FLEX-SCALE

Flexibly Scalable Energy Efficient Networking

ROLE OF X-HAUL SUPPORTING THE FUTURE 6G MOBILE NETWORKS: FLEX-SCALE PERSPECTIVE

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www.6G-flexscale.eu

OVERVIEW

- Scope & Consortium of FLEX-SCALE project
- Evolving Network Requirements
  - 6G traffic expectations
  - 6G x-haul requirements
- Main Innovation Areas & KPIs
  - Multi-Tbps transceivers & Multi-Pbps switches
  - SDN Control & streaming telemetry

EC-FUNDED PROJECT FLEX-SCALE: CONSORTIUM

Work programme	HORIZON-JTI-SNS-2022
Programme Topic	STREAM-B-01-03
Type of action	HORIZON-JU-RIA
Project acronym:	FLEX-SCALE
Contact person:	Prof. Ioannis Tomkos (UPAT)
List of participants:	

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CONSORZIO NAZIONALE INTERUNIVERSITARIO PER LE TELECOMUNICAZIONI
CENTRE TECNOLOGIC DE TELECOMUNICACIONS DE CATALUNYA
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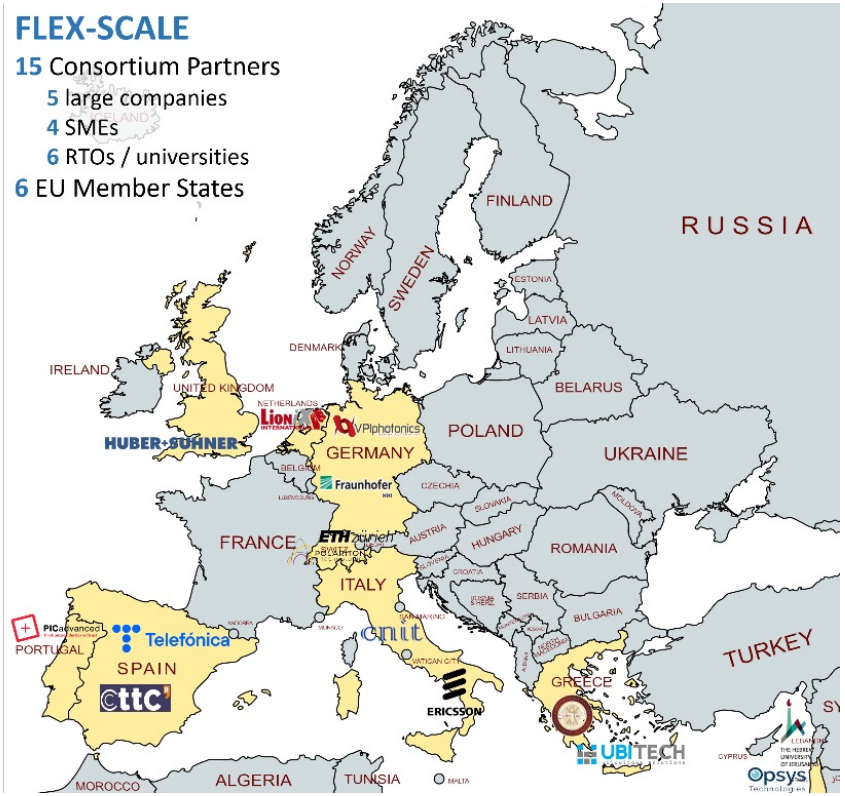
FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
THE HEBREW UNIVERSITY OF JERUSALEM
LIONIX INTERNATIONAL BV
OPSYS SENSING TECHNOLOGIES LTD
PICADVANCED, SA
ERICSSON TELECOMUNICAZIONI SPA
TELEFONICA INVESTIGACION Y DESARROLLO SA
UBITECH
VPIPHOTONICS GMBH
EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH
POLARITON TECHNOLOGIES AG

FLEX-SCALE

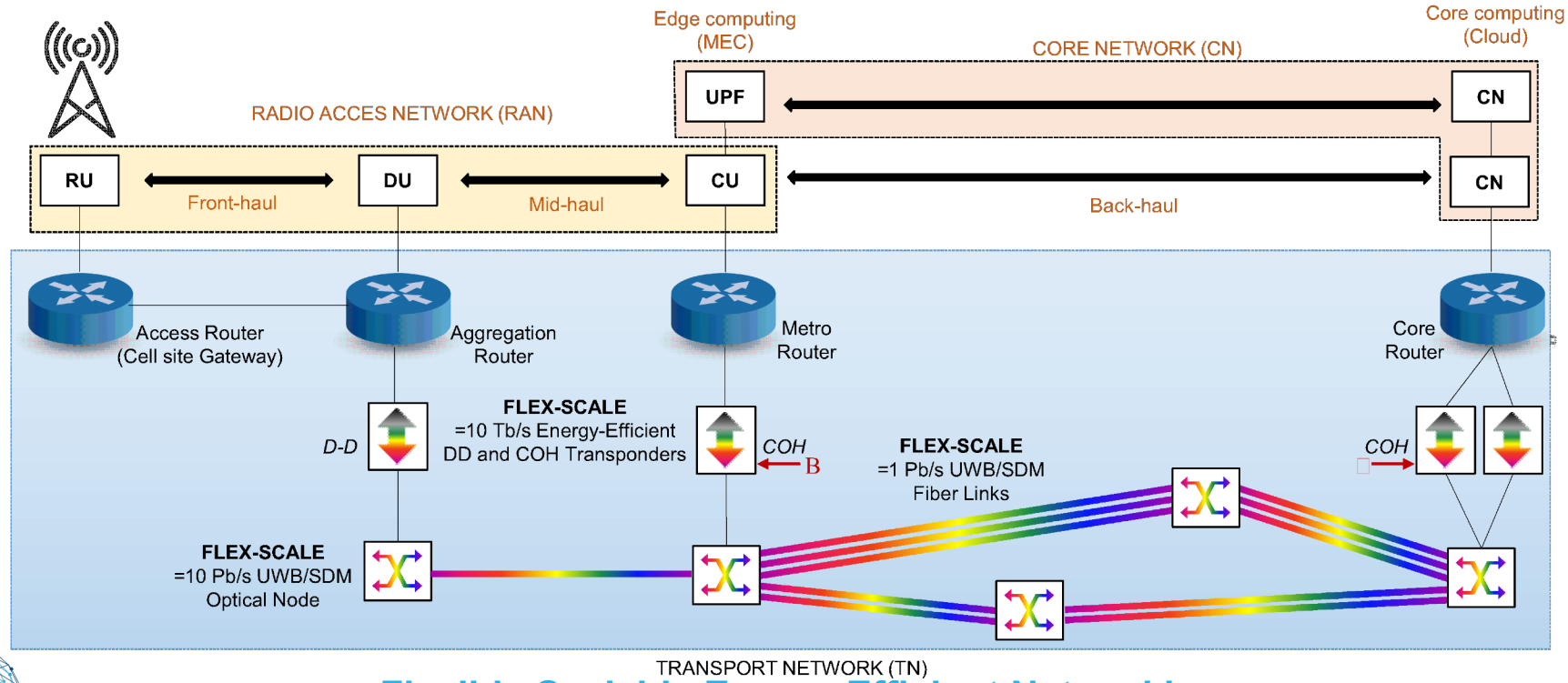
15 Consortium Partners
- **5** large companies
- **4** SMEs
- **6** RTOs / universities

6 EU Member States

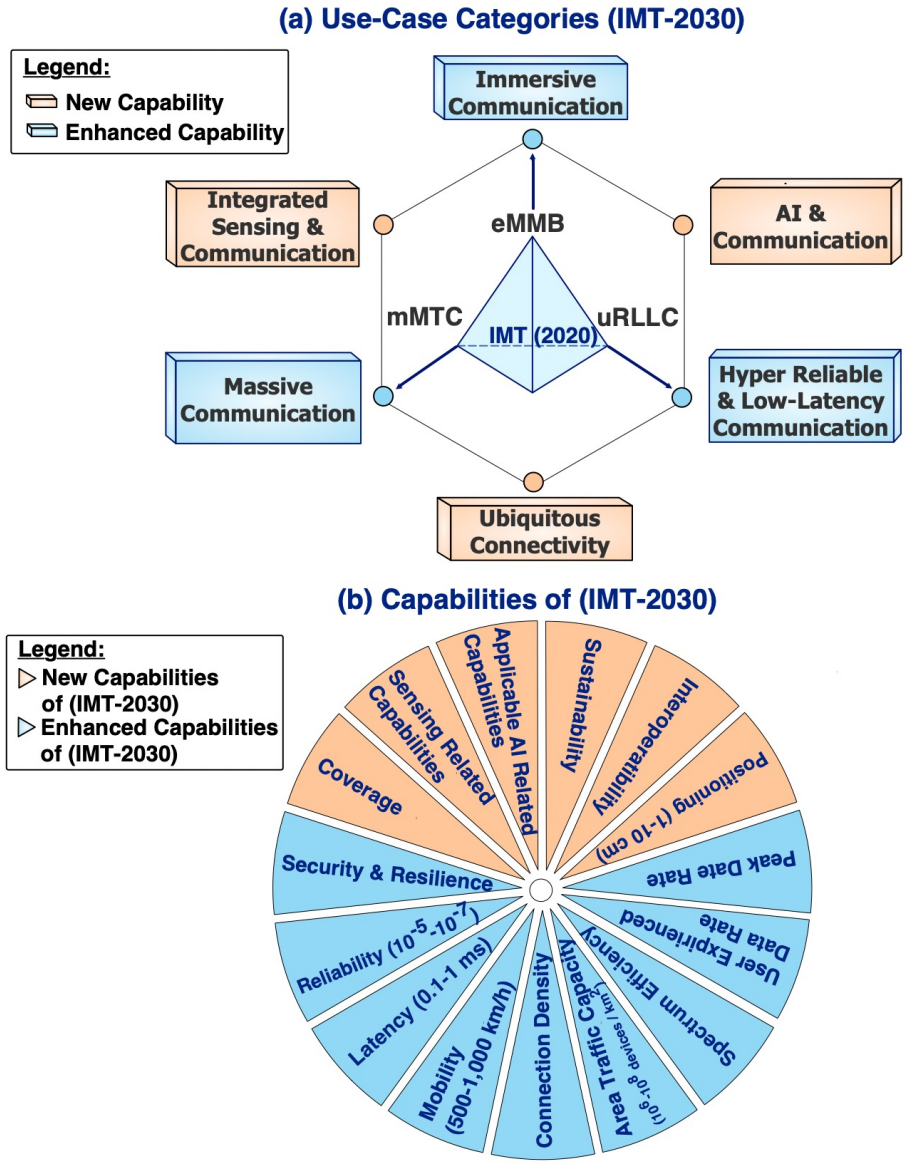


EC-FUNDED PROJECT FLEX-SCALE SCOPE: 6G OPTICAL MID/BACK-HAUL

- FLEX-SCALE consortium develops innovations that will enable flexible capacity scaling of 6G x-haul networks, while ensuring security and reducing costs & energy consumption per packet-flows, by utilizing:
  - Optoelectronic interfaces of line-systems to scale to ≥10 Tb/s,
  - Network link capacities to scale ≥1 Pb/s by utilizing UWB/SDM multiplexing schemes
  - Optical switching node capacities to scale to ~tens Pb/s
  - SDN automation of packet-optical x-haul network operation

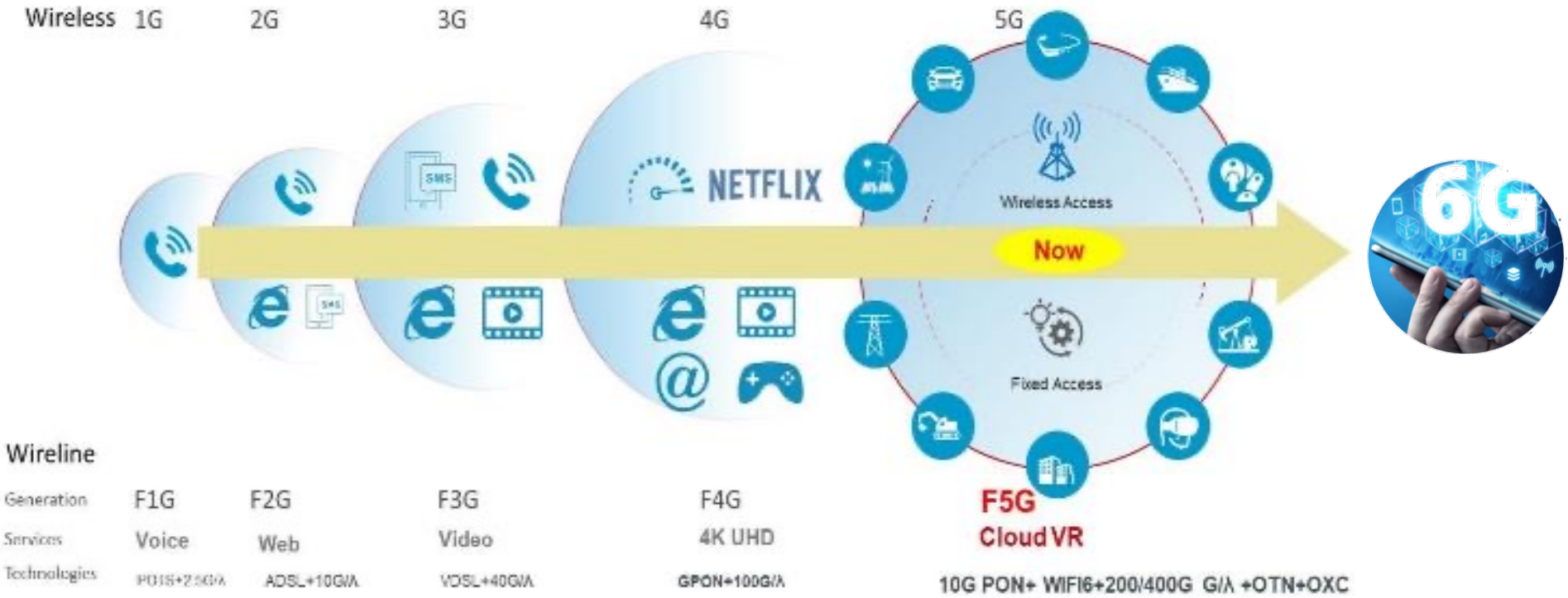


IMT-2023 USE-CASES FAMILIES & CAPABILITIES



- The vision for the upcoming 6G networks, as outlined by ITU-R, defines the overall objectives, capabilities and expected applications of the “International Mobile Telecommunications for 2030” (IMT-2030)
- IMT-2030 encompasses the development of *three new categories of use cases* (Ubiquitous Connectivity, AI and Communication, Integrated Sensing and Communications), together *with three evolved categories from IMT-2020* (eMBB → Immersive Communication, mMTC → Massive Communication, uRLLC → Hyper Reliable & Low-Latency Communication)
- IMT-2030 advances the capabilities specified by IMT-2020 and introduces new capabilities related e.g. with AI & sensing

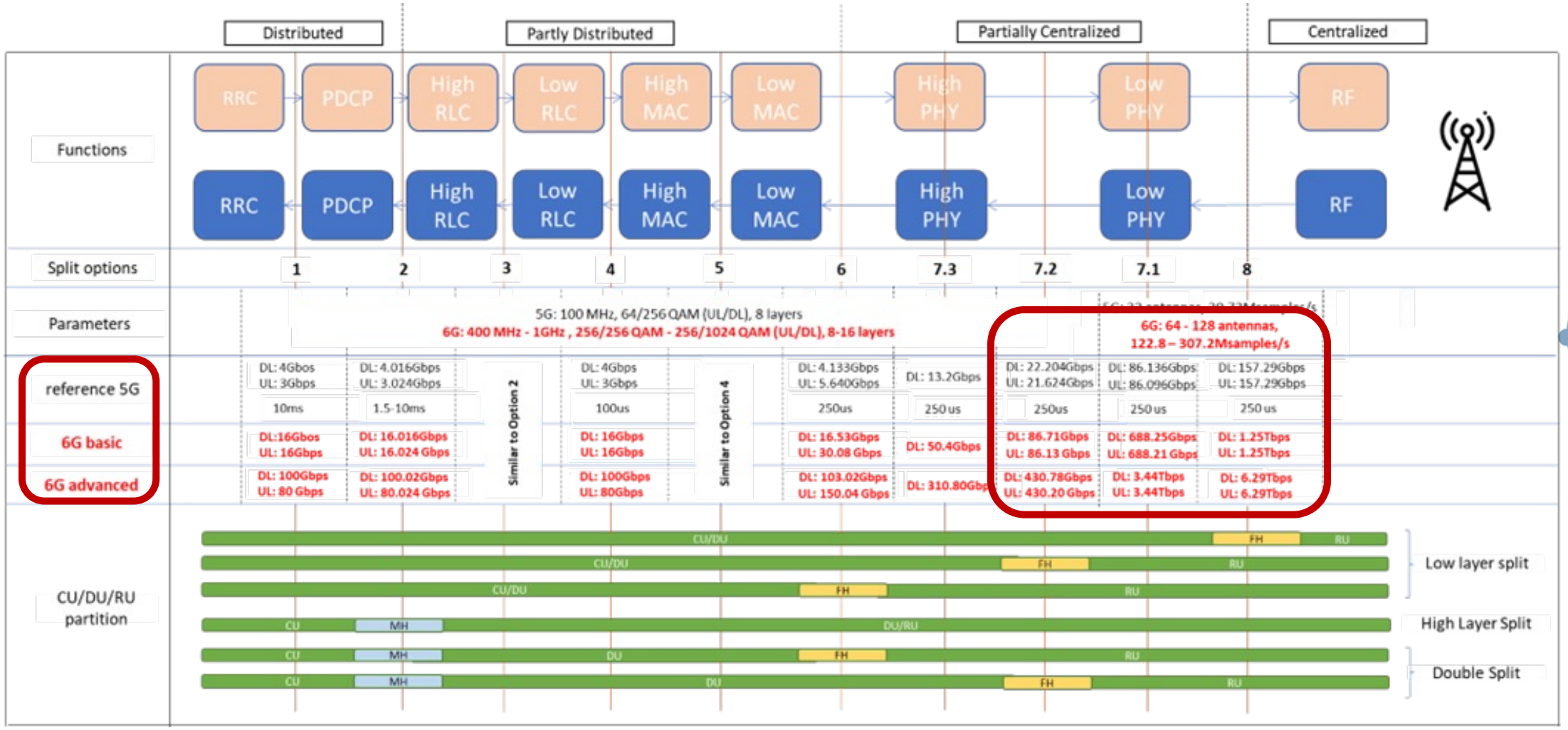
BOTH WIRELESS & FIXED NETWORKS EVOLVE IN PARALLEL AND ARE CONVERGING TOWARDS 6G NETWORKS



- The development of the wireless and wireline telecom generations followed a different path up to the 5th generation *when the two started being closer interrelated*
  - The term "5G" refers to the fifth generation of wireless networks
  - The term "F5G" refers to the fifth generation of wireline networks
- This evolving convergence of fixed/wireless infrastructures, alongside with computing, storage and sensing infrastructures will give rise to "6G" networks

REF: "A Vision of 6th Generation of Fixed Networks (F6G): Challenges and Proposed Directions", D Uzunidis, …, I. Tomkos, 2023

E5G/6G FRONTHAUL NETWORK TRAFFIC



- There are tremendous anticipated future traffic requirements expected to arise due to the emerging new use-cases/applications!

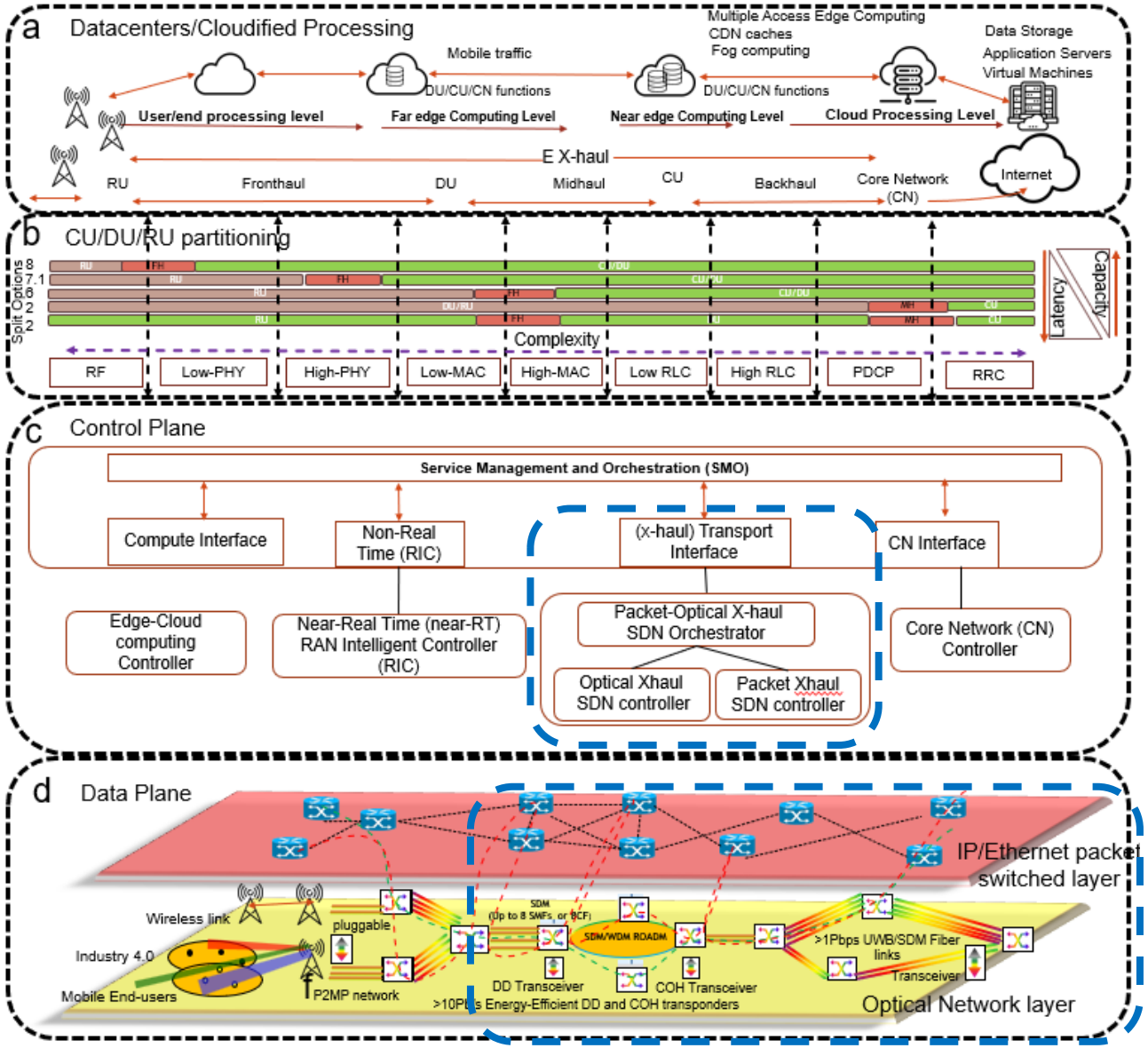
E5G/6G BACKBONE/ACCESS TRANSPORT NETWORK KPIS

FLEX-SCALE targets

	Target KPI	Current (2020)	Short term evo (2025)	Mid-term evo (2028)	Long-term evo (2030)
Metro/Core	Spectrum	5THz	15THz	30THz	50THz
	Port speed	400Gb/s	1.6Tb/s	3.2Tb/s	6.4Tb/s
	Bandwidth	<75GHz	<300GHz	<600GHz	<1200GHz
	Line capacity	25Tb/s	200Tb/s	600Tb/s	1.5Pb/s
	Node capacity	150Tb/s	1.2Tb/s	3.6Pb/s	9Pb/s
Access	PON speeds	10Gb/s	50Gb/s	100Gb/s	>200Gb/s
	User data rate (consumer)	~100Mb/s	~1Gb/s	>2.5Gb/s	>5Gb/s
	User data rate (business)	~1Gb/s	~10Gb/s	>25Gb/s	>50Gb/s
	Latency	< 1 ms	< 0.1 ms	< 0.01 ms	< 0.001 ms
	Power consumption	100% (baseline)	40%	30%	20%
	Service provisioning	Hour	Minute	Second	< Second
	Network operations	Operator controlled, reactive	Intent-based, proactive	Self-diagnosing	Self-optimizing

- Optical transport requirements roadmap developed by EC's NetWorld2020 Strategic Research and Innovation Agenda 2021

FLEX-SCALE DEVELOPS SIGNIFICANT CAPABILITIES FOR THE 6G NETWORKS X-HAUL

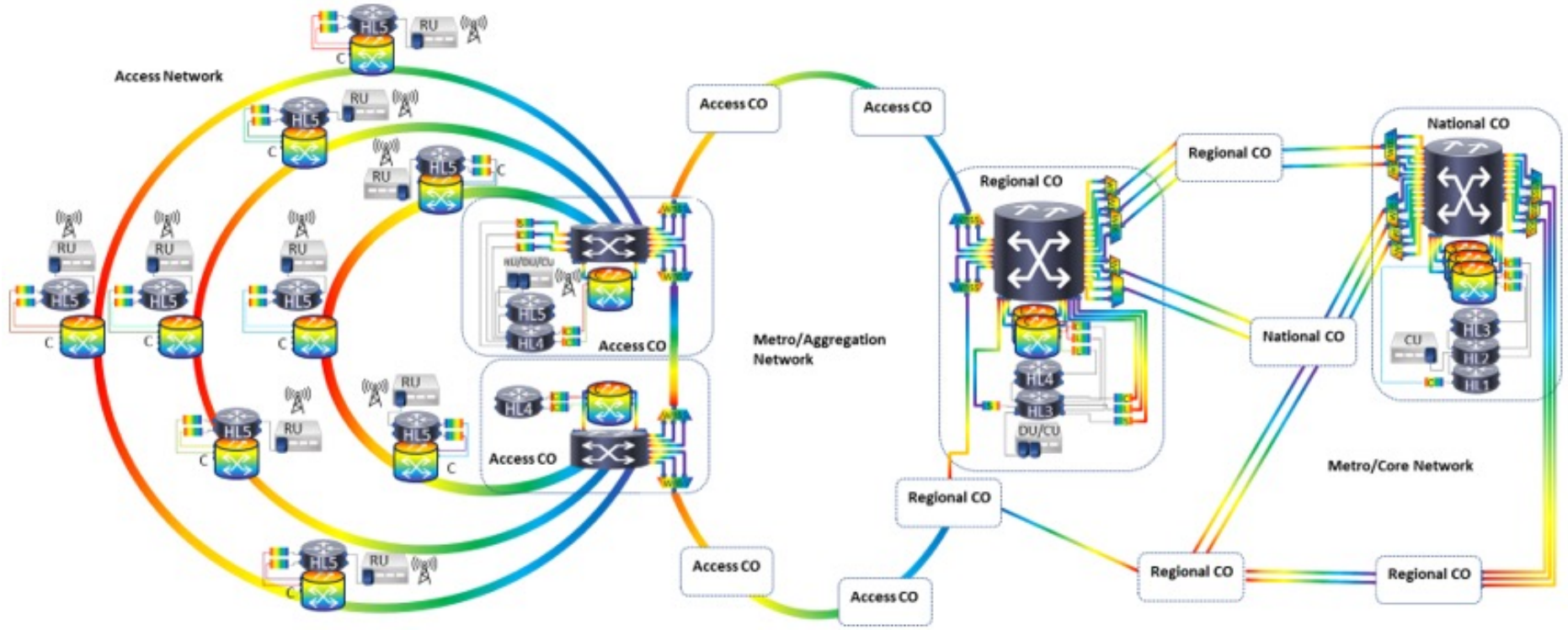


- The 6G networks segments span from the wireless access (radio + optical) to the IP/optical x-haul and the core.
- The desired operation of the network infrastructure is enabled by a number of Network Functions (NFs; VNFs & CNFs) that realize the required intelligent and highly performing connectivity among a myriad of end-user wireless devices.
- The SMO Control and Management & Orchestration planes provides the intelligence to orchestrate the entire network operation, according to the SDN & NFVO concepts.
- NFs should be flexibly deployed across a horizontally disaggregated, cloudified and virtualized optical-wireless network infrastructure consisting of distributed datacenters where computing and signal processing is performed

REF: I. Tomkos et.al., “The X-factor of 6G Networks” IEEE IT Professional Magazine, 2024

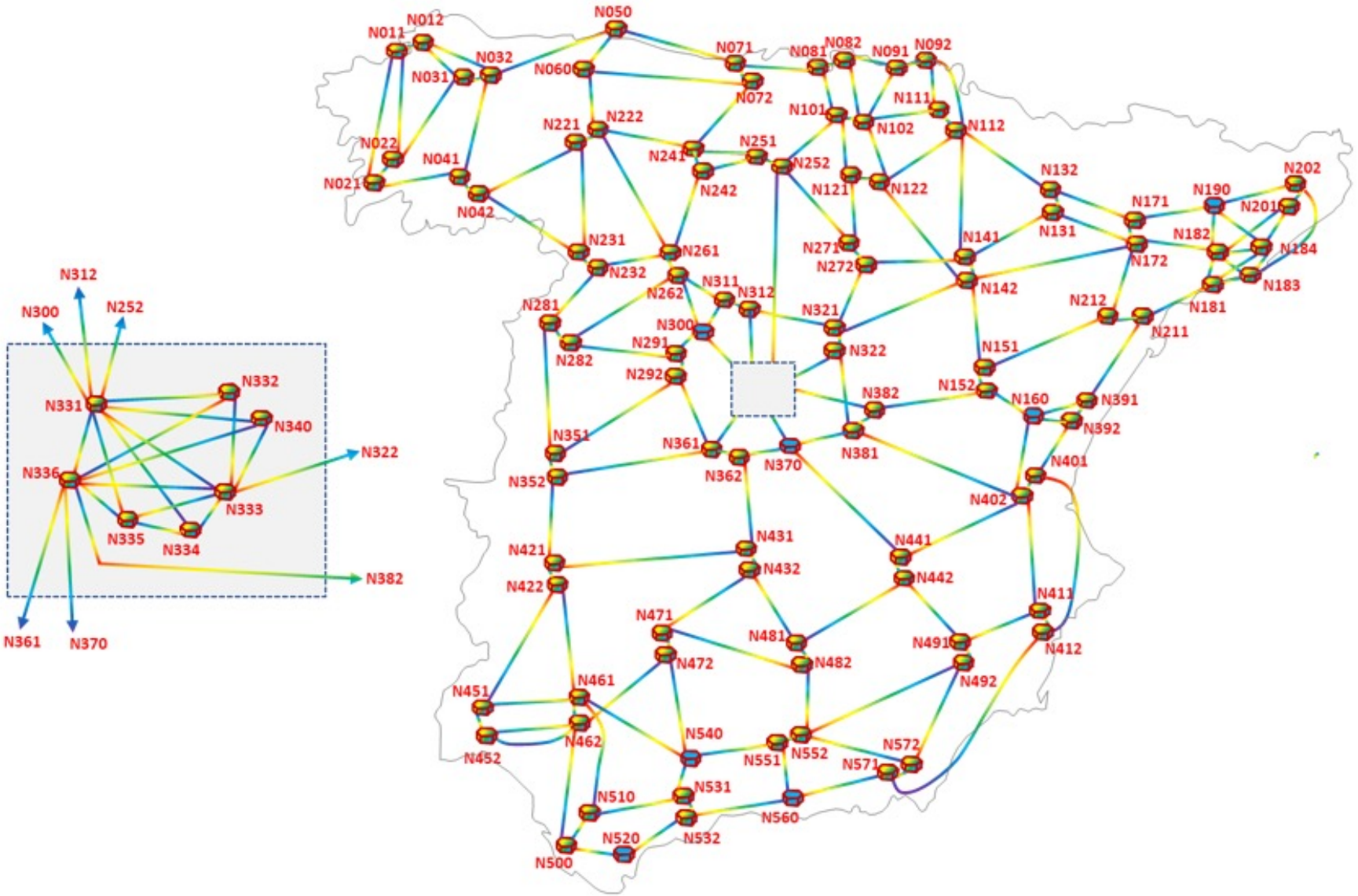
FLEX-SCALE REFERENCE NETWORK ARCHITECTURE

- 6G Traffic aggregation at different network segments



	OXC for full fibre switching		Band transponder
WBSS	Waveband Selective Switch		CPU
	Intraband OXC	BBU	Broadband Baseband Unit
HLx	Router		
S C L	DWDM transponder		
S C L	Band transponder		

NATIONAL REFERENCE NETWORK TOPOLOGY



FLEX-SCALE NETWORK DESIGN – QUESTIONS TO ADDRESS

Questions

Optical Transceiver
What are the main parameters, BoM, cost, power efficiency of the transceiver? What is the key performance metric?

Optical Node
What are the main parameters, BoM, cost, power efficiency of the node? What is the key performance metric?

Network Topology
Will we use one network topology? Will we use realistic parameters, e.g. amplification span distances, traffic matrices?

Fiber Parameters
What are the realistic fiber parameters per λ? Are all fibers the same, e.g. similar parameters?

Network control
What is the additional cost/power consumption posed by the network control operations?

Transceiver parameters | Network Topology | Number of bands, fibers

Node Parameters | Fiber Parameters

Cost | Capacity

Blocking | Energy Consumption

Possible Answers

Optical Transceiver
Power, MF, Baud rate, power consumption, number of elements (e.g. MZMs) ?
EVM, BER, SNR ?

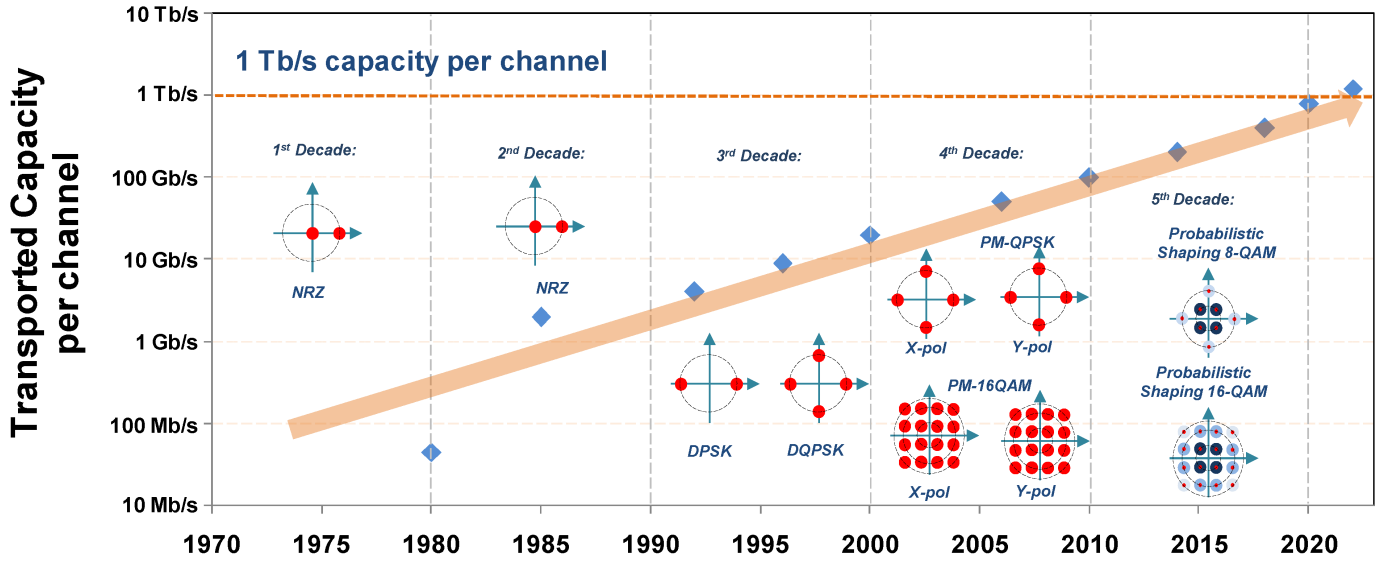
Optical Node
Loss, amplification gain, Impact of filters in terms of Power penalty, … ?

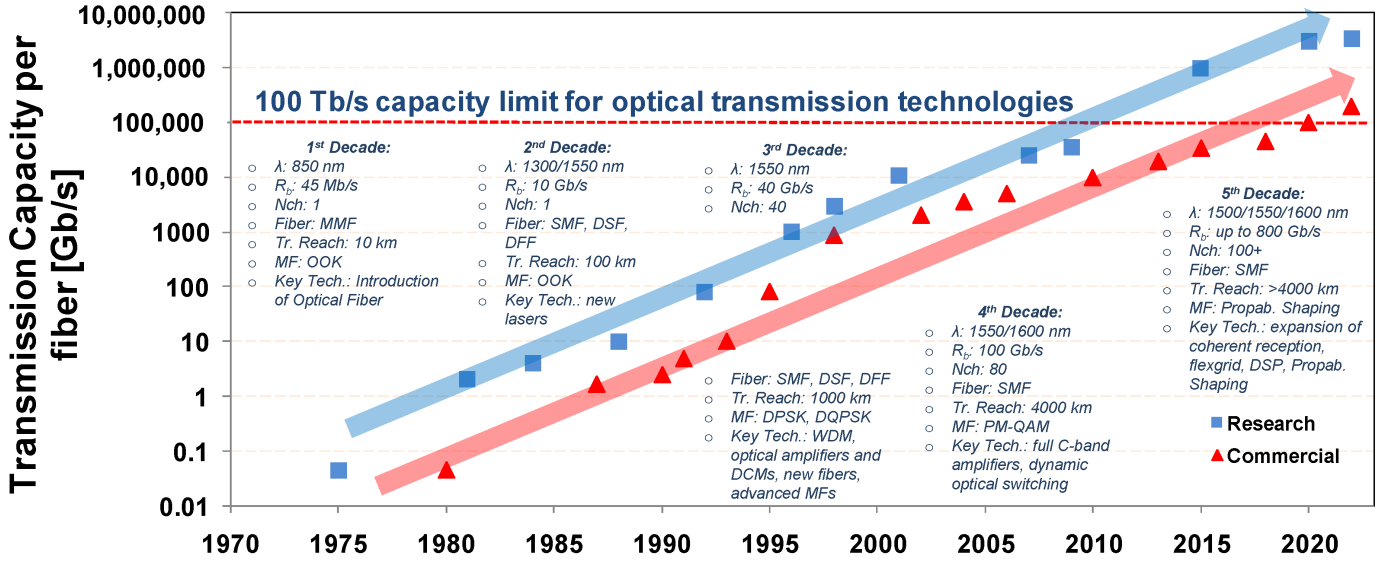
Network Topology
?

Fiber Parameters
?

Network control
?

EVOLUTION OF CAPACITY PER CHANNEL AND PER FIBER

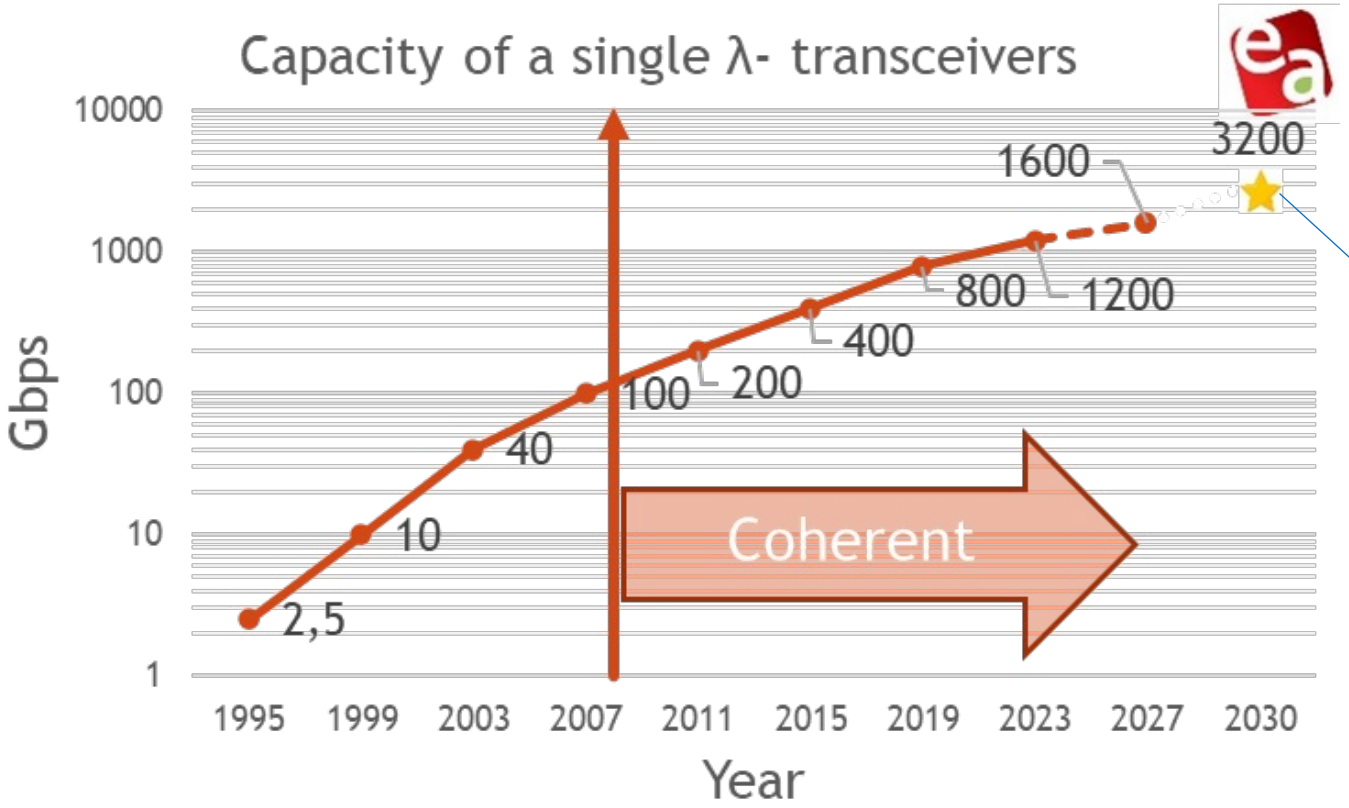




Ref: "Fifty Years of Fixed Optical Networks Evolution: A Survey of Architectural and Technological Developments in a Layered Approach", D Uzunidis, M Logothetis, A Stavdas, D Hillerkuss, I Tomkos; Telecom Journal, 2022

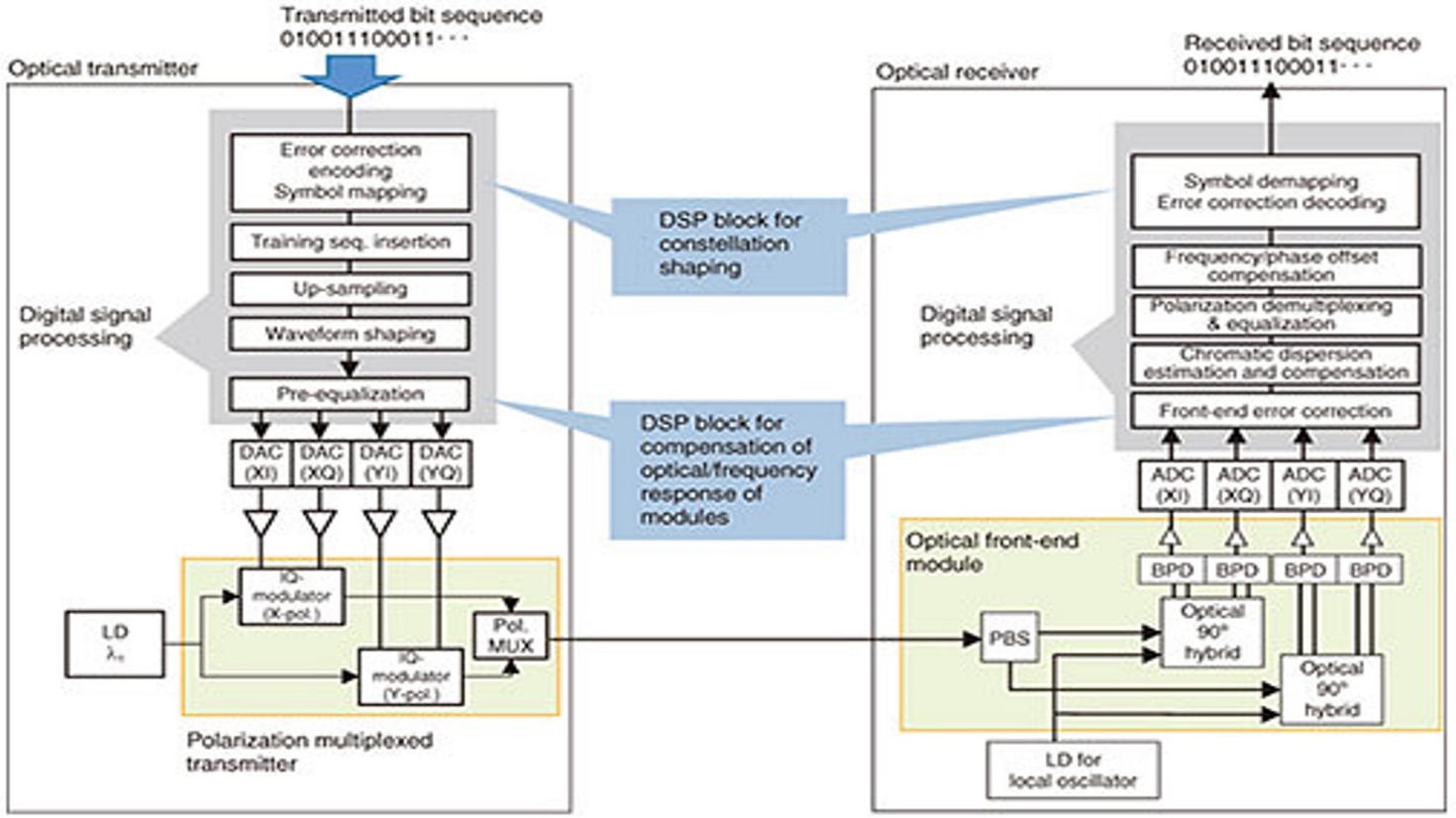
THE "HOLLY-GRAIL" TRX: SINGLE-Λ FIBER I/O TRANSCEIVERS ENABLING 1.6TBPS AND 3.2TBPS

- Utilizing parallelism in the Spectral or/and Spatial domains is an obvious choice to scale the **CAPACITY** of line-systems and networks
- However, the "Holly-Grail" of the Ethernet Alliance and other industrial associations and companies is a single-λ single-fiber I/O TRx that offers the highest capacity
  - New cost/energy-efficient Coherent TRx solutions are sought to support this evolution



A cost/energy efficient and scalable Tx solution is developed by FLEX-SCALE project, offering today 3.2Tbps using commercial components

ISSUES WITH TODAY'S DSP-BASED OPTICAL TRANSCEIVERS (TRX)



ADC: analog-to-digital converter
BPD: balanced photo detector
DAC: digital-to-analog converter

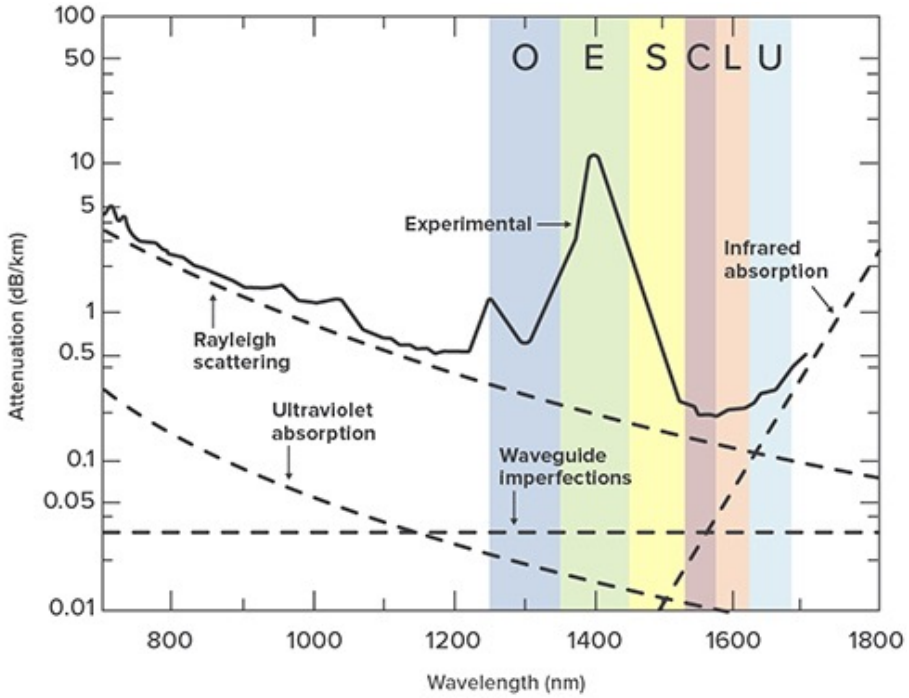
DSP: digital signal processor
IQ: in-phase and quadrature
LD: laser diode

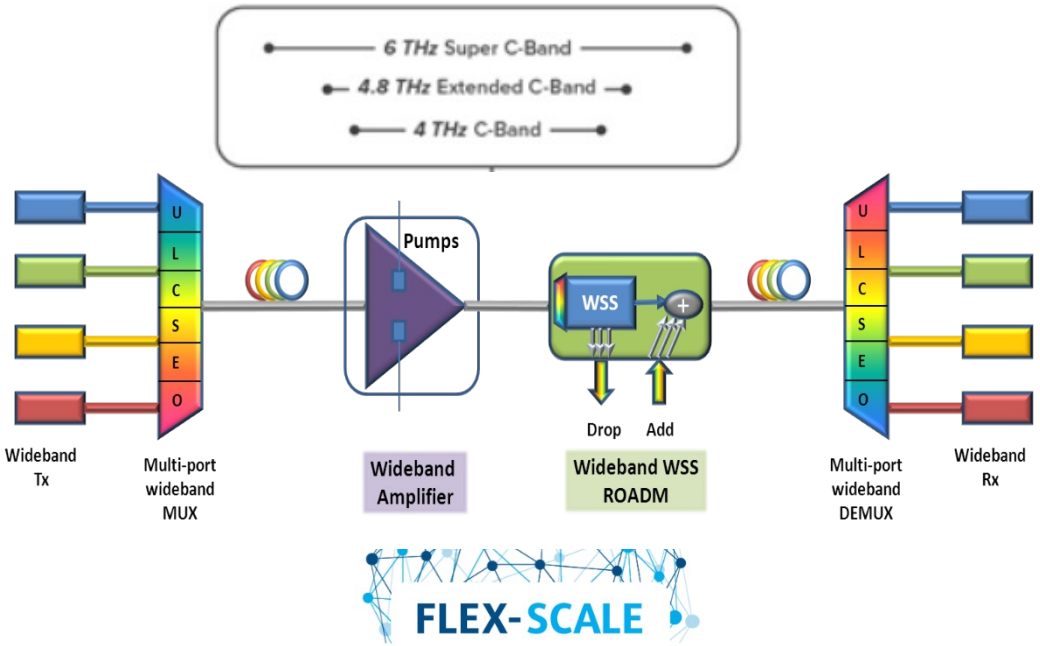
MUX: multiplexer
PBS: polarization beam splitter
Pol.: polarization

- DSP enables tremendous performance improvements by reducing the deleterious impact of optical transmission and switching related impairments, but has also tremendous negative impacts in power consumption and cost
- Some network segments (e.g. access and intra-datacenter) cannot afford the high cost/power per bit and therefore research is focused on simplified coherent systems…

WHAT'S NEXT IN LINE-SYSTEM CAPACITY GROWTH? → UWB

- **Ultra-Wide-band (UWB) WDM** transmission systems promise to multiply the link capacity by a factor of 5-10, compared to extended/super C-band systems and C+L band systems that are commercially available)



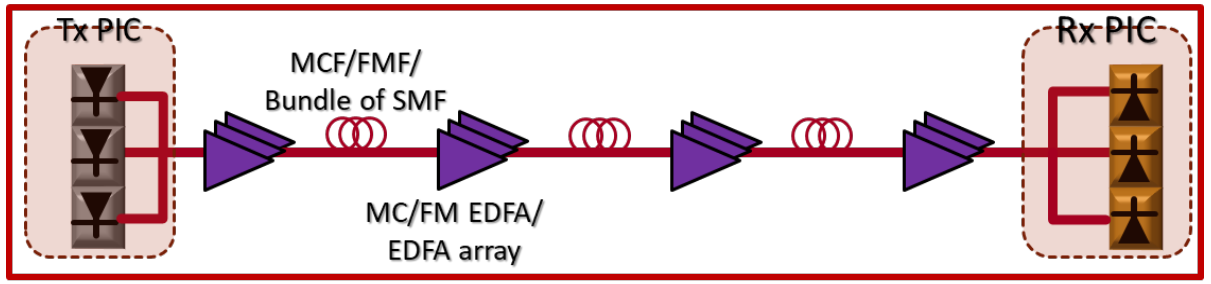


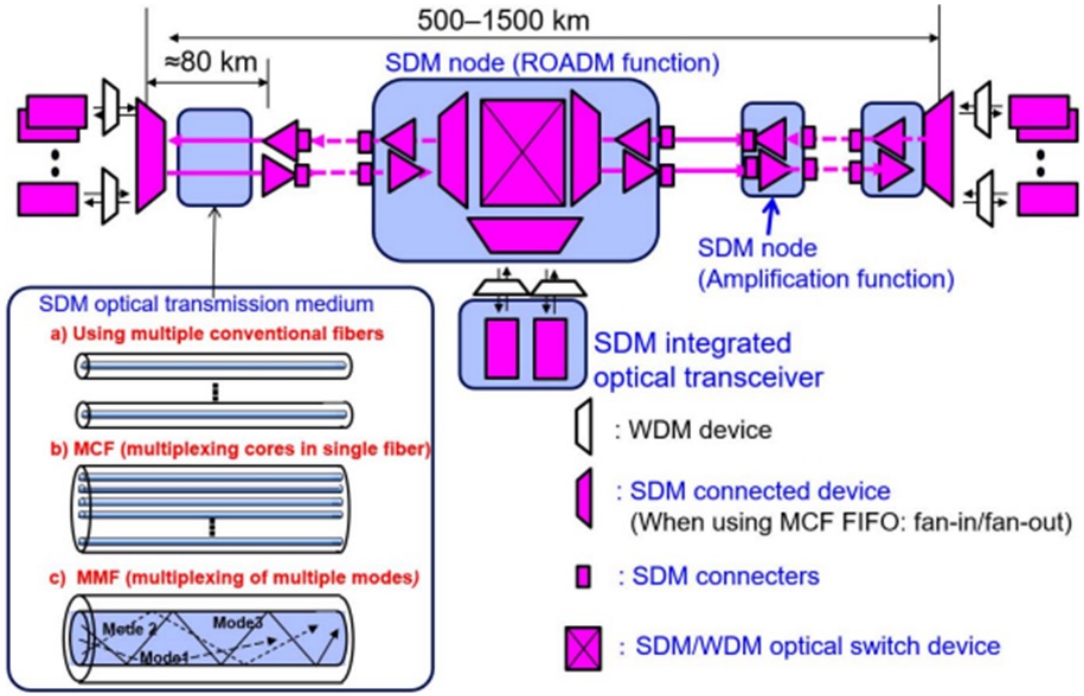
- Developments are required with respect to all system elements in order to enable UWB transmission systems
  - Transceivers
  - Amplifiers/Pumps
  - WSSs/ROADMs

On-going debate: multi-fiber or multi-band systems?
REF: "Investigation of mid-term network migration scenarios comparing multi-band and multi-fiber deployments", B Shariati, PS Khodashenas, JM Rivas-Moscoso, S Ben-Ezra, D Klonidis, I. Tomkos, OFC 2016

WHAT'S NEXT IN LINE-SYSTEM CAPACITY GROWTH? → SDM

- Efficient use of the space-domain requires development of new fibers and components that can support **"space-division-multiplexing" (SDM)**.
  - Essentially integration of parallel systems.





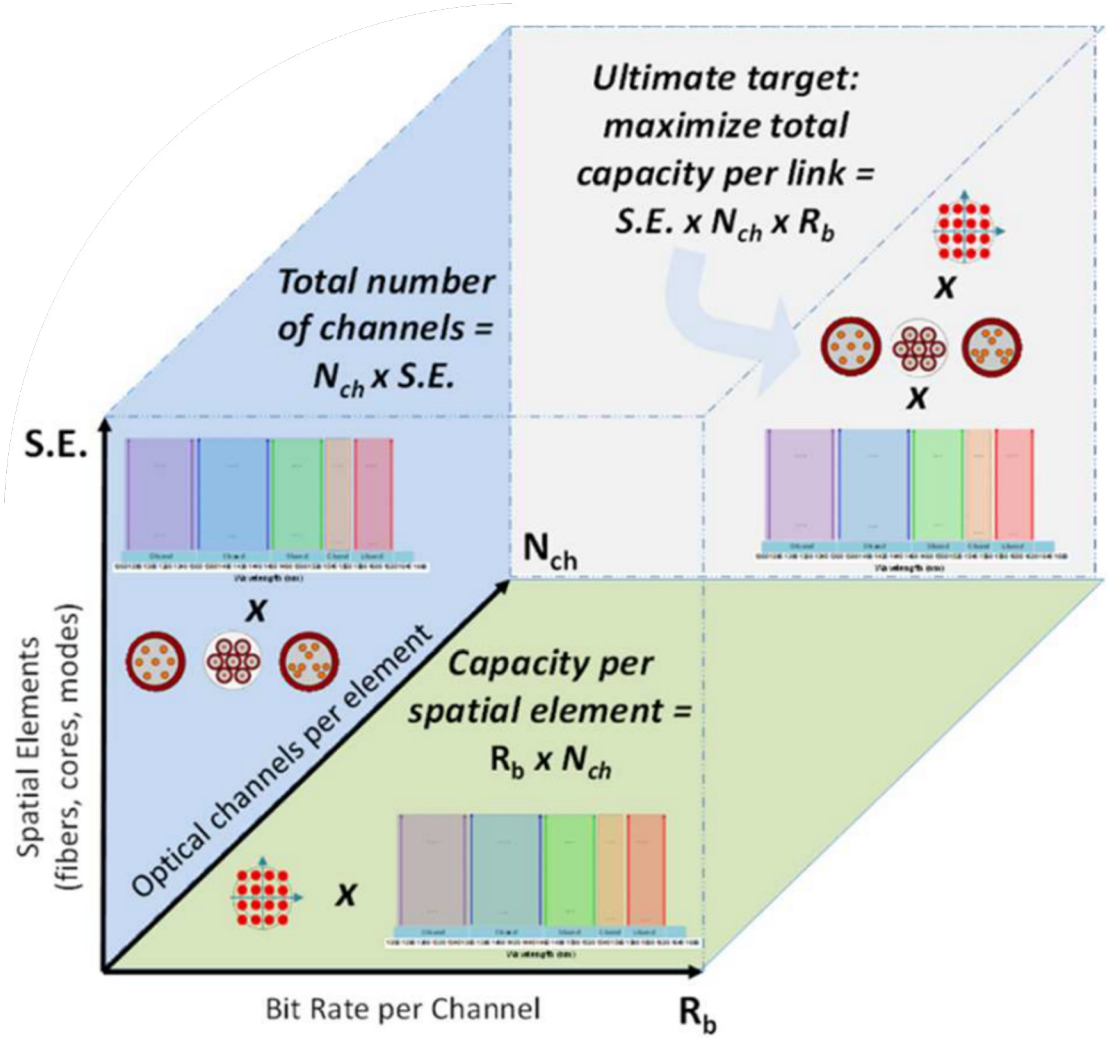
REF: "Optical switching in future fiber-optic networks utilizing spectral and spatial degrees of freedom", DM Marom, Y Miyamoto, DT Neilson, and I Tomkos, Proceedings of the IEEE 110 (11), 1835-1852

FLEX-SCALE INNOVATION AREA-1: SCALING OPTICAL BACK-HAUL VIA SDM & UWB APPROACHES

- In future 6G networks, the required x-haul link capacities and switching nodes throughput are expected to exceed in the future 10 Pbit/s and 100 Pbit/s, respectively.

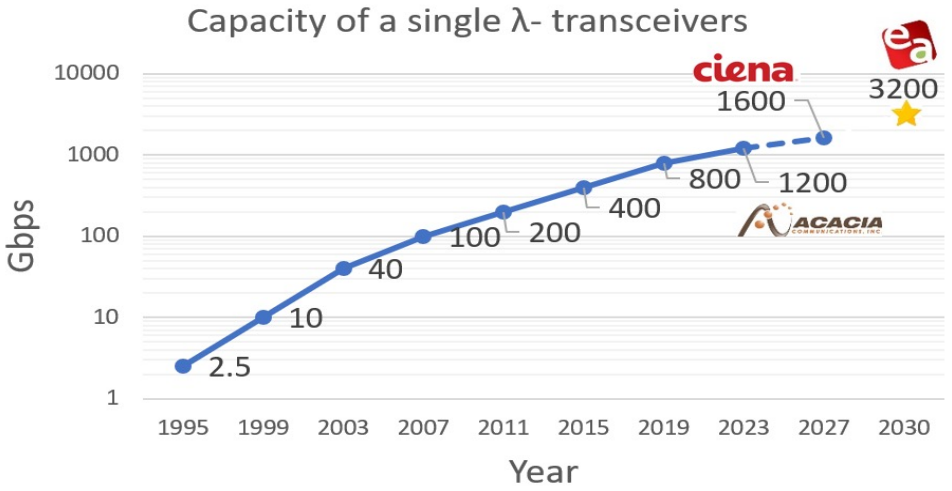
- Novel UWB and SDM multiplexing approaches are promising approaches to scale not only the total system capacity, but also the optical network node throughput.

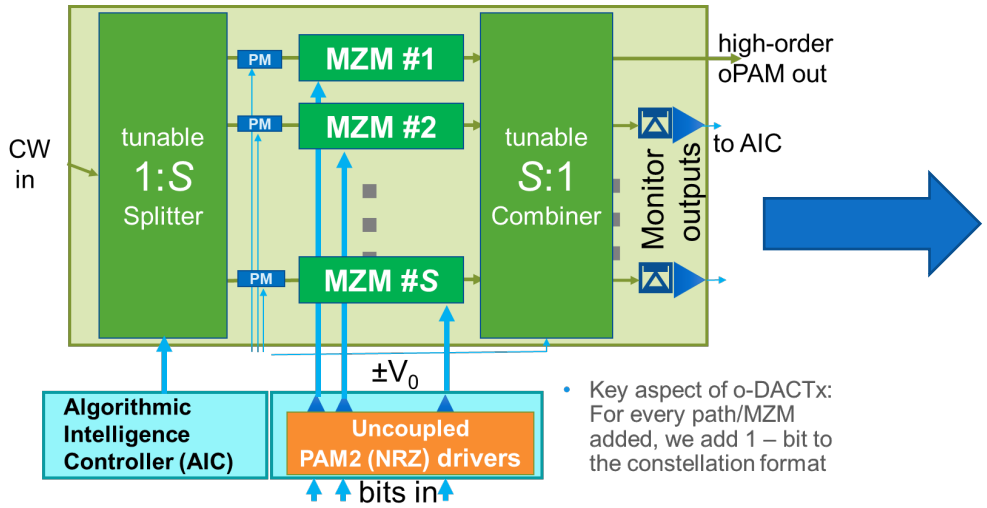
- **FLEX SCALE** utilizes novel transmission and switching related innovations relying on UWB/SDM to efficiently utilize all available capacity scaling approaches, while also contributing to significant reductions in the power consumption of the entire network.



FLEX-SCALE INNOVATION AREA-2: ULTRA-HIGH-SPEED, ENERGY-EFFICIENT, FLEXIBLY PROGRAMMABLE TRANSCEIVERS

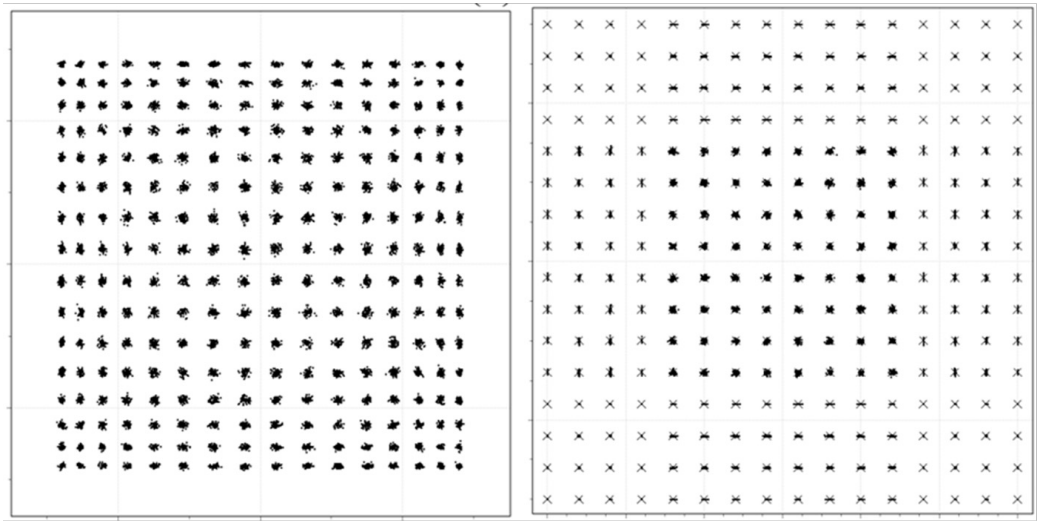
- FLEX-SCALE targets to achieve the next generation transceivers characteristics (beyond 1.6Tbps)
- This transmitter architecture can realize with today's commercially available electronics/photonics components (MZMs & PAM drivers), bit-rate scalability at multiples of what the conventional/alternative approaches can offer
- It can offer today 1.6Tbps with PAM-2/4 electronic drivers while it achieves high energy-efficiency per bit and enormous improvements in EVM.





- Key aspect of o-DACTx: For every path/MZM added, we add 1 – bit to the constellation format

256-QAM constellations



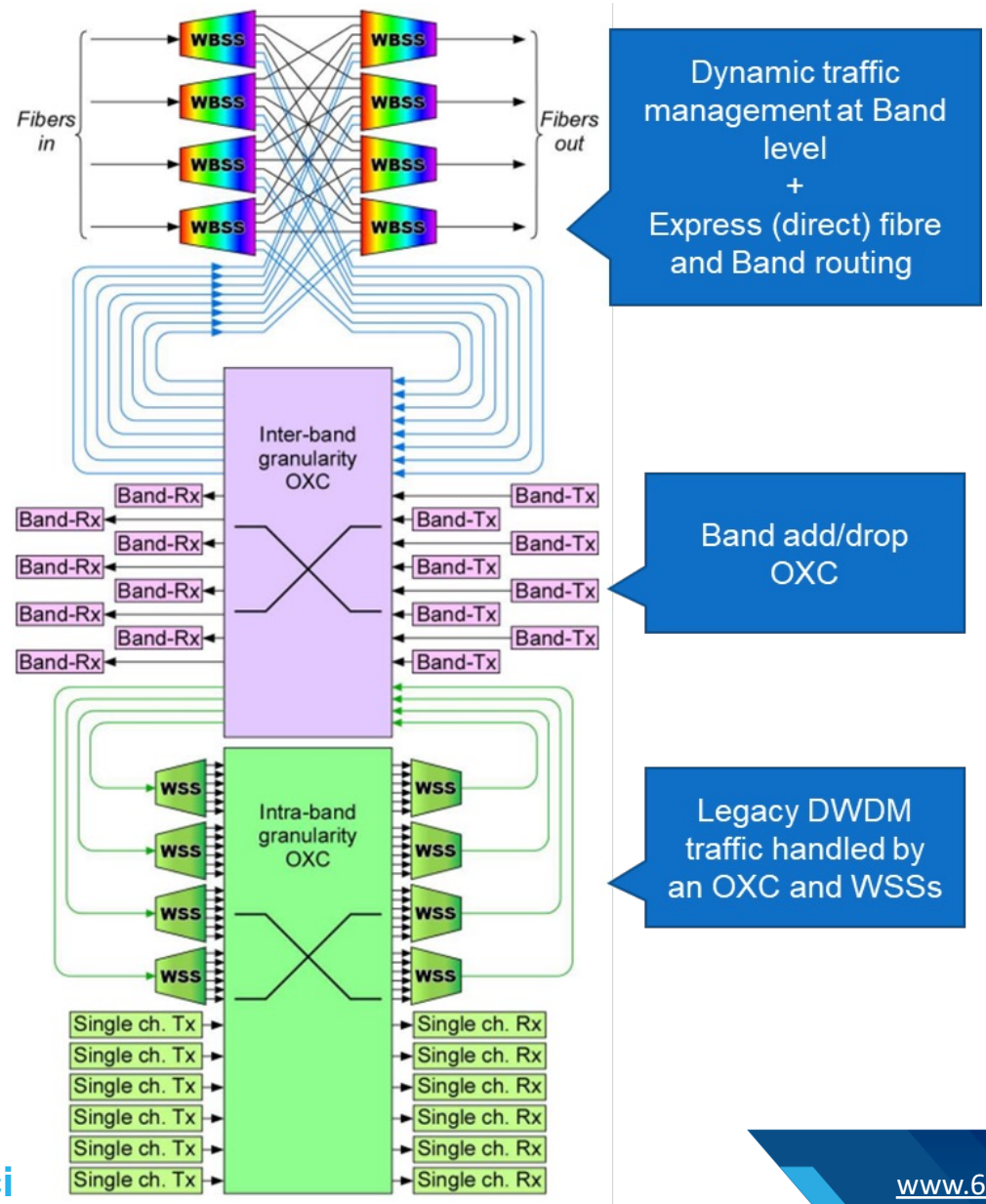
Conventional Tx vs o-DAC based Tx

REF: "Accurate power-efficient format-scalable multi-parallel optical digital-to-analogue conversion", M Nazarathy, I Tomkos, Photonics, 2021

FLEX-SCALE INNOVATION AREA-3: MULTI-GRANULAR OPTICAL NODE ARCHITECTURE

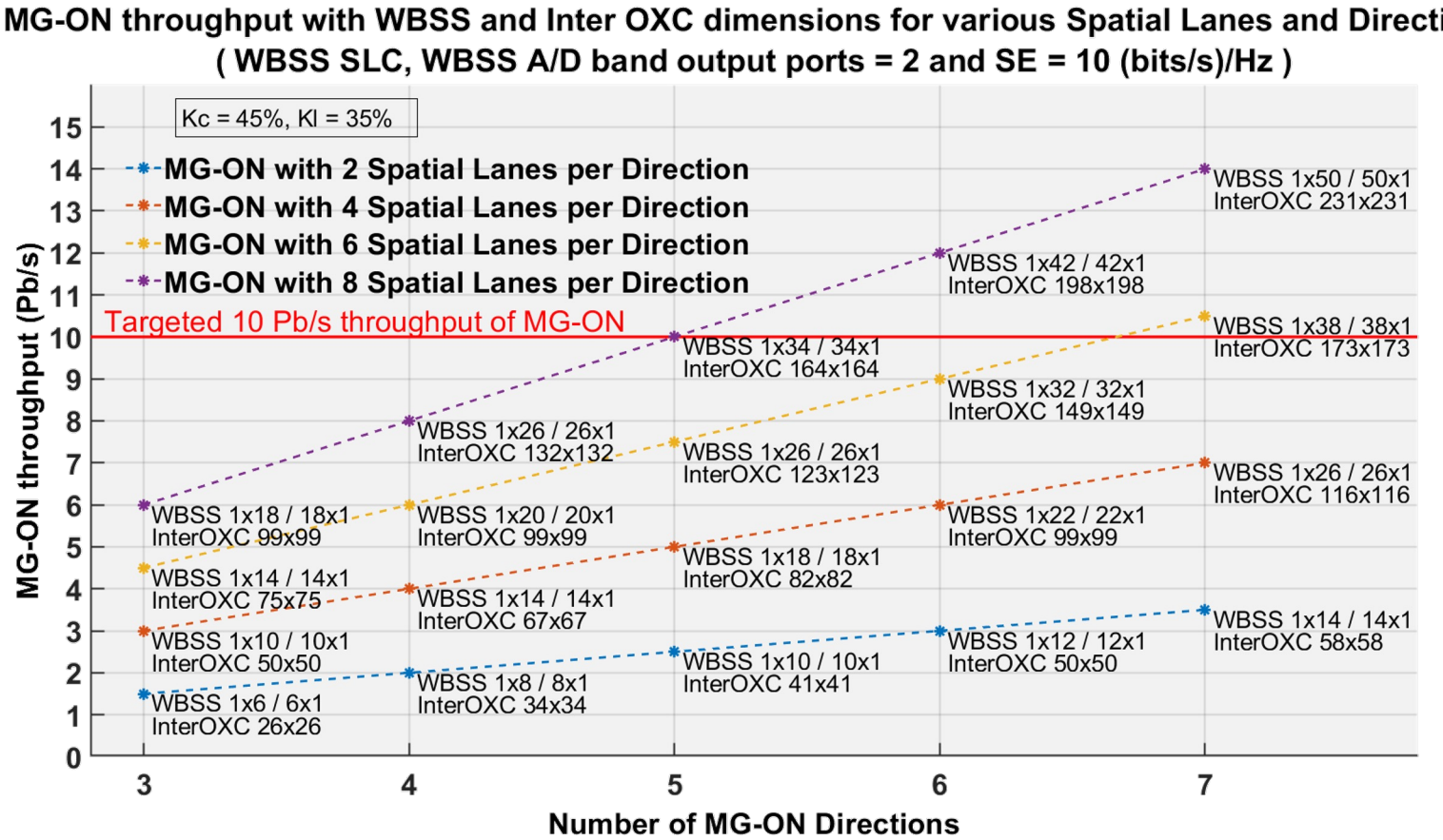
- The FLEX-SCALE Optical Switching Node architecture is based on a novel Multi-Granular architecture (MG-ON) and a new switching subsystem that can realize reconfigurable WaveBand-Selective Switching (WBSS), in addition to Spatial (i.e. fibers) and Spectral (i.e. wavelengths) Lanes switching using enhanced Optical Xross Connects (OXCs) and Wavelength Selective Switching (WSS)

  - The WBSS is implemented as a compact programmable and rapidly reconfigurable PIC that is capable of dynamically processing the entire UWB WDM optical spectrum and as demanded dynamically carve portions of the spectrum into flexibly-defined, continuous and flat spectral bands, which are subsequently switched to multiple output ports.



MG-ON THROUGHPUT SCALING TO +10 PB/S

- Net-throughput of the MG-ON for various number of directions (*D*) of the node and for different number of spatial lanes per direction (*S*) is depicted at the figure (assuming on Band-TRxs of SE=10bit/s/Hz, also developed in FLEX-SCALE, resulting in 0.2 Pb/s throughput per fibre: **a)** small (*D*=3, 4), **b)** medium (*D*=5, 6) and **c)** large-scale node (*D*=7), for four different numbers of spatial lanes per direction (*S*=2, 4, 6, 8).
  - **10 Pb/s** is achieved with 1×34 and 34×1 WBSSs and a 164×164 Inter-OXC (for *D*=5 and *S*=8)

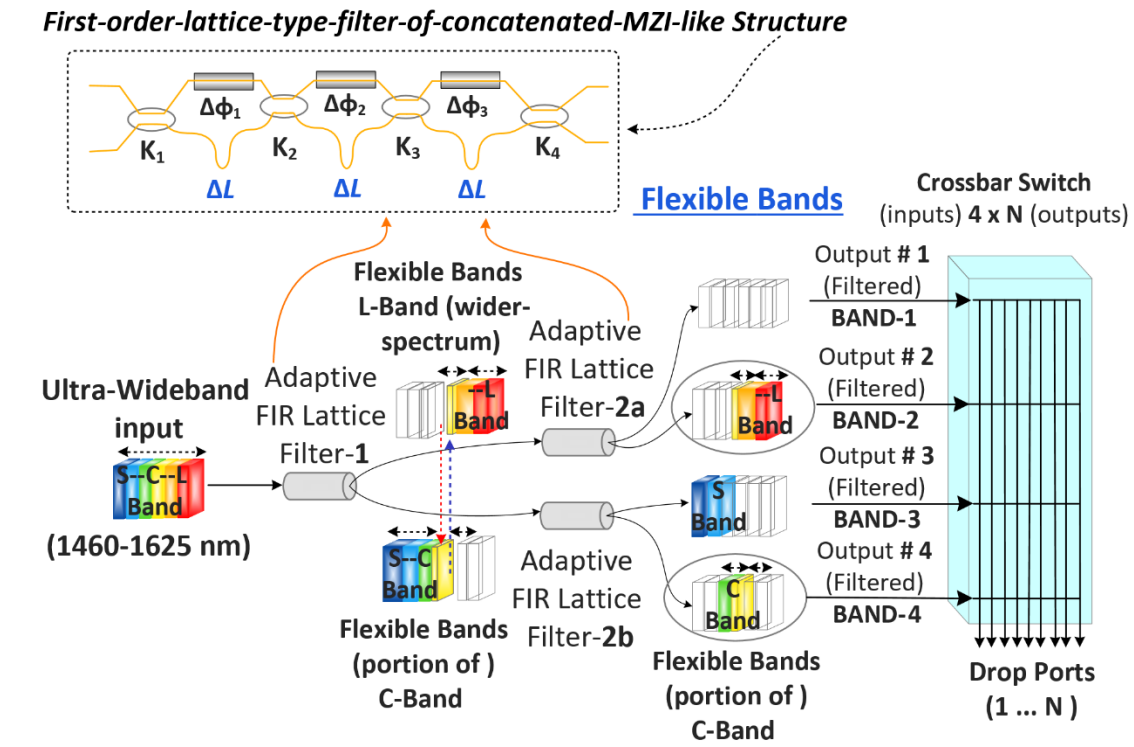


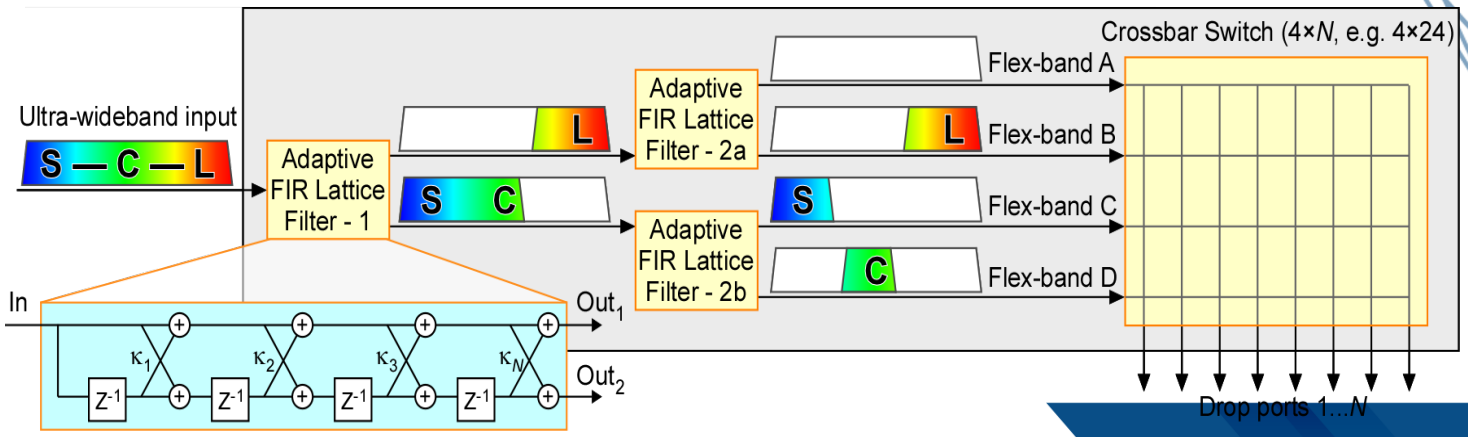
REF: C. Papapavlou, and I. Tomkos, "Scalability Analysis and Switching Hardware Requirements for a Novel Multi-Granular SDM/UWB 10 Pbps Optical Node," ECOC 2023, Glasgow, 2023.

FLEX-SCALE INNOVATION AREA-4: WAVEBAND-SELECTIVE SWITCH ON A CHIP

- Internal structure of WaveBand Selective Switch (WBSS), comprising adaptive filtering stages followed by spatial crossbar switch to output fibre ports.

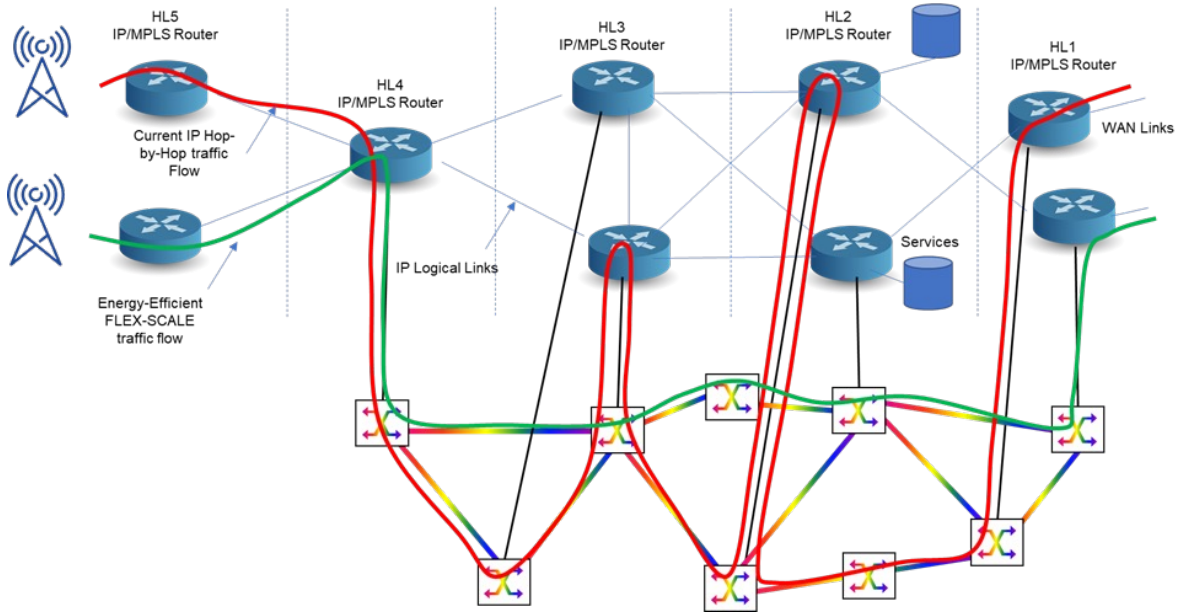
- The WaveBand-selective switch (WBSS) is based on photonic integrated FIR filters, implemented using programmable photonics, that are dynamically adjusting their passbands to carve out disjoint, flexible spectral bands.
  - Output port scale-up is implemented using a 4×N crossbar switch implemented also with Mach-Zehnder modulators.





FLEX-SCALE INNOVATION AREA-5: MULTI-LAYER PACKET OVER OPTICAL TRANSPORT

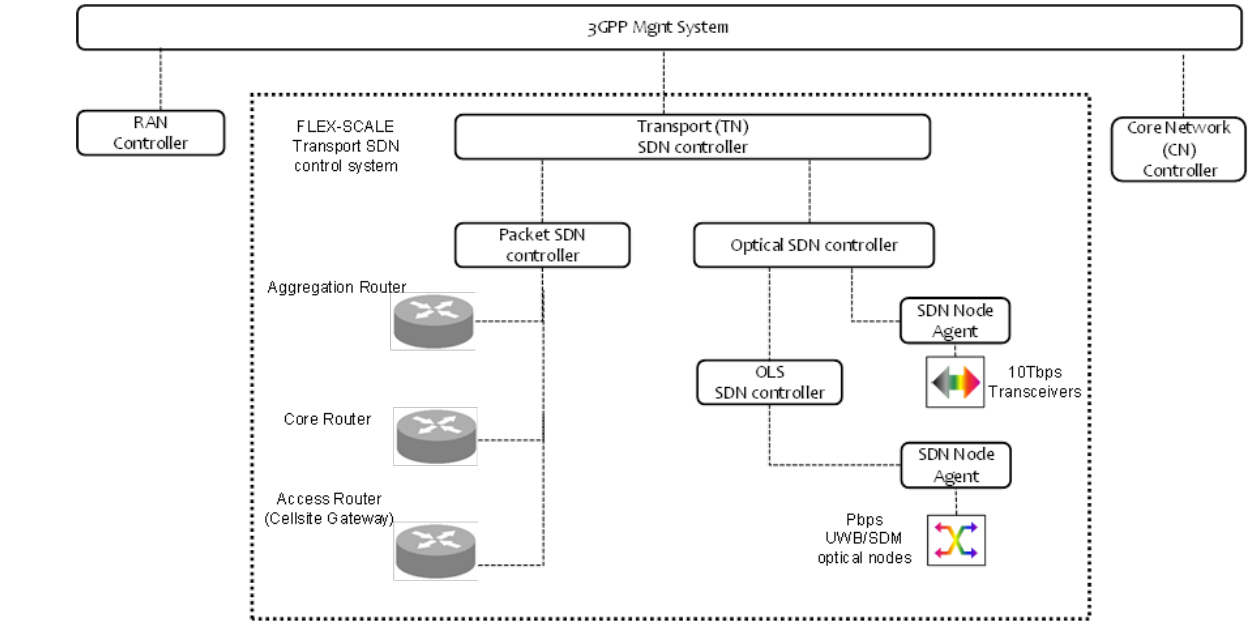
- 5G/6G transport network design heavily relies on multi-layer technology featuring IP routers on top of optical nodes (ON) with optical wavelength channel add/drops (or ROADMs).
- The IP layer is arranged in an aggregation/distribution structure with five hierarchy levels (HLs): access (HL5), first Level of aggregation (HL4), second level of aggregation/transit (HL3), service (HL2) and core/interconnection (HL1).
  - These IP routers interface with the optical networks, through optical transponders with SFP, QSFP and OSFP pluggable transceivers working at 1 and 10 Gb/s (HL5), 100 and 200 Gb/s (HL4/HL3), and 400 and more recently up to 800 Gb/s (HL2/HL1). Notably, Commercial optical transceivers are also evolving from 400 and 800Gb/s line interfaces to 1.2 and 1.6Tb/s.
  - Currently, traffic flows from base stations to the core must go throw energy-hungry HL5, HL4, HL3, HL2 and HL1 IP routers, as shown in the Figure (e.g., red traffic flow), through hop-by-hop IP transport.
    - FLEX-SCALE will investigate novel routings mechanisms to allow to bypass IP

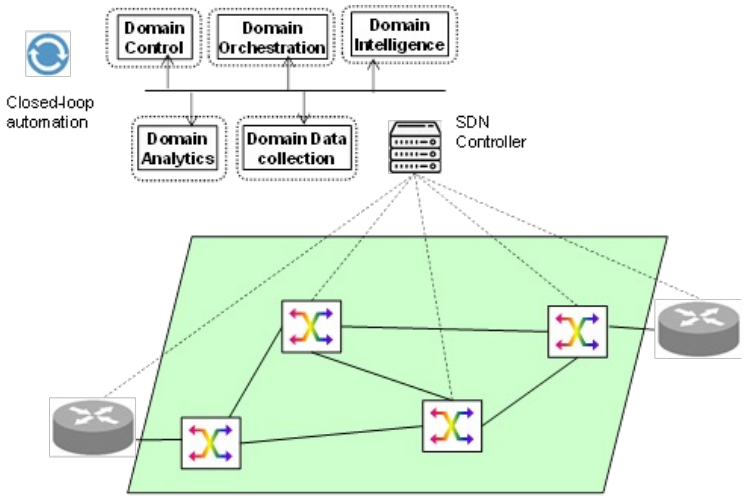


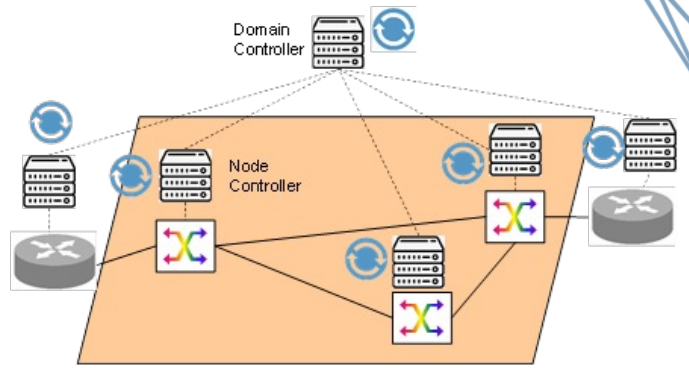
FLEX-SCALE INNOVATION AREA-6: SDN CONTROL & STREAMING TELEMETRY FOR 6G TRANSPORT NETWORKS

- FLEX-SCALE develops an autonomous SDN network operating system that controls the key network devices such as the multi-Pb/s UWB/SDM optical node and the 10 Tb/s transceiver.

- With the utilization of novel ML-enabled algorithms will ensure the optimization of joint management of packet flows and optical channels with the goal to reduce the energy consumption while maintaining a low blocking probability under dynamic traffic conditions.







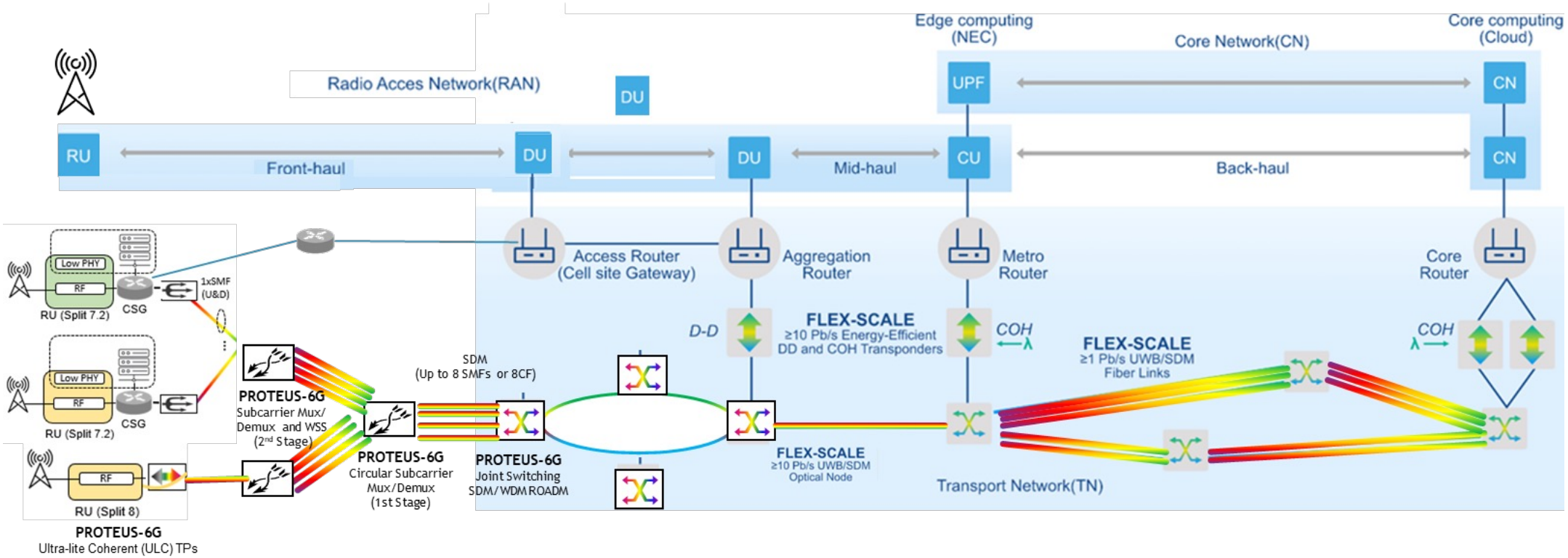
ADDRESSING SRIA REQUIREMENTS VIA THE FLEX-SCALE INNOVATIONS

	SRIA targets	What we address	Target achieved
Spectrum	15 - 30 THz	UWB (S+C+L – Bands) (1460-1625 nm, ~ 21THz)	👍
Port speed	1.6 – 3.2 Tb/s	1.6 Tb/s	👍
Bandwidth	<300 GHz - < 600 GHz	(1)	Under development
Line capacity	200 – 600 Tb/s	(2)	👍
Node capacity	1.2 – 3.6 Pb/s	10 Pb/s (3)	👍
Latency	<100µs - <10 µs	<10 µs (4)	👍
Power consumption of WBSS		≤ 13 fJ/bit (5)	Under development
Per-band MG-node throughput		>80 Tb/s (6)	Under development

SUMMARY

- Evolving Network Requirements
  - 6G traffic expectations
  - 6G x-haul network requirements
- Main Innovation Areas of FLEX-SCALE project
  - Multi-Tbps transceivers & Multi-Pbps switches
  - SDN Control & streaming telemetry
- Targets set by industry/academic associations for 6G x-haul at 2030 can be met by FLEX-SCALE project activities!

6G X-HAUL VISION: ADVANCED OPTICAL NETWORKING INNOVATIONS TO ENABLE 6G NETWORK APPLICATIONS



PROTEUS-6G

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FLEX-SCALE

Flexibly Scalable Energy Efficient Networking

THANKS FOR YOUR ATTENTION!

FLEX-SCALE

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