Advancing Towards Optical Network-as-a-Service Empowered by the Physical Layer Digital Twin

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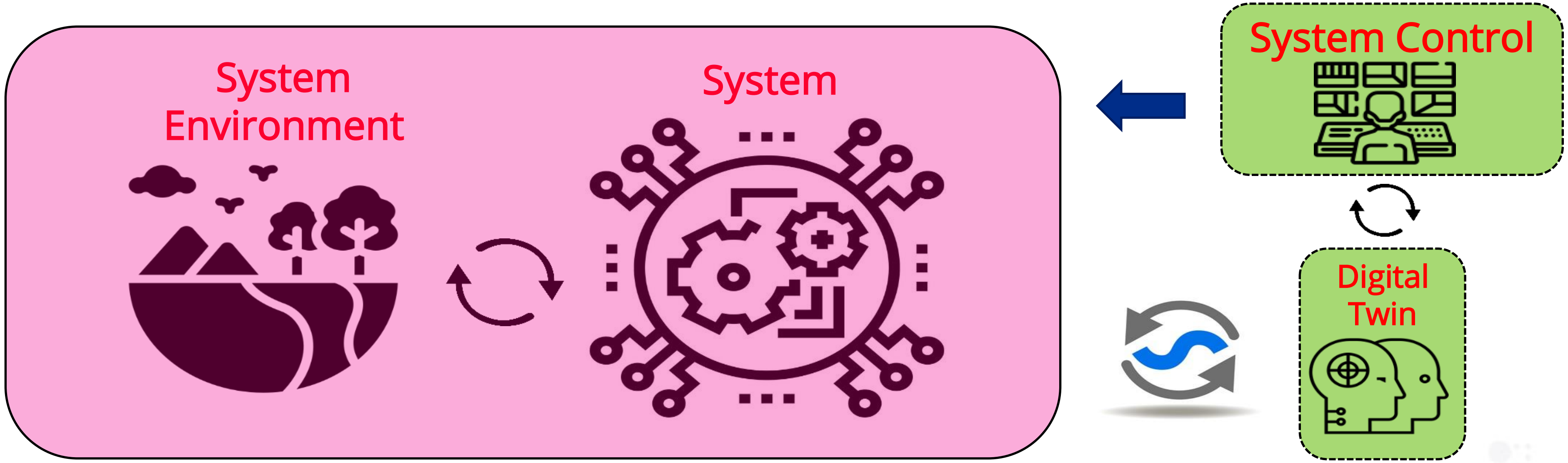
WORKSHOP GARR 2023

NET MAKERS

The Concept of Digital Twin

The concept was first introduced by the NASA as *“an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin”*

In general, the digital twin is a high-fidelity model of the system and the system environment impact which can be used to emulate the *real* twin



The Digital Twin Concept in Physical Layer of Optical Networks

PHY-DT

OpenConfig

Open ROADM

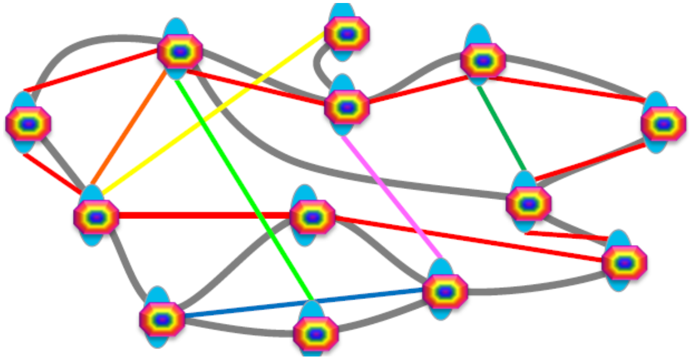
Open API

Netconf/YANG

Topology, fibers, OA sites

Cognitive data retrieving from telemetry by AI/ML

Digital Models of transparent optical transport on NE



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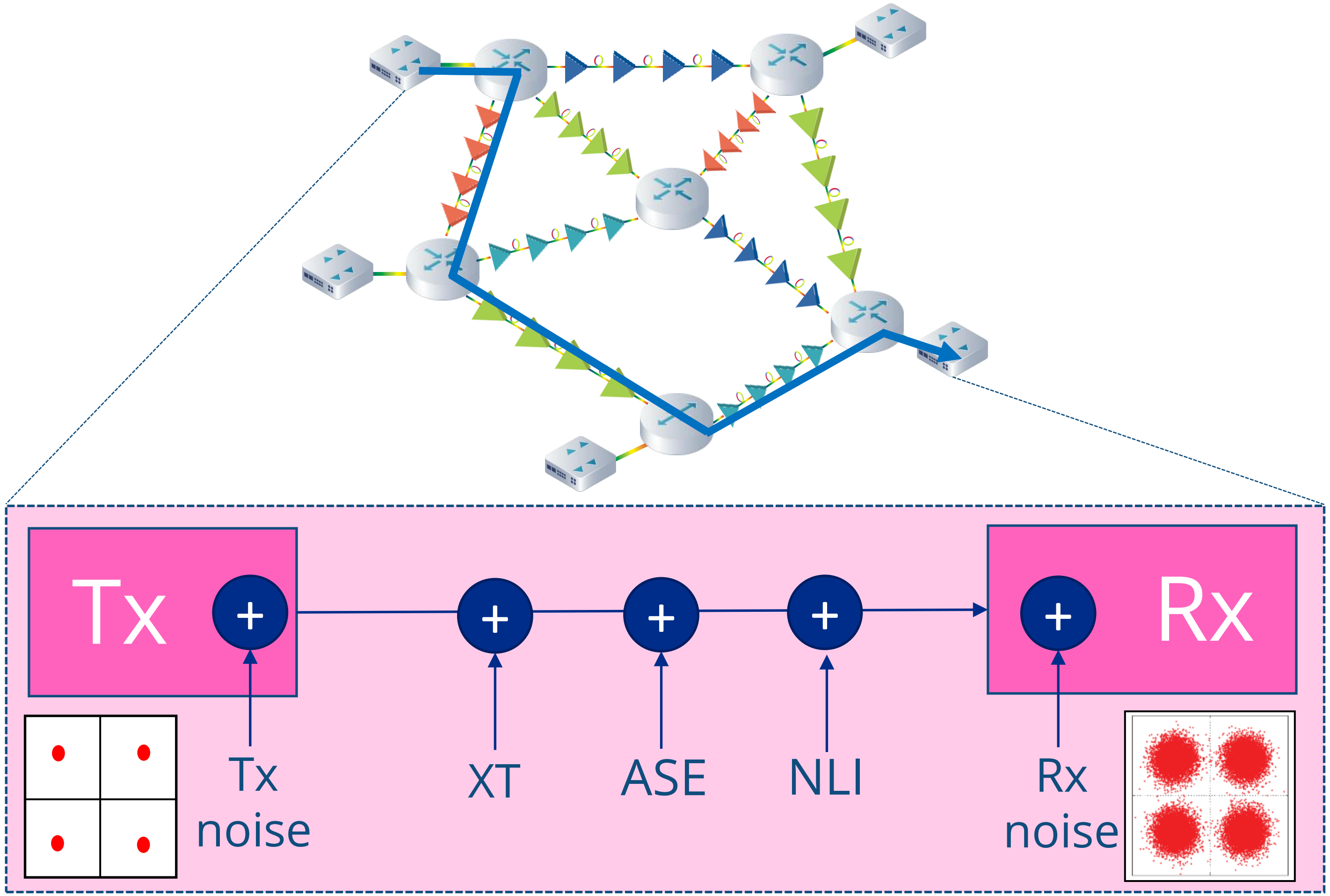
TAPI

Physical Layer Model in Optical Networks

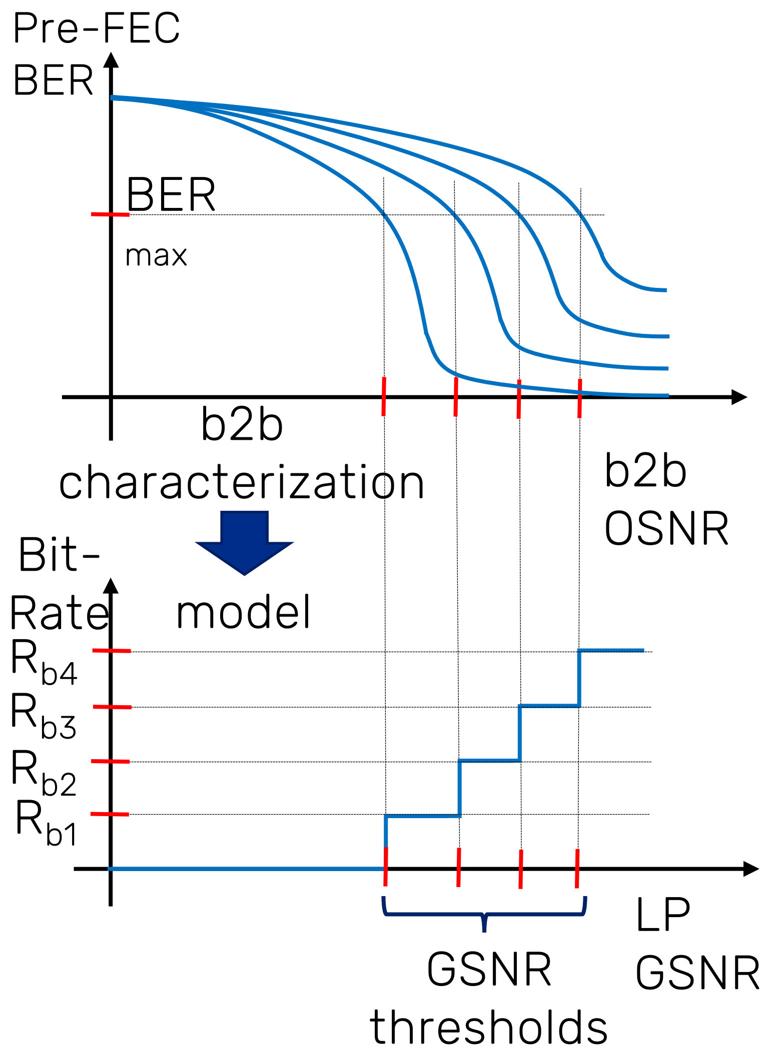


- All noise sources well approximated as Gaussian noise in channel bandwidth roughly for |D|> 2 s/nm/km
- Given the optical control, transparent lightpaths well approximated as dual polarization AWGN channels, whose performance is fully characterized by the GSNR

$$GSNR = \frac{P_{CUT}}{\underbrace{P_{ASE} + P_{NLI} + P_{XT}}}$$

noise contributions evaluated on the symbol rate R_s as the Rx implements the matched filter

Dual Polarization Coherent Transceivers Model



a) Look-up table model based on GSNR thresholds

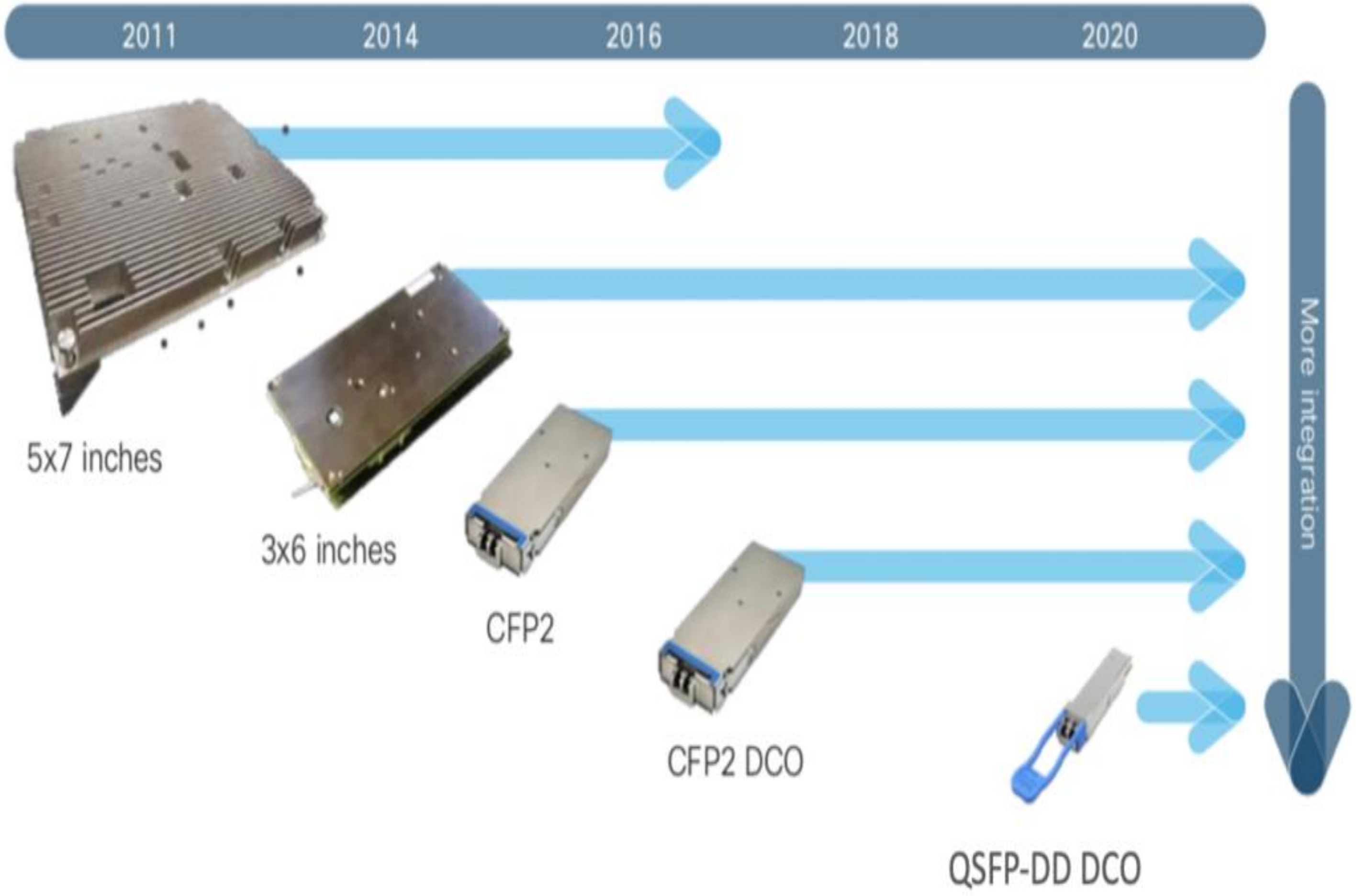
Operational Mode	Modulation Format	Symbol Rate [Gbaud]	Roll off	Bit Rate [Gbps]	GSNR Thresholds [dB]	Max CD [ps/nm]	Max DGD [ps]	Min-max power [dBm]
Mode 1	MF_1	R_{s1}	α_1	R_{b1}	$GSNR_{th,1}$	CD_{max1}	DGD_{max1}	
…	…	…	…		….	…	…	
Mode N	MF_N	R_{sN}	α_N	R_{bN}	$GSNR_{th,N}$	CD_{maxN}	DGD_{maxN}	

b) Semi-analytical model

$$BER = k_1 \mathrm{erfc}\left(k_2 \sqrt{\frac{1}{\frac{1}{GSNR} + \frac{1}{SNR_{TRX}}}} \right)$$

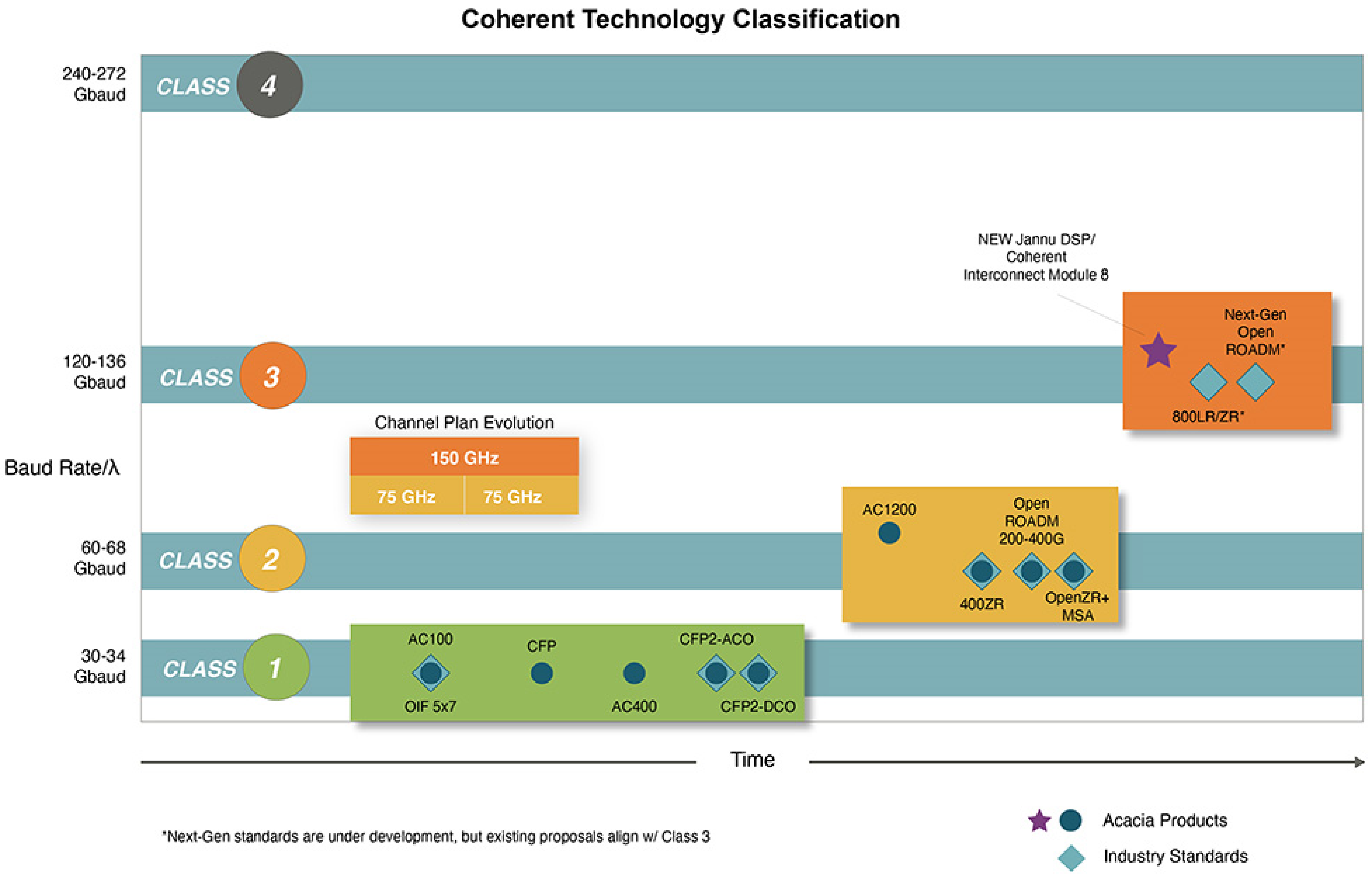
K_1 and K_2 depend on the modulation format

Dual Polarization Coherent Transceivers Evolution

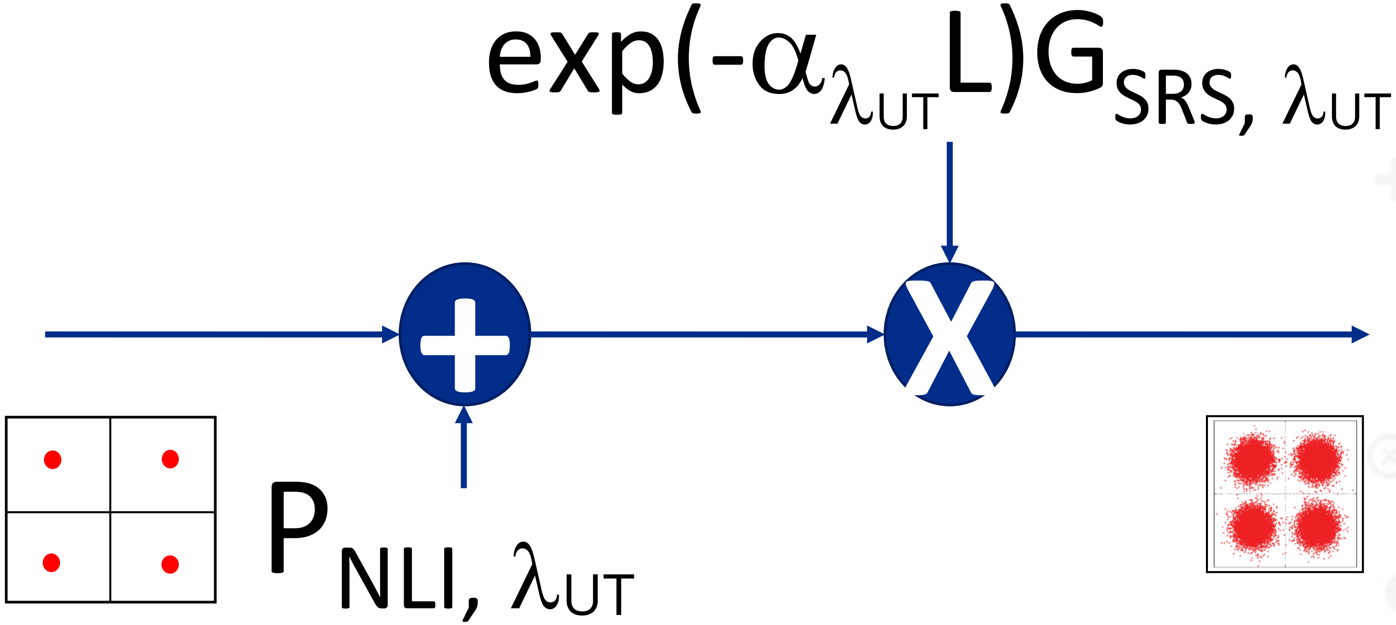


ZR/ZR+

Dual Polarization Coherent Transceivers: Standard Evolution



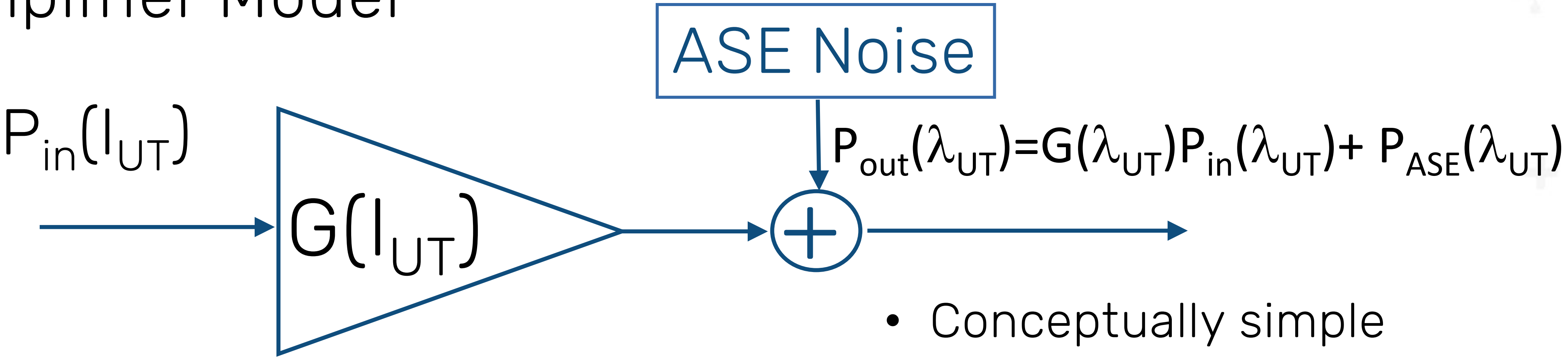
Fiber Propagation: NLI, LOSS, SRS



- It has been extensively proved that fiber propagation can be effectively and accurately modeled as a Gaussian noise (NLI) and by the intrinsic loss and the SRS effect
- Main issues inducing uncertainties are
  - From typically unknown lumped losses
  - Mixed fiber type
  - Extremely low CD |D|< 2 ps/nm/km
- AI may help in augmenting the knowledge (fiber type, connector losses)

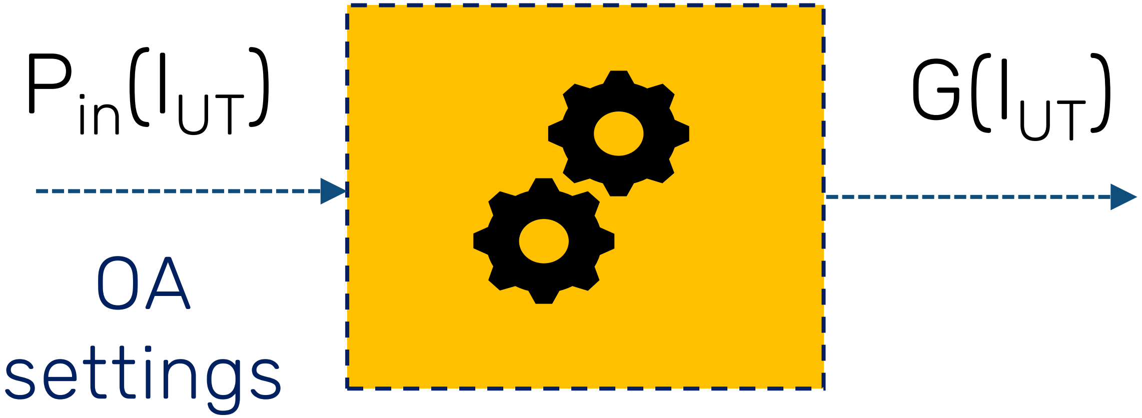
Optical Amplifier Model

THE PHYSICAL LAYER EFFECT



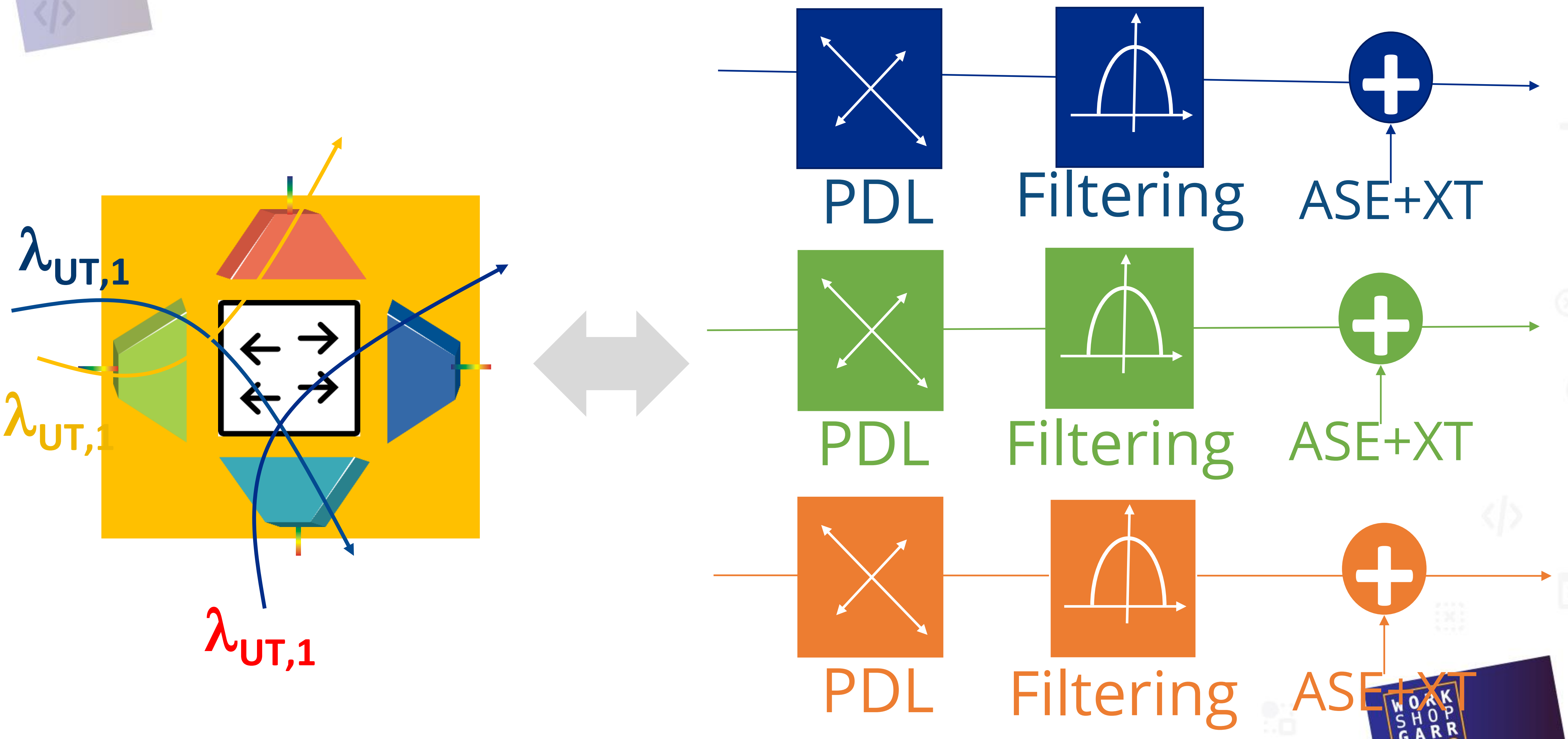
- Conceptually simple
- Practically issues are
  - Spectral load dependence
  - Ripple
  - Input power
  - Vendor dependence
- ML model can be an effective solution

THE MODEL



$$P_{ASE}(\lambda_{UT})=hf_{UT}\ NF(\lambda_{UT})G(\lambda_{UT})Rs$$

ROADM model



λUT,1
λUT,1
λUT,1
PDL
Filtering
ASE+XT
PDL
Filtering
ASE+XT
PDL
Filtering
ASE+XT

GNPy as Physical Layer Digital Twin

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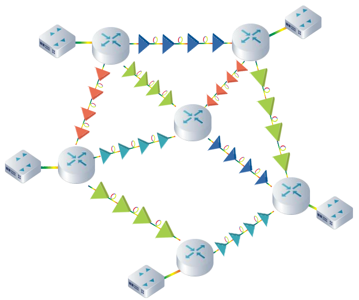
Topology, fibers, OA sites

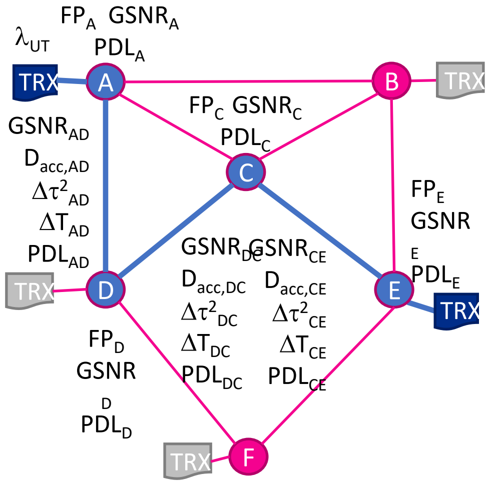
Cognitive data retrieving from telemetry by AI/ML

$$GSNR_{AE} = \frac{1}{\frac{1}{GSNR_{AD}} + \frac{1}{GSNR_{DC}} + \frac{1}{GSNR_{CE}}}$$

$$GSNR_{AE,eff,dB} = 10\log_{10}\left(GSNR_{AE}\right) - pen_{AE}\left\{CD, PMD, PDL, FP\right\}$$



GNPy



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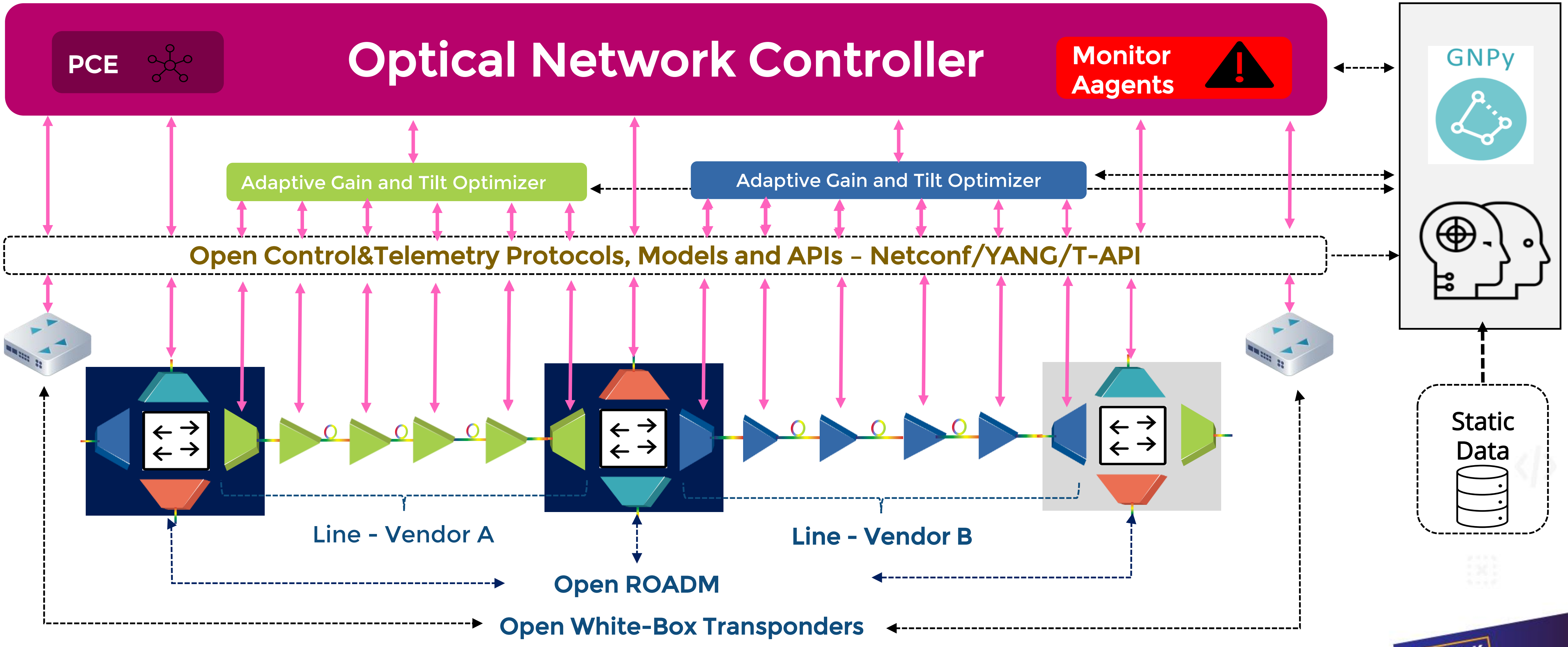
MAIN CHALLENGES

Vittorio Curri, "GNPy model of the physical layer for open and disaggregated optical networking ," J. Opt. Commun. Netw. 14, C92-C104 (2022)

Optical Network-as-a-Service



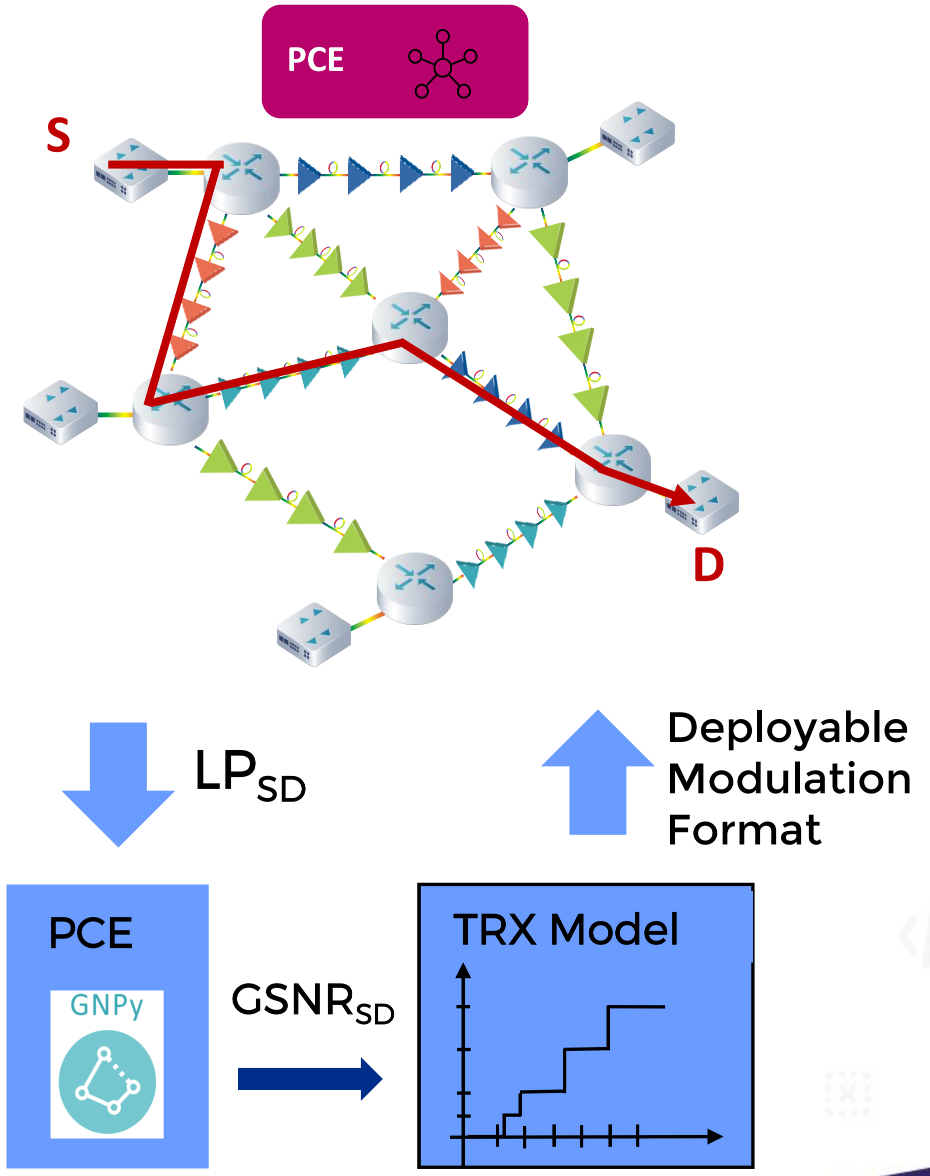
SDN Paradigm in Optical Networks

- The optical control plane operates independently of the optical data plane.
- The optical infrastructure can be controlled separately from the active traffic, making it a viable infrastructure-as-a-service option.
- The optical infrastructure supports multi-vendor compatibility, with a partially disaggregated architecture being the most practical approach—accommodating optical lines from different vendors along the network.
- The network can host traffic from various vendors, promoting interoperability and diversity.
- The network serves as a platform for different operators and services, offering network and spectral slicing for enhanced flexibility.
- Network-as-a-service becomes essential in the context of IP over WDM (IPoWDM).
- The optical infrastructure can seamlessly manage 'alien' services, including sensing, transmission and distribution of time/frequency (T/F), and quantum key distribution (QKD).

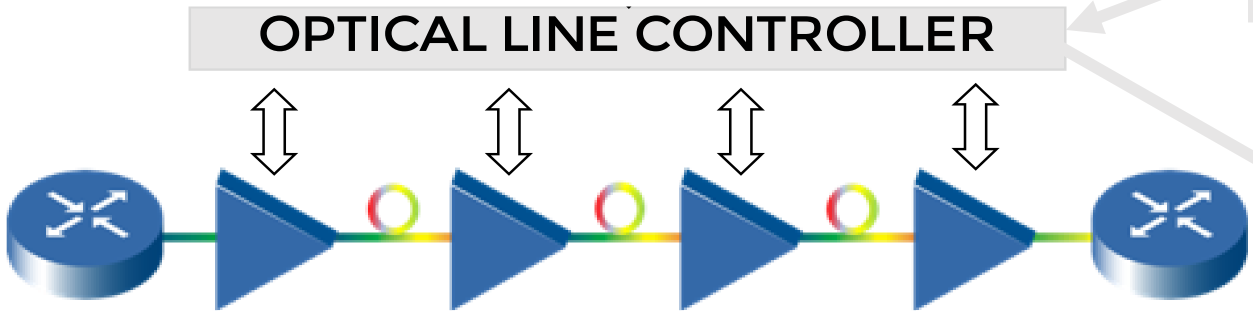
Lighth-Path Computation and Optical Line Controller

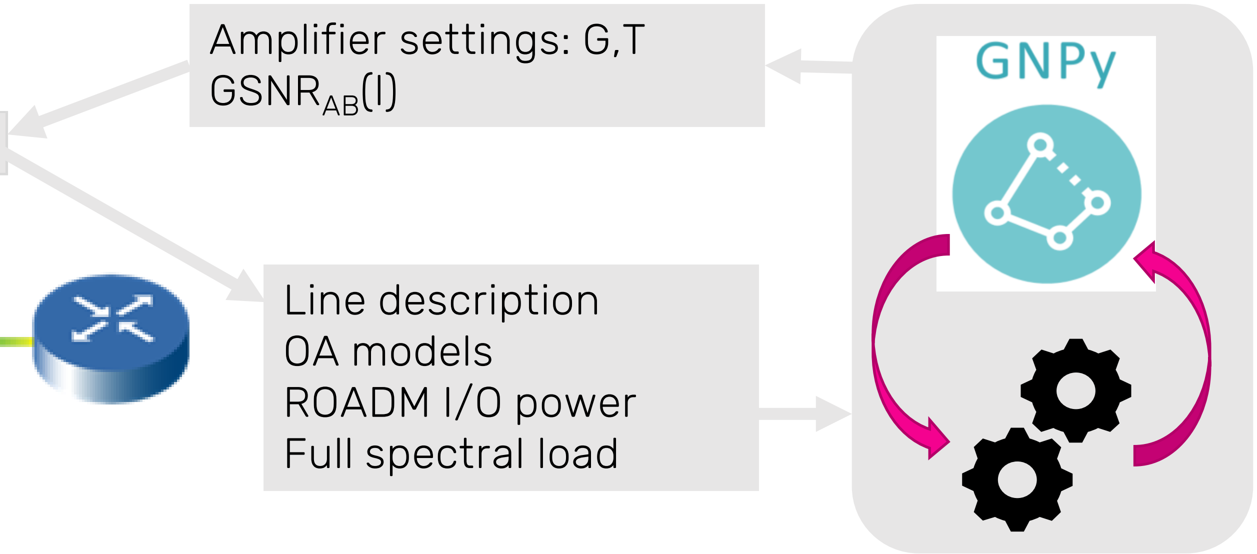
The GNPy scientific core is ready

- GNPy can be effectively used for PCE for either end-of-life or current status
- All experimental results confirm great accuracy
- Assist minimizing the margin with a statistical approach
- Missing features
  - Topology availability
  - Open interfaces and models
  - Open TRX models



Optical Line Controller





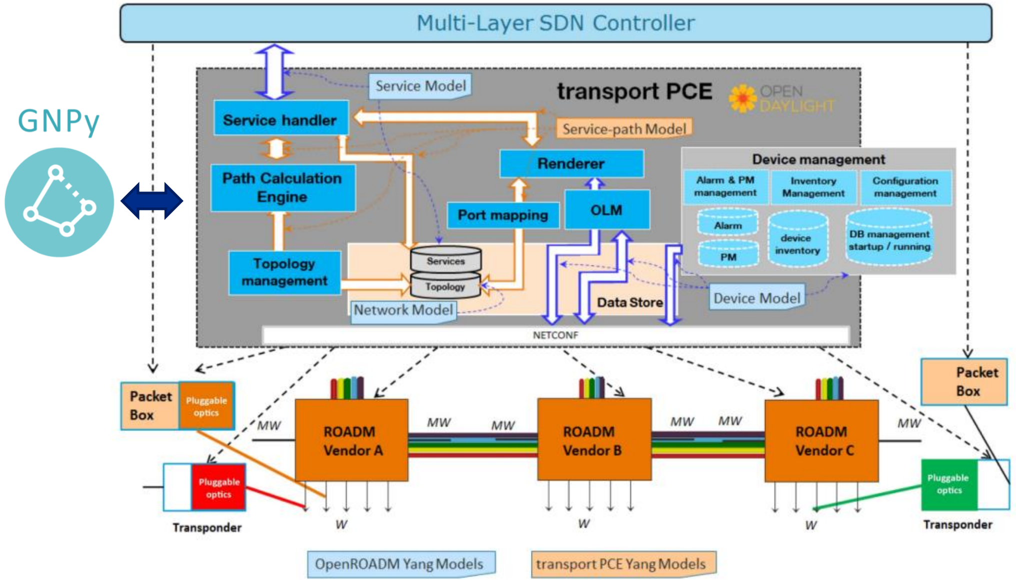
Adaptive Gain and Tilt Optimization

$$
\begin{cases}
\max\limits_{OA\ settings} & \left\{\overline{GSNR_{OLS}}\right\} \\
\min\limits_{OA\ settings} & \left\{\left\langle \left(GSNR_{OLS}(f) - \overline{GSNR_{OLS}}\right)^2 \right\rangle\right\} \\
P_{OLS,in}(f) & = P_{ROADM,out}(f) \\
P_{OLS,out}(f) & = P_{ROADM,in}(f)
\end{cases}
$$

Open ROADM: TransportPCE

- OpenROADM developed an optical controller: OpenDaylight TransportPCE project for an OpenROADM-compliant software-defined networking controller

- TransportPCE relies on GNPY for impairment-aware path calculation



M. Birk *et al.*, "The OpenROADM initiative," JOCN 2020

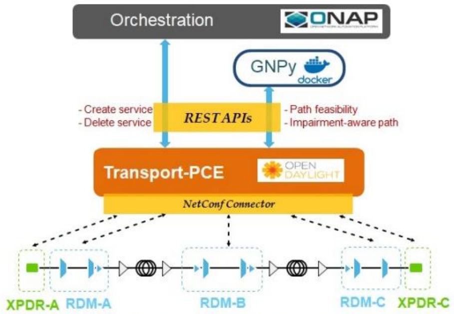
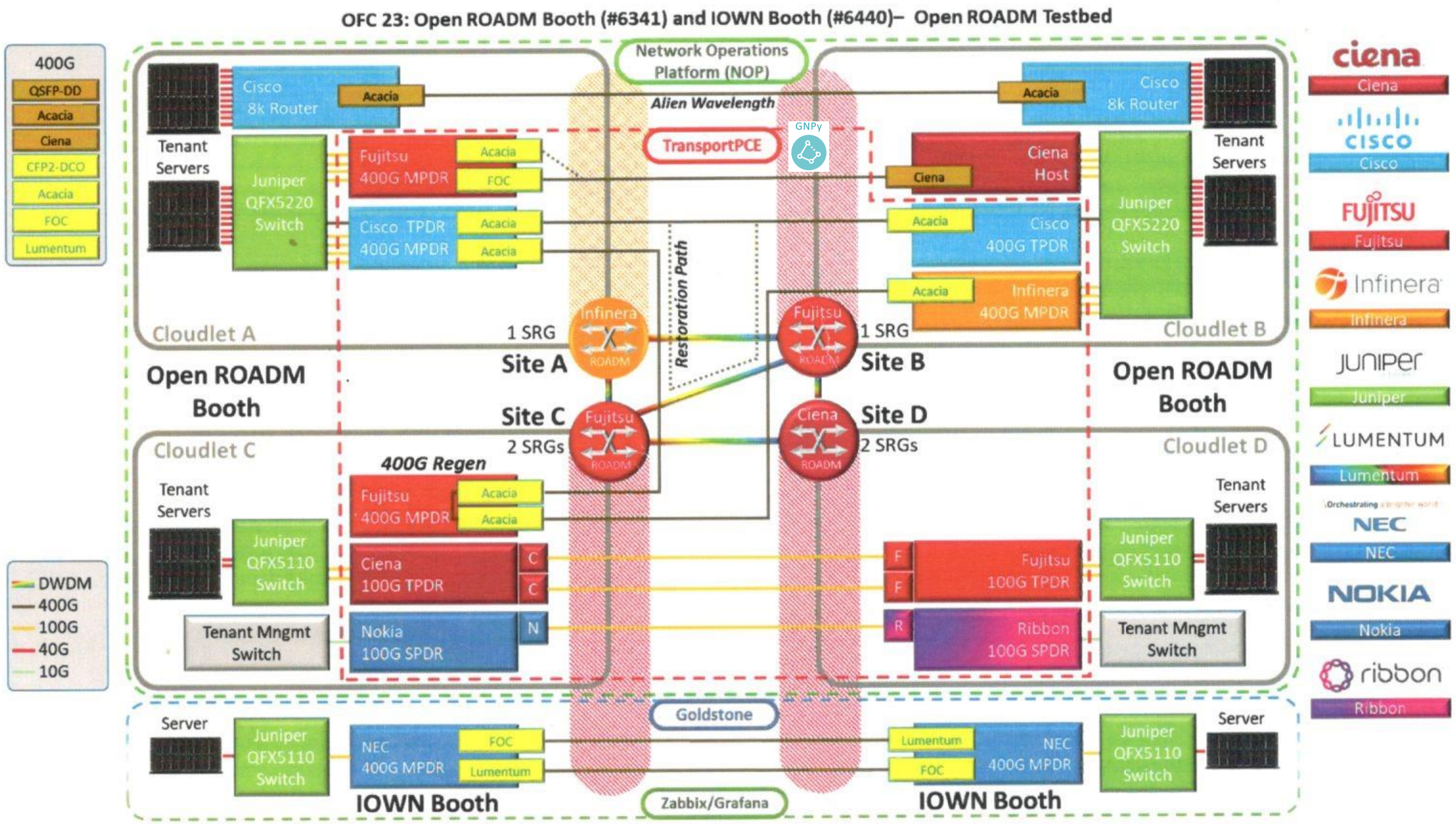
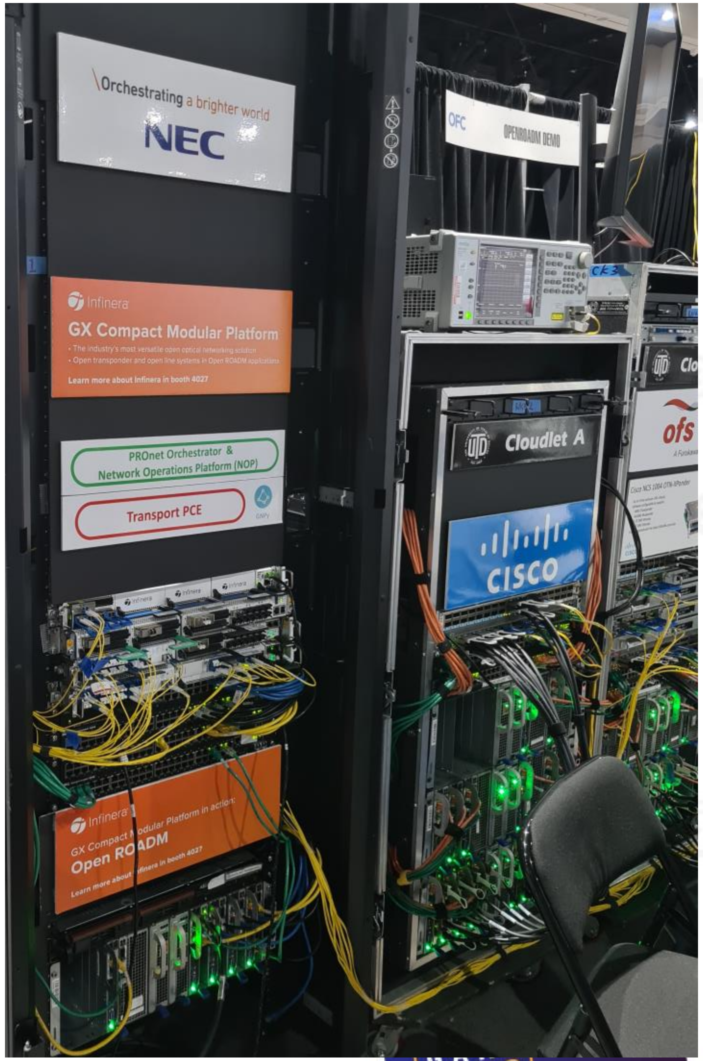


Fig. 1: Interaction between T-PCE and external modules

A. Triki *et al.*, "Open-Source QoT Estimation for Impairment-Aware Path Computation in OpenROADM Compliant Network," ECOC 2020

Open ROADM Demo OFC23





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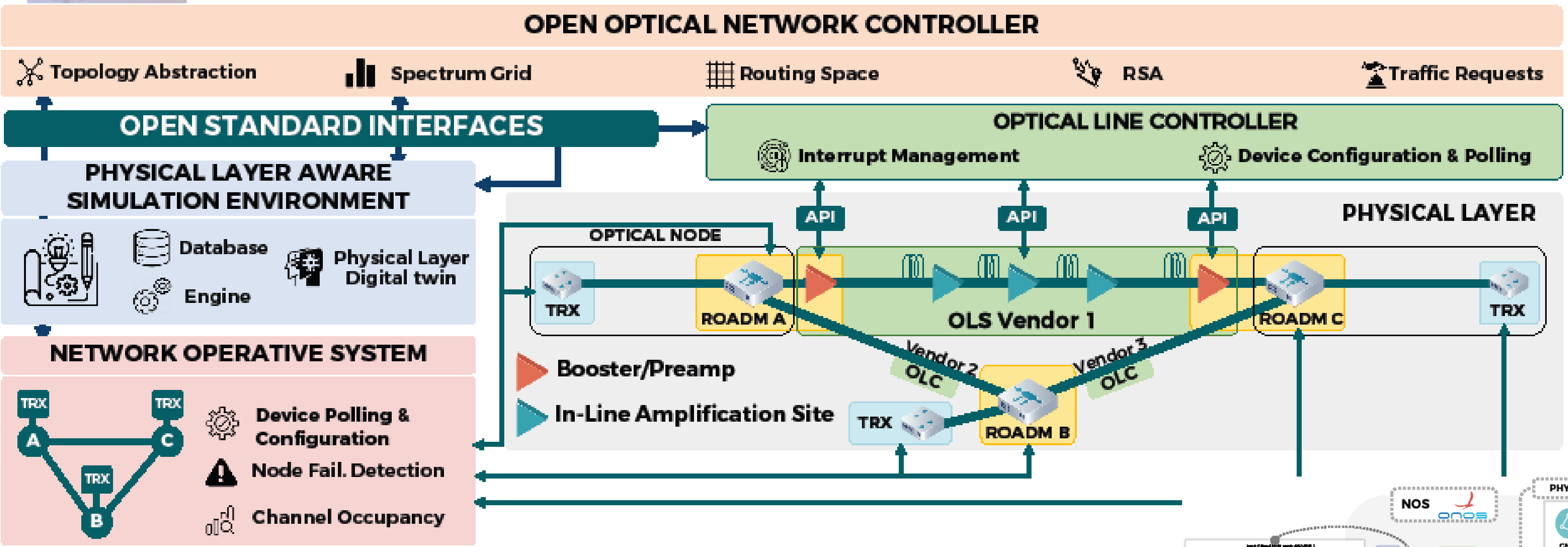
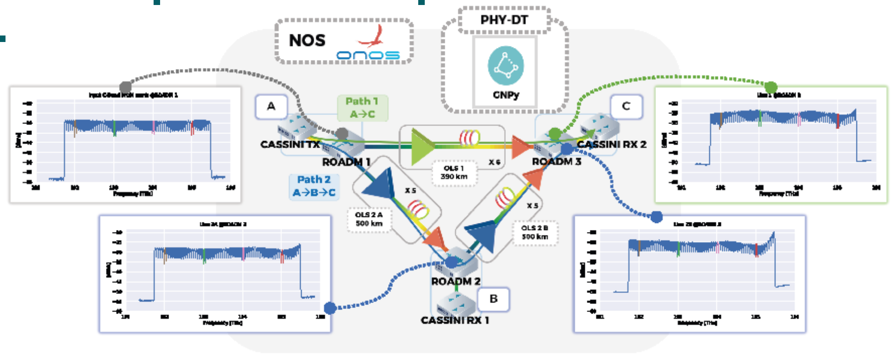
Experimental PoC at The PoliTo/Links Lab





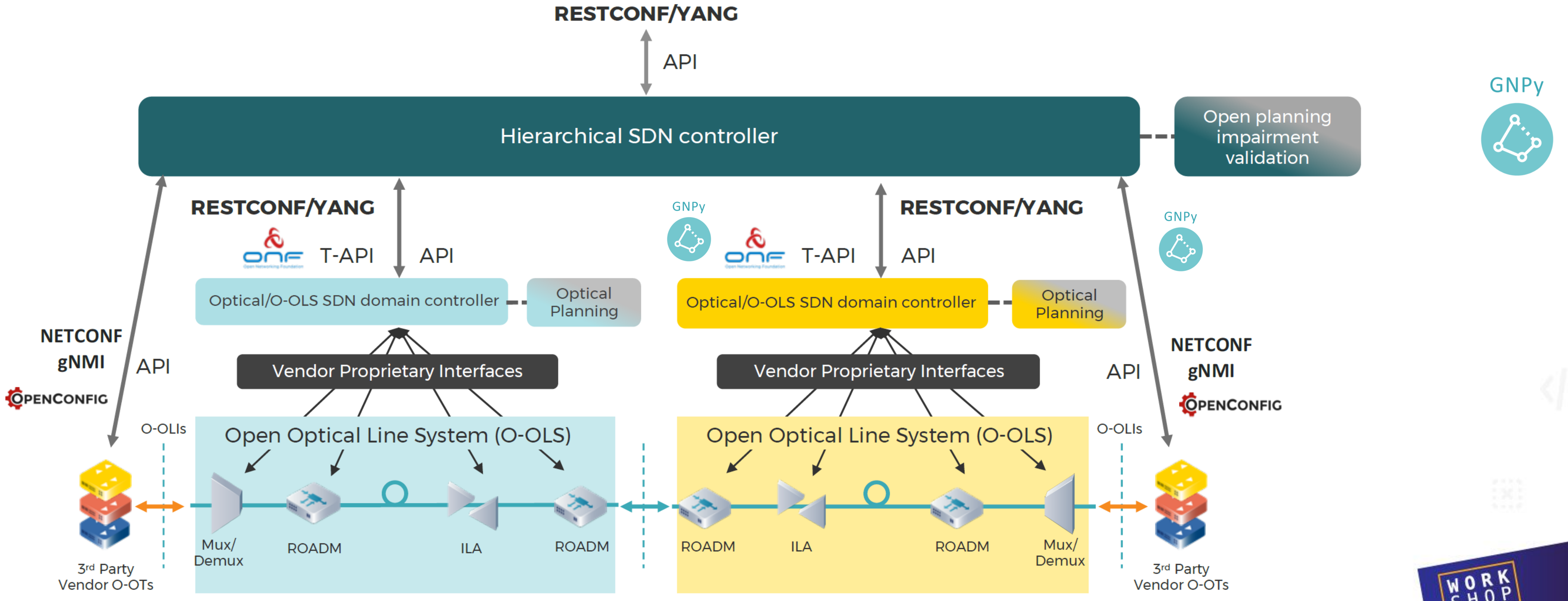
- Based on GNPy as PHY-DT
- Cognitive OLC including fiber identification
- ML-based OA model
- Failure detection&recovery

Giacomo Borraccini, Stefano Straullu, Alessio Giorgetti, Renato Ambrosone, Emanuele Virgillito, Andrea D'Amico, Rocco D'Ingillo, Francesco Aquilino, Antonino Nespola, Nicola Sambo, Filippo Cugini, Vittorio Curri, Experimental Demonstration of Partially Disaggregated Optical Network Control Using the Physical Layer Digital Twin, IEEE Transactions on Network and Service Management, 2023

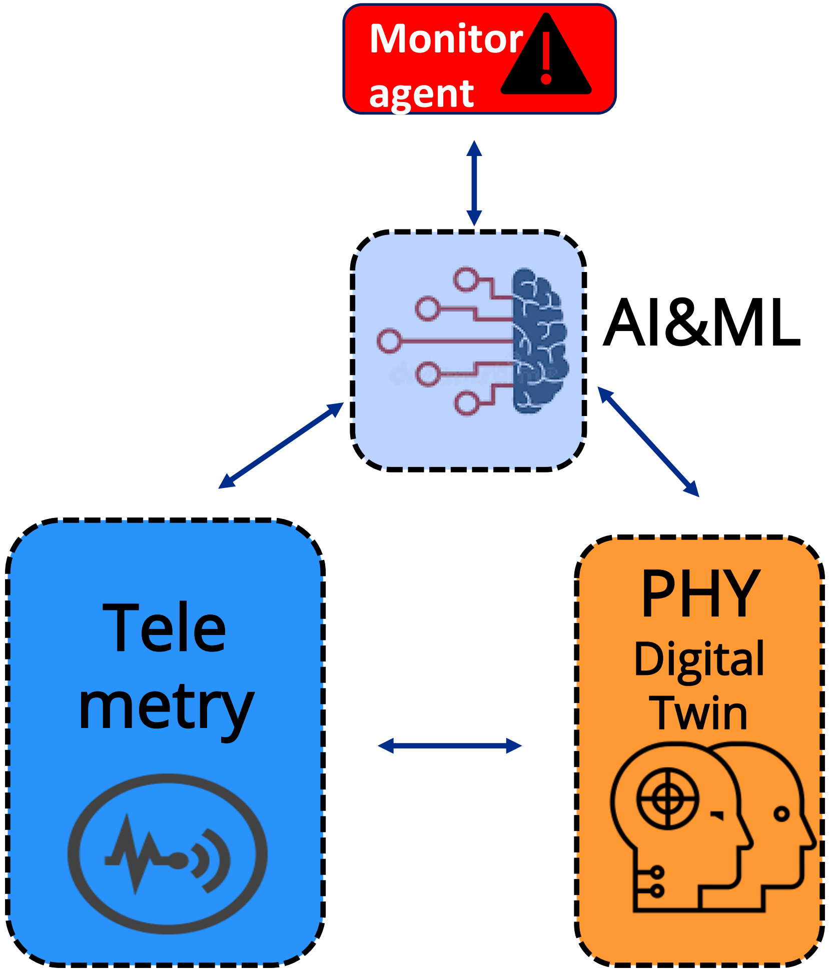
Telecom Infra Project

TIP OOPT MUST Optical Whitepaper

Target Architecture: Disaggregated Open Optical Networks



Telemetry and the Monitor Agents



- The monitoring agents read telemetry and rely on PHY-DT
- Use ML&AI methods
- Aim at
  - Detecting and localizing failure
  - Predicting incoming failure
  - Self-healing functionalities
  - Performing the PHY tomography (e.g., fiber type, losses, etc…)

- May also perform environmental sensing (e.g. earthquake) and PHY cybersecurity

Conclusion

- The physical layer digital twin serves as the catalyst for harnessing optical network infrastructure and spectrum as a service. It empowers the Software-Defined Networking (SDN) paradigm to extend its reach down to the physical layer, with no insurmountable technological or scientific barriers. The primary challenges lie in the standardization of interfaces, protocols, and models.

- This shift towards network-as-a-service opens the doors to accommodating diverse, 'alien' services, while the opening and standardization of telemetry data facilitates the deployment of monitoring agents, facilitating physical layer tomography and self-healing capabilities. These agents are essential for both the network itself and the broader network geographical footprint.

- As we progress towards IP over WDM, this perspective is set to gain even more momentum, promising a future where optical networks become even more flexible, adaptable, and aligned with the evolving needs of technology and services

Questions?

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TELECOM INFRA PROJECT

EU

European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART")