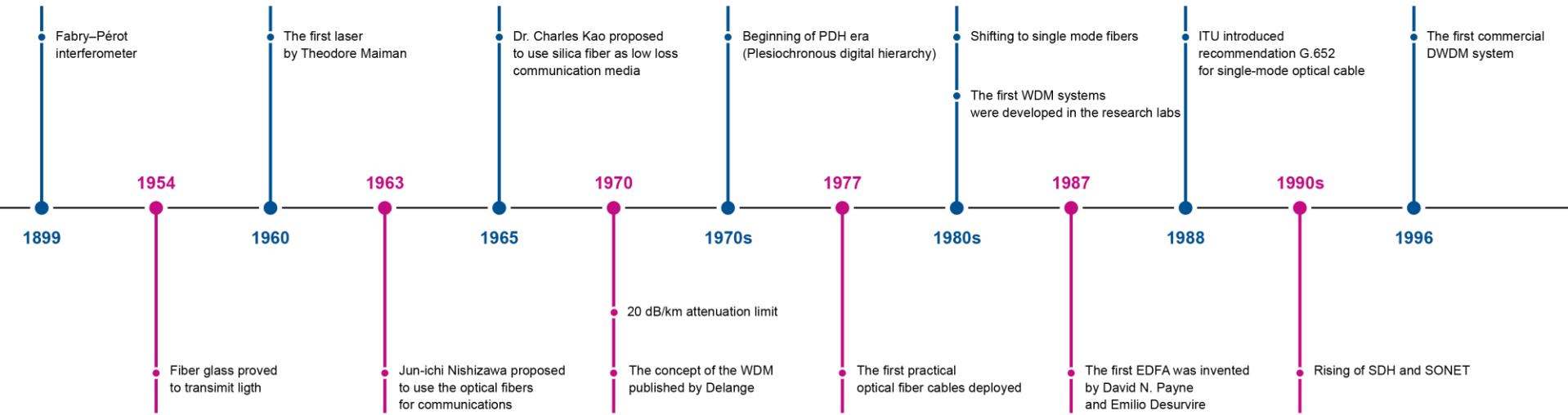


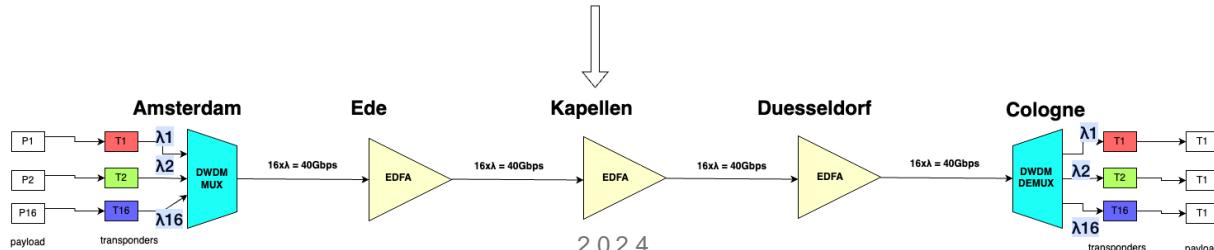
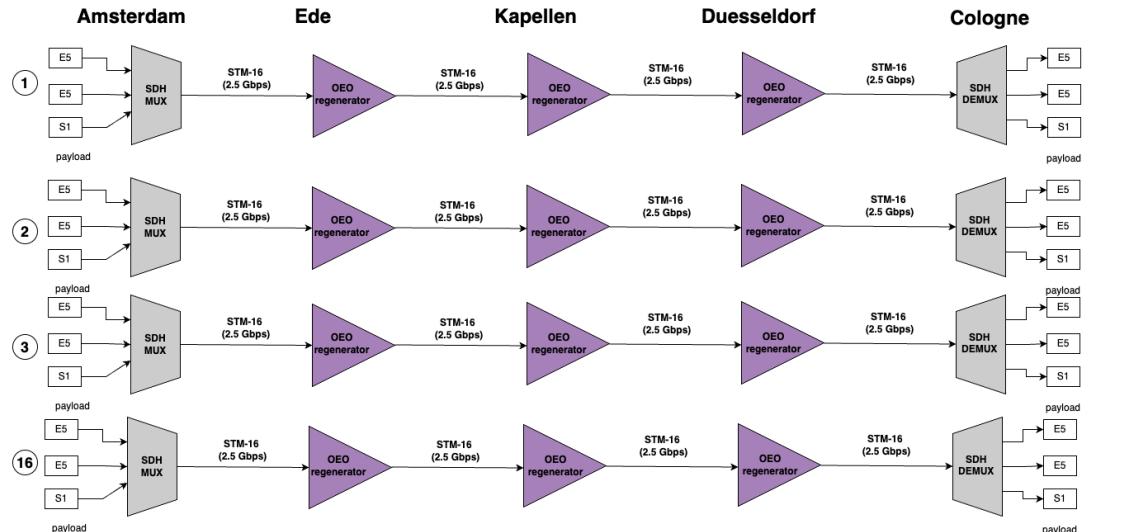
A Brief History of DWDM

YURII POLOVYI
NLNOG 2024

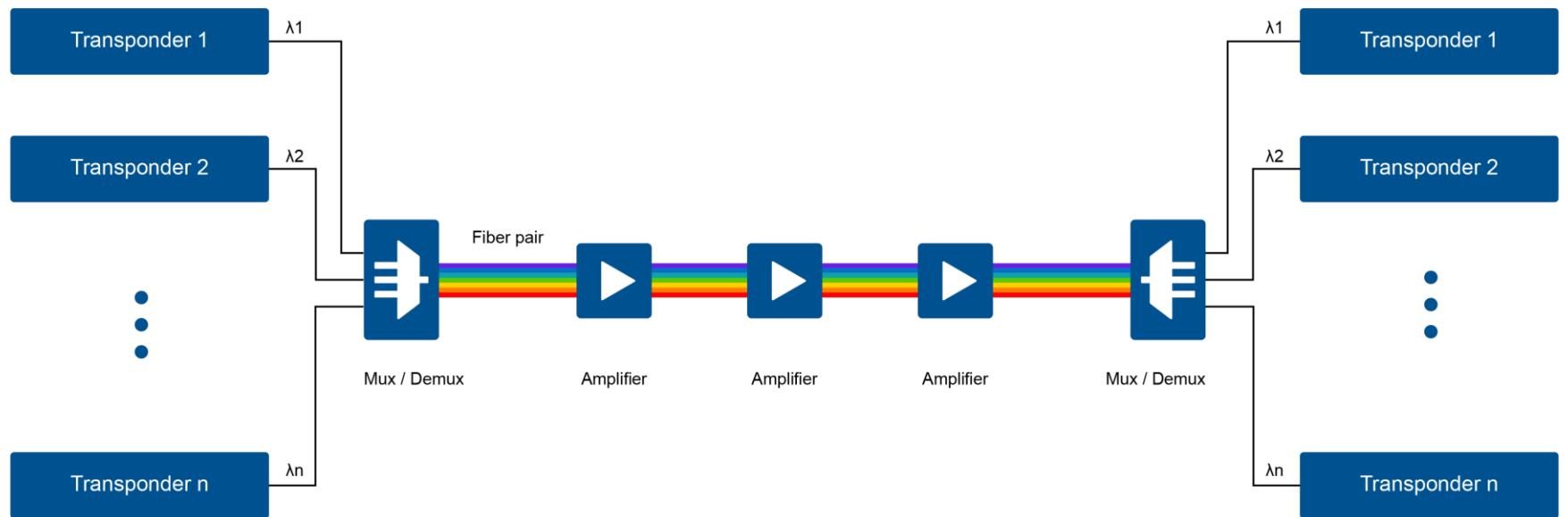
Early days of the fiber optic communication



40G SDH vs DWDM (1996)

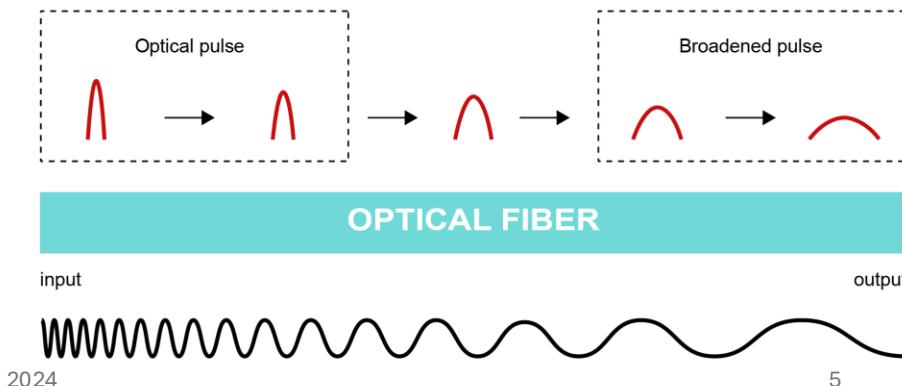
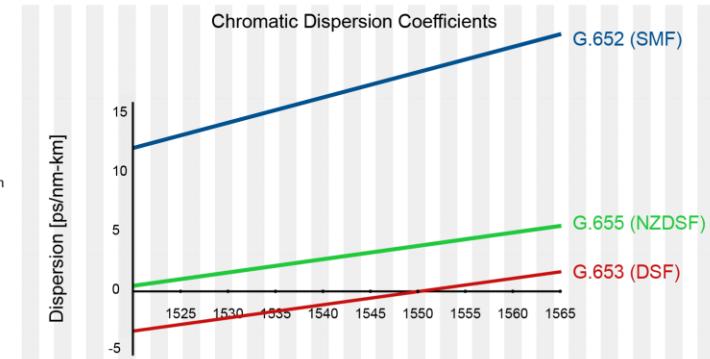
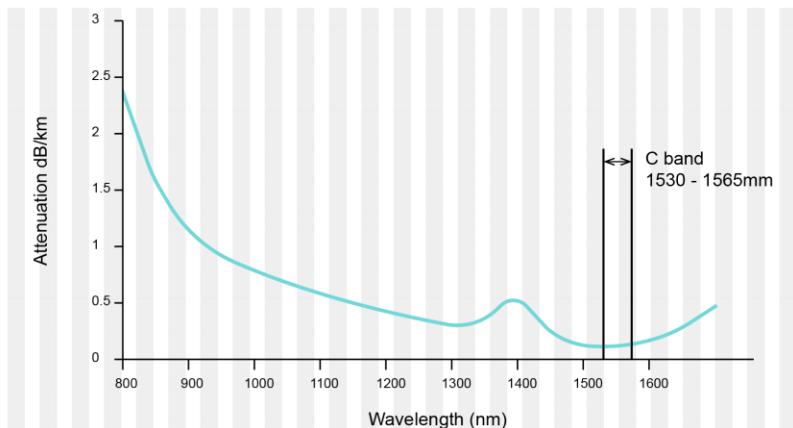
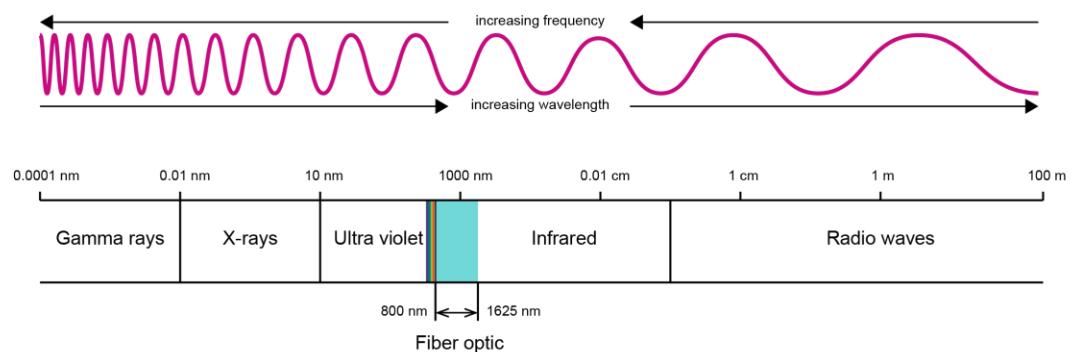


Key elements of a DWDM system

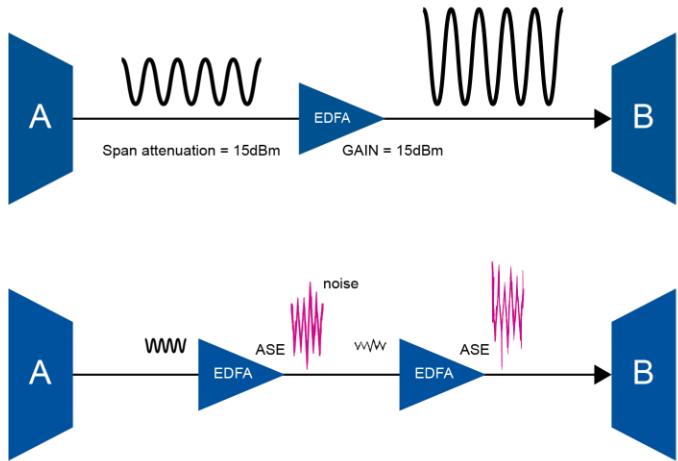


Media - a single mode fiber

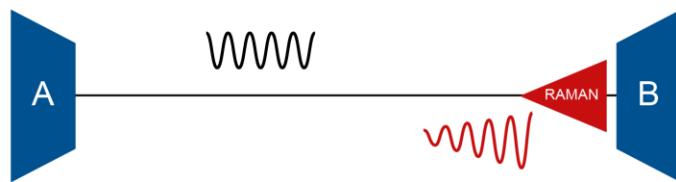
Electro Magnetic Spectrum



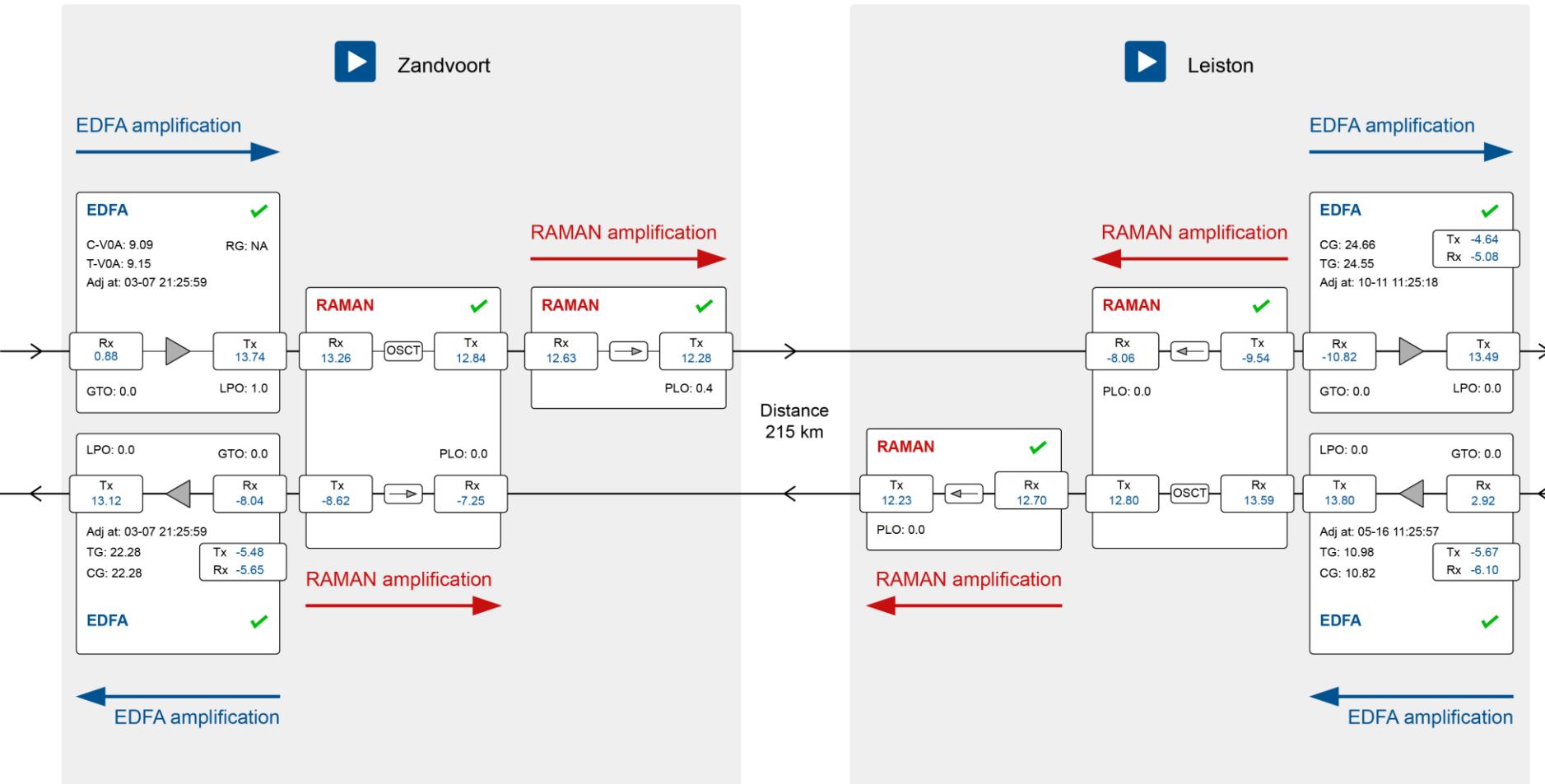
Erbium-doped fiber amplification (EDFA)



RAMAN amplification



ASE - Amplified Spontaneous Emission

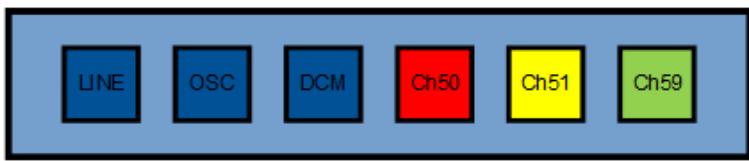


Multiplexing and demultiplexing

Fixed Optical Add-Drop Multiplexers (FOADM)

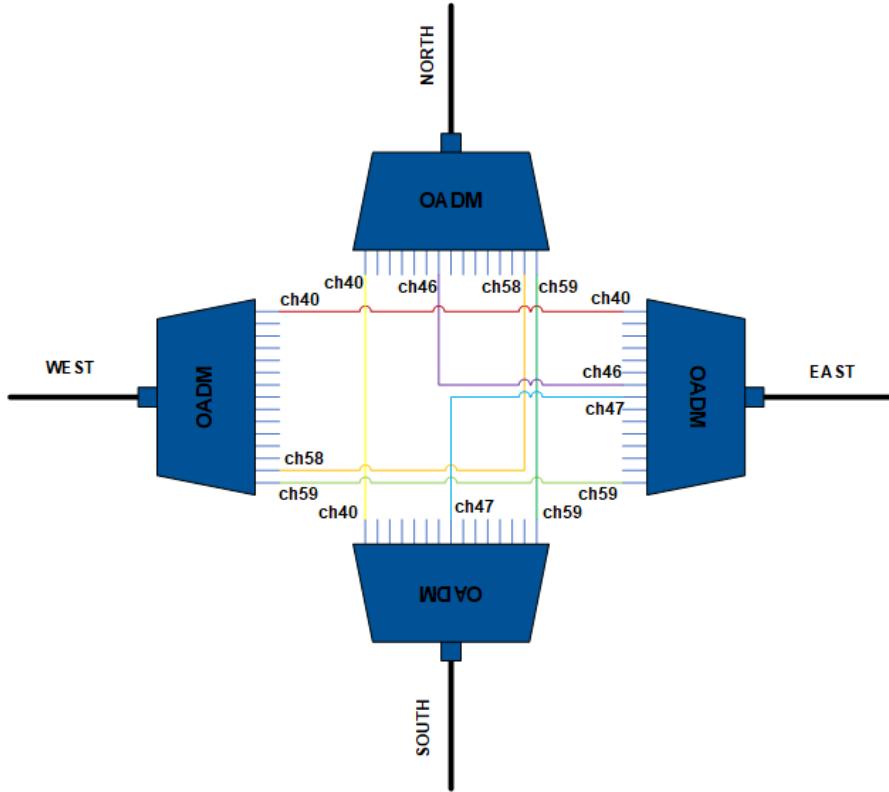
Early OADM

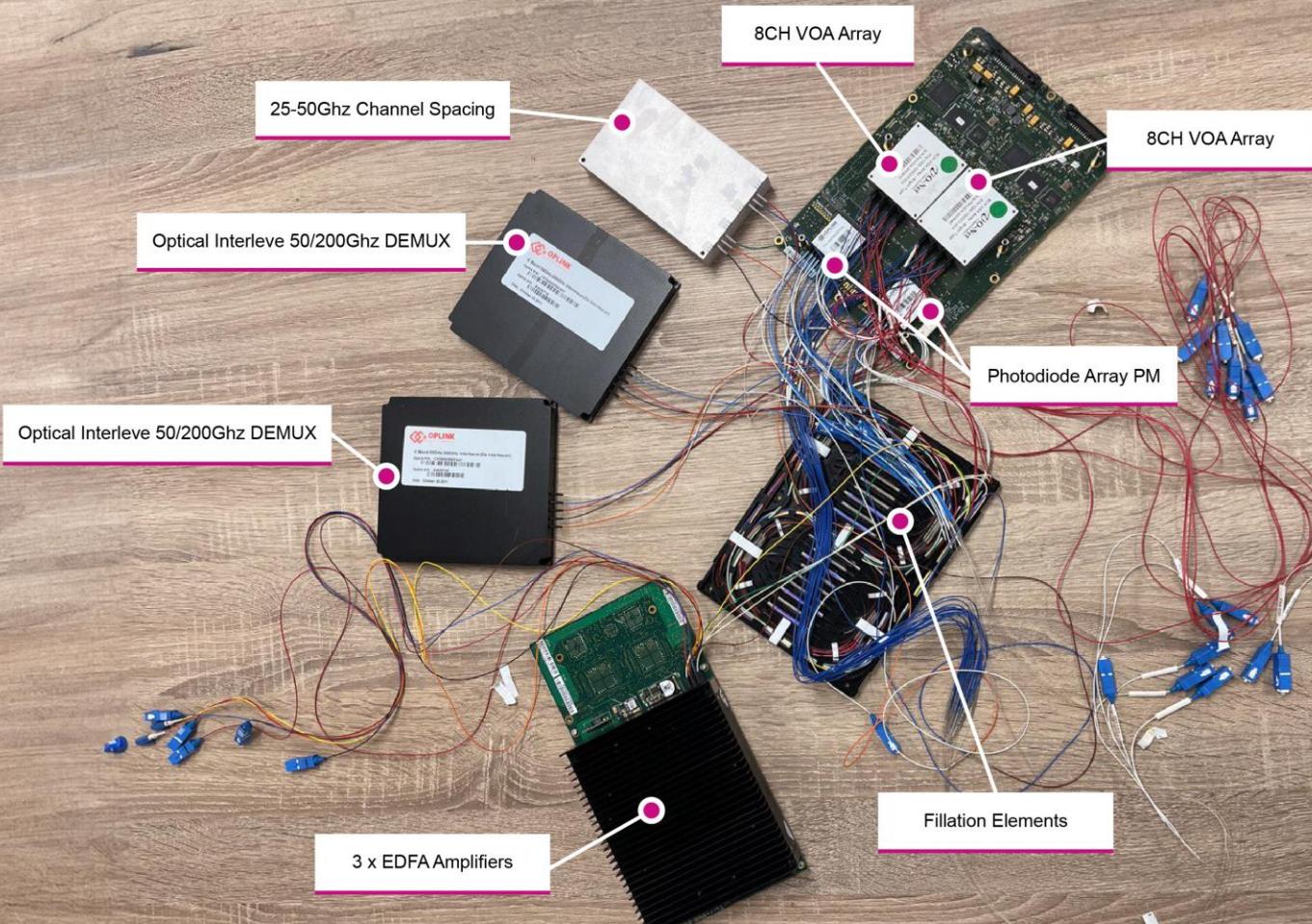
- Fixed wavelength grid
- Manual add-drop only
- Fixed signal width
- Vendor lock



Powered by

- Athermal arrayed wave guide (AWG)
- Thin film filter (TFF)



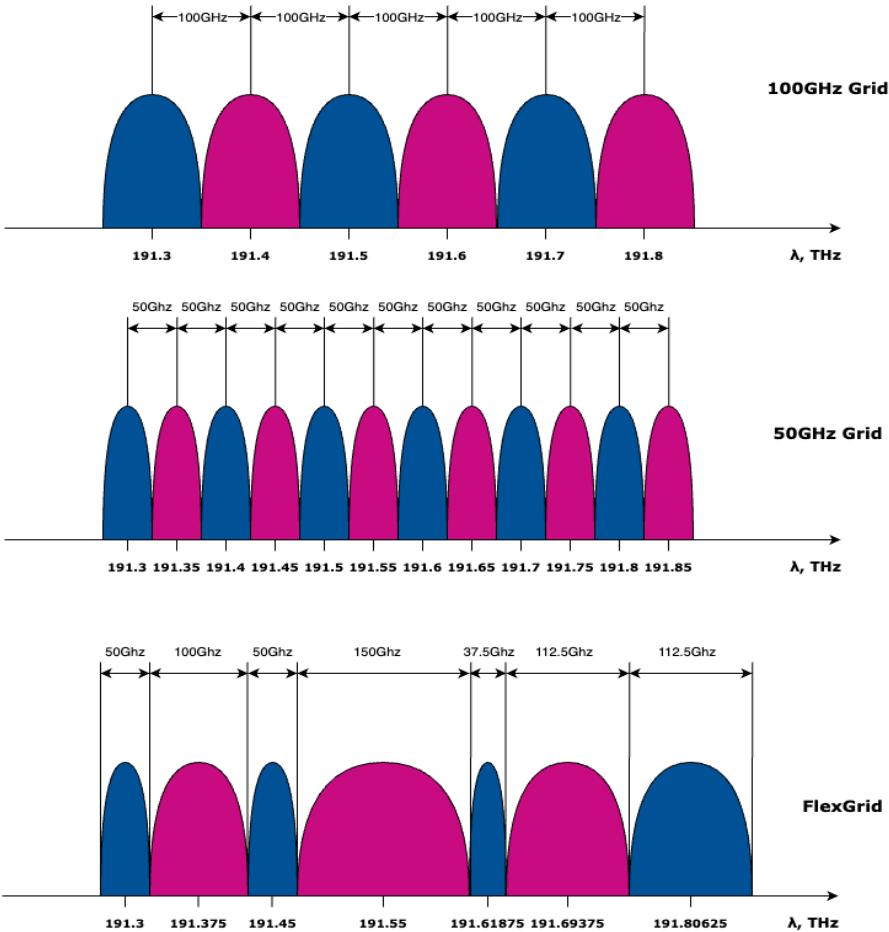


Reconfigurable OADM (ROADM)

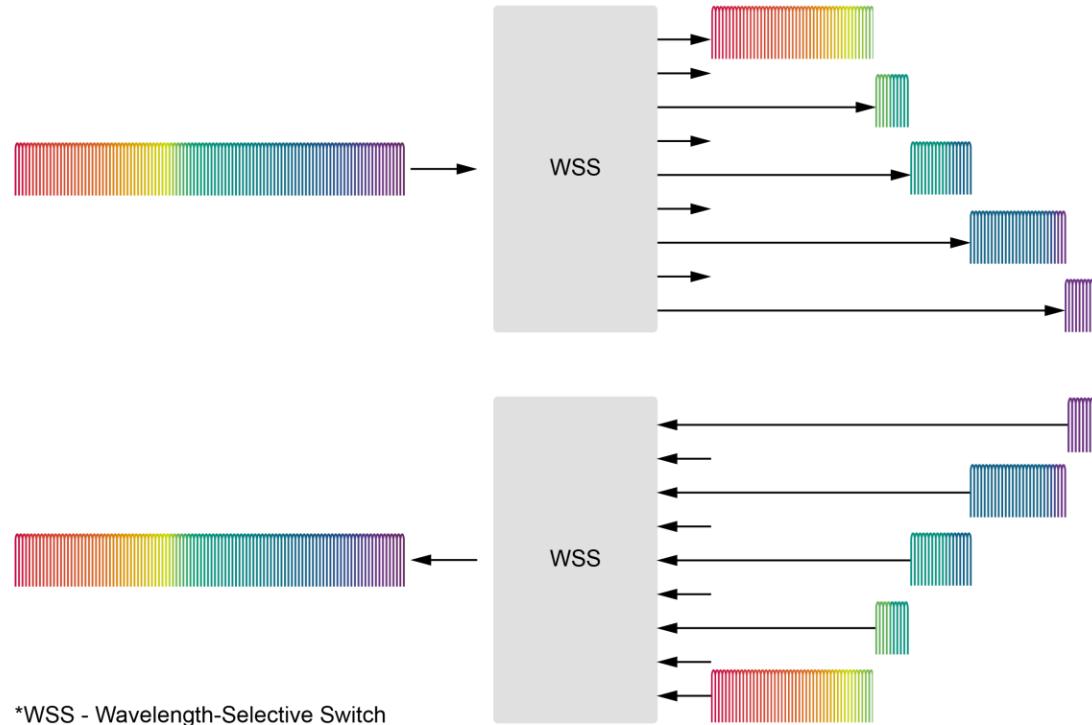
- Flexible wavelength planning
- Fully reconfigurable add-drops
- Flexible signal width (granularity)
- Open ROADM

Powered by

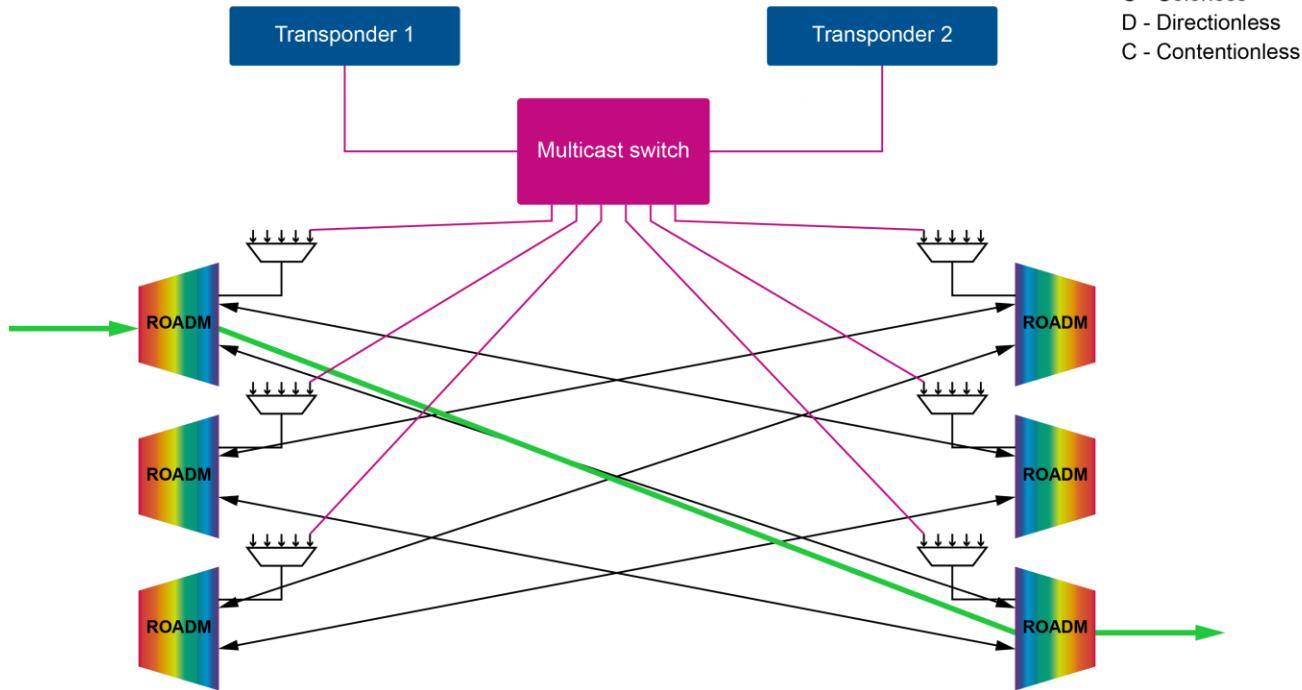
- light processing
- microelectromechanical systems mirrors
- liquid crystal
- liquid crystal on silicon



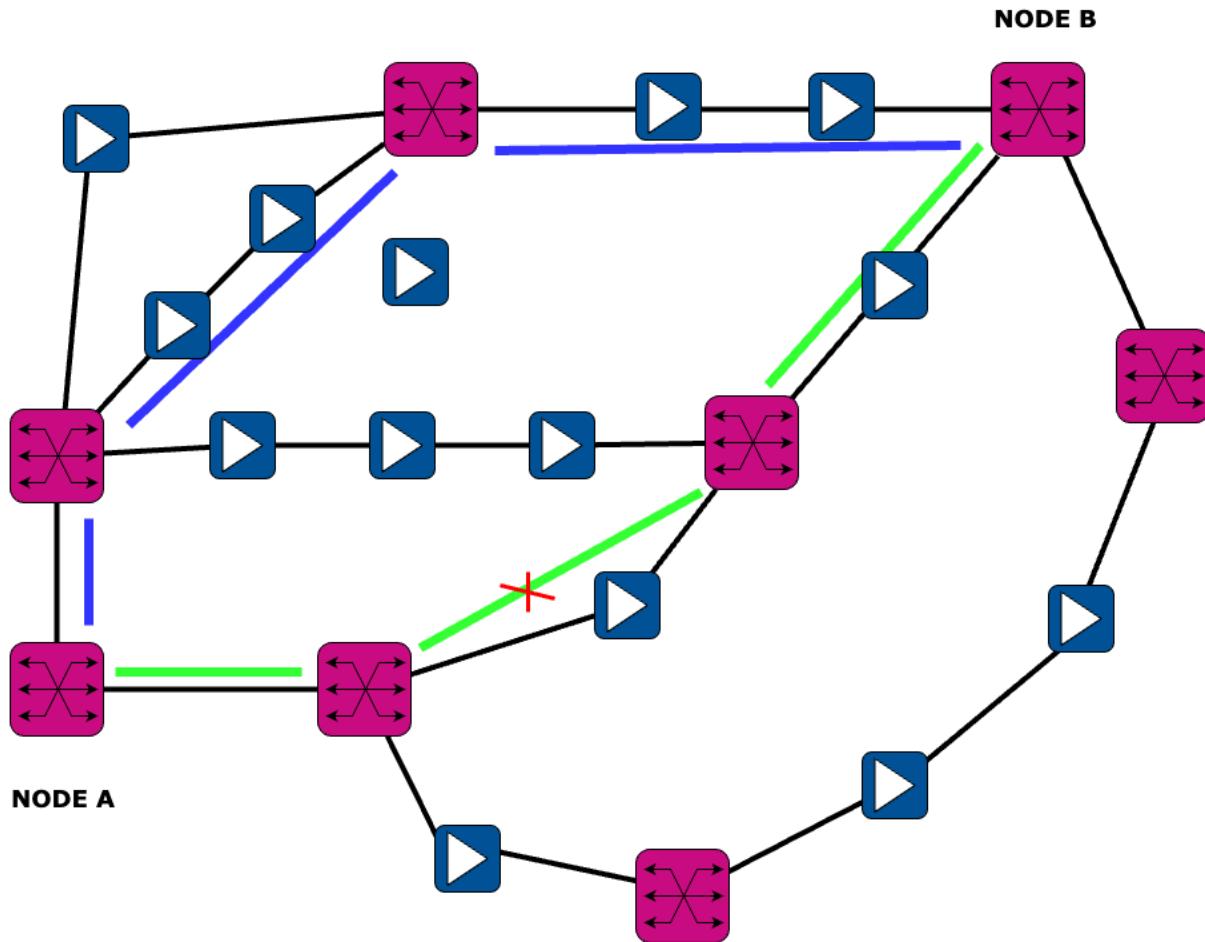
WSS - Heart of ROADM



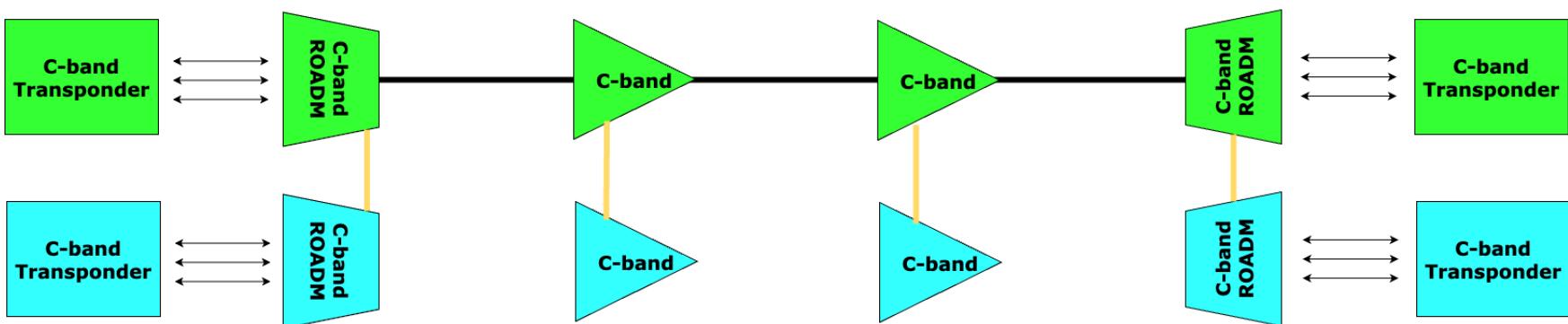
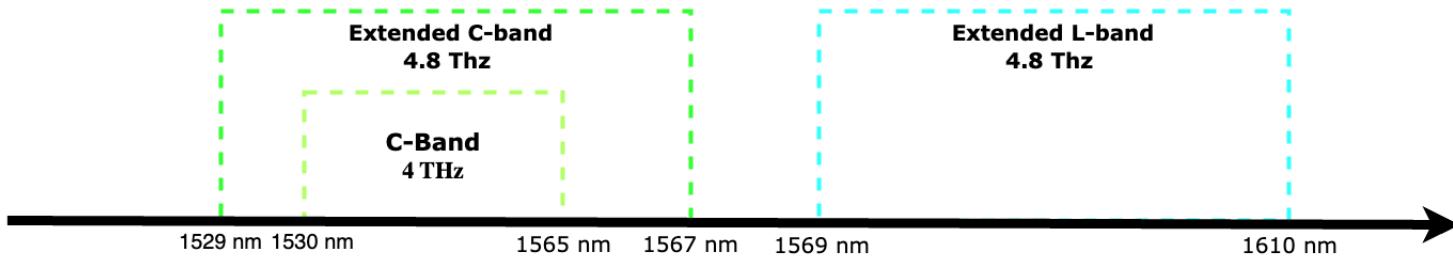
CDC ROADM



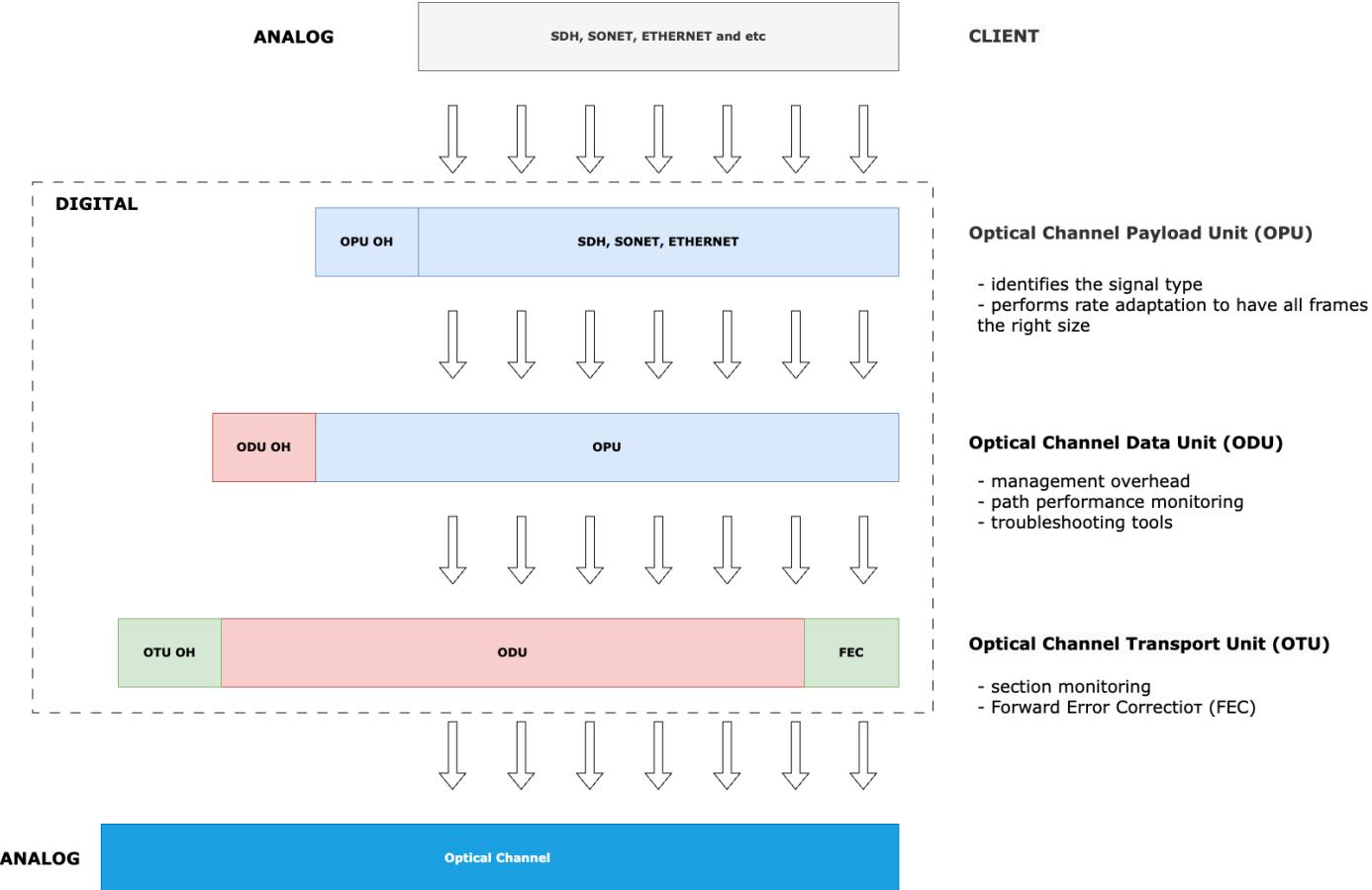
Power of Flexibility

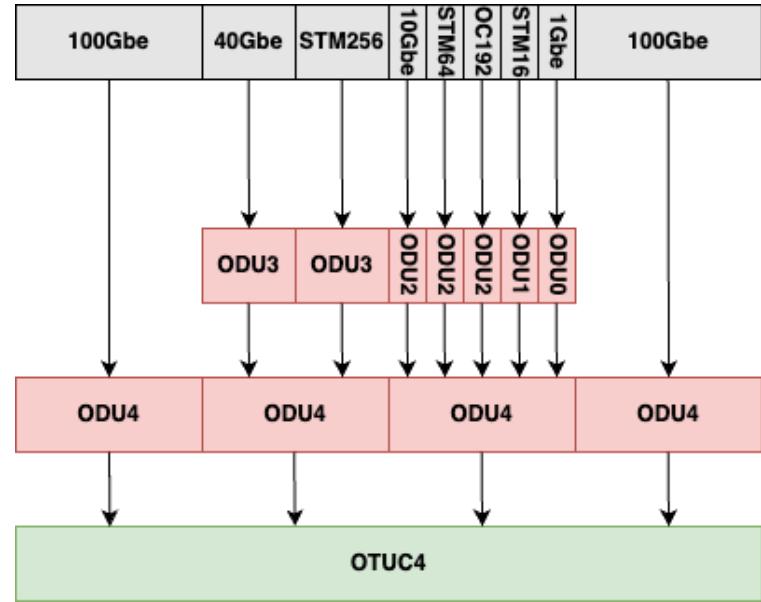
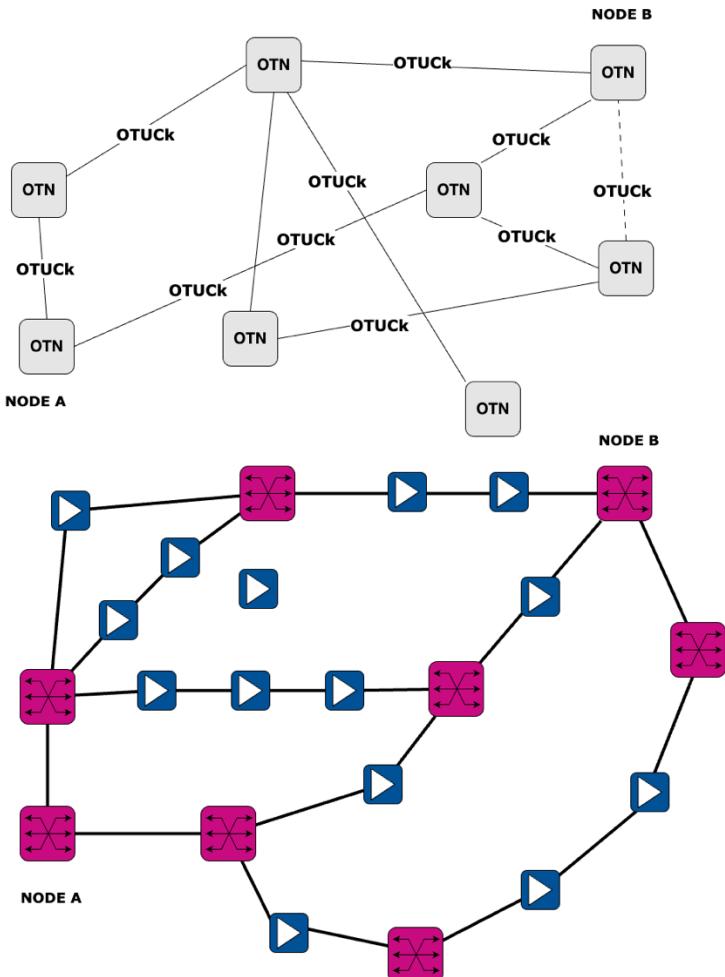


Extended C+L band



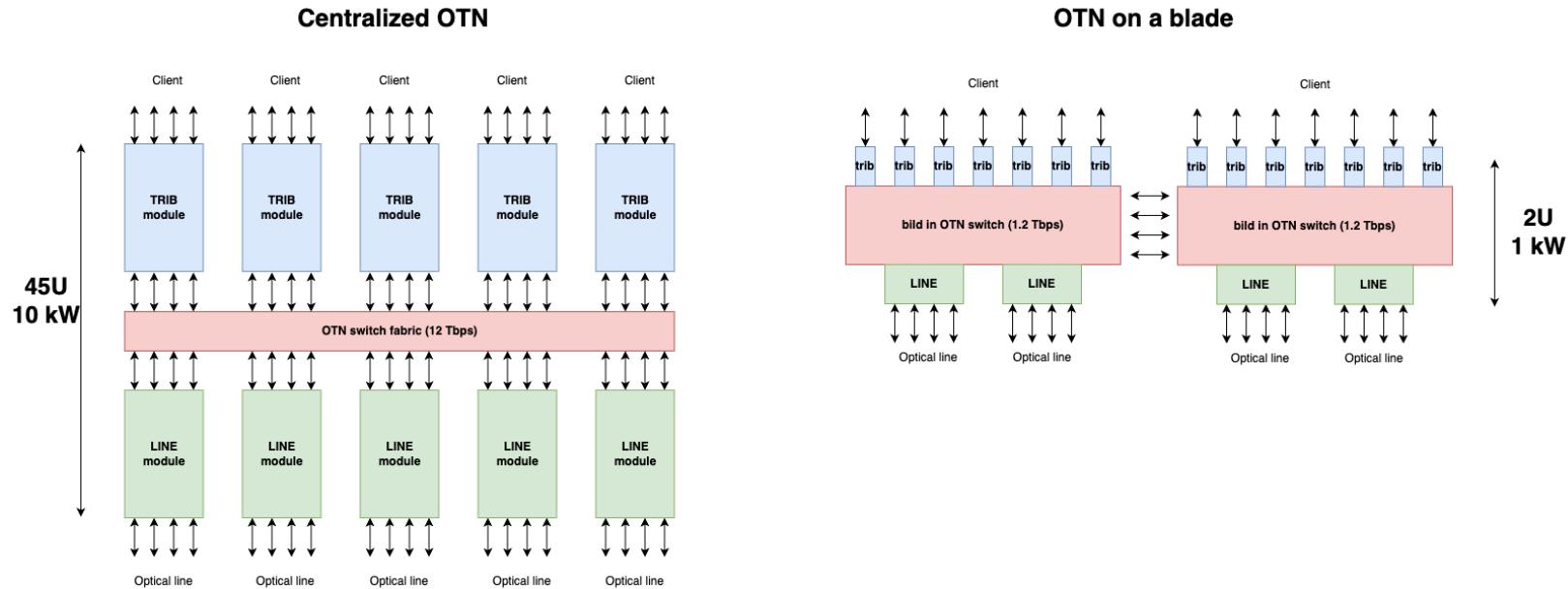
A level above - Optical Transport Network (OTN)



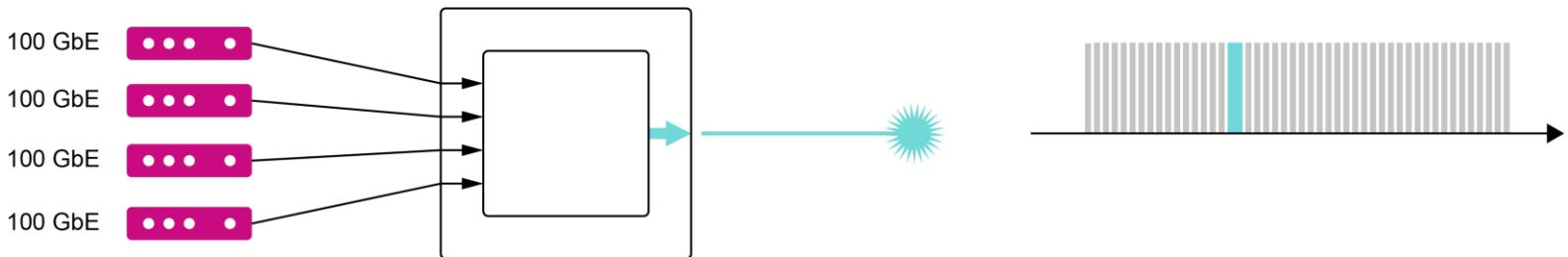


OTU type	ODU Type	OPU Type	Rate	Payload
OTU0	ODU0	OPU0	1.25 Gbps	1Gbe, STM1, STM4
OTU1	ODU1	OPU1	2.5 Gbps	STM16, OC48
OTU2	ODU2	OPU2	10 Gbps	STM64, OC192, 10Gbe
OTU3	ODU3	OPU3	40 Gbps	STM256, OC768, 40Gbe
OTU4	ODU4	OPU4	100 Gbps	100Gbe
OTU _k	$k \times ODU4$	$k \times OPU4$	$k \times 100Gbps$	$k \times 100Gbe$

OTN: shifting to a distributive approach



Transponder



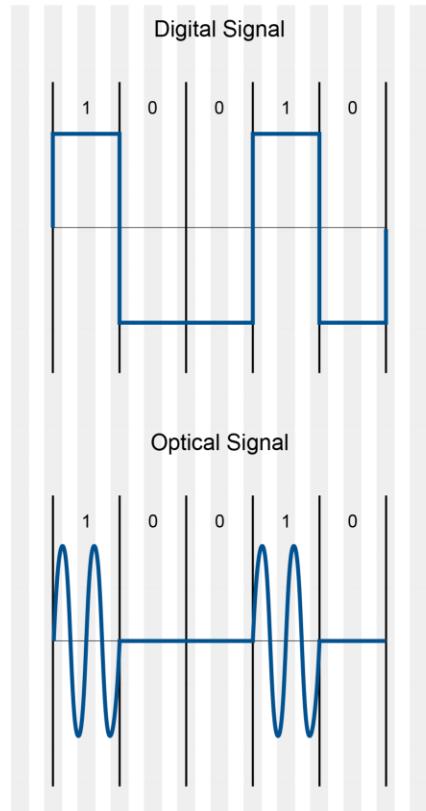
Transponder

Accept client signals
Convert to digital
OTN wrap and FEC
Modulate and Channelize

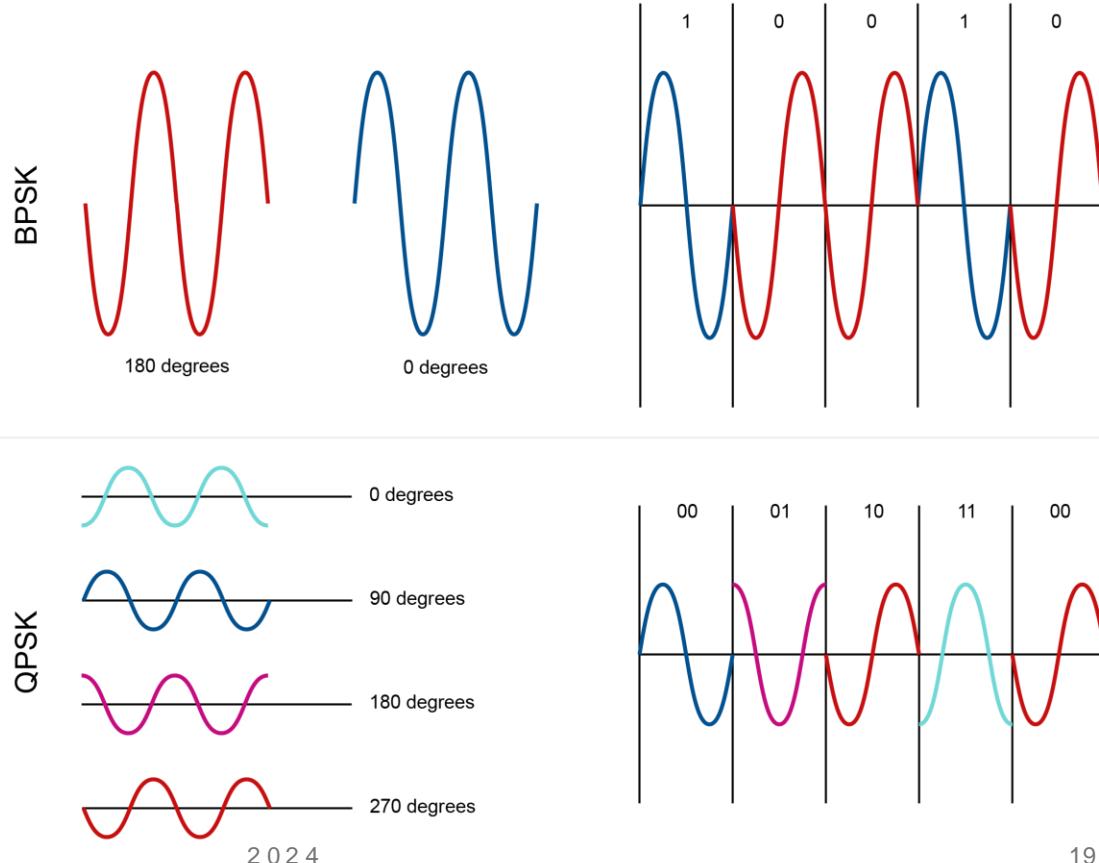
Direct detection for 10G modulation

Coherent detection + Digital Signal Processing for higher order modulations.

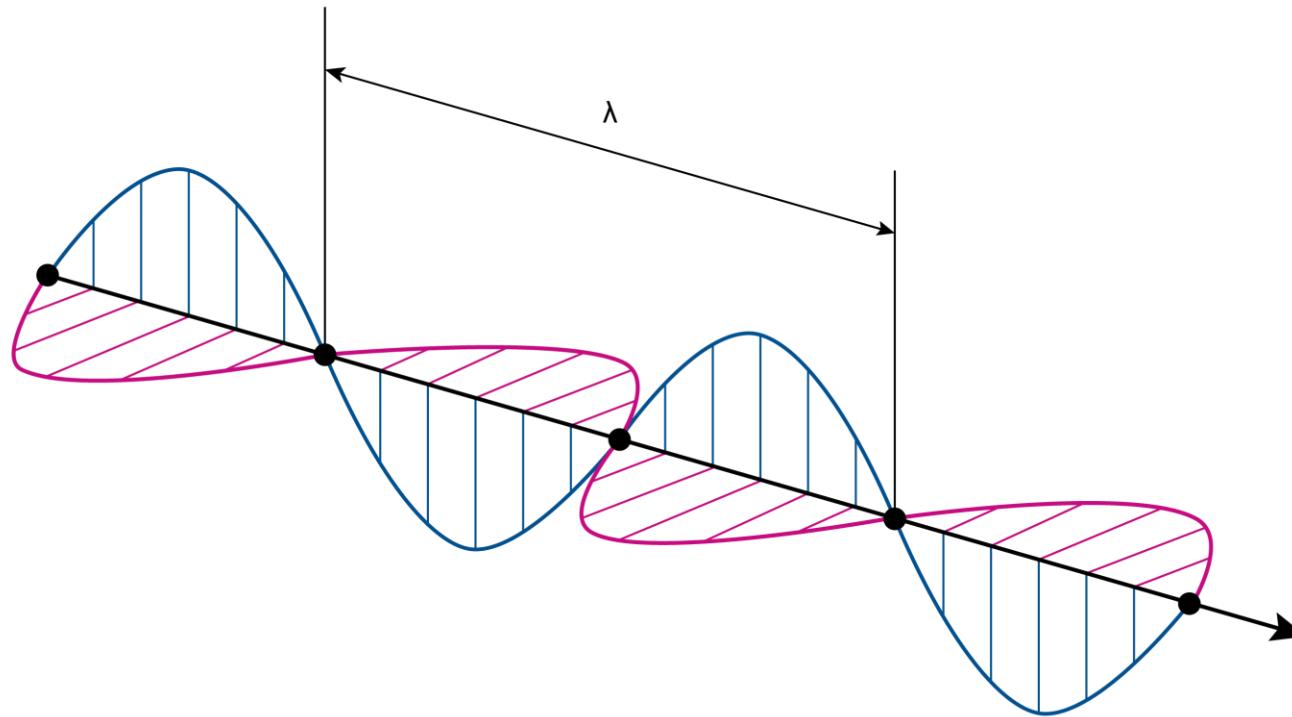
Amplitude Modulation On–Off Keying (OOK)



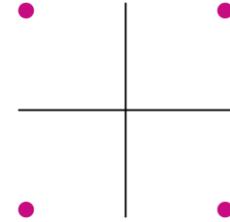
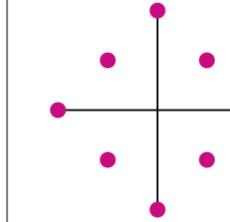
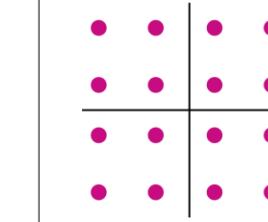
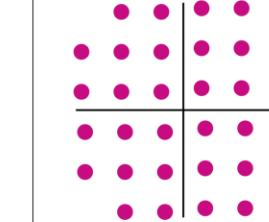
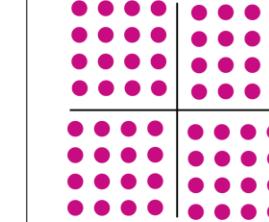
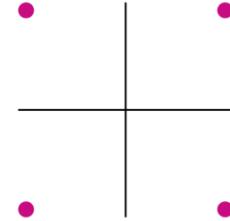
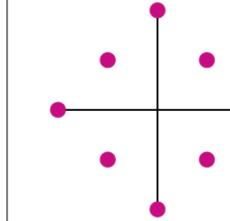
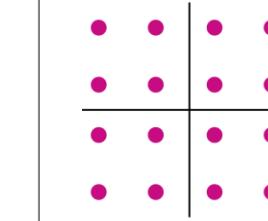
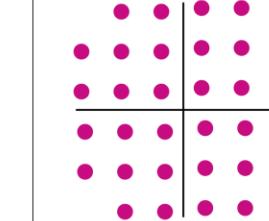
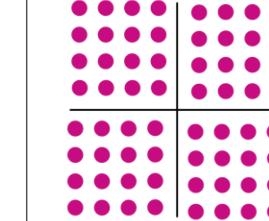
Phase Shift Keying Modulation



Polarization Modulation

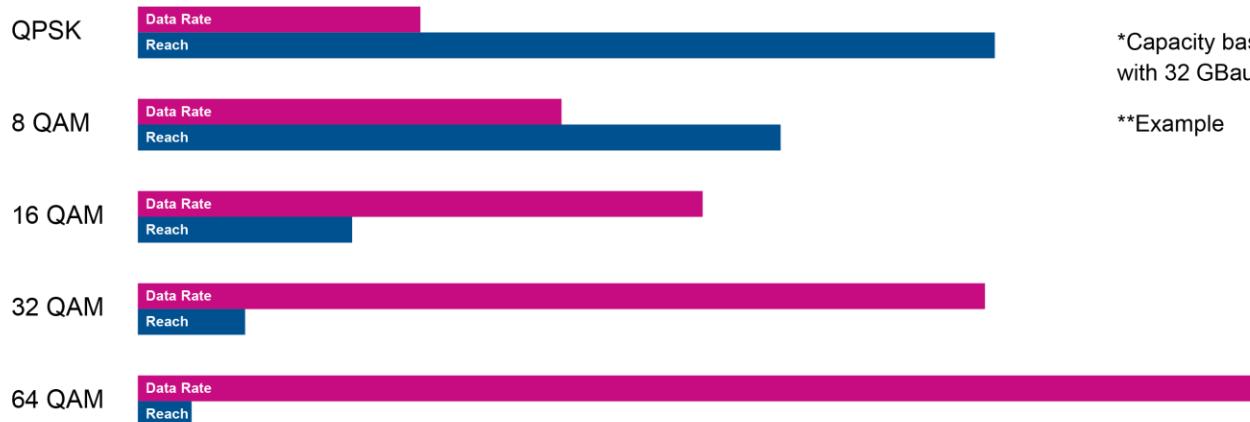


Higher order modulation

	PM-QPSK	PM-8QAM	PM-16QAM	PM-32QAM	PM-64QAM
X-Polarization	2 bits 	3 bits 	4 bits 	5 bits 	6 bits 
	2 bits 	3 bits 	4 bits 	5 bits 	6 bits 
	4 bits/symbol	6 bits/symbol	8 bits/symbol	10 bits/symbol	12 bits/symbol

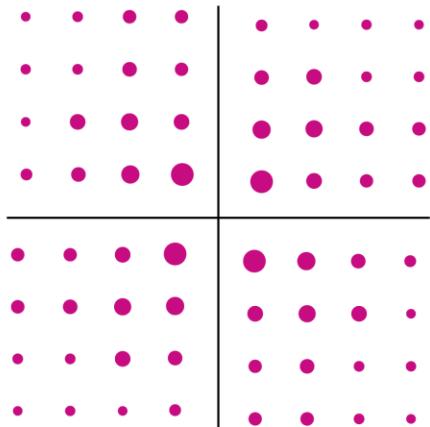
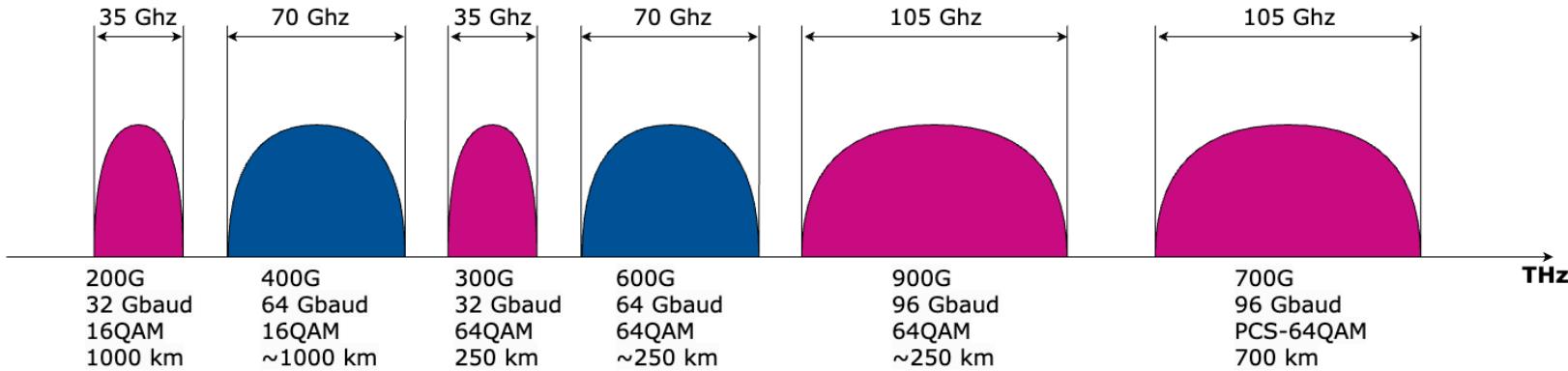
Reach issue: modulation and baud rate

Modulation	Constellation points	Number of bits per polarisation	Bits increase compering to QPSK	Reach reduction compering to QPSK	Capacity*, Gbps	Reach**, km
QPSK	4	2	0.00%	0.00%	100	4000
8 QAM	8	3	50.00%	50.00%	150	2000
16 QAM	16	4	100.00%	75.00%	200	1000
32 QAM	32	5	150.00%	87.50%	250	500
64 QAM	64	6	200.00%	93.75%	300	250



*Capacity based on using x and y polarisations with 32 GBaud rate with 20% FEC

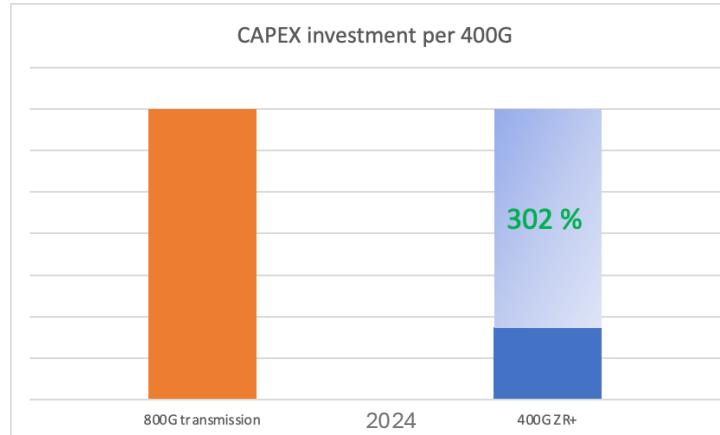
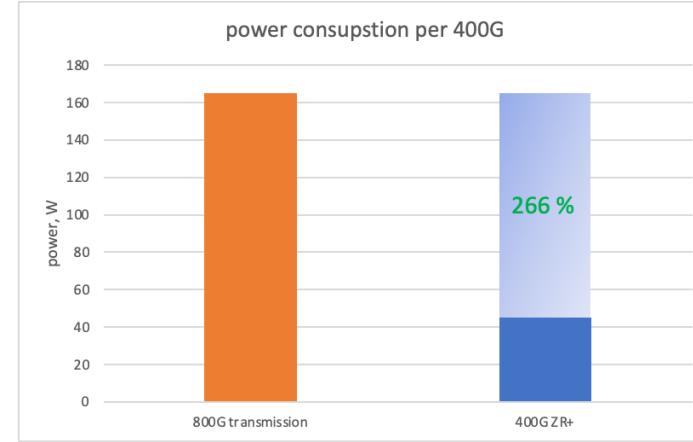
**Example



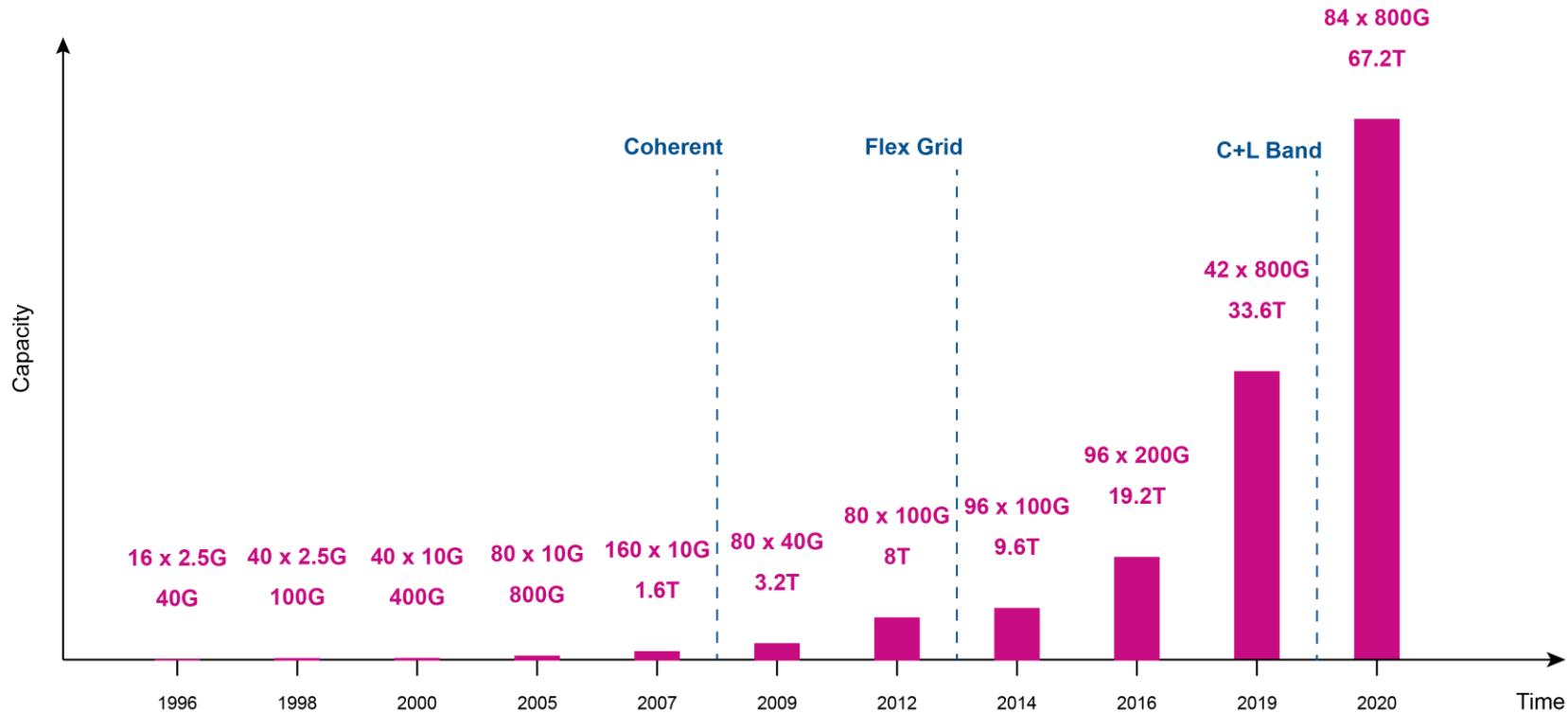
Probabilistic Constellation Shaping

- Granularity
- Reduced Nonlinearities
- Baud Rate Flexibility

Spectral Efficiency vs common sense

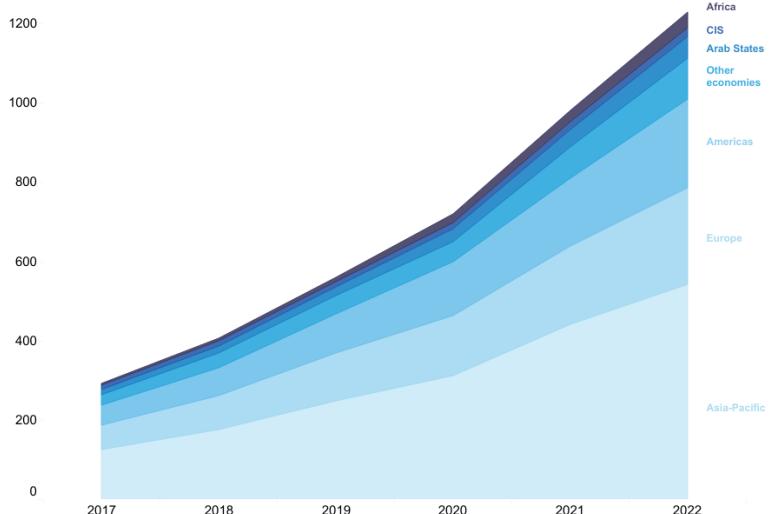


DWDM Capacity over Time

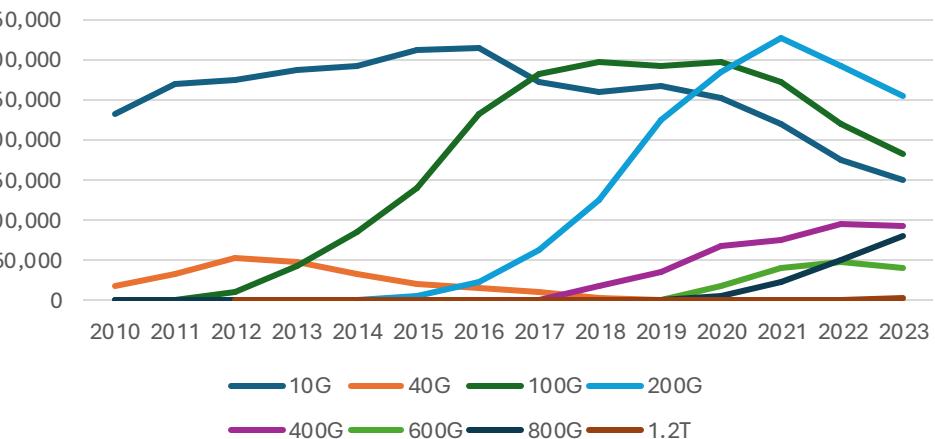


International bandwidth

International bandwidth usage by region, Tbit/s



LINE port rates GLOBAL



Source: Dell'Oro Forecast from 2019 for 10G, July 2024 for 100G-1.2T

Note: 1 Terabit = 1'000'000 Megabit.

Source: ITU

