# Optical Interconnects in Radio Access

Use Cases and Enabling Technologies for Future RAN Architectures

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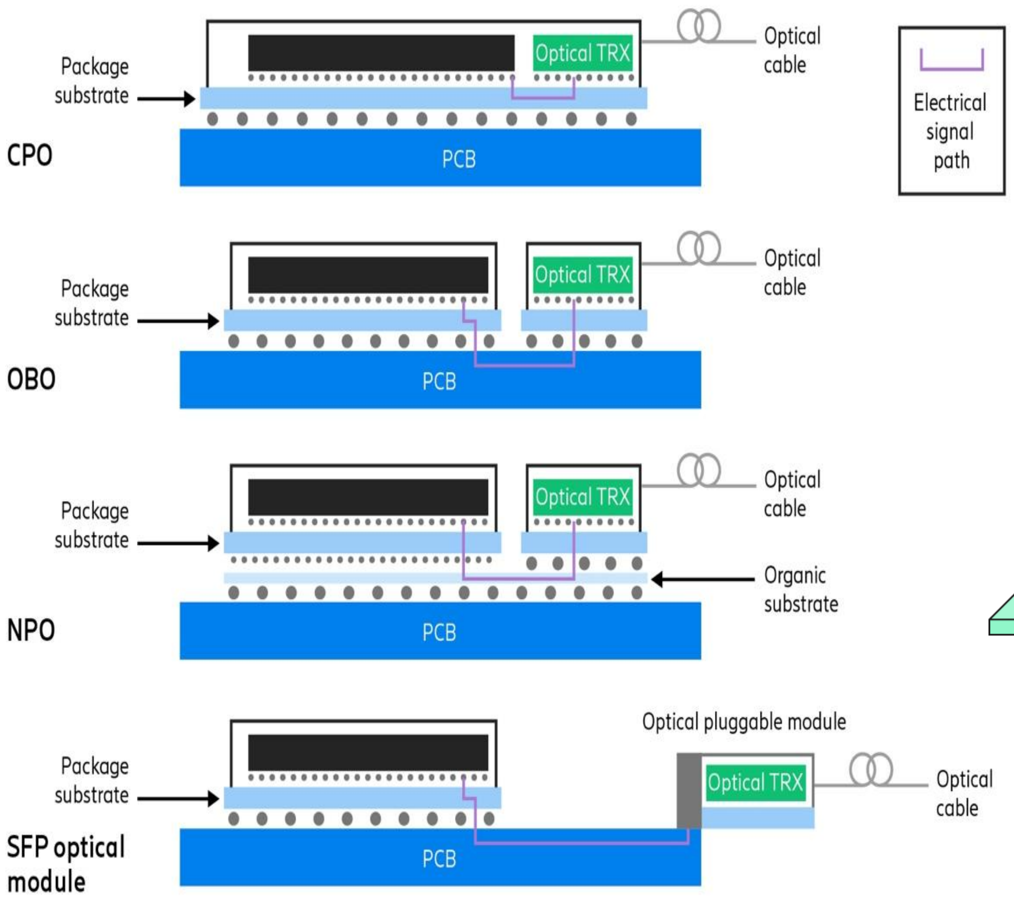
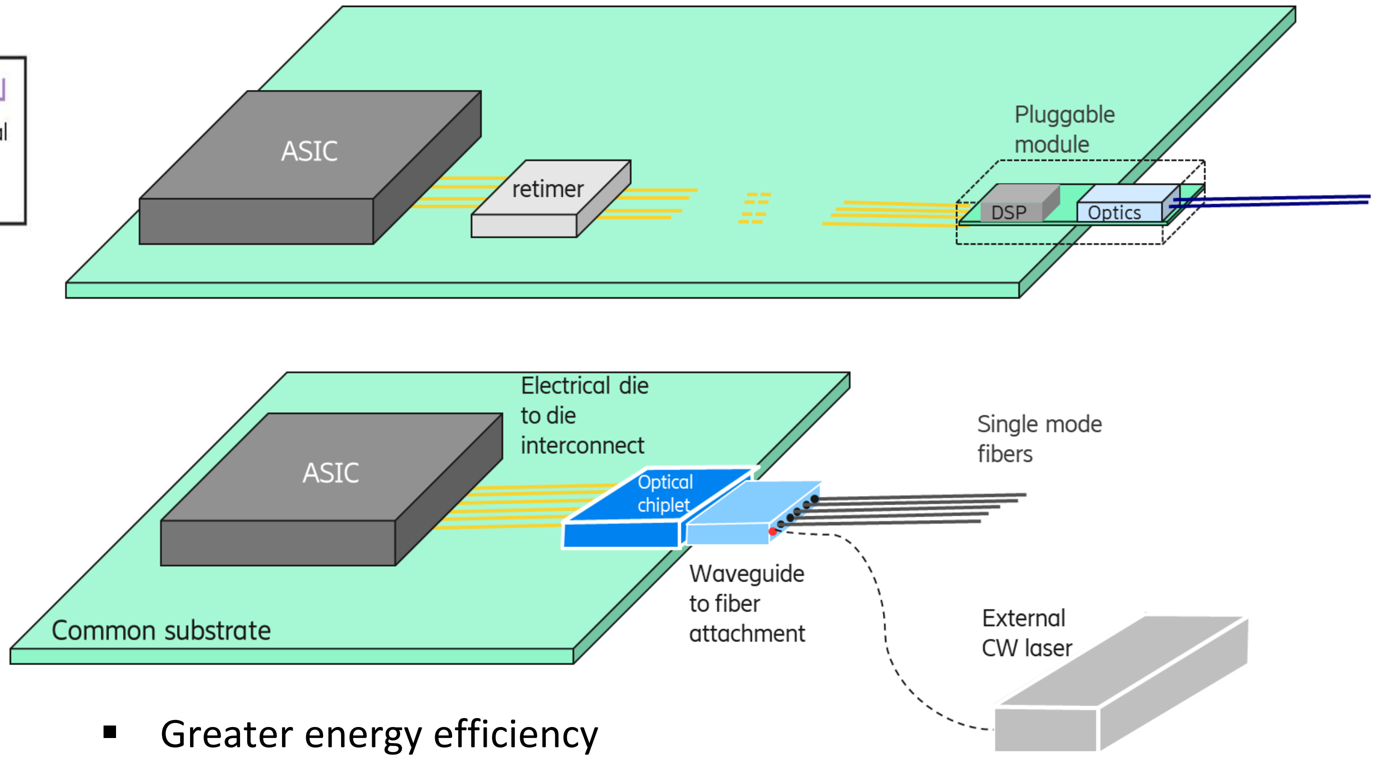
# Why optical interconnects are essential in radio systems

- Always increasing bandwidth and high data rates
  - Increasing the RF to cm-wave (~ 7-15 GHz), mm-wave (~ 26-43 GHz) and sub-THz (~ 90-300 GHz) to achieve high data rates on air, internal data processing volumes become of the order of several hundreds Gb up to 1 Tb → R. Sabella *et al.*, "Microwave and High-Speed Photonics Applications to 6G Systems," in JLT, vol. 43, no. 21, 1 Nov.1, 2025
- Today, RAN uses pluggable optical transceivers for fronthaul (FH) and electrical interconnects for on board chip-to-chip interconnects, but as the bitrate per lane evolves from 100 to 200 and 400 Gbit/s, signal integrity, thermal dissipation and energy consumption become critical.
- Co-packaged optics (CPO) is experiencing a rapid market growth pulled by the AI-driven demand for capacity and may/should be adopted (and adapted) for RAN needs→ F. Cavaliere *et al.*, "Co-Packaged Optics Opportunities in Radio-Access Networks," in *Ericsson Technology Review*, vol. 2023, no. 12, Nov. 2023
  – Estimated energy saving with CPO is -50% for the optical module, -30% including the ASIC

# CPO and NPO concept: shortening the electrical lines to avoid DSP & re-time

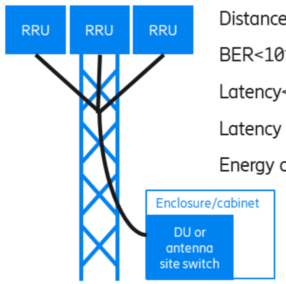



- Greater energy efficiency (-50% power at transceiver level)
- Small footprint (enabling dense node designs)
- Silicon Photonics optical chiplets operating at ASIC-like temperatures (external laser)

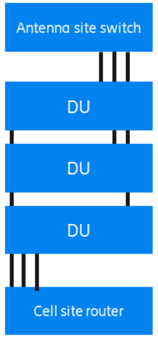
# Adapting CPO to radio systems

### Site connectivity




Distance <500m
BER<$10^{-15}$ post FEC
Latency<200ns
Latency determinism <0.2 ns
Energy consumption 10 pJ/bit

### Intra-site connectivity

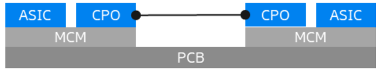


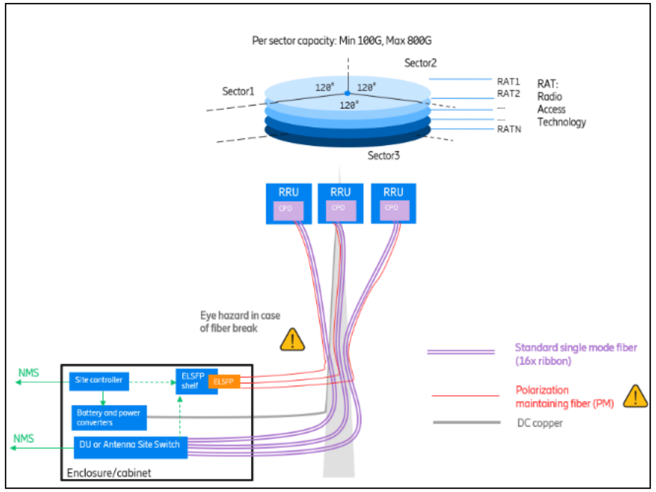

Distance <3m
BER<$10^{-15}$ post FEC
Latency<200ns
Latency determinism <0.05 ns
Energy consumption <6pJ/bit

### On Board connectivity

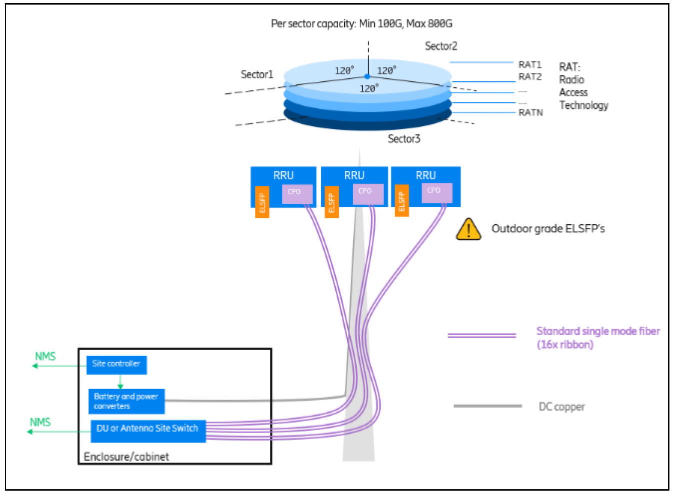
Distance <2m
BER<$10^{-15}$ (possibkly without FEC)
Latency<10ns
Latency determinism <0.05 ns
Energy consumption <3pJ/bit

Optical interconnect




Macro site based on CPO, ELSFP in the cabinet




Macro site based on CPO, high temp ELSFP in the radio

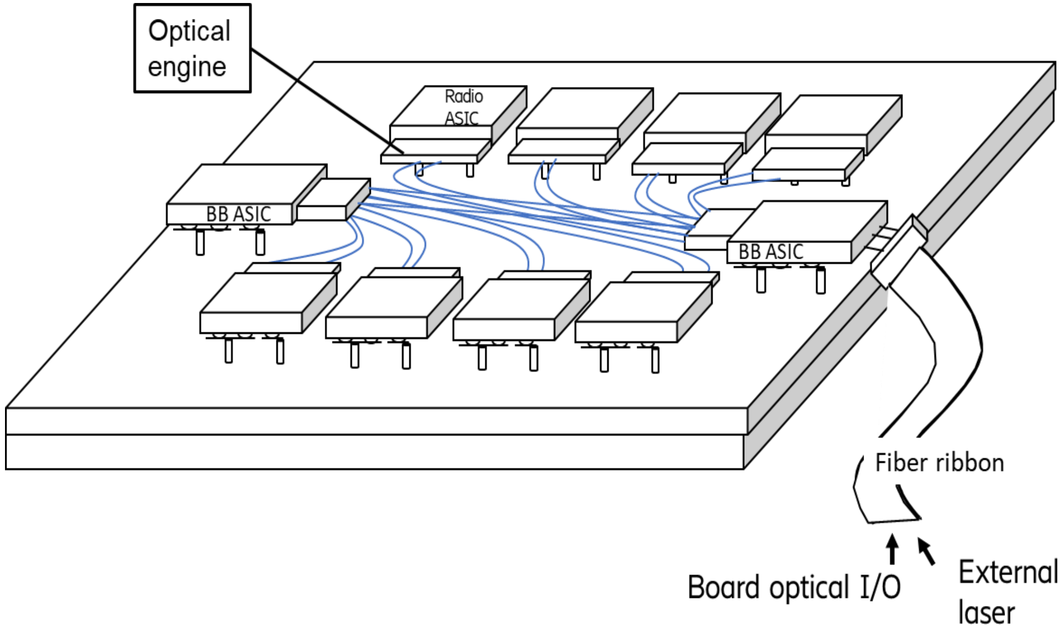
- Developed for AI-optimized DC and multi-Tbit/s switches, CPO finds application also in RAN
- RAN-specific requirements
  - MTBF (~15 years): Broadcom and Meta recently reported that CPO systems demonstrated a 5x lower serviceable failure rate compared to equivalent systems using pluggable transceivers.
  - Hosting the ELSP: options discussed in this Ericsson Technology Review
  - Use of SMF is instead of PMF: we owen patents on polarization incentive laser sources and PIC for polarization recovery

# Summary of CPO benefits in radio systems

- Do radio systems need the formidable bandwidth density (e.g., 6.4 Terabit/s in a few millimeter square) offered by CPO ?
- Not in the short/medium term CPO or NPO make the design future proof:
  - Less dependence on SERDES roadmap (200G/lane CPO can be used at lower rates)
  - Lower power consumption and lower latency: no need for extra retimers, MLSE or heavy FEC
  - No crosstalk as in electrical lanes
  - One design for any practical distance (optical links impairments are negligible, all penalty is generated at the e/o and o/e interfaces)
  - Use of optical interconnect intra-board allows to use cheaper PCB (no need for high-performance materials, lower number of PCB layers), reduces constraints on component placement, and offer the opportunity to increase modularity and reuse across different board sizes and system architectures

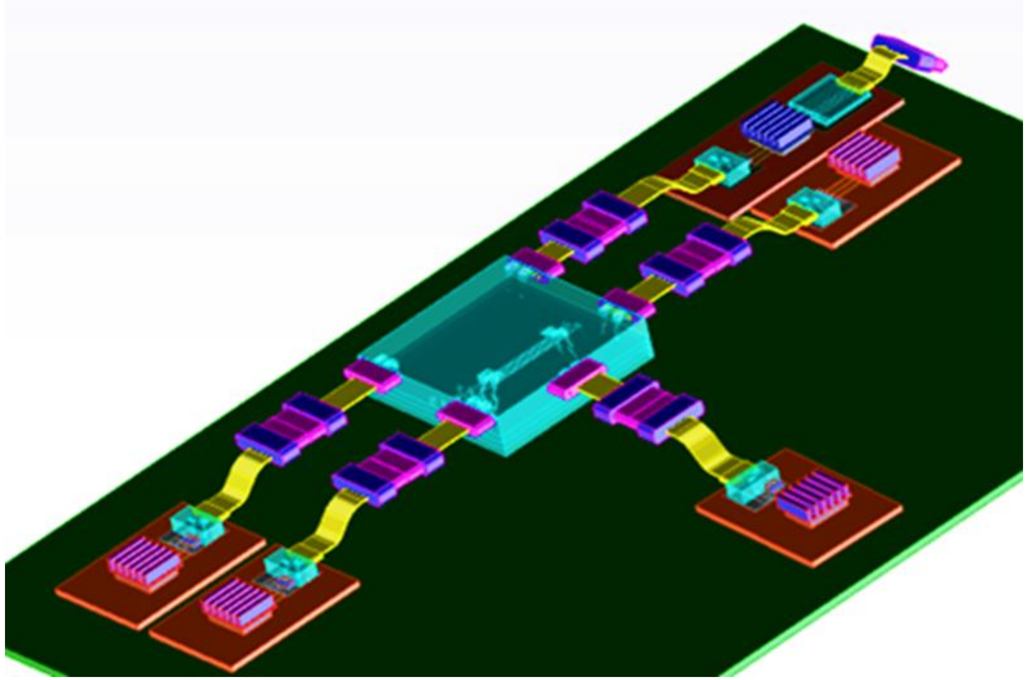
# Optical PCB

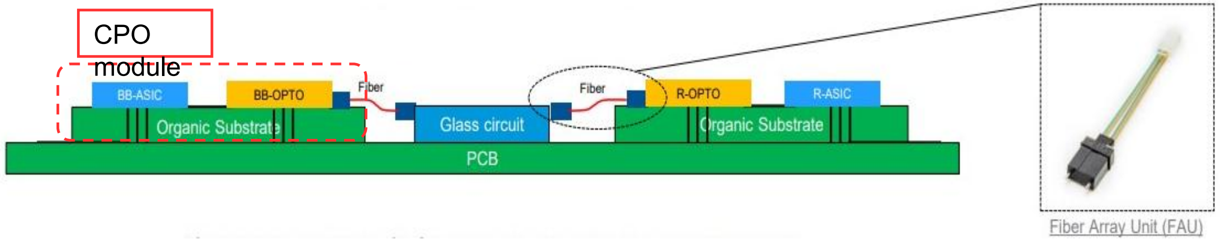
- One important aspect using CPO or NPO is the density of modules to interconnect, which would benefit from more compact optical interconnection networks , for example optical PCBs
- There are two main types of Optical PCBs
  - Glass layers. placed on top of the PCB or used as substrate, that contain the network of optical waveguides
  - Waveguides embedded in the PCB, typically made in polymer.

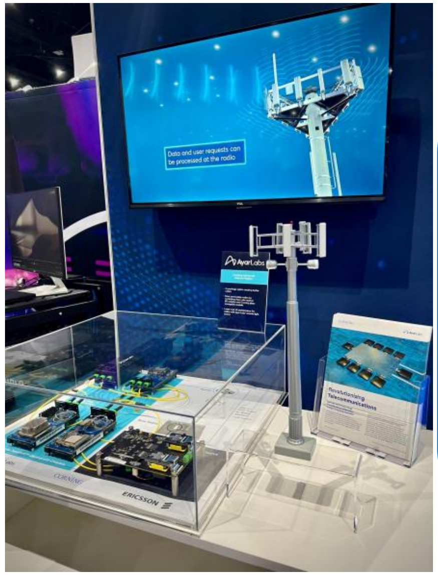


# Glass layers on the PCB

- The glass device contains polarization maintaining optical waveguides at very low loss (0.01dB/cm),
- Advantages:
  - Optical waveguide can cross without crosstalk
  - Compatible with optical Engines/CPO with standard fiber connector
  - Low impact on existing production processes (the device is external to the PCB)
  - Reflow-solderable: it is possible to mount the glass on the PCB before its assembly.





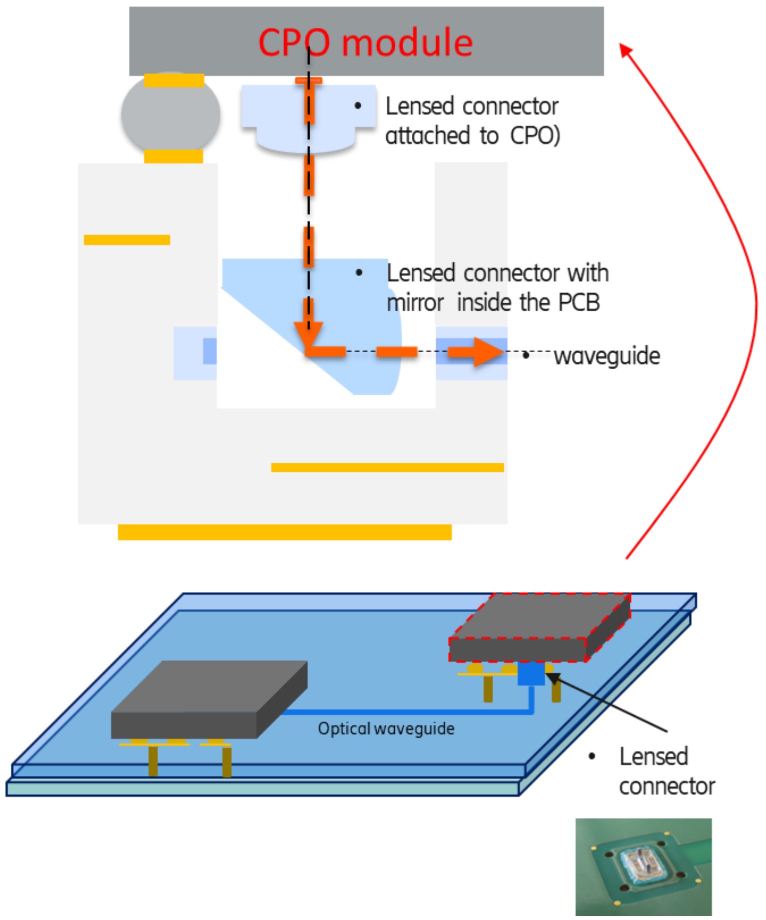



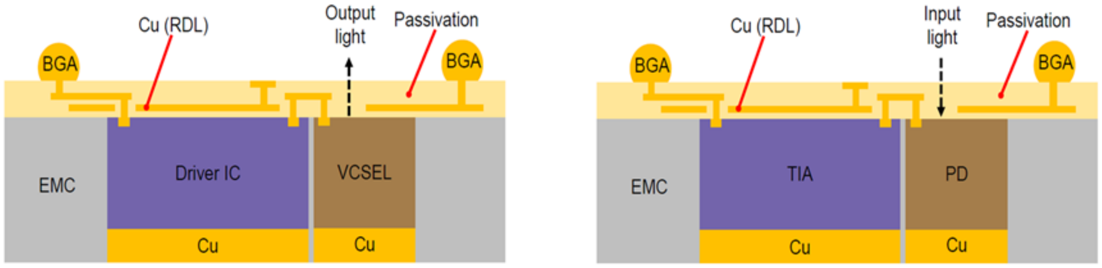
**OFC2024 demo**

A solution combining optical engines and a glass layer was demonstrated by Ericsson, Corning and Ayar Labs at OFC 2024, featuring 16 Tbit/s in a network of 48 waveguides on glass, 16 of which dedicated to the delivery of ELSs.

# Optical waveguides embedded in the layers of a PCB

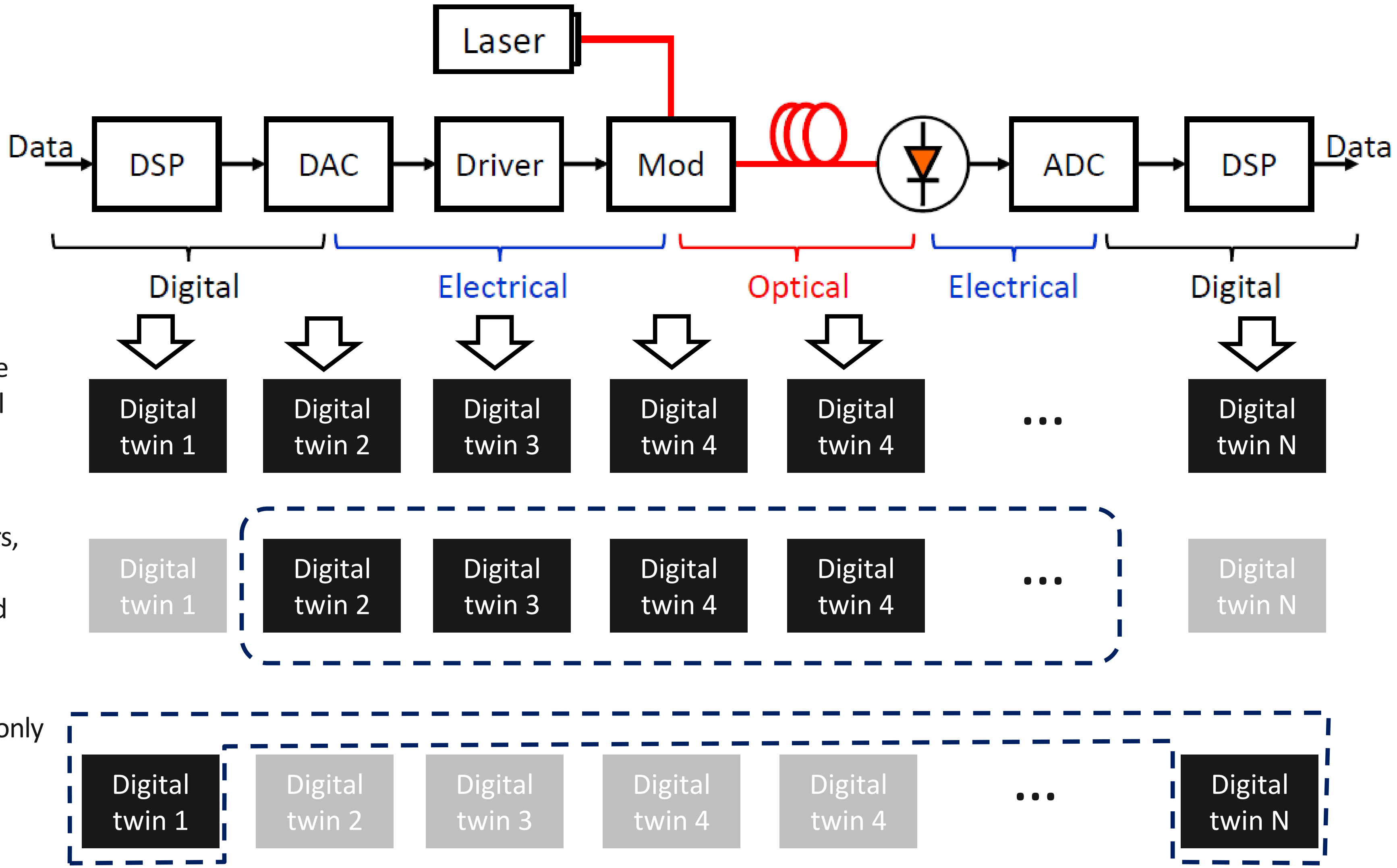
- Compact optical interconnection solution (optical and electrical lines integrated in the same board)
- The assembly of modules on the board needs the alignment of both electrical pads and optical ports
- Fabrication of embedded waveguides already compatible with the production processes of standard electrical PCBs
- The assembly of optical modules on the board needs further developments
  - Micro-optics (e.g., arrays of parabolic mirrors) can be used to deflect light ivertically towards an optical port in the chip
  - The optical port would no longer use standard connectors, e.g., MPO connectors, but would be a fibreless connection with a lensed port aligned to the optical output of the board.
- This packaging is proposed in the figure where the chip has an optical I/O located on the bottom side of the module, together with the BGA



# AI in optical interconnects

Despite their ostensible simplicity, interconnection links are complex to optimize, due to number of independent variables to set.
At 200 Gbit/s and 400 Gbit/s, multi-level modulation, pre-distortion, equalization and FEC are necessary to achieve error-free operation, as well as optimal calibration settings for Tx and Rx, leading to operational complexity and energy consumption.



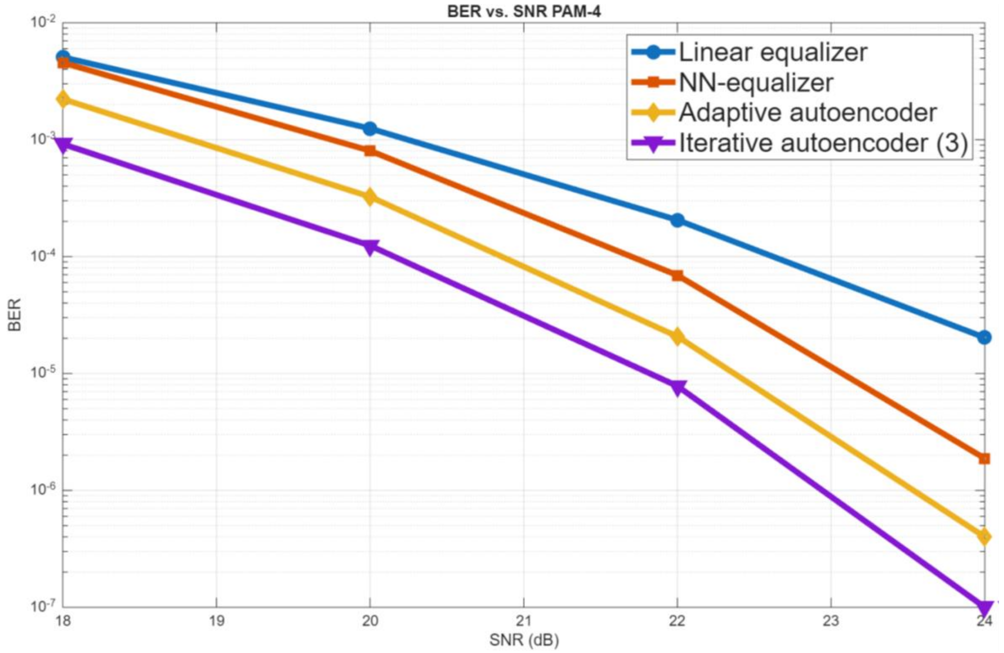

**Step 1**: create digital twins of all components of the link: digital, electrical, optical . Electrical and optical models are physics-inspired differentiable NN structure, allowing for gradient backpropagation.

**Step 2**: supervised learning of unknown parameters, while directly embedding available physical knowledge, by means of experimental or simulated datasets.

**Step 3**: Freeze the digital twin of the link and train only the DSP blocks (unsupervised learning. e.g., autoencoder), using NN structures within practical implementation constraints

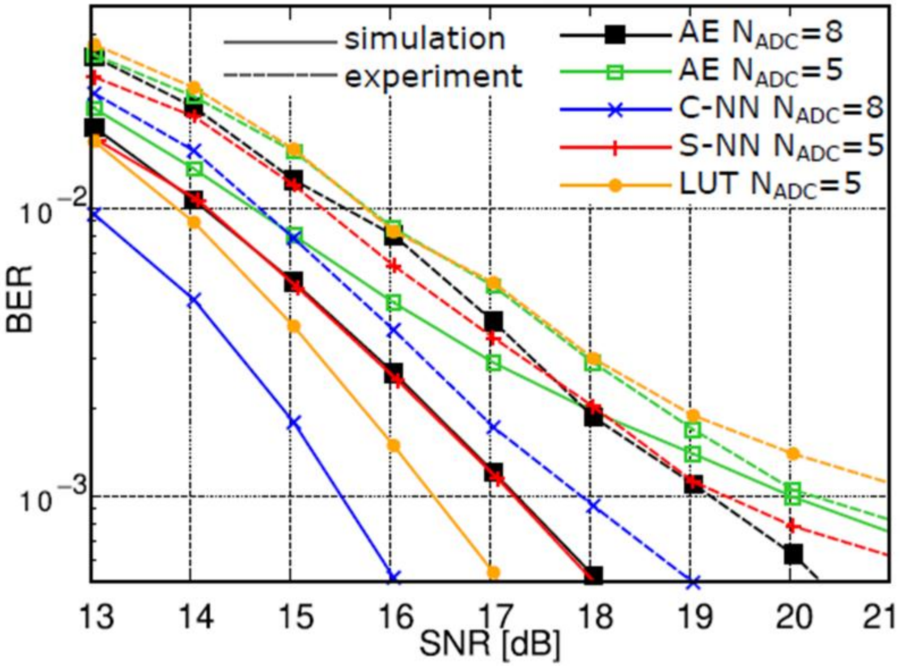
# Preliminary results

- Simulations with PAM4




- Simulations and experiments with Bi-PAM4

C-NN: context window=11, S-NN: context window =5



# Where's business?