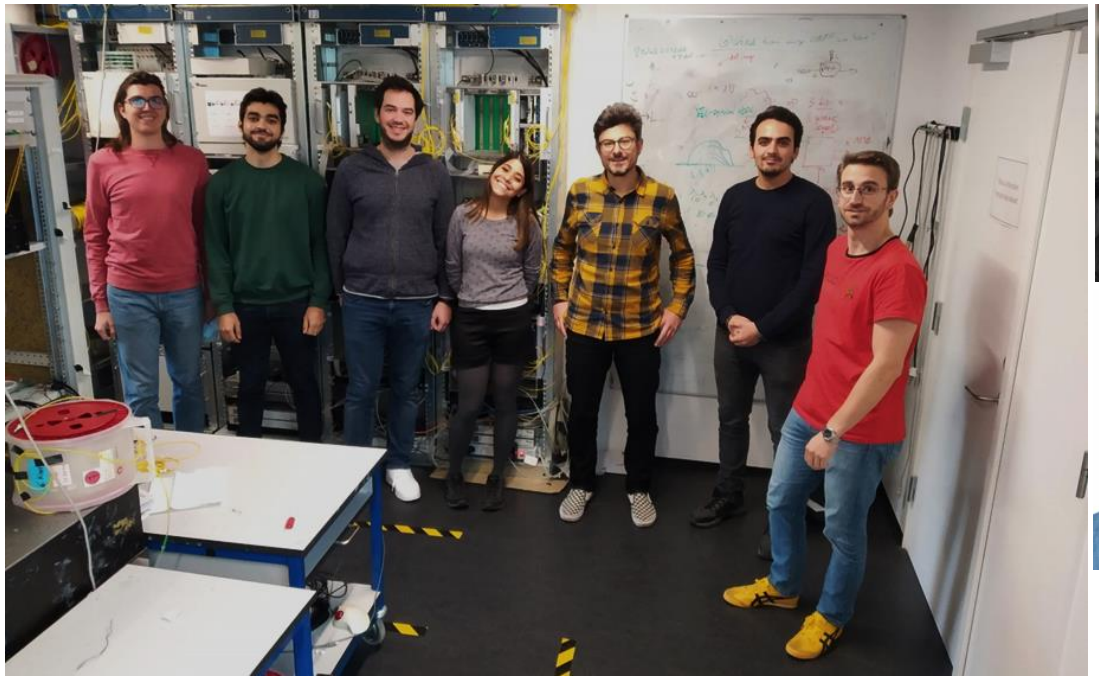


K. Sozos, et al. ECOC 2021

Summary

- We reviewed two promising NN-based equalizers for IM/DD transmission links
  - Time-delay Feedforward Neural Networks
    - Trainable with backpropagation but with size growing linearly with the required memory
  - Reservoir computing
    - Single ridge regression training but potentially more hardware demanding (high redundancy)
- Both schemes showed good improvement especially in conjunction with a novel spectrally-sliced receiver proposed
- Simplified NN-based equalizers are promising tools for extending the reach of IM/DD transmission systems

Thank you for your attention



Open positions

NOKIA Bell Labs

Henning Bülow

Vahid Aref

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