

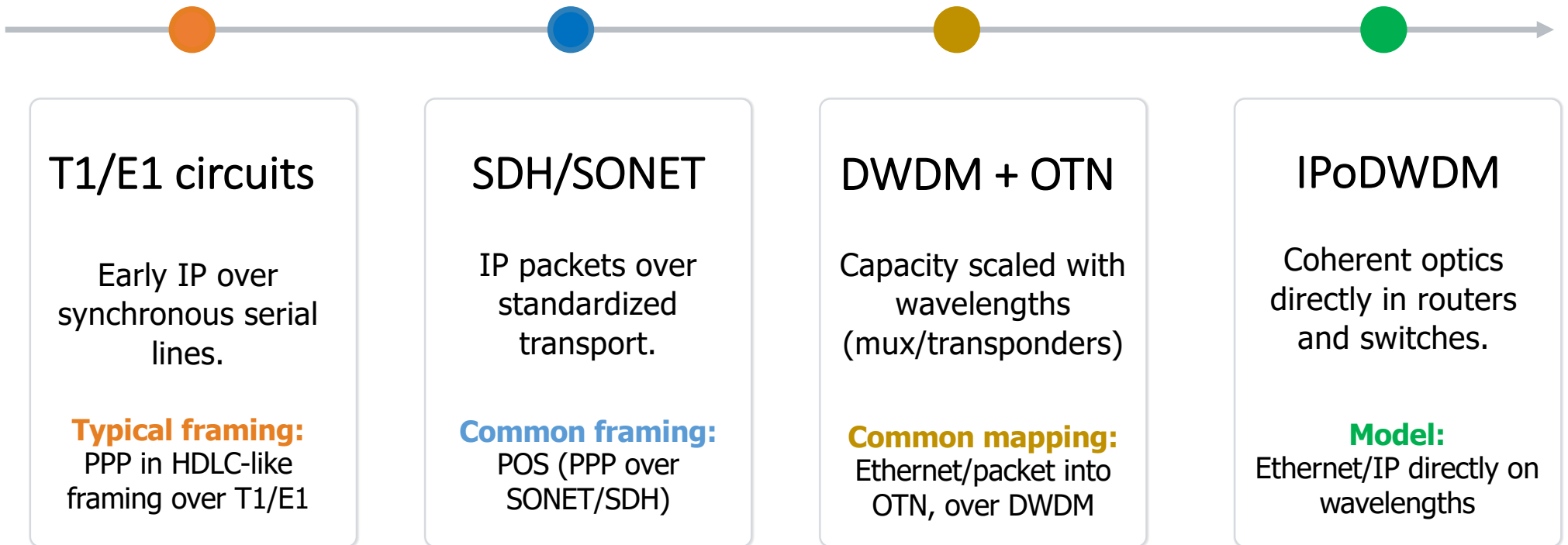
# IP over DWDM

(What IP folks should know)



**Tashi Phuntsho** | Technology Evangelist @FLEXOPTIX

# IP over Transport - Evolution



## T1/E1 circuits

Early IP over synchronous serial lines.

### Typical framing:

PPP in HDLC-like framing over T1/E1

## SDH/SONET

IP packets over standardized transport.

### Common framing:

POS (PPP over SONET/SDH)

## DWDM + OTN

Capacity scaled with wavelengths (mux/transponders)

### Common mapping:

Ethernet/packet into OTN, over DWDM

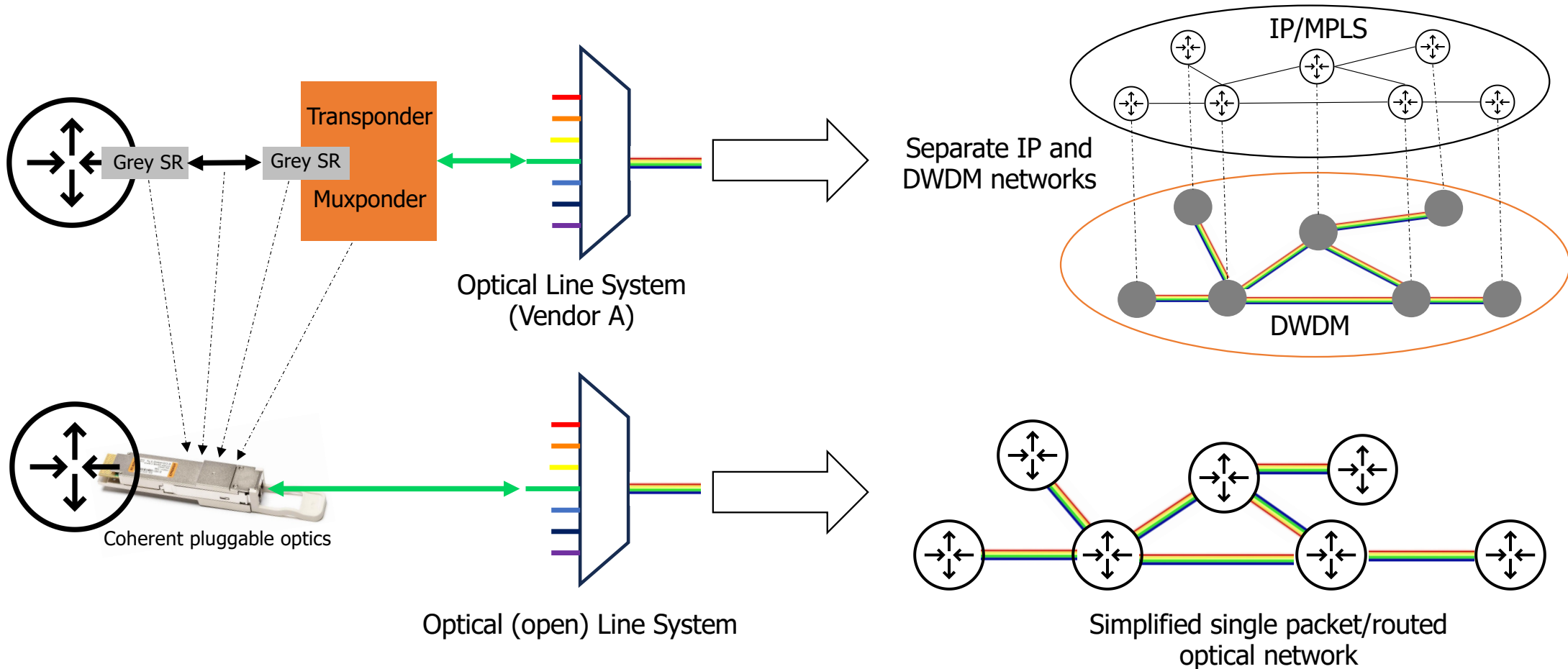
## IPoDWDM

Coherent optics directly in routers and switches.

### Model:

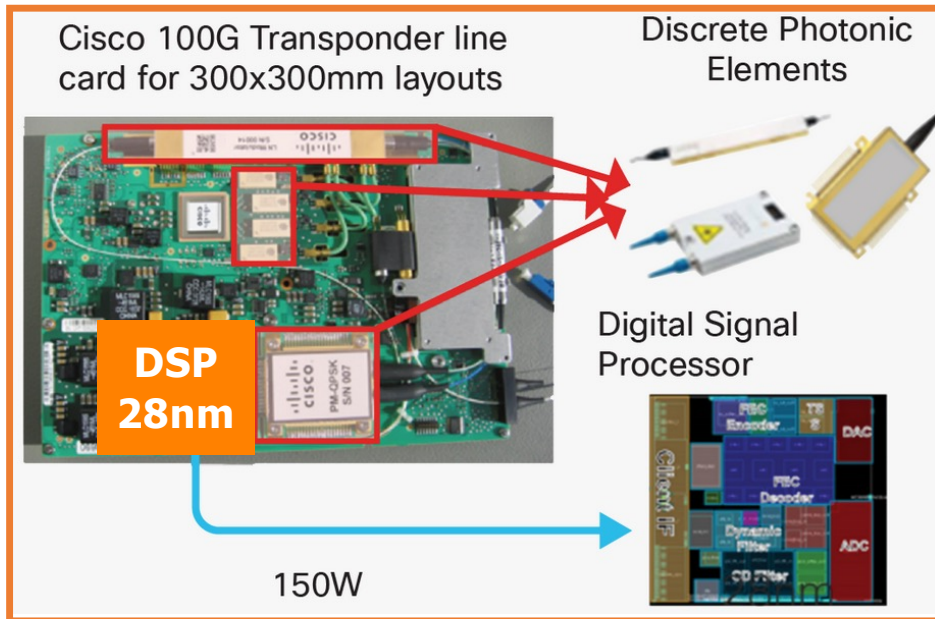
Ethernet/IP directly on wavelengths

# Traditional IP and DWDM → IP-over-DWDM

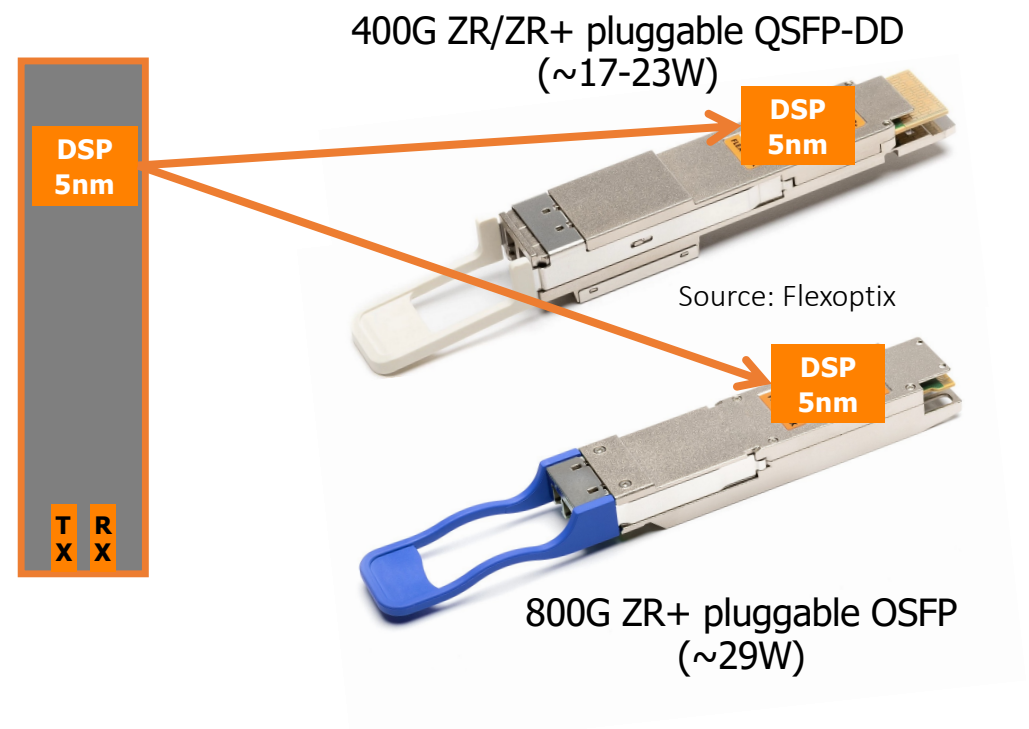
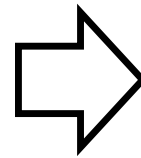


What makes it possible?

# Coherent Optics became **Pluggable**



Source: Cisco Systems



- Router/switch friendly **form factors**
- Reduced **power-consumed per-bit** and **\$\$ per-bit**

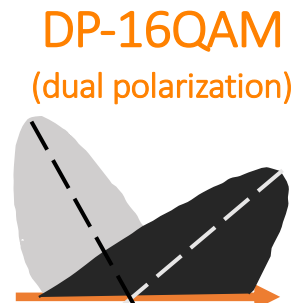
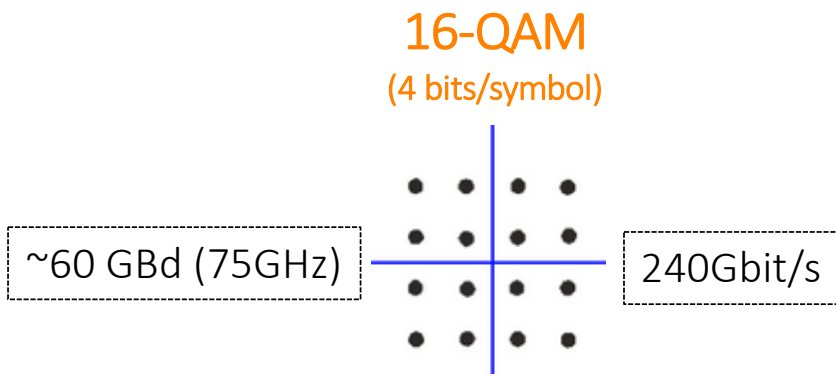
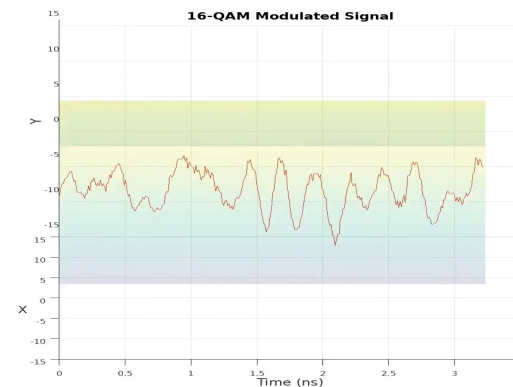
# Coherent Optics: Recap

Use higher order modulations (more properties of light to encode data)

- Amplitude and Phase: QPSK/8QAM/16QAM

Two different polarizations carry two independent data streams:

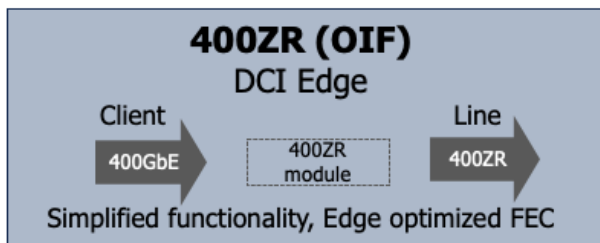
- Doubling the bit rate for the same symbol rate



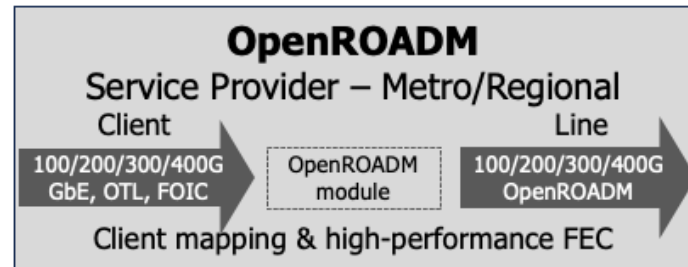
480Gbit/s  
(400GbE ~ 425Gbit/s)

} ~55Gbit/s  
overhead for FEC  
and pilot signal

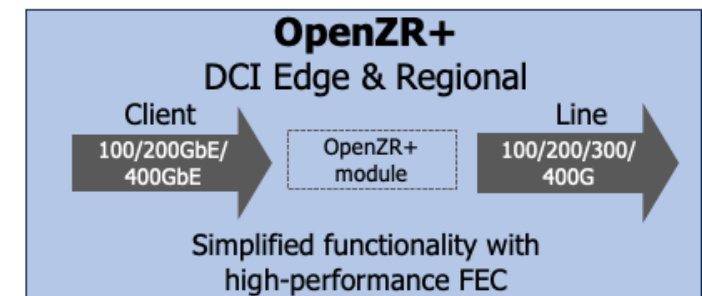
# Open Standards & Disaggregation



**Interoperable Ecosystem:**  
400ZR standardised coherent interfaces across vendors



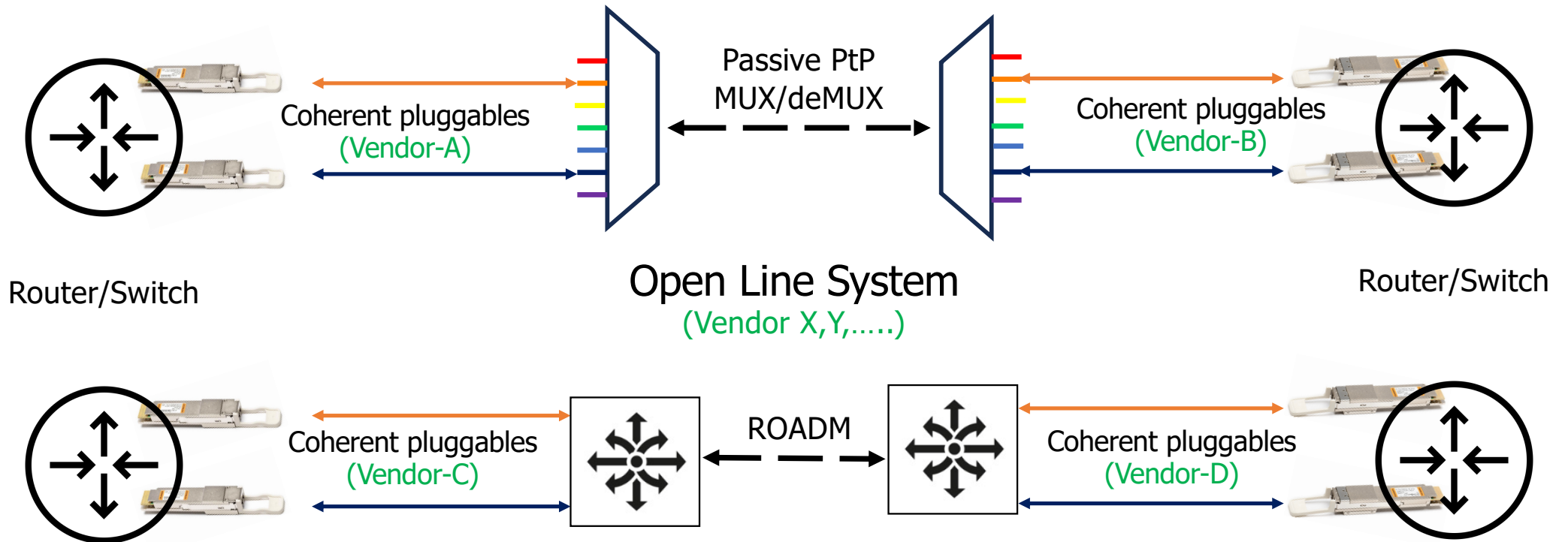
**Disaggregated Transport:**  
Open line systems reduced dependence on closed end-to-end optical stacks



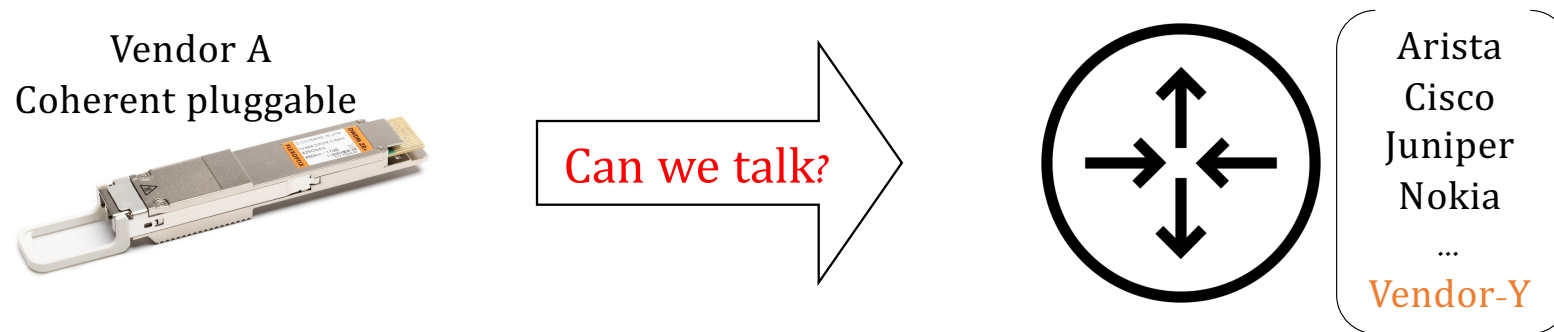
**OpenZR+ MSA:**  
Extended coherent plugs into broader regional long-haul use cases

From an **integrated single-vendor system** → To more **open interoperable (multi-vendor) system**

# Disaggregation: IP-over-DWDM



# Interoperability with Hosts



## C-CMIS: Coherent Common Management Interface Specification

- Defined by OIF ([CMIS v5.3](#) & [C-CMIS v1.4](#))
- Defines how coherent plugs communicate with hosts for **management and control**
- Helps make coherent plugs **more portable across different host platforms**

Current Interval [15:23:05 Sun Dec 14 2025 - 15:32:25 Sun Dec 14 2025]

Parameter	MIN	AVG	MAX
CD(Short) [ps/nm]	1093.00	1093.00	1093.00
DGD[ps]	1.00	1.00	1.00
RX PWR[dBm]	-9.22	-9.14	-8.97
TX PWR[dBm]	-1.04	-1.00	-0.97
OSNR[dB]	23.10	23.38	23.40
RX CHAN PWR[dBm]	-13.26	-13.05	-12.82
ESNR[dB]	14.30	14.41	14.50
LASER BIAS[mA]	278.60	279.10	279.29
FREQ OFF[Mhz]	162.00	257.48	346.00
SOP RATE[krad/s]	0.00	0.00	0.00
PDL[dB]	0.60	0.76	1.00
SOPMD[ps^2]	26.62	47.59	72.06

EC BITS : 0  
UC WORDS : 0

Parameter	MIN	AVG	MAX
PREFEC BER	8.50e-03	8.75e-03	9.60e-03
POSTFEC BER	0.00e+00	0.00e+00	0.00e+00
Q FACTOR[dB]	7.30	7.46	7.50
Q MARGIN[dB]	0.80	0.90	1.00

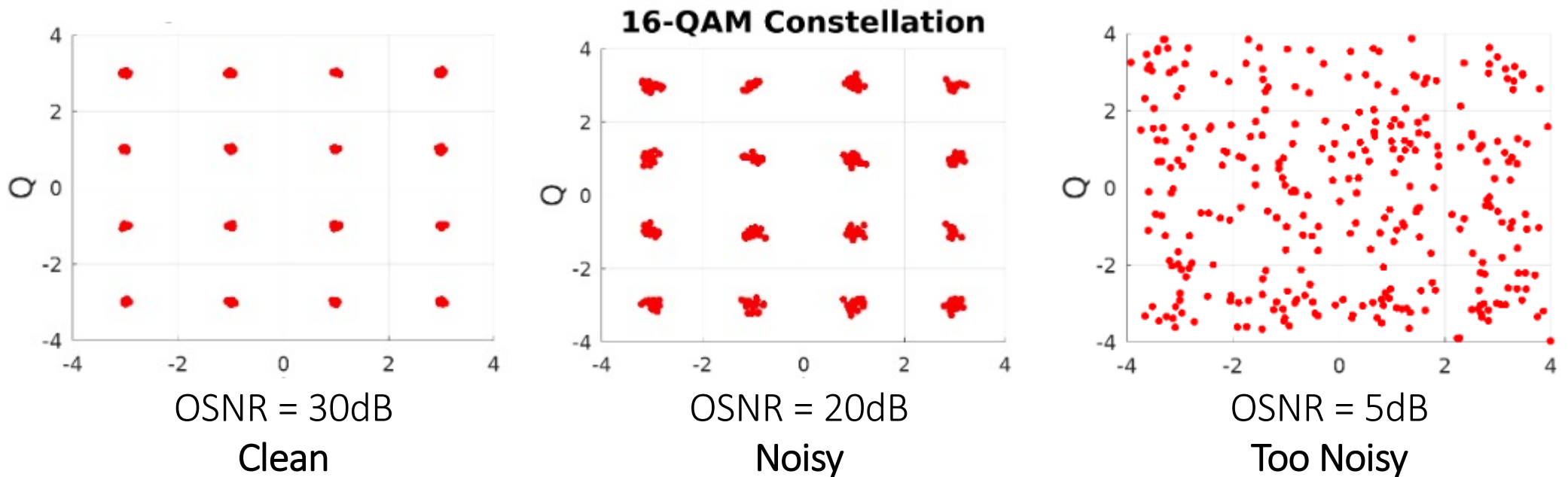
## Optical telemetry directly on routers and switches:

- Consolidate control and mgmt. for IP and optical
- Proactively act at upper layers (model/event-driven automation)

Example:

Host-side coherent telemetry 400G ZR+ on Cisco N93600CD-GX (Dec 2025 DrukREN)

# (O)SNR and Bit Errors



Higher OSNR: cleaner signal, easier to detect 0s and 1s ~ lower bit errors

Lower OSNR: noisier signal, harder to make out 0s and 1s ~ higher bit errors

# Improved FEC (with multi-rate options)

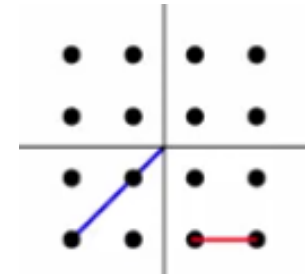
Mode	Modulation	FEC	OSNR threshold	Pre-FEC BER threshold	Operational Benefits	Indicative Reach Range*
400G ZR (OIF)	DP-16QAM	cFEC	26 dB	$1.25 \times 10^{-2}$	DCI links/short reach - Lower power - Less tolerant to noise	~120 Km
400G ZR+ MSA	DP-16QAM	oFEC	24 dB	$2.0 \times 10^{-2}$	Can handle poorer link conditions: - <i>Tolerate lower OSNR</i> - <i>Longer reach</i> - <i>Trade capacity for reach</i>	~480 Km
300G ZR+	DP-8QAM		21 dB			~600 Km
200G ZR+	DP-QPSK		16 dB			~1000 Km
100G ZR+	DP-QPSK		12.5 dB			~2000 Km

\*Actual reach depends on span loss, amplification, filtering/ROADM design, channel loading, etc.

# Probabilistic Shaping

In conventional QAM:

- Points **further from origin** require **higher energy**
- All constellation points used **equally**



PCS changes the probability of using each symbol:

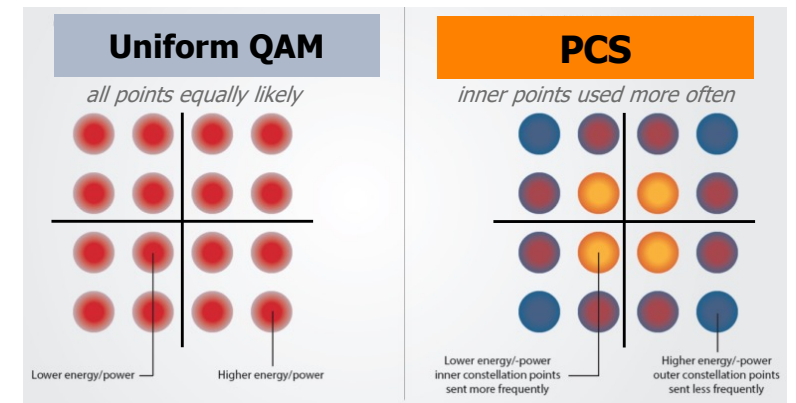
- Low energy (inner) symbols used more often
- High energy (outer) symbols used less often

Why this matters?

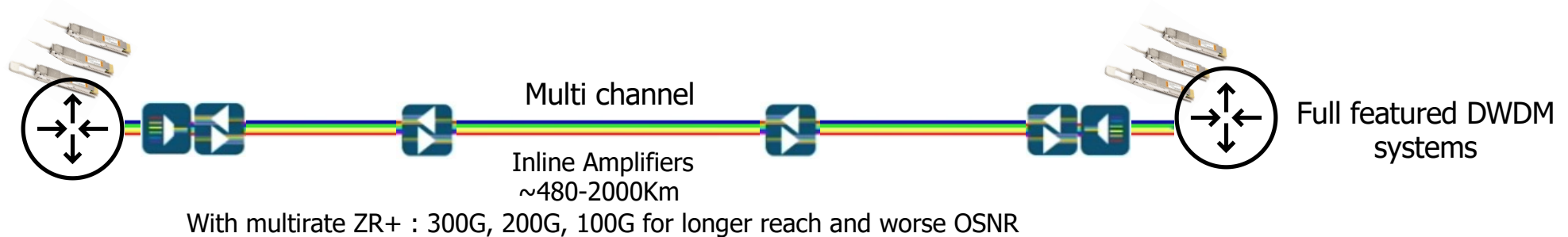
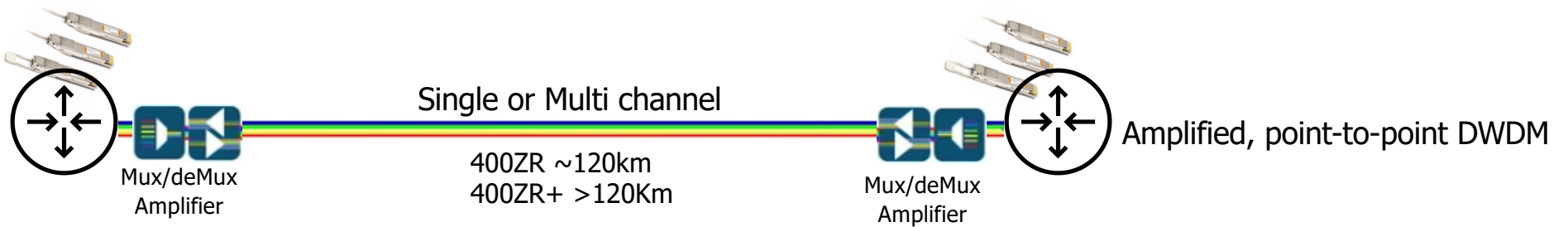
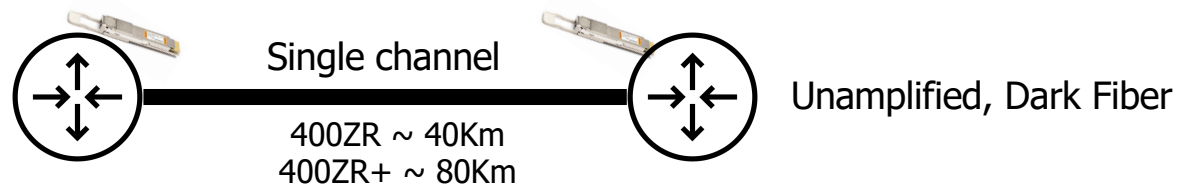
Lower average symbol energy

→ **Lower required OSNR** for a given payload

→ Can tradeoff for **extra reach** on marginal links, or **capacity** on good links

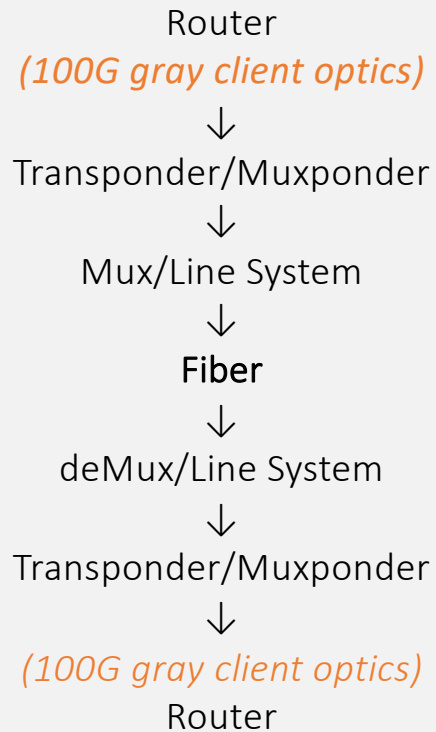


# IPoDWDM Options



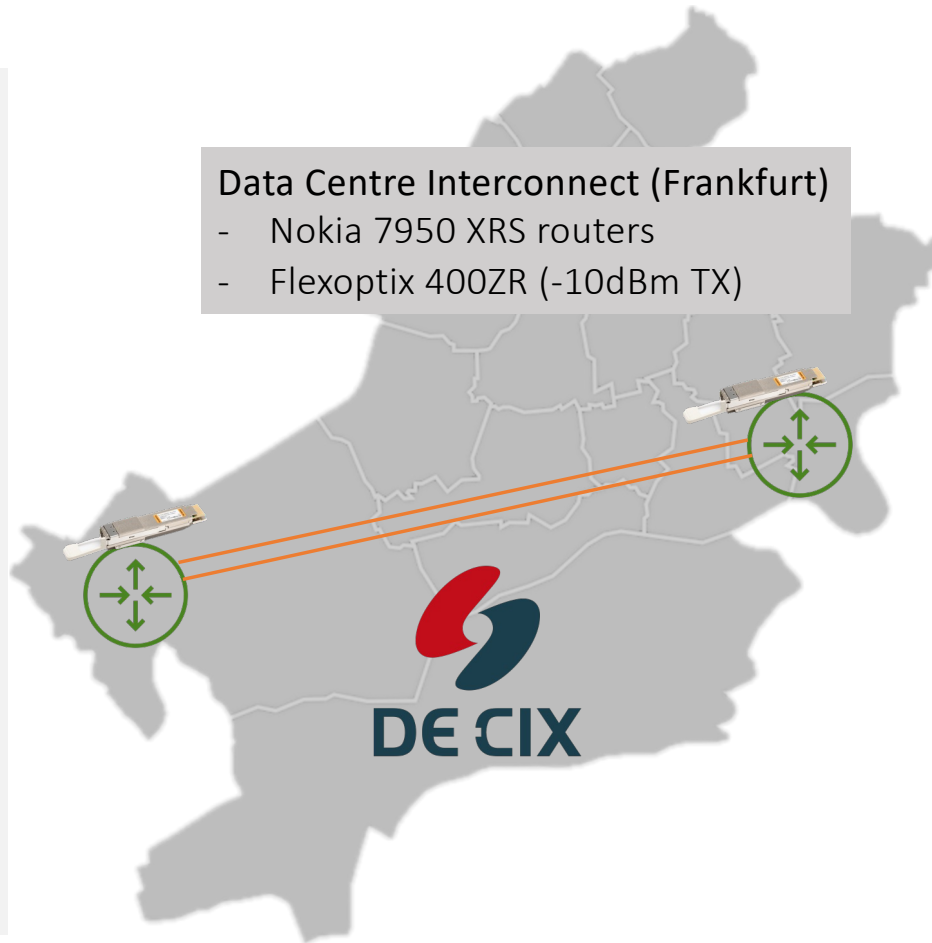
# IPoDWDM for simple DCI

## Existing setup:

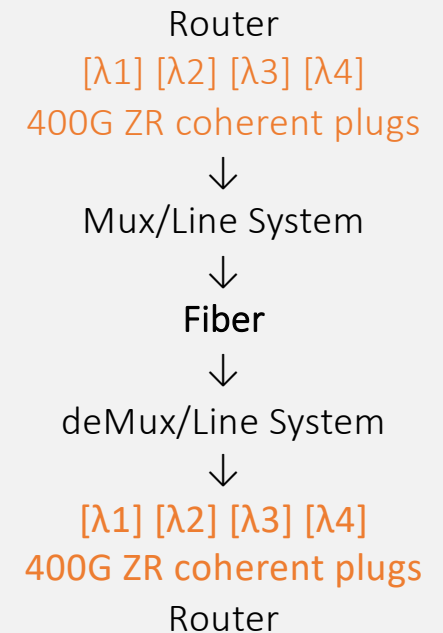


## Data Centre Interconnect (Frankfurt)

- Nokia 7950 XRS routers
- Flexoptix 400ZR (-10dBm TX)



## IPoDWDM setup:



# Compatibility (Application Mode)

```
Nokia 7950 XRS# show port 8/1/c7
```

```
=====
Coherent Optical Module
=====
```

```
Cfg Tx Target Power: 1.00 dBm
Cfg Rx LOS Thresh : -23.00 dBm
```

```
Present Rx Channel : 23
Cfg Rx Channel : 23
```

```
Disp Control Mode : automatic
Cfg Dispersion : 0 ps/nm
CPR Window Size : 32 symbols
Compatibility : openZrpOfec1
Cfg Tx Power Min : -22.90 dBm
```

```
Sweep Start Disp : -25500 ps/nm
```

Application Mode	MSA format	Nokia Compatibility
1	OIF 400ZR, amplified	oif-400g-zr
2	OIF 400ZR, unamplified	
3	OpenZR+ MSA	openZrpOfec1
4	OpenZR+ MSA	
5	OpenZR+ MSA	openZrpOfec1
6	OpenZR+ MSA, Enhanced	openZrpOfec2
7	OpenZR+ MSA, Enhanced	
8	OpenZR+ MSA, Enhanced	openZrpOfec2
9	OpenZR+ MSA	openZrpOfec1
10	OpenZR+ MSA	openZrpOfec2
11	OpenZR+ MSA	openZrpOfec1
12	OpenZR+ MSA, Enhanced	
13	OIF 400ZR, amplified	oif-400g-zr
14	OpenZR+ MSA, Enhanced	openZrpOfec2
15	OpenZR+ MSA	

```
Nokia 7950 XRS# show port 8/1/c7
```

```
=====
QSFP-DD Connector
=====
```

```
Description : -
Interface : 8/1/c7
FP Number : 2
...
Breakout : c1-400g
RS-FEC Config Mode : None
```

```
Transceiver Data
```

```
...
Laser Tunability : flex-tunable
Config Freq (MHz) : 0
Oper Freq (MHz) : 192300000
Fine Tune Range : 6000 MHz
Supported Grids : 100GHz 75GHz 50GHz 25GHz
```

```
Optical Compliance: 400G-ZR-Amp 400G-ZR-Unamp
```

```
Link Length support: Unknown
```

```
100GBASE-R | 1x CAUI-4 w/o FEC (4x25G) | oFEC DP-QPSK | 30.1GBd
```

# Aside: Application Modes

Coherent transceivers support (advertise) multiple config options

- *modulation schemes, FEC, spacing, CD, baud rates, etc.*
- aka 'application modes'

General Parameters:

Application Code	Host Interface	Baud Rate [GBd]	Modulation	Bandwidth	FEC	Media Lane Reach	Power Consumption
AppCode 1	400GAUI-8	59.843	DP-16QAM	400GbE	cFEC	120 km (amplified)	22.5 W (max)
AppCode 2	400GAUI-8	59.843	DP-16QAM	400GbE	cFEC	80km (unamplified)	22.5 W (typ)
AppCode 3	4x100GAUI-2	59.843	DP-16QAM	4x100GbE	cFEC	120km (unamplified)	22.5 W (max)
AppCode 4	4x100GAUI-2	59.843	DP-16QAM	4x100GbE	cFEC	80km (amplified)	23.5 W (typ)
AppCode 5	400GAUI-8	60.138	DP-16QAM	400GbE	oFEC	80km (unamplified)	23.5 W (max)
AppCode 6	4x100GAUI-2	60.138	DP-16QAM	4x100GbE	oFEC	480km (amplified)	23.5 W (typ)
AppCode 7	3x100GAUI-2	60.138	DP-8QAM	3x100GbE	oFEC	480km (amplified)	23.5 W (max)

Select the desired application code based on network requirements:

- Avoids configuring parameters through the CLI
- ensures the module works correctly ~ host/optics side mapping

[Flexoptix 400G ZR/ZR+](#)

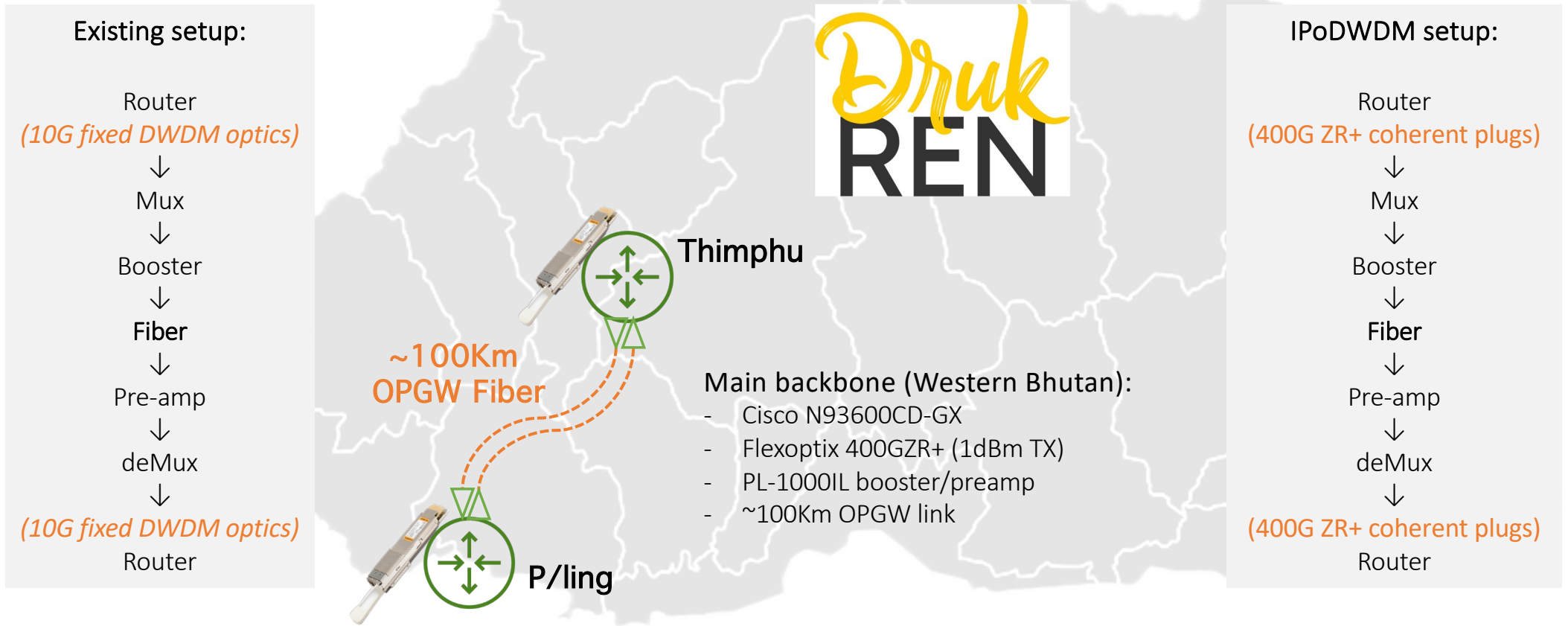
Coherent Parameters:

Application Code	Coherent Standard	Rx OSNR Tolerance	Rx Sensitivity @ OSNR	CD Tolerance max @0.5 dB OSNR Penalty	DGD Max (PMD tolerance)	Pre-FEC BER Limit	Post-FEC BER
AppCode 1	400G ZR DWDM	>26 dB/0.1 nm	-12 dBm OSNR >26dB	±2,400 ps/nm	33 ps	~1.22E-2	<1E-15
AppCode 2	400G ZR Grey, unamplified	>26 dB/0.1 nm	-20 dBm (400ZR) OSNR >34dB	±2,400 ps/nm	33 ps	~1.22E-2	<1E-15
AppCode 3	4*100G ZR DWDM	>26 dB/0.1 nm	-12 dBm OSNR >26dB	±2,400 ps/nm	33 ps	~1.22E-2	<1E-15
AppCode 4	4*100G ZR Grey, unamplified	>26 dB/0.1 nm	-20 dBm (400ZR) OSNR >34dB	±2,400 ps/nm	33 ps	~1.22E-2	<1E-15
AppCode 5	400G ZR+ DWDM	>24 dB/0.1 nm	-12 dBm OSNR >24dB	±20,000 ps/nm	66 ps	1.7E-2 – 2.0E-2	<1E-15
AppCode 6	4*100G ZR+ DWDM	>24 dB/0.1 nm	-12 dBm OSNR >24dB	±20,000 ps/nm	66 ps	1.7E-2 – 2.0E-2	<1E-15
AppCode 7	3*100G ZR+ DWDM	>21 dB/0.1 nm	-15 dBm OSNR >21dB	±40,000 ps/nm	83 ps	1.7E-2 – 2.0E-2	<1E-15

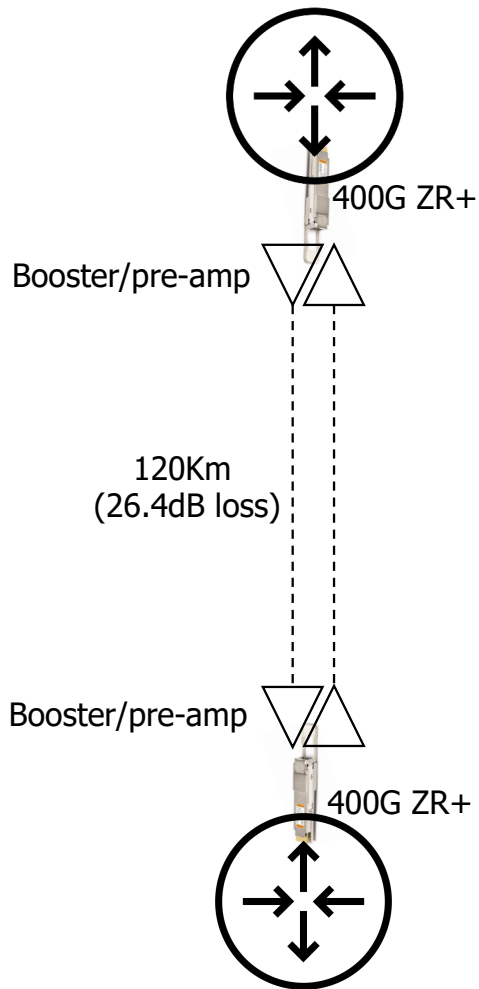
JunOS `set interfaces <interface> optics-options application [options]`

IOS XR `(config)#controller optics <interface>`  
`((config-Optics))#appsel simple code <app-code>`  
`((config-Optics))#commit`

# IPoDWDM for amplified PtP links



# IPoDWDM for amplified PtP links

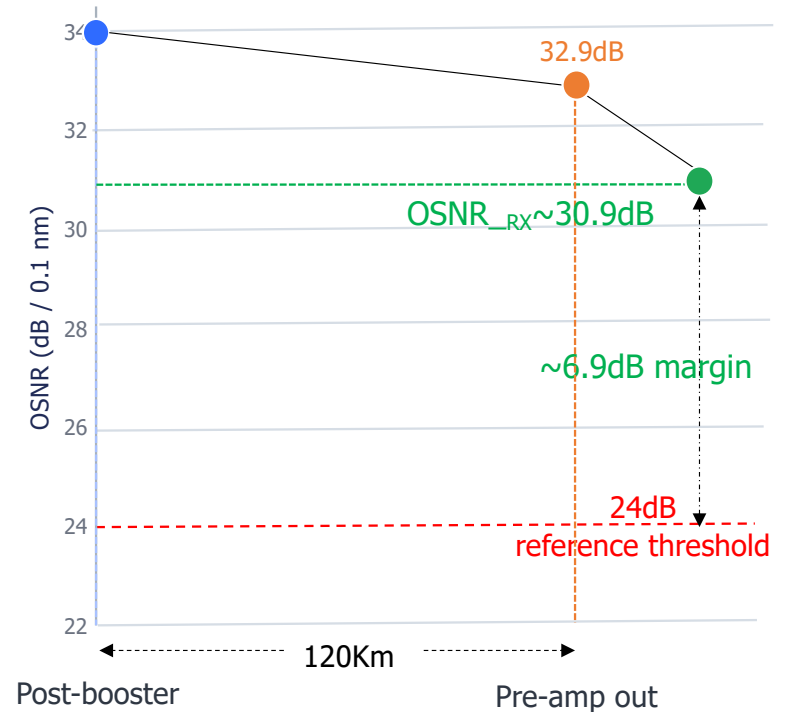


## Assumptions:

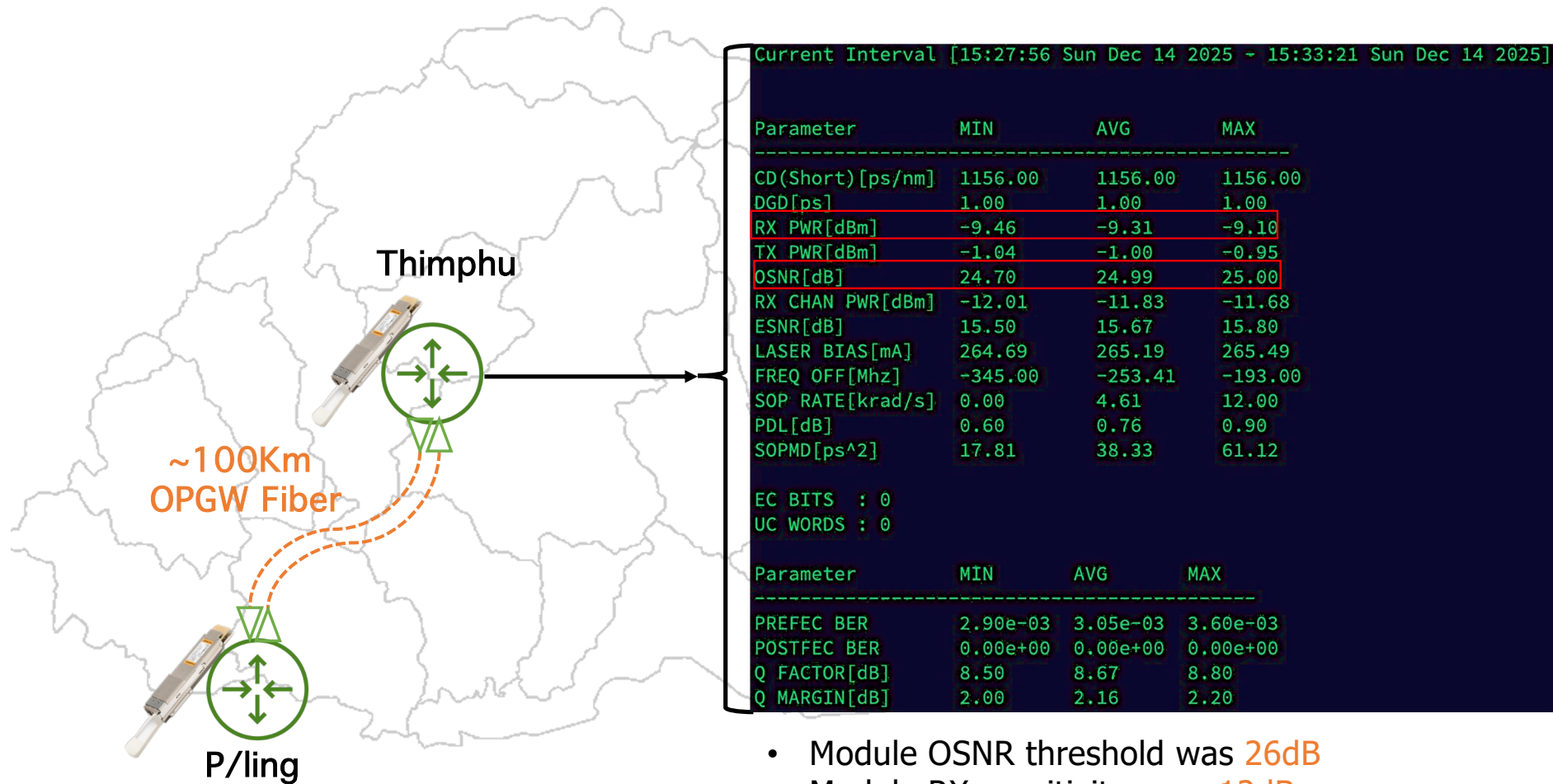
- Coherent optics: 400ZR+ (+3dBm)
- Amplifier: 10dB gain, 5dB NF
- Fiber loss: 0.22dB/km
- Practical penalty: 2dB

## Result:

- Final RX power  $\sim -3.4$ dBm
- Final OSNR  $\sim 30.9$ dB
- OSNR margin  $\sim 6.9$ dB



# IPoDWDM for amplified PtP links



- Module OSNR threshold was 26dB
- Module RX sensitivity was -12dBm

# Aside: Q Margin (Q Factor)

## Q-factor (quality factor):

- How well a signal can be distinguished from noise ~ quantifies the (O)SNR
- Higher Q-factor → more distinguishable signal → fewer bit errors

## Q-margin:


- Gap between the current (measured) pre-FEC BER and the error free threshold in dB
  - ~ how much more degradation can be accepted before hitting the threshold
- Higher is better

```
EC BITS : 0
UC WORDS : 0
```

Parameter	MIN	AVG	MAX
PREFEC BER	2.90e-03	3.05e-03	3.60e-03
POSTFEC BER	0.00e+00	0.00e+00	0.00e+00
Q FACTOR[dB]	8.50	8.67	8.80
Q MARGIN[dB]	2.00	2.16	2.20

# Long-haul IPoDWDM

Long-haul links often limited by noise margin

- Each amplifier restores power
    - But also adds ASE noise (noise figure) ~ noise cannot be removed
  - OSNR declines gradually ~ higher bit errors
  - How many ILAs (span distance, amplifier noise figure, etc.) need to be well planned
    - Measure/calculate E2E OSNR vs OSNR threshold of the module
- \* Modern coherent plugs allow trading capacity for reach
- Lower OSNR requirements for lower bit rates
- 

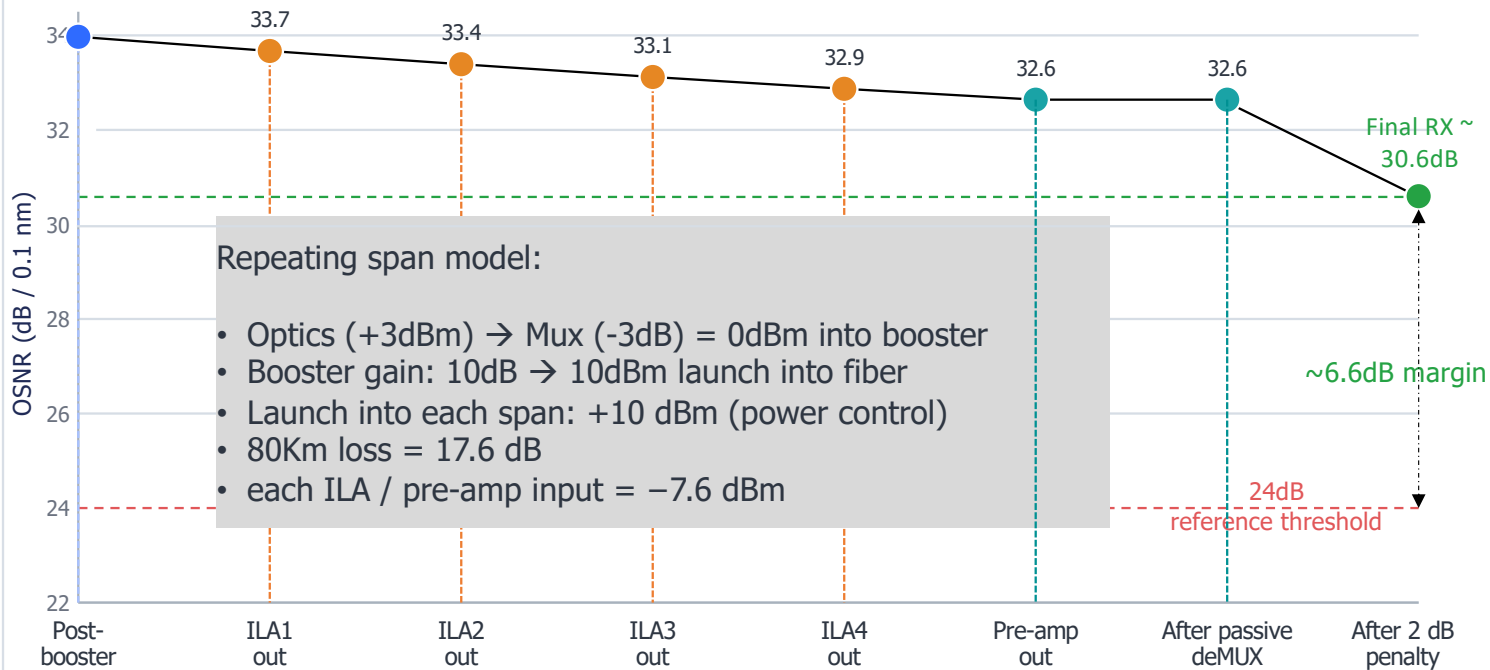
# 400ZR+ OSNR: 5x80Km with ILAs

## Method: Incremental OSNR

34dB TX in-band OSNR | booster → Mux, pre-amp → deMux | fixed 10dB gain for booster/pre-amp

### Assumptions:

0.22dB/km fibre, +3dBm optics, 3dB loss for Mux/deMux, 5dB NF, 2dB practical penalty



## Worked calculations

### ILA / pre-amp contribution:

Input at each stage = -7.6 dBm

OSNR<sub>stage</sub> = 58 + Pin - NF

= 58 + (-7.6) - 5 = **45.4 dB** per ILA/pre-amp

### E2E OSNR:

Using linear inverse-sum accumulation:

=  $-10\log_{10}(10^{-34/10} + 5 \times 10^{-45.4/10})$

= **32.6 dB**

After 2dB practical penalty ~ **30.6dB**

### After Passive deMUX:

RX power =  $-7.6 + 10^{-3} = -0.6$  dBm

~ (-12dBm margin)

OSNR change ~ 0 dB

### Takeaway:

OSNR degrades gradually from ASE: **~6.6dB** above the 24dB threshold!

# IPoDWDM: ROADM Networks

## Launch power matters:

- Pluggable TX power VS per-channel input power of ROADMs (typically -3dBm to 0dBm)
- Will need high power coherent plugs (ZR+: from -5dBm to +3dBm)

## Alien-wavelength integration:

- Confirm your line system supports alien waves
- Co-existence with existing live wavelengths
  - Will filters distort or reshape it?
  - Will amplifiers (gain) and equalization (per-channel power balance) handle it correctly?

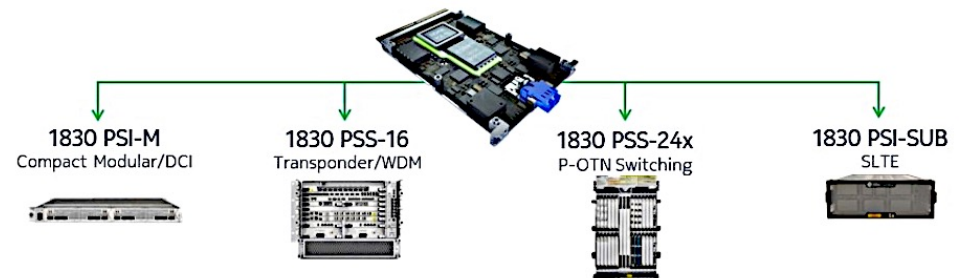
## Carry out route-by-route suitability

- Is every route a pluggable route?
- For challenging routes, would an embedded optics work better?
  - Eg: to achieve reach/distance, trade with lower capacity/bit rate (lower spectral efficiency)

# Aside: Embedded Optics

Less constrained by size, power and thermal limits:

- Support higher baud rates
- Can apply more aggressive PCS and FEC optimisation
- Benefits from higher-performance DSPs



Nokia's coherent PSE-6s  
Source: Nokia

On more challenging paths:

(*low-OSNR links, long-haul or subsea routes*)

- Line cards with embedded optics can offer better *capacity, reach, or margin* than a pluggable

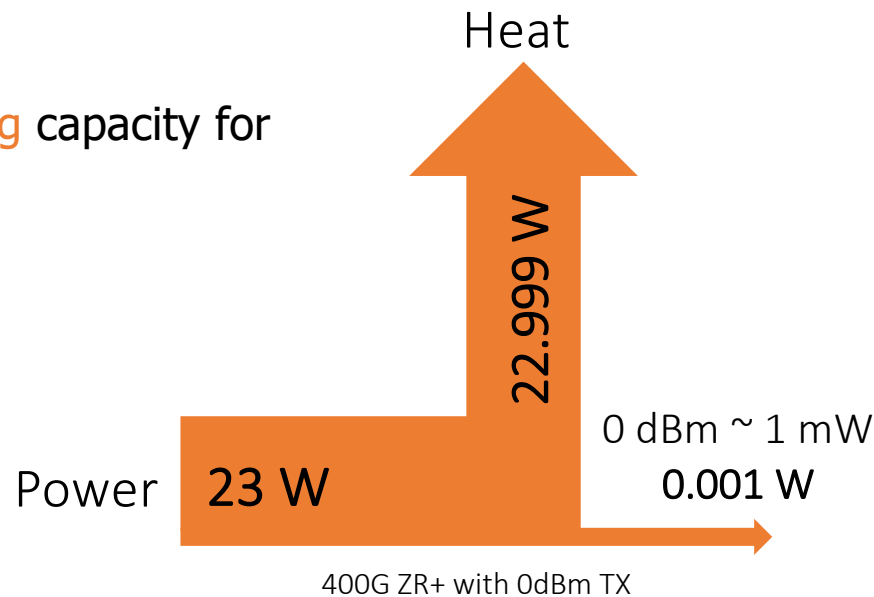
# Power and Cooling Considerations

Power: 19-23W per port with 400GZR/ZR+ coherent plugs

- Verify PSU headroom
- Check per-port budget, adjacent-port derating and supported coherent population

## Cooling checks

- Check rack and room cooling capacity for the added heat



# Other Considerations

## Platform checks:

- Validate router/switch support for the coherent plug
  - Form factors: **OSPF/QSFP-DD**
  - High power: **400G ZR** vs **400G ZR+**
- Confirm **C-CMIS** / **application mode** support for the plug

## Network Management:

- Verify the host exposes the required **coherent telemetry**
- Verify your NMS and automation tooling can handle coherent telemetry
  - **ingest, visualize** and **alert on**



# Adoption by Network Operators

Network	Type	Speed	Span	Status	Source
Internet2	R&E	400G backbone links	600 Km	Production	<a href="#">Internet2</a>
Arelion	CSP	400G ZR+	675 Km	Production	<a href="#">Arelion</a>
RETN	CSP	400G backbone links	300Km ~ 950 Km	Production	<a href="#">RETN</a>
Colt	CSP	800G ZR+	667 Km	Trial	<a href="#">Colt</a>
GÉANT	R&E	400G ULH	3400 Km	Trial	<a href="#">GÉANT</a>
AARNet	R&E	400G ULH	4600 Km	Trial	<a href="#">AARNet</a>
BKNIX	IXP	400G ZR+	40Km	Unamplified DCI	
DrukREN	R&E	400G ZR+	96Km	Amplified Backbone	

# IPoDWDM - Who should care?

You should, if you:

- Own and operate your own optical network (or dark fiber)
- Need lower cost-per-bit ~ power-per-bit
- If aggregate bandwidth is >100G (scaling towards 400G and beyond)
- Need both metro interconnects and regional reach
- Want to simplify multilayer IP and optical architectures

# What it means going forward?

## Coherent telemetry lives on the router

- IP folks will need basic understanding of DWDM and coherent optics

## IP and optical operations will converge

- Design, provisioning, and troubleshooting will require closer collaboration
- Fault isolation will increasingly span both IP and optical domains

## Disaggregation will continue to expand deployment choice

- Operators can adopt multi-vendor optical components more flexibly
- 

