IP over DWDM

(What IP folks should know)

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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)

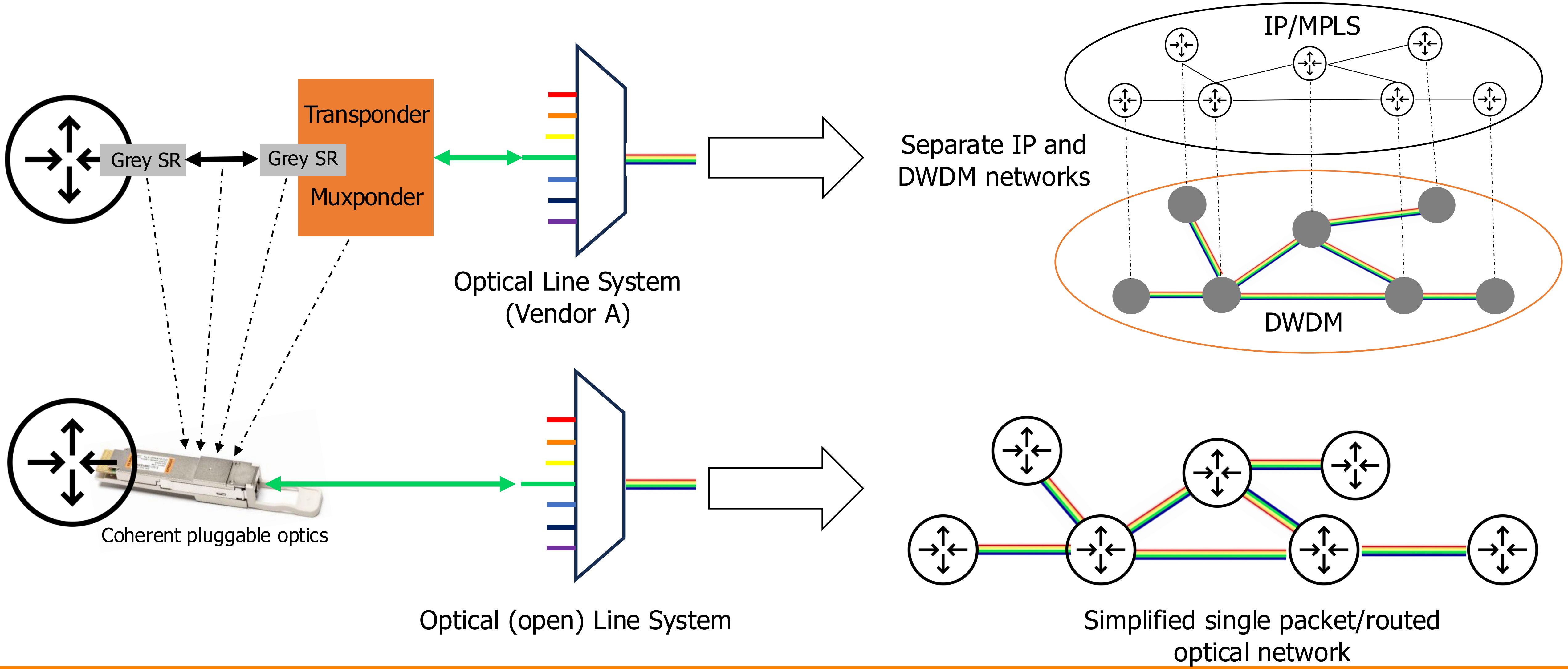
Common mapping:
Ethernet/packet into OTN, over DWDM

IPoDWDM

Coherent optics directly in routers and switches.

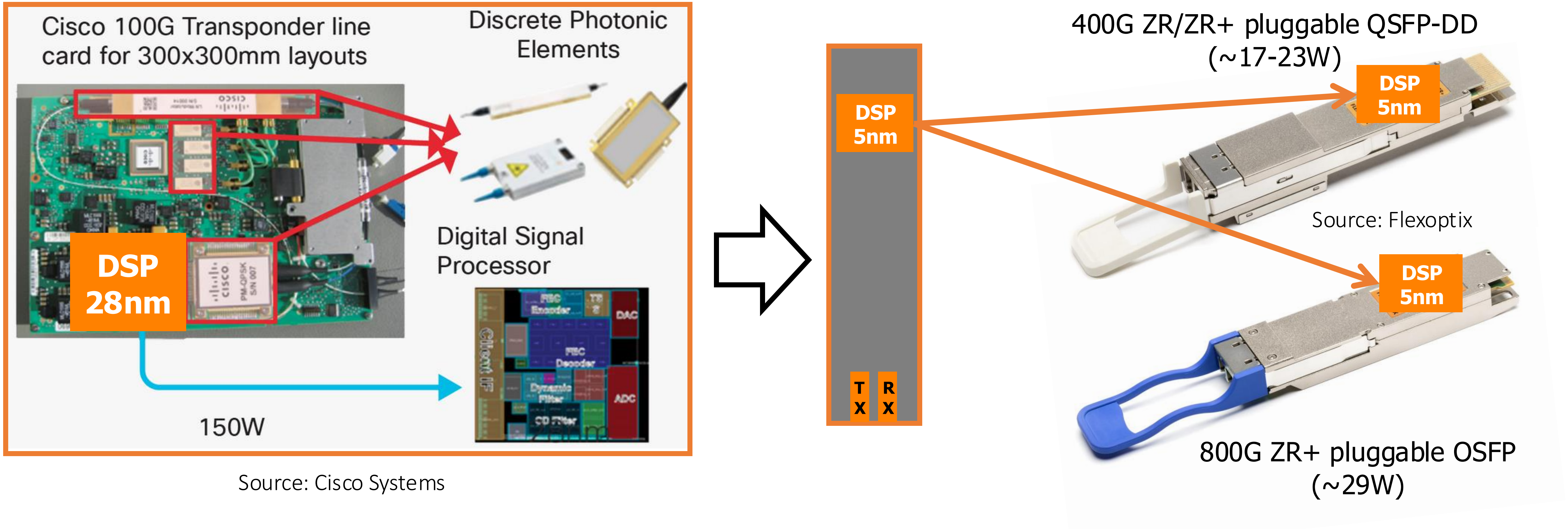
Model:
Ethernet/IP directly on wavelengths

Traditional IP and DWDM → IP-over-DWDM



What makes it possible?

Coherent Optics became **Pluggable**



- 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)

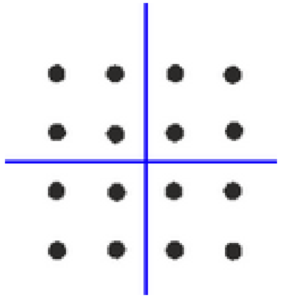
- Amplitude and Phase: QPSK/8QAM/16QAM

Two different polarizations carry two independent data streams:

- Doubling the bit rate for the same symbol rate

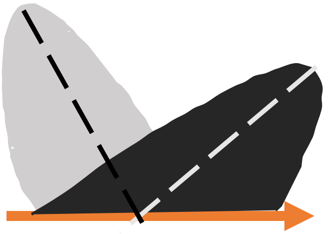
16-QAM
(4 bits/symbol)

~60 GBd (75GHz)



240Gbit/s

DP-16QAM
(dual polarization)

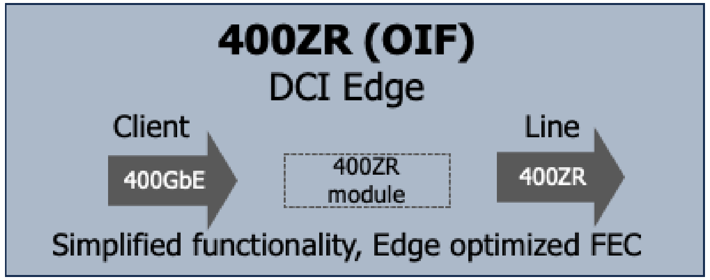


480Gbit/s
(400GbE~ 425Gbit/s)

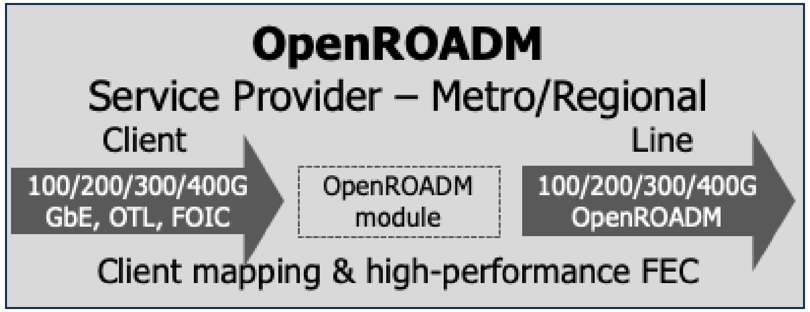
~55Gbit/s

overhead for FEC and pilot signal

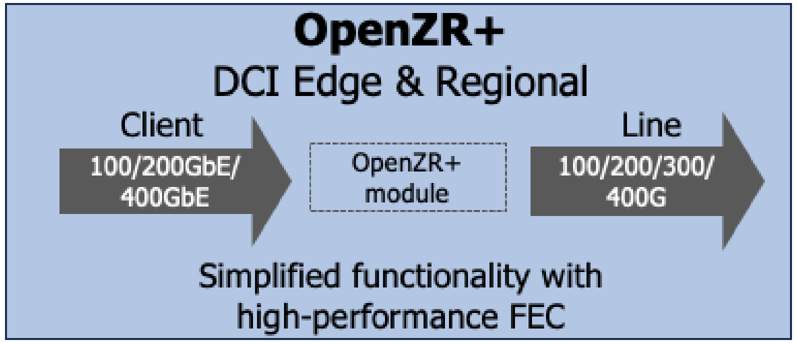
Open Standards & Disaggregation



Interoperable Ecosystem:
400ZR standardised coherent interfaces across vendors



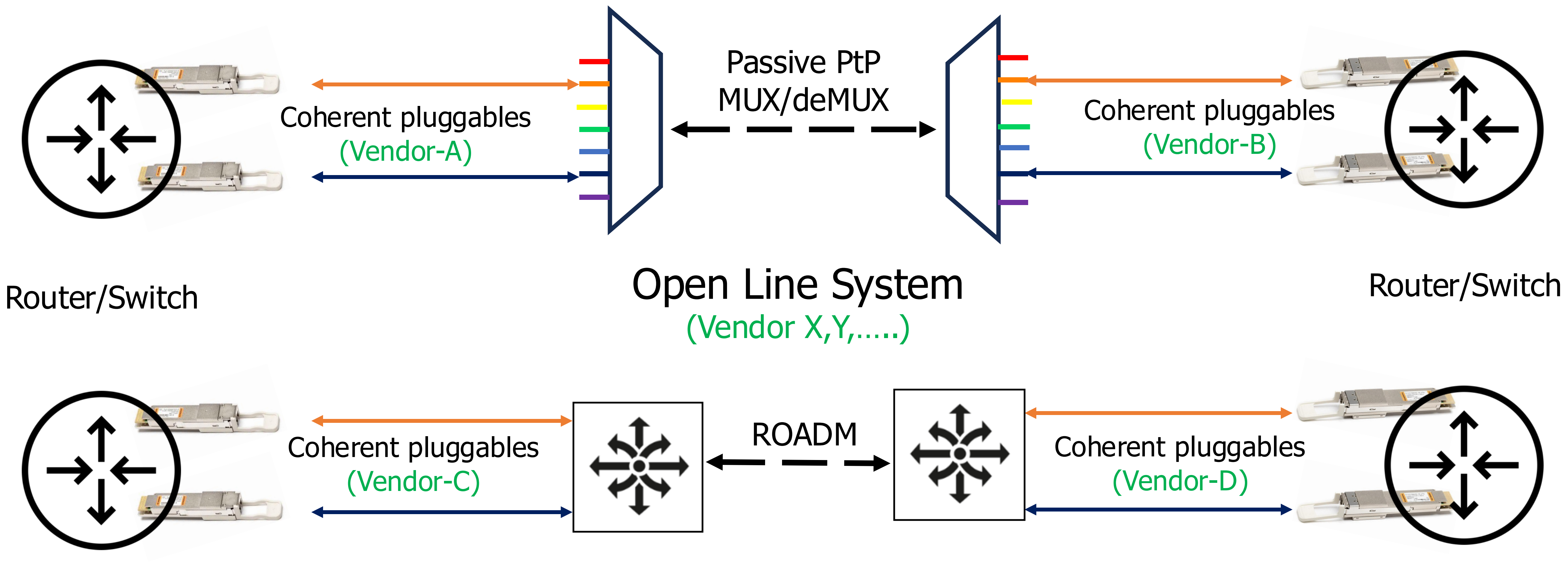
Disaggregated Transport:
Open line systems reduced dependence on closed end-to-end optical stacks



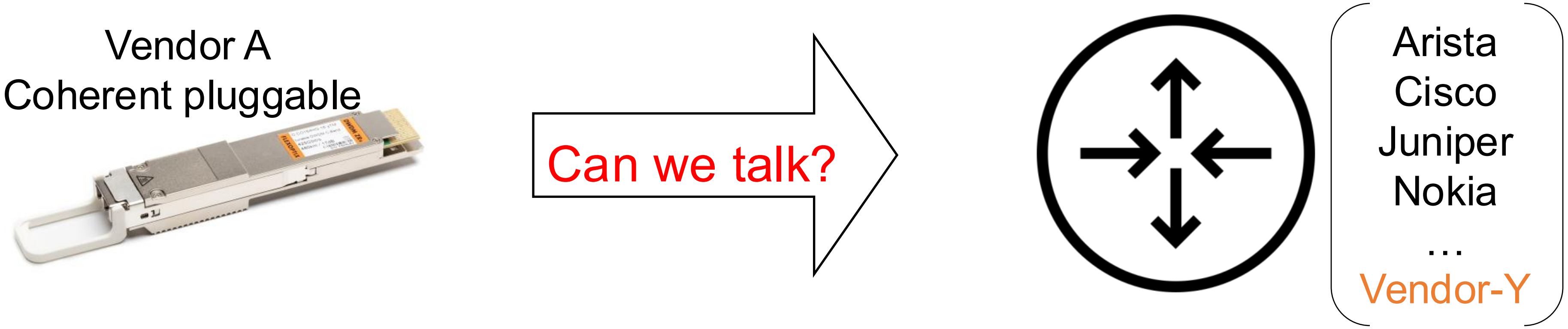
OpenZR+ MSA:
Extended coherent plugs into broader regional long-haul use cases

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
```

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

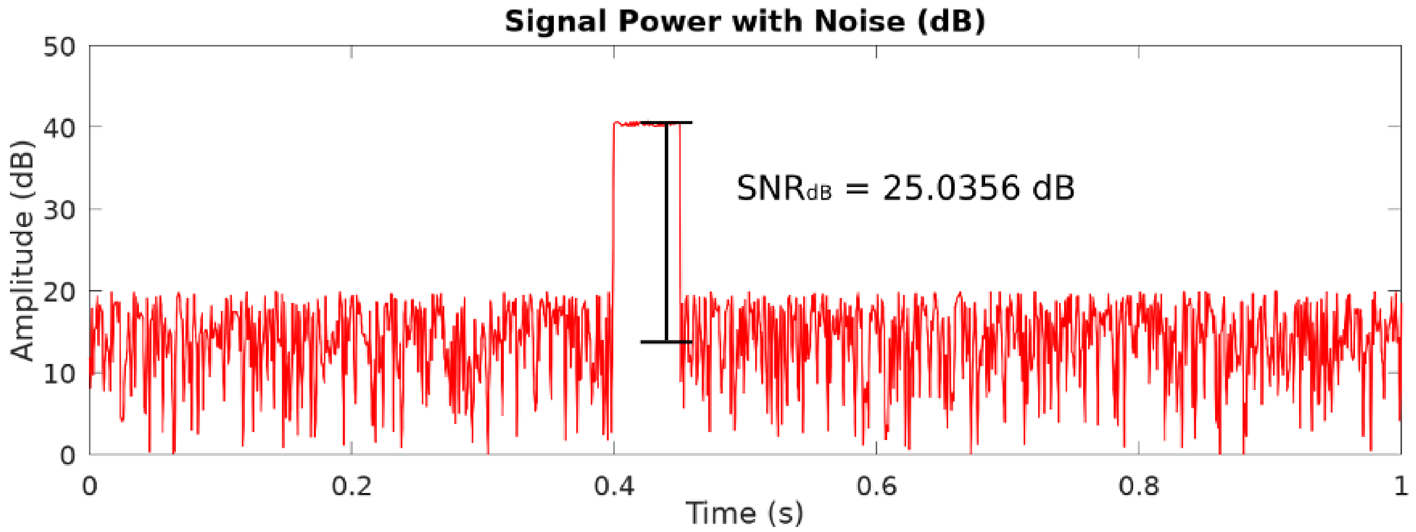
Optical telemetry directly on routers and switches:

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

Optical signal-to-noise ratio (OSNR)

OSNR compares optical signal power to noise power
- (log) ratio of signal power to noise power

Higher OSNR ~ cleaner signal: easier for receiver to detect and decode



OSNR = 0dB

(O)SNR and Bit Errors

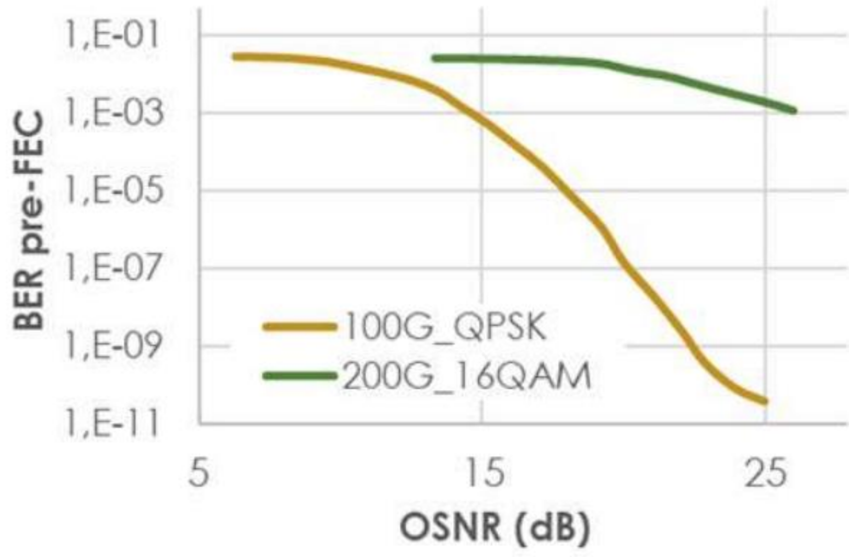
Bit Error Rate (BER) = errored bits / transmitted bits

$\text{BER} = 10^{-9}$ one error bit for every 1 billion bits transmitted!

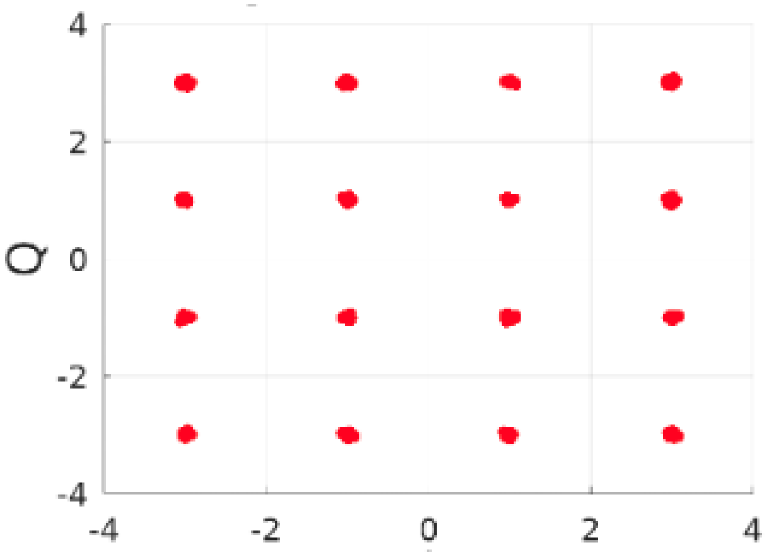
(O)SNR directly affects BER:

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

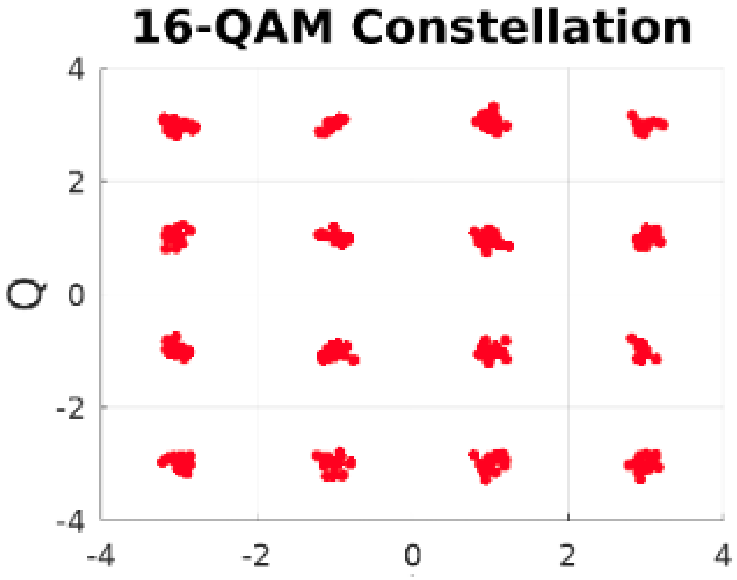
→ Lower OSNR: noisier signal, harder to make out 0s and 1s ~ higher bit errors



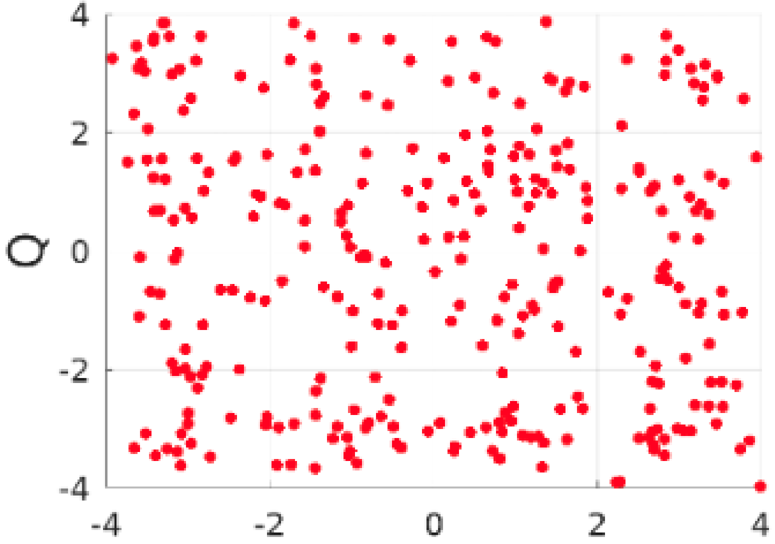
(O)SNR and Bit Errors



OSNR = 30dB
Clean



OSNR = 20dB
Noisy



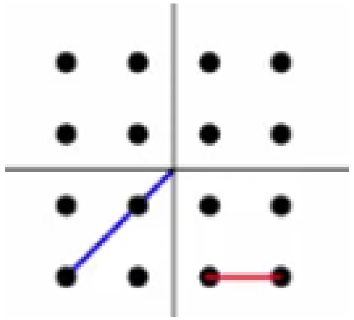
OSNR = 5dB
Too Noisy

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	1.25×10^{-2}	DCI links/short reach - Lower power - Less tolerant to noise	~120 Km
400G ZR+ MSA	DP-16QAM	oFEC	24 dB	2.0×10^{-2}	Can handle poorer link conditions: - *Tolerate lower OSNR* - *Longer reach* - *Trade capacity for reach*	~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

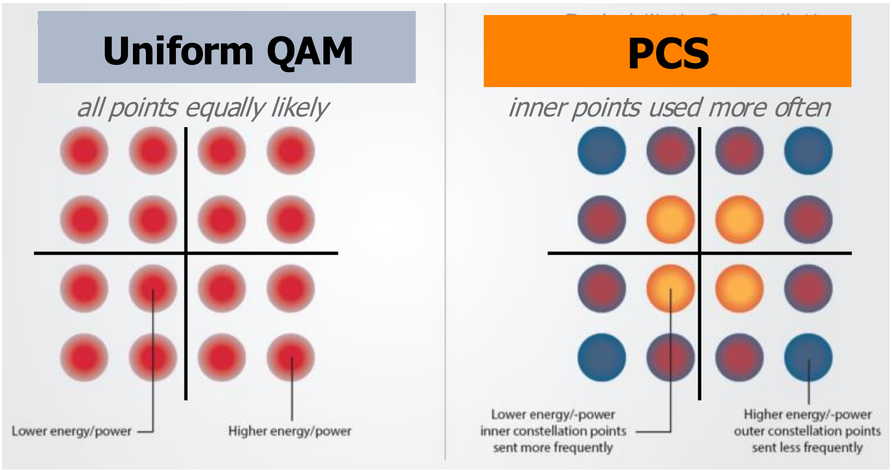
*Actual reach depends on span loss, amplification, filtering/ROADM design, channel loading, etc.

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



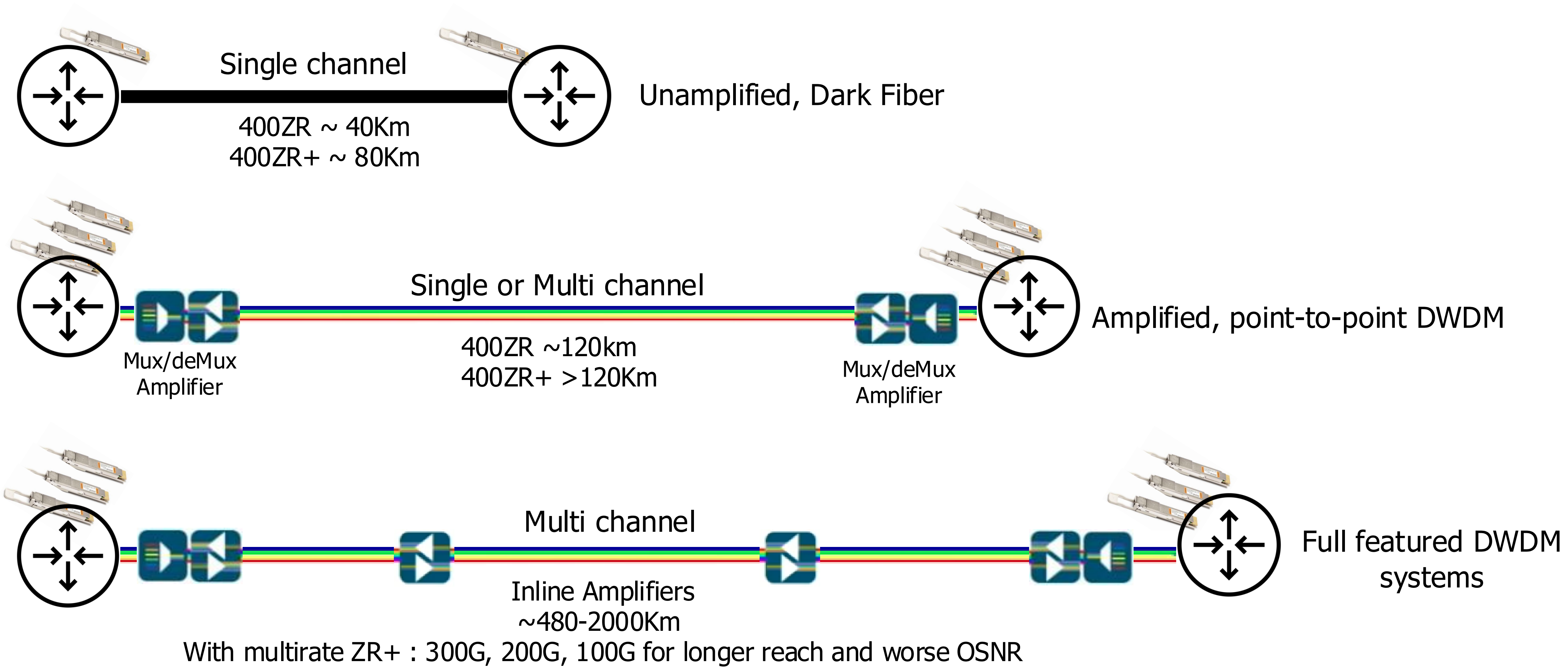
Why this matters?

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



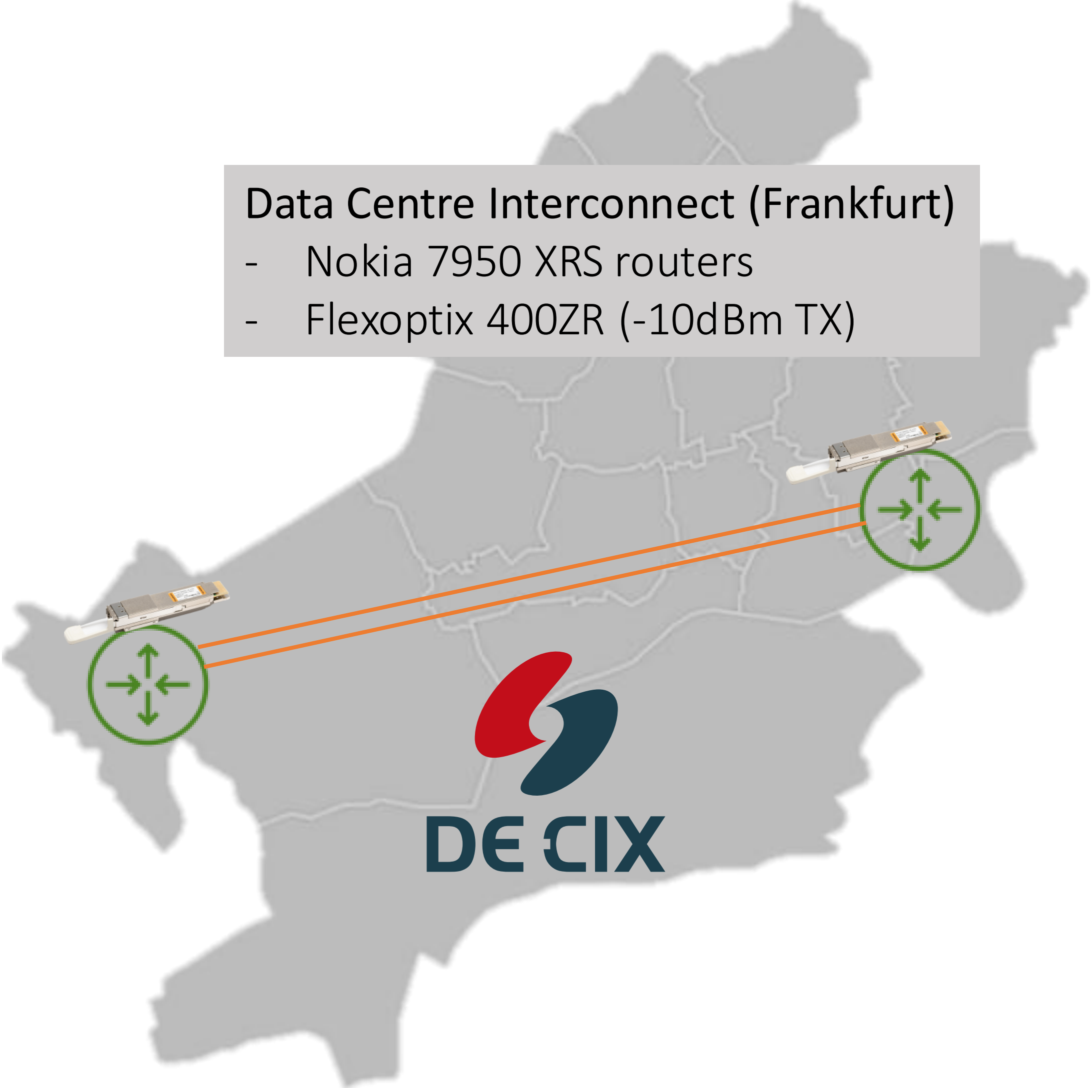
IPoDWDM for simple DCI

Existing setup:

Router
(100G gray client optics)
↓
Transponder/Muxponder
↓
Mux/Line System
↓
Fiber
↓
deMux/Line System
↓
Transponder/Muxponder
↓
(100G gray client optics)
Router

Data Centre Interconnect (Frankfurt)

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



IPoDWDM setup:

Router
[λ1] [λ2] [λ3] [λ4]
400G ZR coherent plugs
↓
Mux/Line System
↓
Fiber
↓
deMux/Line System
↓
[λ1] [λ2] [λ3] [λ4]
400G ZR coherent plugs
Router

Compatibility (Application Mode)

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

===============================================================================
Coherent Optical Module
===============================================================================
Cfg Tx Target Power:   1.00 dBm              Present Rx Channel : 23
Cfg Rx LOS Thresh  : -23.00 dBm              Cfg Rx Channel     : 23

Disp Control Mode  : automatic               Sweep Start Disp   : -25500 ps/nm
Cfg Dispersion     :         0 ps/nm
CPR Window Size    : 32 symbols
Compatibility      : openZrpOfec1
Cfg Tx Power Min   : -22.90 dBm
```

Application Mode	MSA format	Nokia Compatibility						
1	OIF 400ZR, amplified	oif-400g-zr	4(					
2	OIF 400ZR, unamplified		4(					
3	OpenZR+ MSA	openZrpOfec1	4(					
4	OpenZR+ MSA		2:					
5	OpenZR+ MSA	openZrpOfec1	4:					
6	OpenZR+ MSA, Enhanced	openZrpOfec2	4(					
7	OpenZR+ MSA, Enhanced		2:					
8	OpenZR+ MSA, Enhanced	openZrpOfec2	4:					
9	OpenZR+ MSA	openZrpOfec1	2:					
10	OpenZR+ MSA	openZrpOfec2	1:					
11	OpenZR+ MSA	openZrpOfec1	3:					
12	OpenZR+ MSA, Enhanced		3:					
13	OIF 400ZR, amplified	oif-400g-zr	4:					
14	OpenZR+ MSA, Enhanced	openZrpOfec2	2:					
15	OpenZR+ MSA		100GBASE-R		1x CAUI-4 w/o FEC (4x25G)	oFEC	DP-QPSK	30.1GBd

```
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
...
```

Aside: Application Modes

Coherent transceivers support (and advertise) multiple config options

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

You can select the desired application code based on network requirements:

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

JunOS

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

IOS XR

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

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) 22 W (typ)
AppCode 2	400GAUI-8	59.843	DP-16QAM	400GbE	cFEC	80km (unamplified)	22.5 W (max) 22 W (typ)
AppCode 3	4x100GAUI-2	59.843	DP-16QAM	4x100GbE	cFEC	120km (amplified)	23.5 W (max) 23 W (typ)
AppCode 4	4x100GAUI-2	59.843	DP-16QAM	4x100GbE	cFEC	80km (unamplified)	23.5 W (max) 23 W (typ)
AppCode 5	400GAUI-8	60.138	DP-16QAM	400GbE	oFEC	480km (amplified)	23.5 W (max) 23 W (typ)
AppCode 6	4x100GAUI-2	60.138	DP-16QAM	4x100GbE	oFEC	480km (amplified)	23.5 W (max) 23 W (typ)
AppCode 7	3x100GAUI-2	60.138	DP-8QAM	3x100GbE	oFEC	600km (amplified)	23,5 W (max) 23 W (typ)

[Flexoptix 400G ZR/ZR+]

Coherent Parameters:

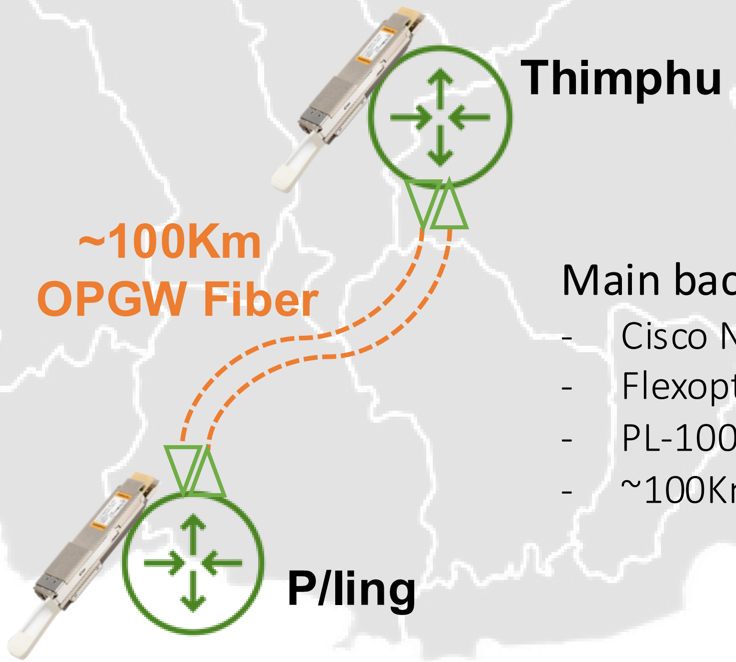
Application Code	Coherent Standard	Rx OSNR Tolerance	Rx Sensitivity @ OSNR	CD Tolerance max @0.5 dB OSNR Penalty	DGD Max (PMD tolerance)	Pre-FEC BER Limit	Post-FEC BER
AppCode 1	400G ZR DWDM	>26 dB/0.1 nm	-12 dBm OSNR >26dB	±2,400 ps/nm	33 ps	~1.22E-2	<1E-15
AppCode 2	400G ZR Grey, unamplified	>26 dB/0.1 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

IPoDWDM for amplified PtP links

Existing setup:

Router
(10G fixed DWDM optics)
↓
Mux
↓
Booster
↓
Fiber
↓
Pre-amp
↓
deMux
↓
(10G fixed DWDM optics)
Router

Druk REN



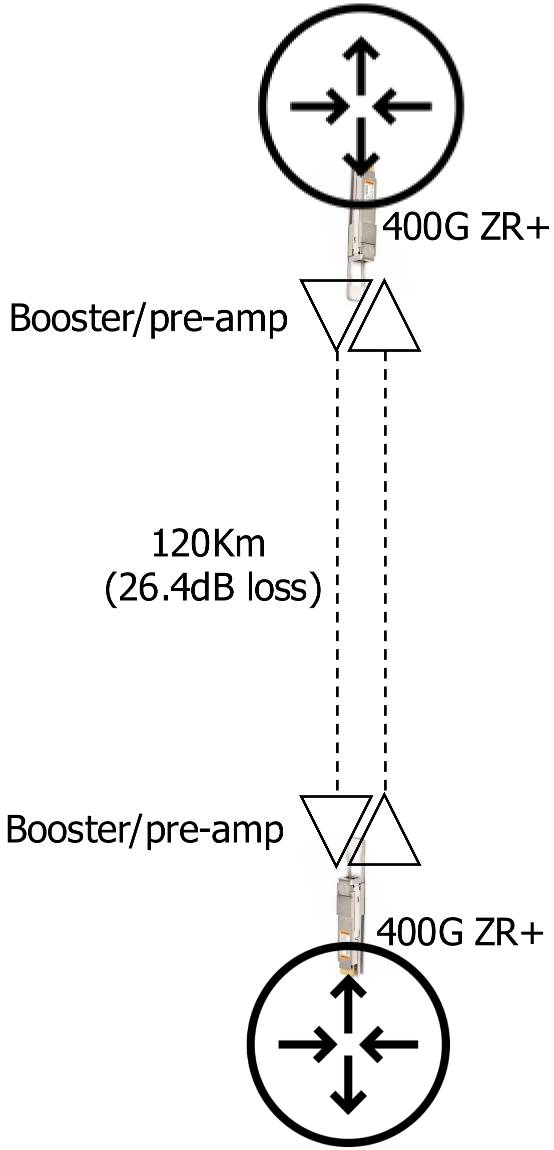
Main backbone (Western Bhutan):

- Cisco N93600CD-GX
- Flexoptix 400GZR+ (1dBm TX)
- PL-1000IL booster/preamp
- ~100Km OPGW link

IPoDWDM setup:

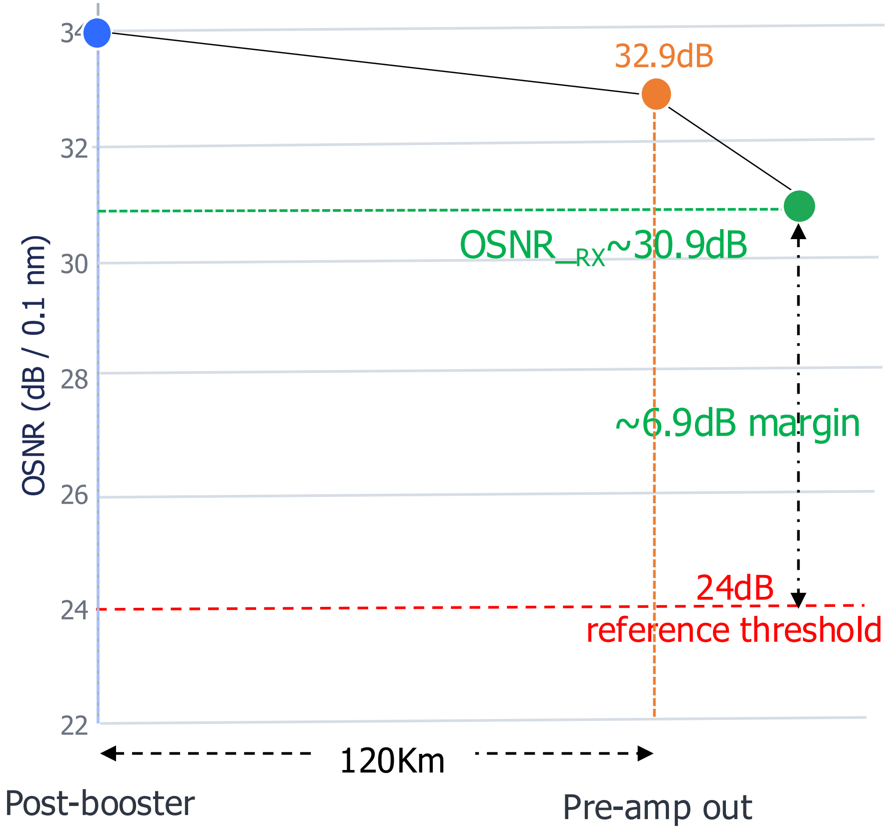
Router
(400G ZR+ coherent plugs)
↓
Mux
↓
Booster
↓
Fiber
↓
Pre-amp
↓
deMux
↓
(400G ZR+ coherent plugs)
Router

IPoDWDM for amplified PtP links

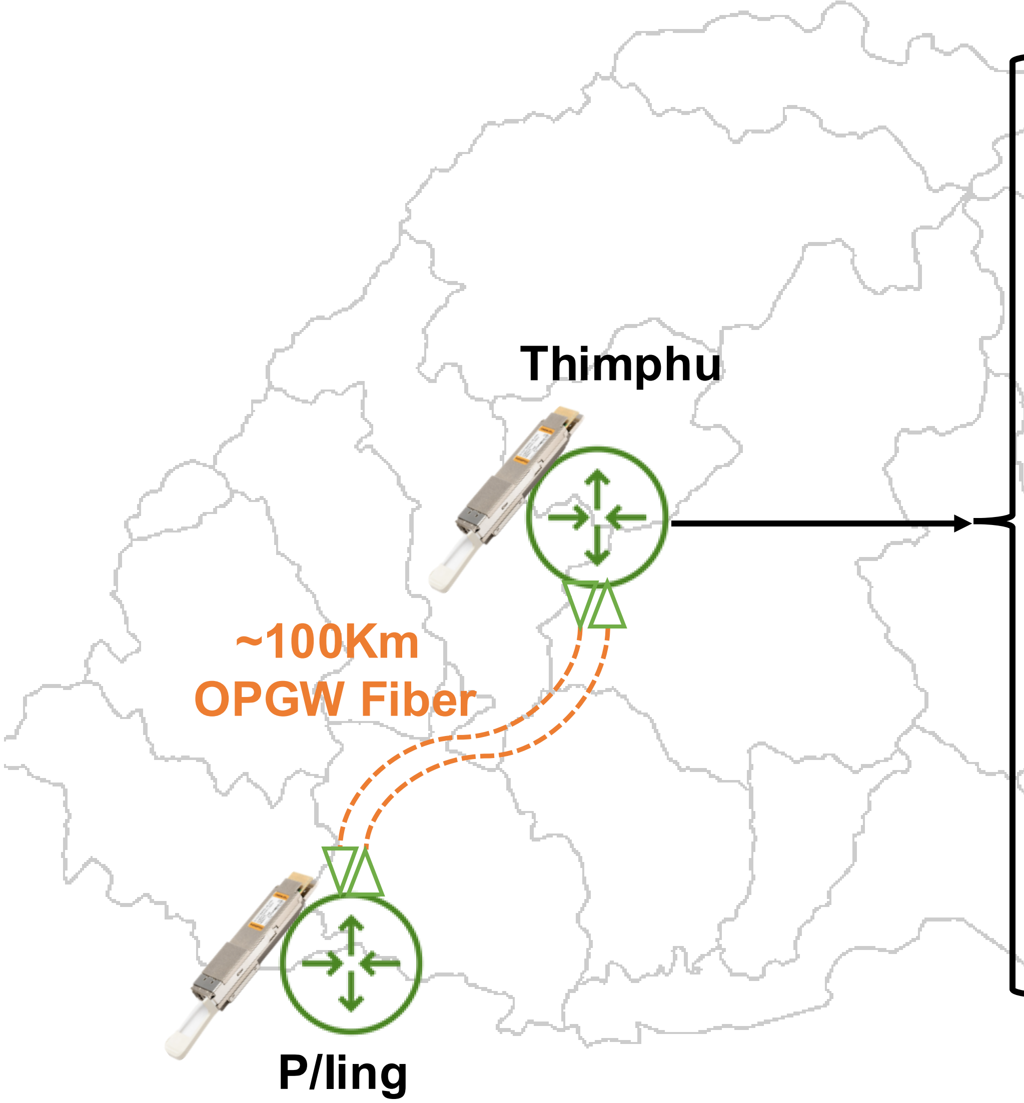


Assumptions:
- Coherent optics: 400ZR+ (+3dBm)
- Amplifier: 10dB gain, 5dB NF
- Fiber loss: 0.22dB/km
- Practical penalty: 2dB

Result:
- Final RX power ~ -3.4dBm
- Final OSNR ~ 30.9dB
- OSNR margin ~ 6.9dB



IPoDWDM for amplified PtP links



Current Interval [15:27:56 Sun Dec 14 2025 - 15:33:21 Sun Dec 14 2025]

Parameter	MIN	AVG	MAX
CD(Short)[ps/nm]	1156.00	1156.00	1156.00
DGD[ps]	1.00	1.00	1.00
RX PWR[dBm]	-9.46	-9.31	-9.10
TX PWR[dBm]	-1.04	-1.00	-0.95
OSNR[dB]	24.70	24.99	25.00
RX CHAN PWR[dBm]	-12.01	-11.83	-11.68
ESNR[dB]	15.50	15.67	15.80
LASER BIAS[mA]	264.69	265.19	265.49
FREQ OFF[Mhz]	-345.00	-253.41	-193.00
SOP RATE[krad/s]	0.00	4.61	12.00
PDL[dB]	0.60	0.76	0.90
SOPMD[ps^2]	17.81	38.33	61.12

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

- Module OSNR threshold was 26dB
- 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. needs 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

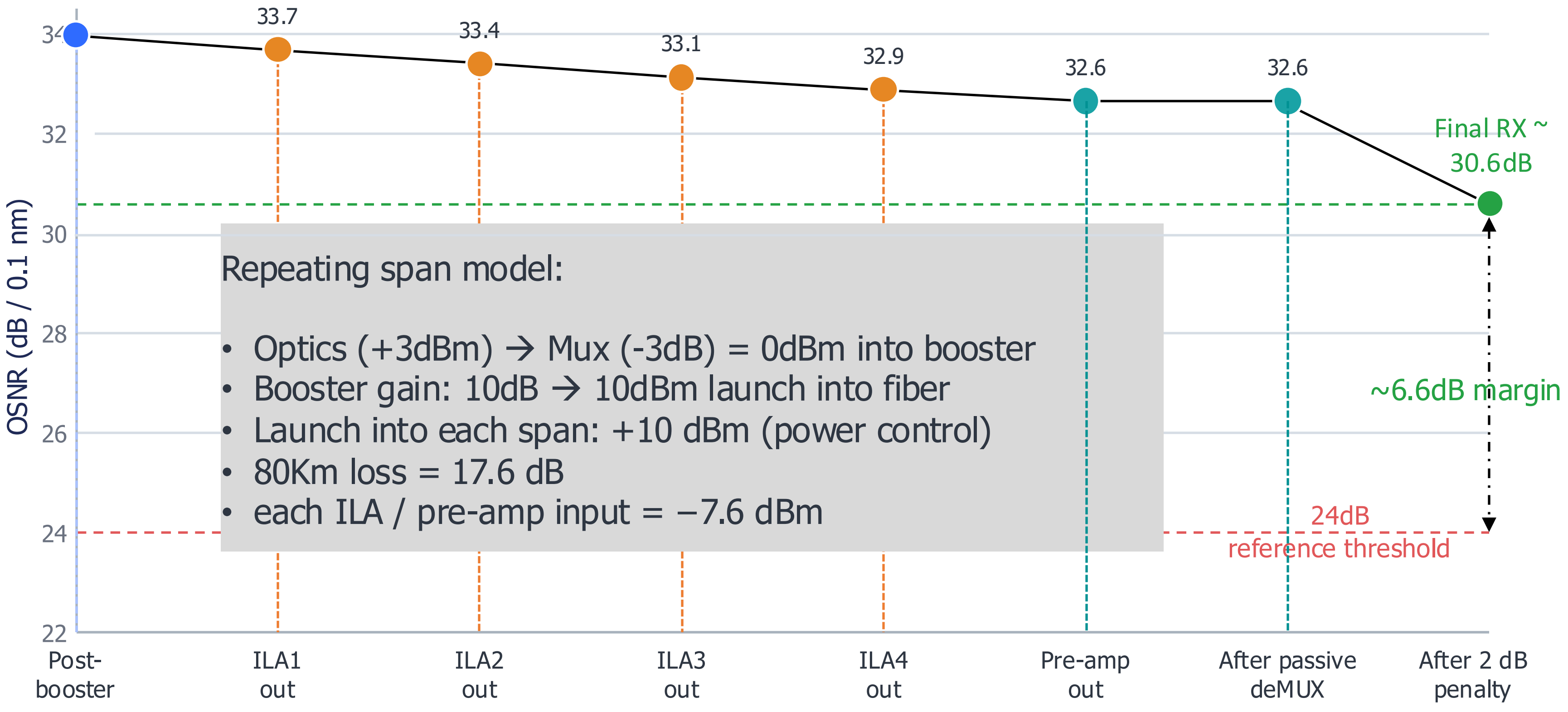
400ZR+ OSNR: 5x80Km with ILAs

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

E2E OSNR:

Using linear inverse-sum accumulation:
$= -10\log10(10^{-34/10}) + 5x10^{-45.4/10})$
= **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?

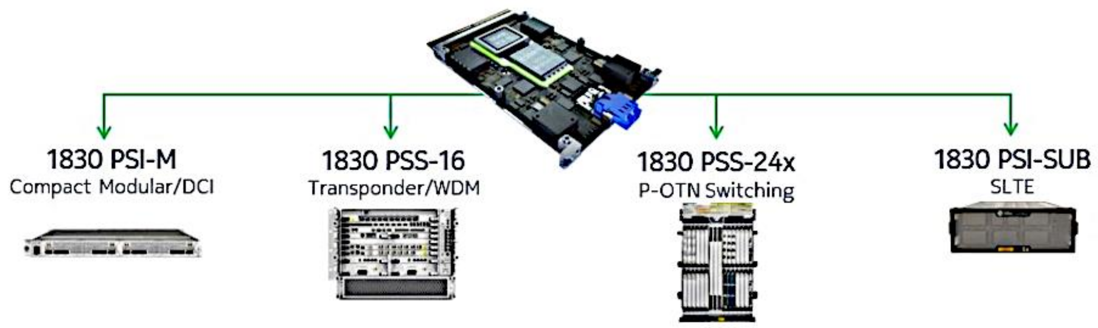
Carry out route-by-route suitability

- 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

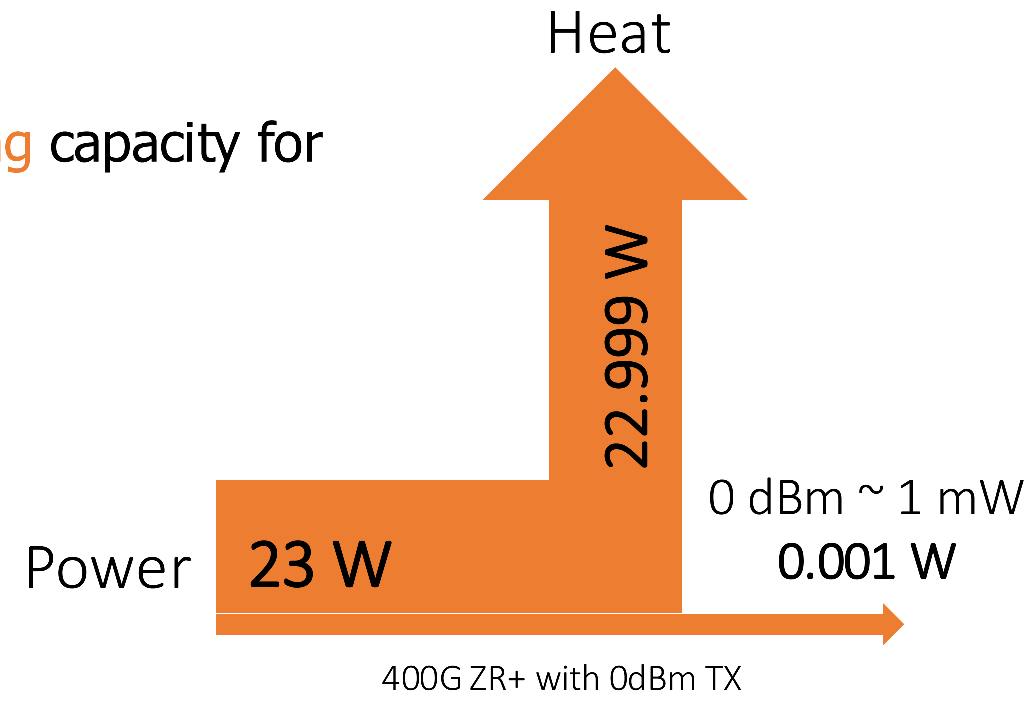
Power and Cooling Considerations

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	Internet2
Arelion	CSP	400G ZR+	675 Km	Production	Arelion
RETN	CSP	400G backbone links	300Km ~ 950 Km	Production	RETN
Colt	CSP	800G ZR+	667 Km	Trial	Colt
GÉANT	R&E	400G ULH	3400 Km	Trial	GÉANT
AARNet	R&E	400G ULH	4600 Km	Trial	AARNet
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
- Are scaling towards 400G (aggregate) 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


LESS
CONFUSION
MORE
CLARITY