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CONNECT
Centre for Future Networks

Towards digital twinning:
a networking journey from closed systems towards open programmable concepts, architecture and infrastructure

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CONNECT and IPIC research centres

Trinity College Dublin
The University of Dublin
Ireland's European Structural and Investment Funds Programmes 2014-2020
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European Union
European Regional Development Fund
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IPIC
BRINGING PHOTONICS TO LIFE

Prof. Marco Ruffini, Ph.D. (2008)

https://marcoruffini.com/

- ✓ Associate Professor and Fellow of TCD
- ✓ PI in CONNECT and IPIC; Head of the Optical Network Architecture lab
- ✓ >150 International publications, 10 patents
- ✓ >€8M raised in competitive funding

- Access Network Virtualisation:
  - The Virtual DBA and Full virtual PON prototype
  - Mesh optical access architectures for densification & edge cloud
- Disaggregated optical networks:
  - Mininet-Optical: network emulation for optical disaggregation
  - Machine learning for Quality of Transmission Estimation
- Fixed-Mobile Convergence:
  - Variable Rate Fronthaul scheme for PON transport
  - SDN based integrated LTE-PON control system
- Open networking testbed experimentation:
  - Converge of OpenRAN, open optical and edge/cloud computing

The Research group

SDN control of quantum networks

OpenRAN Intelligent control

Open Networking testbed

Edge-cloud optimisation

Wireless-optical-MEC convergence

Multi-RAT optimisation

Mininet-Optical

Optical network twin

Mesh PON access

Free space optics backhaul

PON virtualization

Summary of the talk

- Open networking trends
  - Opening mobile base stations
  - Opening the optical transmission layer
  - Opening the central office (access network)

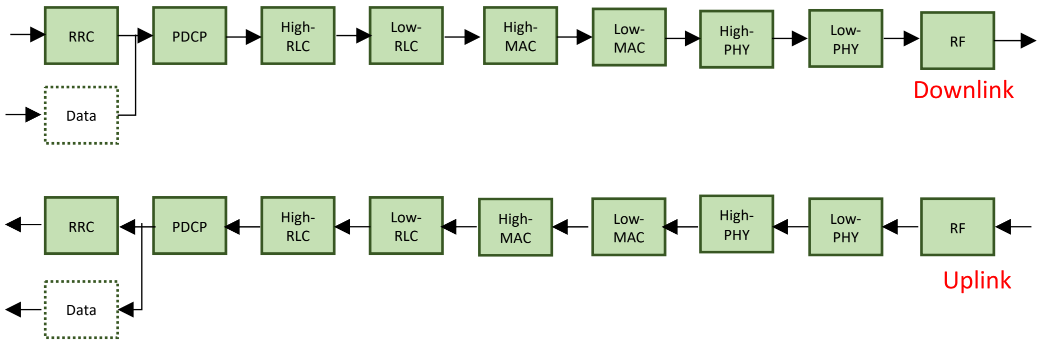
- Linking to our work on PON virtualization (Aka what you can do once it’s in software)
  - Scheduler virtualization and software-based PON
  - Low-latency design
  - Support for MEC / deep edge computing
  - Optical-Wireless convergence
  - Fine-granularity multi-tenancy & blockchain

- Next step and digital twinning
  - Digital twinning an optical network
  - Key role of open testbeds: COSMOS and OpenIreland

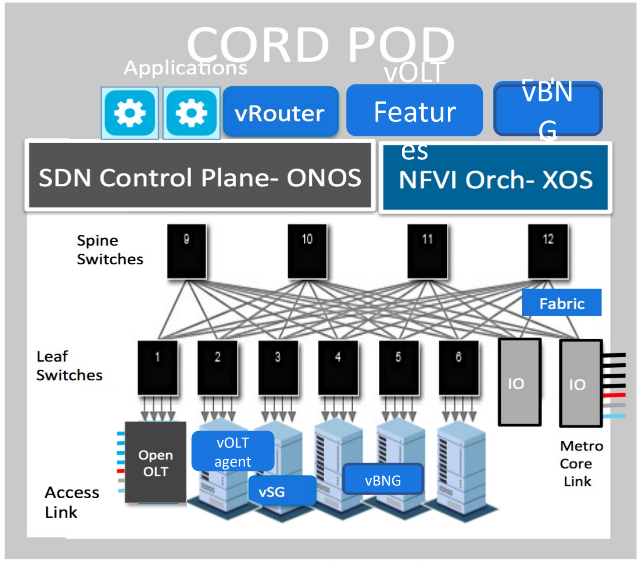
The Network Virtualisation and Open Networking Trend

- Open networking everywhere:

Mobile base stations

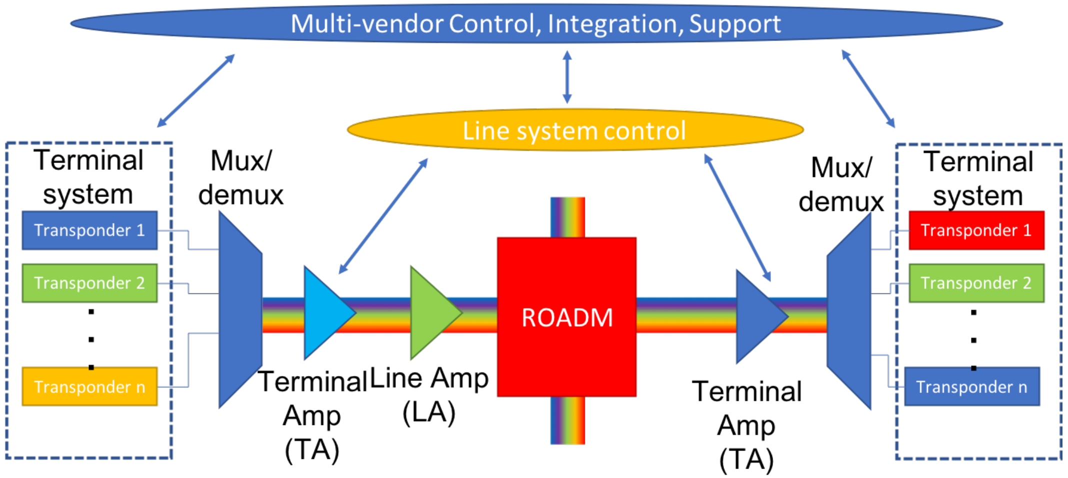


Central Office



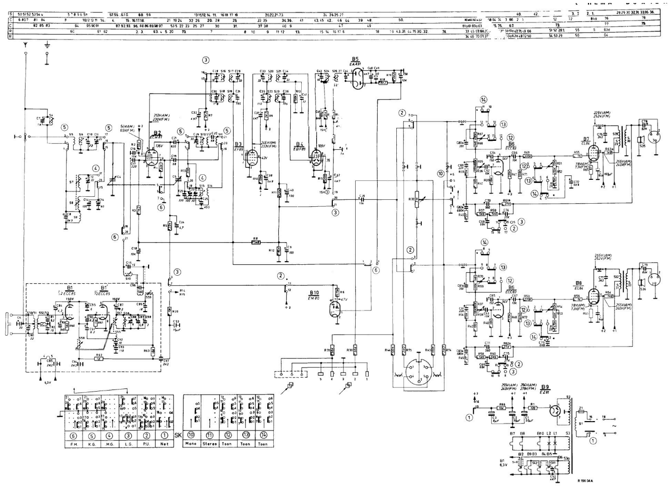
Commodity Hardware

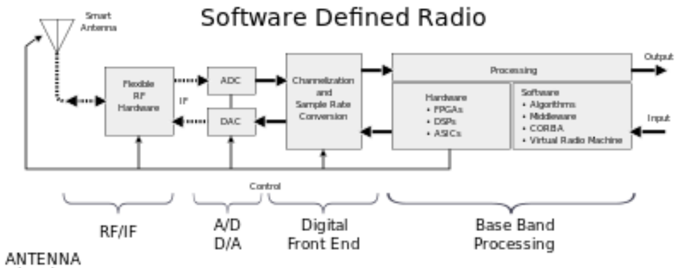
Optical systems

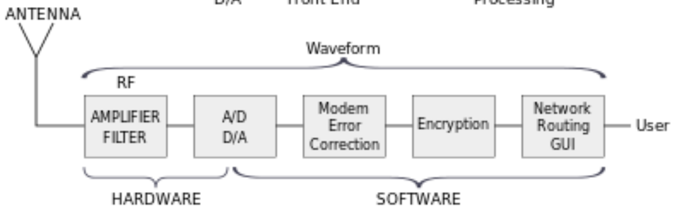


Virtualising the radio

- Long standing trend of moving functions from dedicated hardware to software running on commodity servers
- Software Defined Radio is an early example: GNU radio



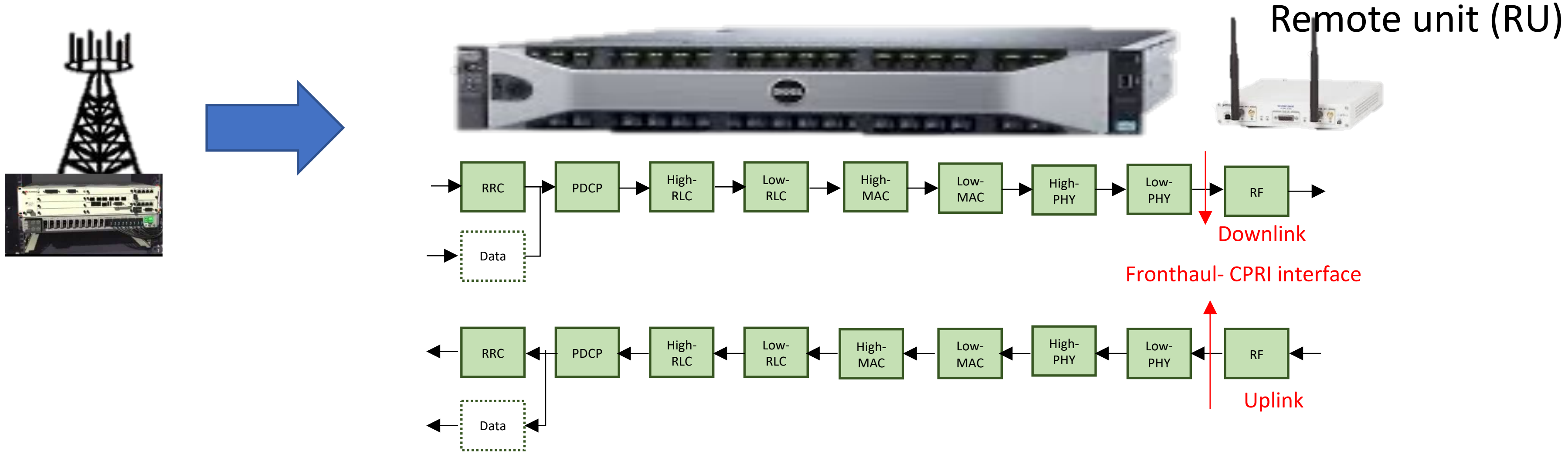




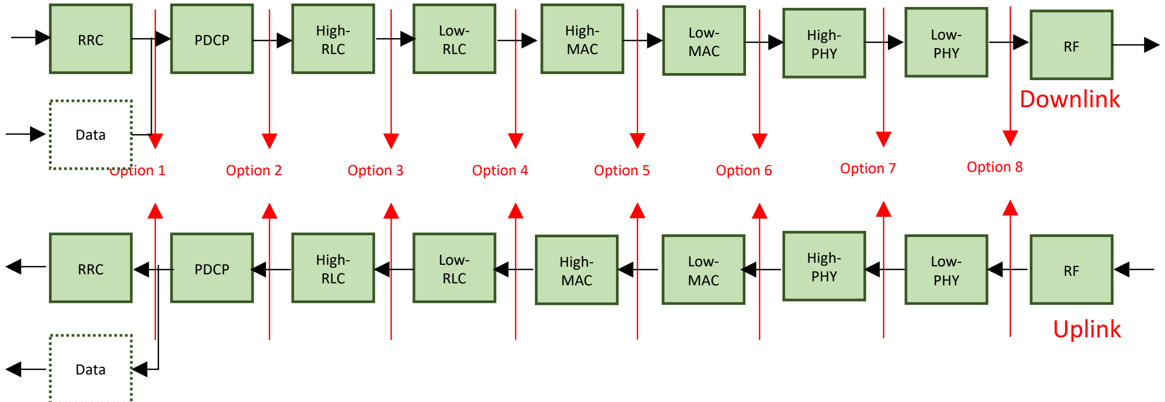
- Advantages:
  - flexibility of adapting transmission format to environment and application
  - coordination with other radios (either distributed or centralized)
  - Integration with other software components…

Opening the base station

- For over 10 years we have been able to do this: run a 4G base station from a laptop

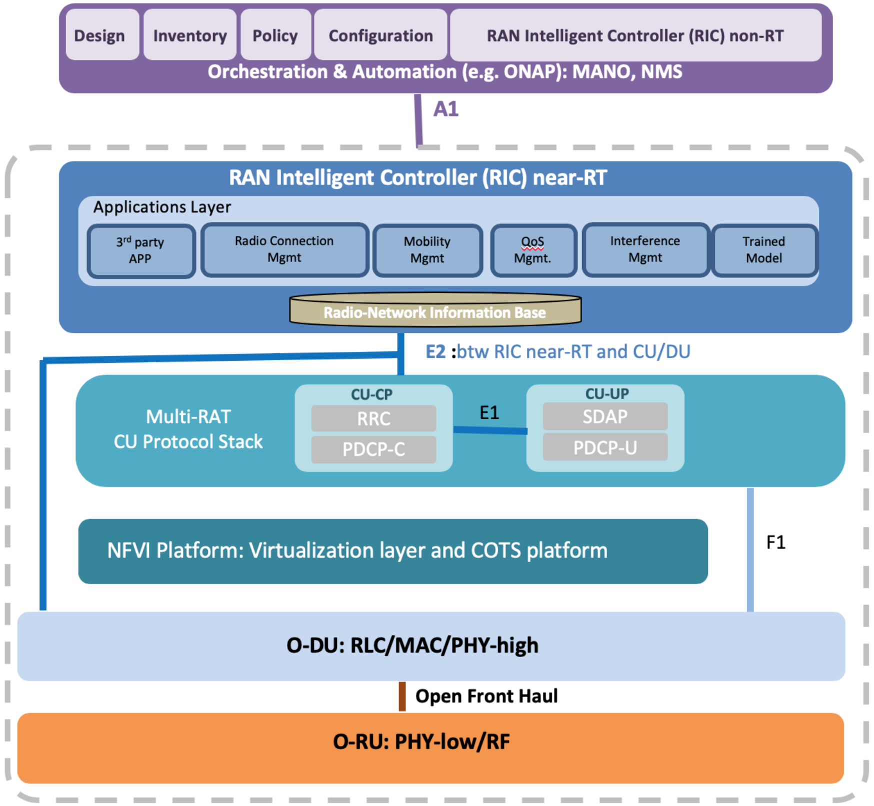


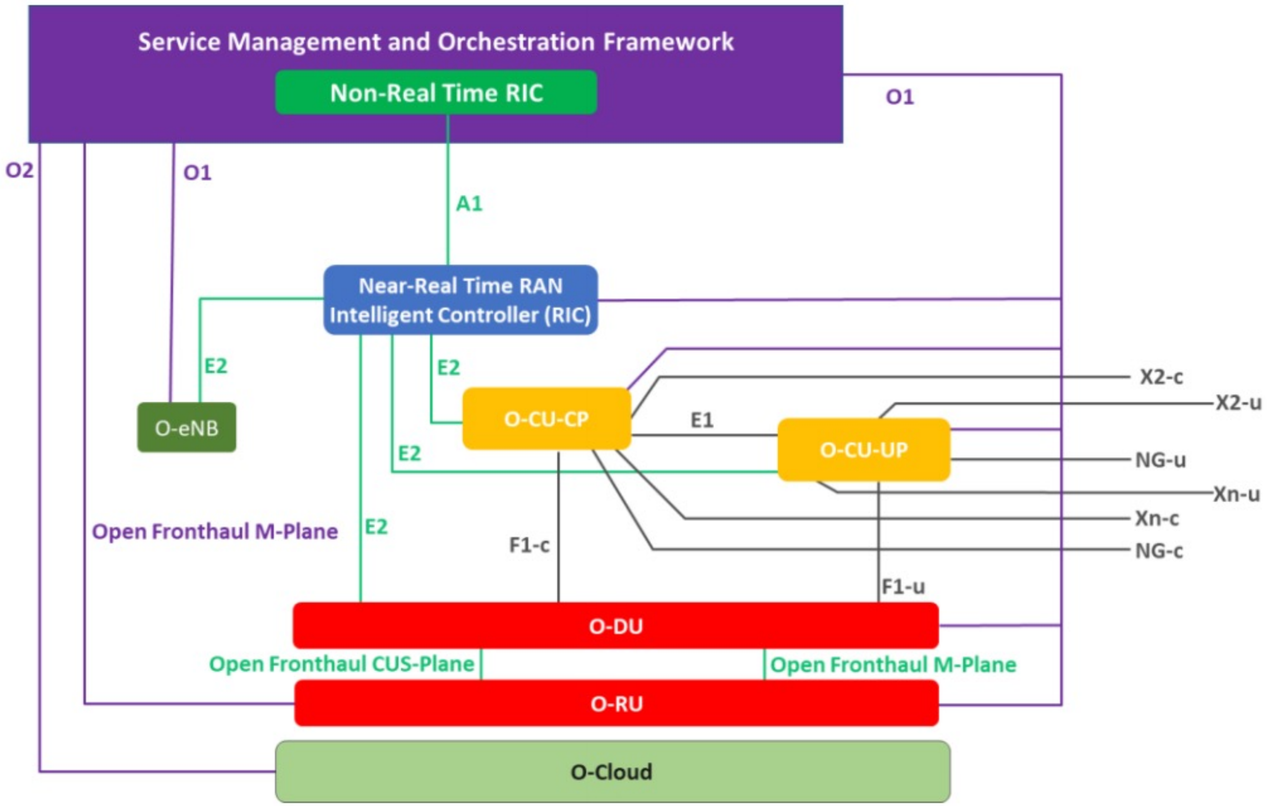
- Over that past 5 years industry fora have come together to define other split points for separating Remote Unit – RU (hardware) from the rest (Distributed Unit and Centralised Unit). Alternatives to CPRI.



OpenRAN

- Split 7.2 being standardised, so you can go and buy an RU and then install the rest as opensource software
- O-RAN is providing standardisation of several interfaces, so the system can be fully open

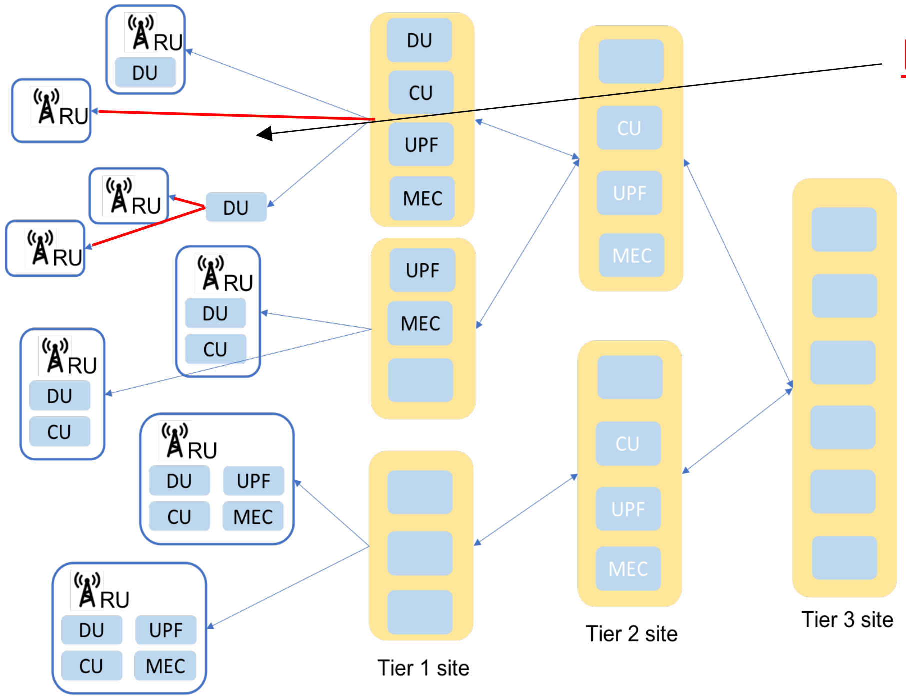




Mobile network disaggregation needs optical transport: wireless-optical convergence

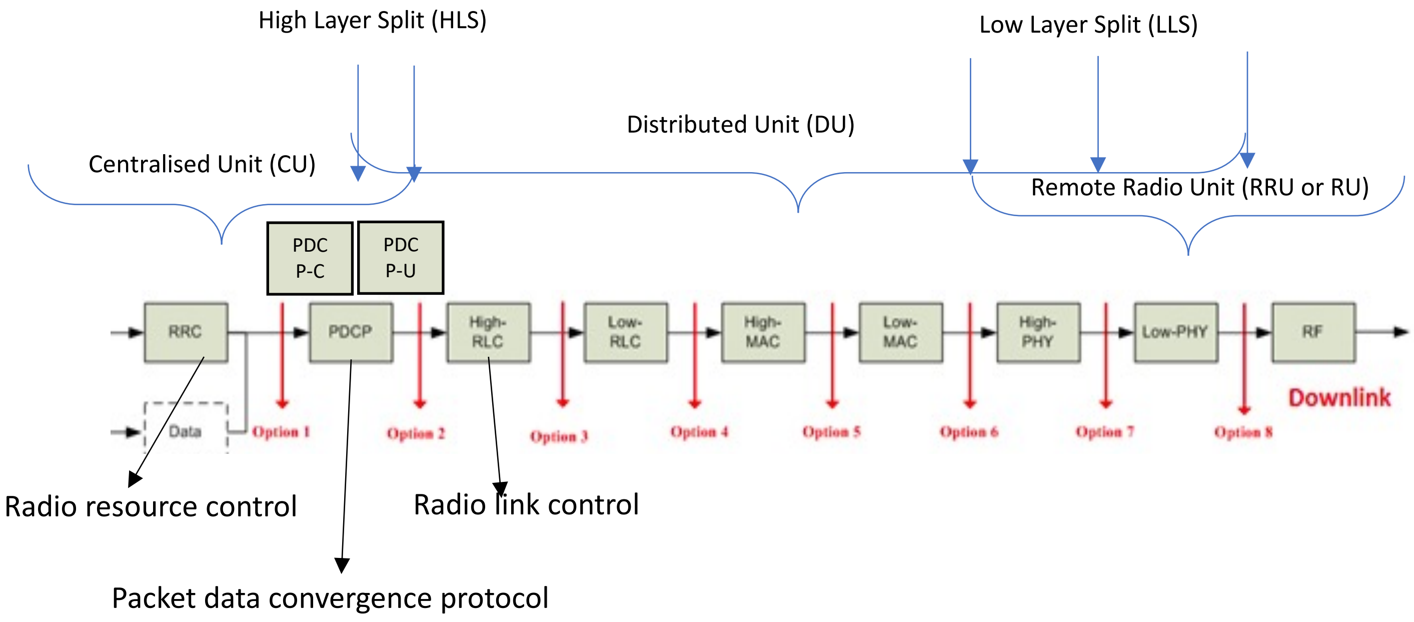
- The different pieces (functions) of the mobile stack can be disaggregated and placed in different locations

LLS is the low latency interface, between RRU and DU



UPF Location	Tier 1	Tier 2	Tier 3
Relative number of sites	1000	100	10
Transport latency (1-way)	0.6 ms	1.2 ms	4.2 ms
Estimated 5G latency (RTT)	9.2 ms [eMBB]	10.4 ms [eMBB]	16.4 ms [eMBB]
	2.2 ms [URLLC]	3.4 ms [URLLC]	9.4 ms [URLLC]

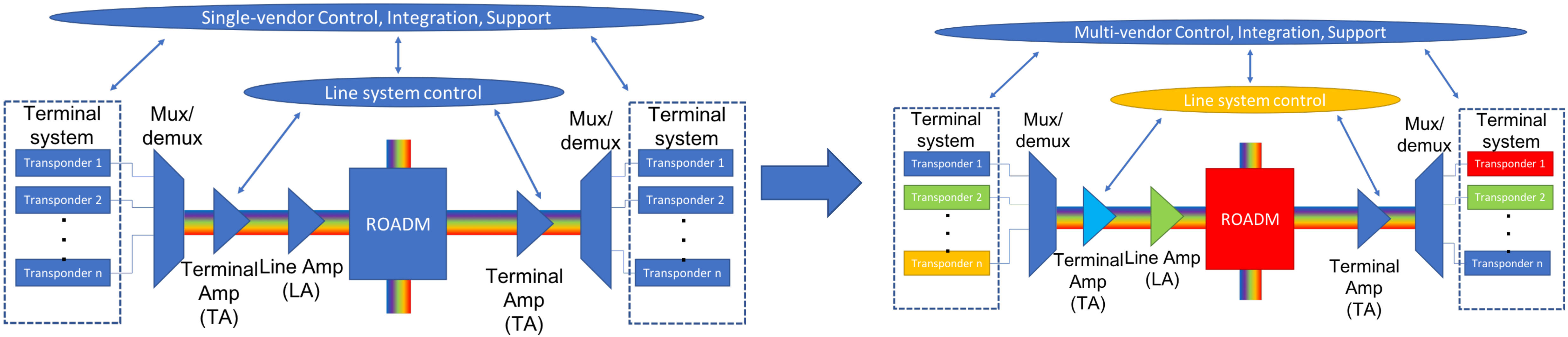
Source: NGMN



C= control plane; U=user plane

Opening the optical layer

- This is a difficult one!
- Optical transmission is analogue, meaning that different devices have different behavior (unlike digital)
- Nonetheless now there are SDN-controlled ”whitebox” devices, like ROADMs, amplifiers and transponders..



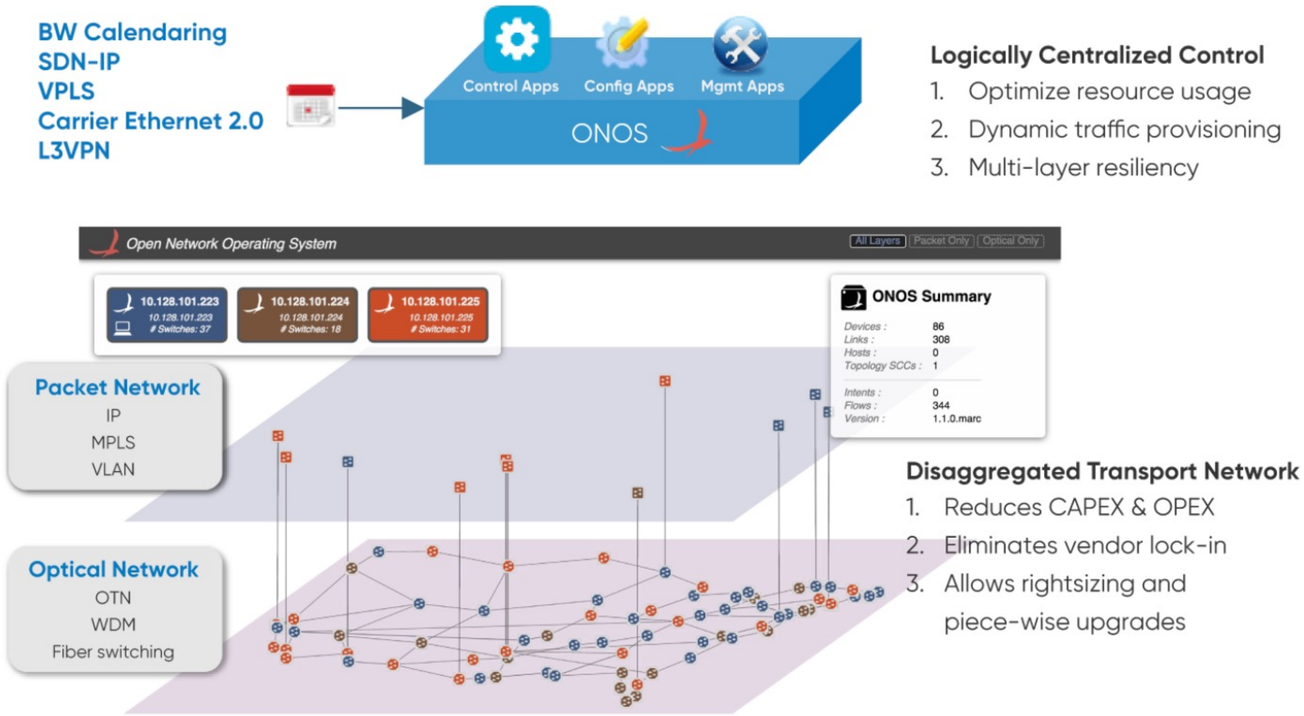
Pros and Cons of disaggregation

Pros:

- Open market of component from multiple vendors brings cost down
- No vendor lock-in, faster network upgrades
- Possibility of full integration with other control layers to achieve dynamic, fast, end-to-end optical **re-configurability and programmability**

Challenges:

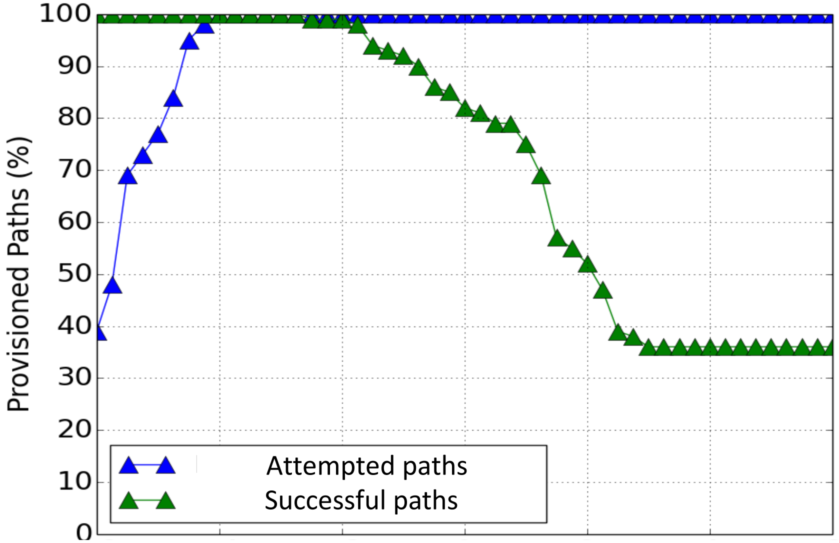
- Building an end-to-end analog system
  - How to do end-to-end system optimization with components whose behavior is not well known?
  - Avoid use of large margins



Source: https://www.opennetworking.org

Metro vs core

- Meaning of effect on margins:



More conservative

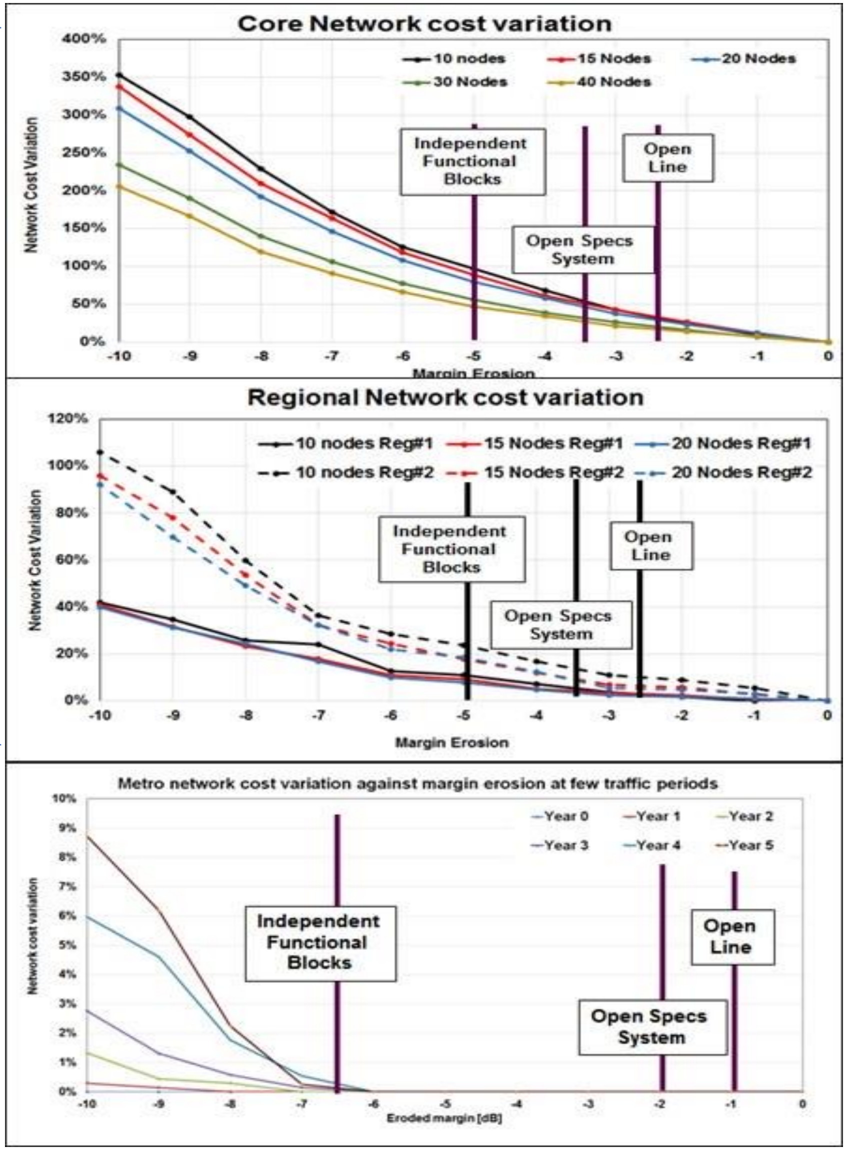
More aggressive

X axis: how conservative are the margins

Alan A. Díaz-Montiel et al. Performance Analysis of QoT Estimator in SDN-Controlled ROADM Networks. Proc. of Optical Network Design and Modeling conference (ONDM), May 2018

Effect on cost of core and regional network shown to be substantial due to low available margins

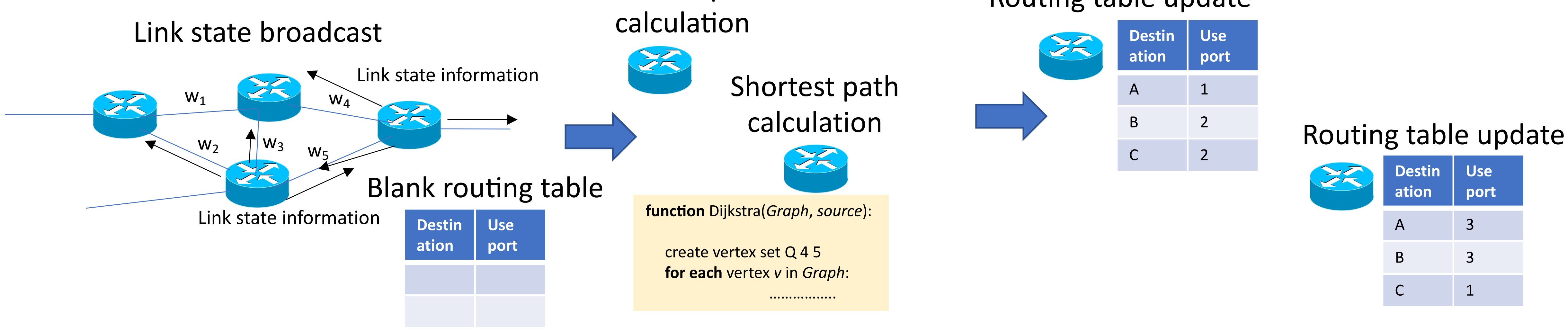
Effect on metro though is negligible, as the metro has larger margins



Source: M. Bleanger, M, O'Sullivan and P, Littlewood. Margin requirement of disaggregating the DWDM transport system and its consequence on application economics. M1E.2, OFC '18

Opening switches and routers

- From distributed approach:



Destination	Use port

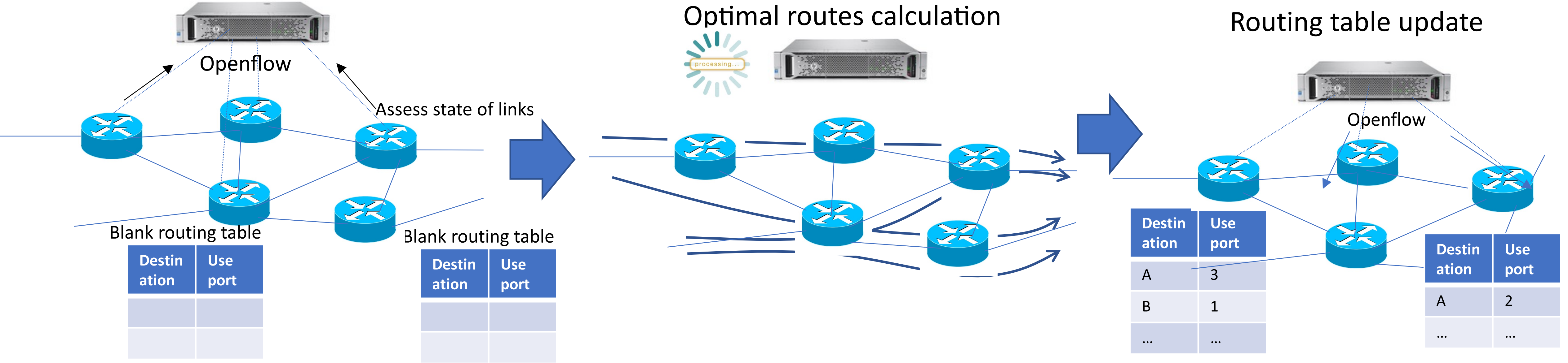
```
function Dijkstra(Graph, source):

    create vertex set Q 4 5
    for each vertex v in Graph:
           ……………..
```

Destination	Use port
A	1
B	2
C	2

Destination	Use port
A	3
B	3
C	1

- To centralized (control/data plane separation)



Destination	Use port

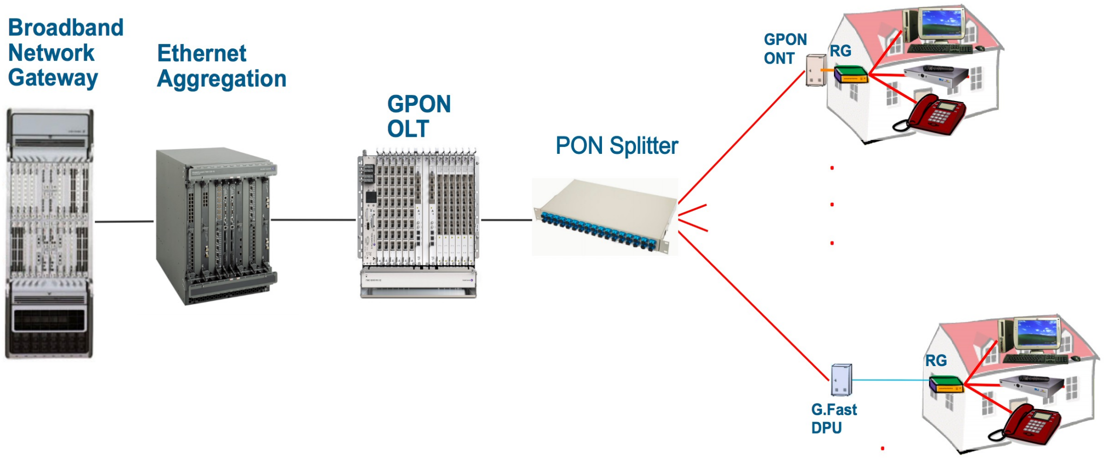
Destination	Use port

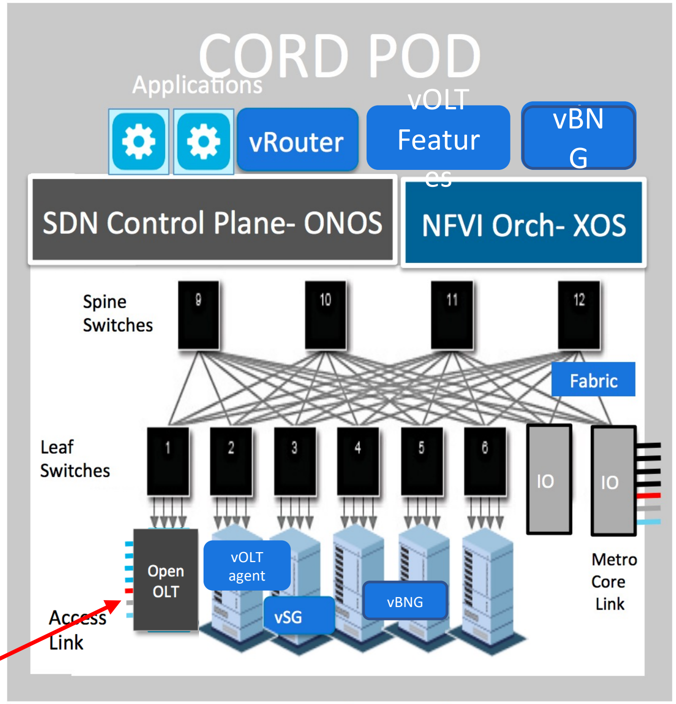
Destination	Use port
A	3
B	1
…	…

Destination	Use port
A	2
…	…

Opening the central office

- Over the past 10 years the concept has evolved from academic research and individual devices, to telecoms network scale.
- The central office is being "Softwarised" or "Cloudified". Started in 2015 with the Central Office Rearchitected as a Data Centre (CORD), from Stanford and AT&T, then turned into the Open Networking Foundation (ONF).





Commodity Hardware

This has now evolved into the SDN-Enabled Broadband (SEBA)

And more recently into a converged MEC/Cloud - AETHER

PON scheduler in HW pizza-box

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  - Scheduler virtualization and software-based PON
  - Low-latency design
  - Support for MEC / deep edge computing
  - Optical-Wireless convergence
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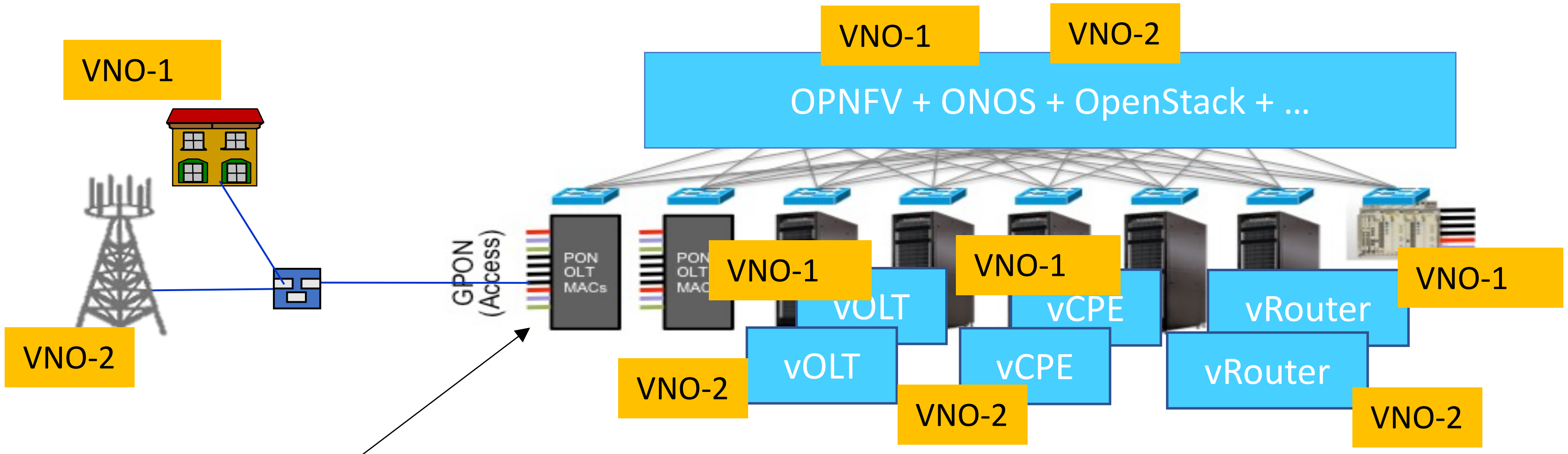
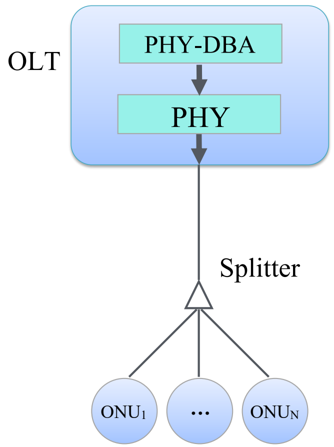
- Next step and digital twinning
  - Digital twinning an optical network
  - Key role of open testbeds: COSMOS and OpenIreland

Is CORD virtualization enough for PONs?

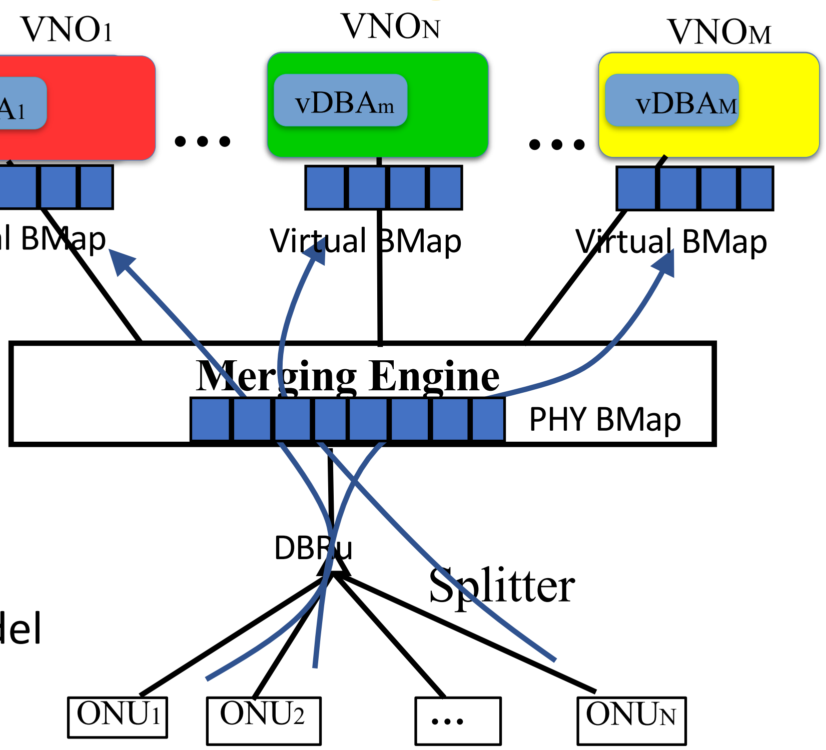


- Functions are virtualized and multiple instances can be assigned to different Virtual Network Operators (VNOs)
- … but for example Dynamic Bandwidth Allocation (DBA) is carried out in hardware

Full disaggregation of the OLT with upstream frame slicing



Current physical DBA model



vDBA model

- Work on DBA virtualization to enable fine-grained control to different tenants.
- Also other use cases: e.g., for service differentiation, for mobile front haul (more on this later)
- Also included in BBF TR-402 “PON Abstraction Interface for Time-critical Applications” and recently in TR-370i2 “Fixed Access Network Sharing (FANS)

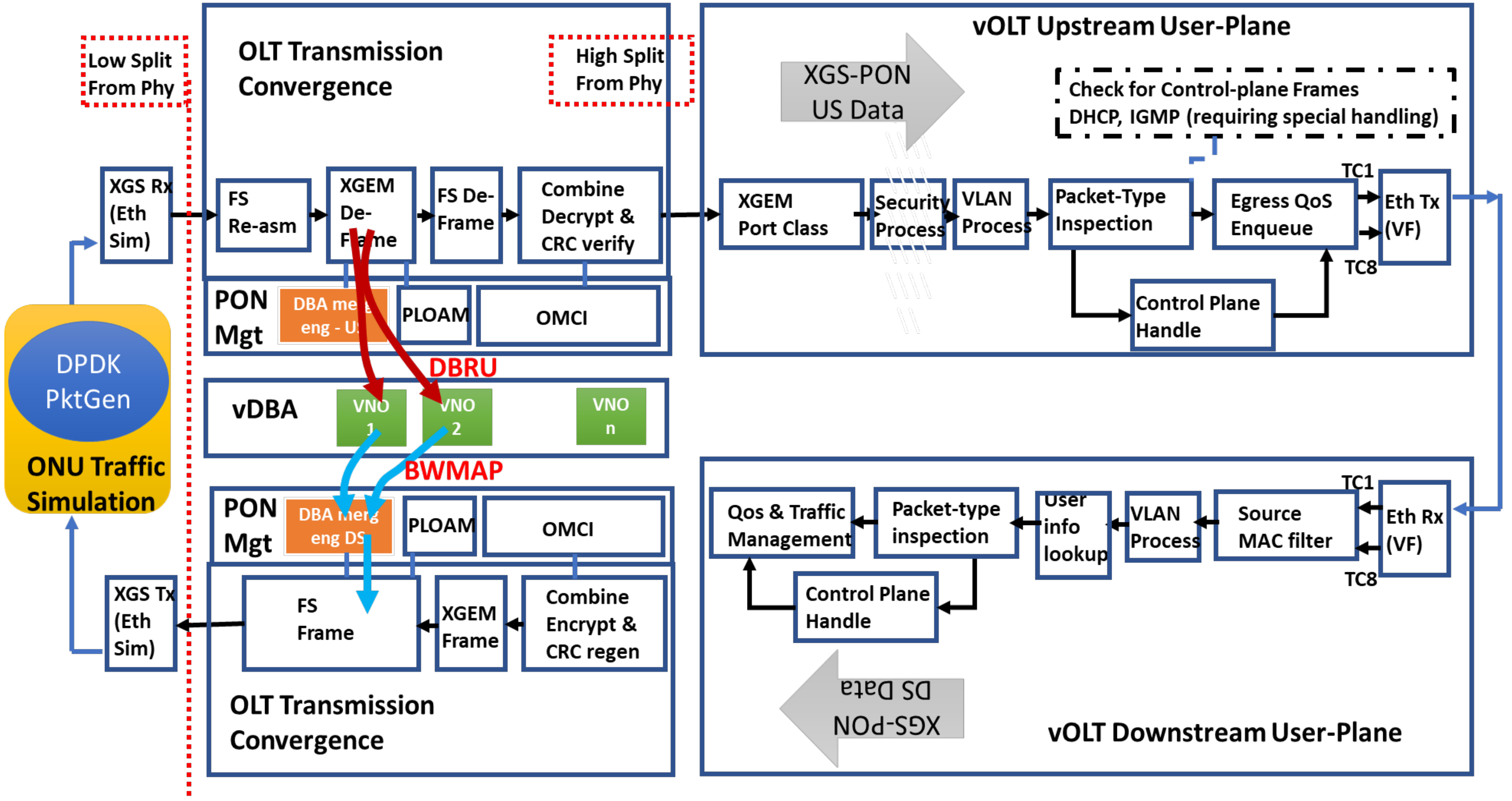
The virtual PON implementation

XGS-PON compliant protocol implemented in software

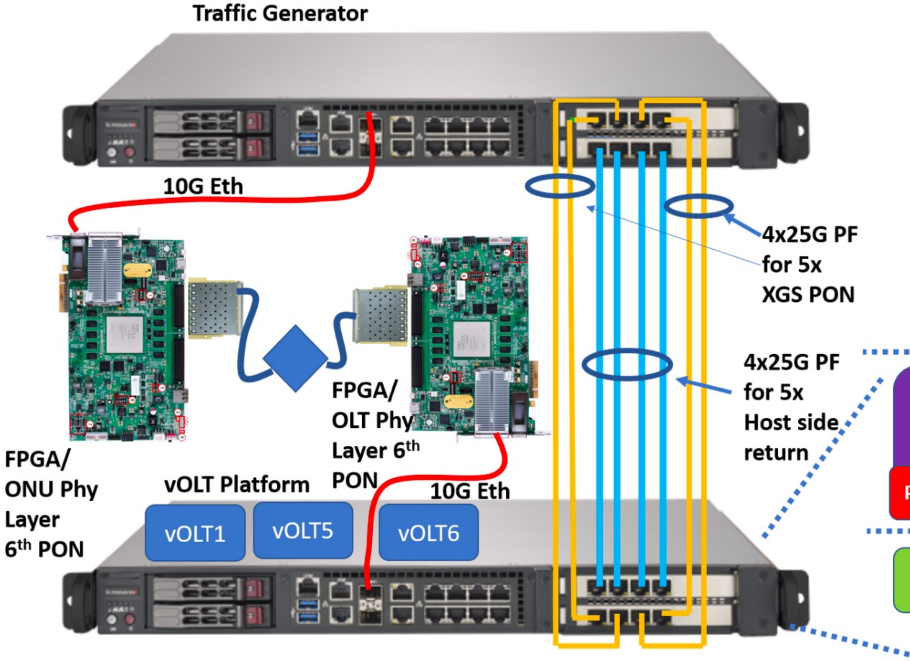
Two implementations:

- High split: part of the protocol in GPP (i.e., Intel Xeon) software, part in dedicated programmable hardware (FPGA)
- Low-split: all is done in the GPP

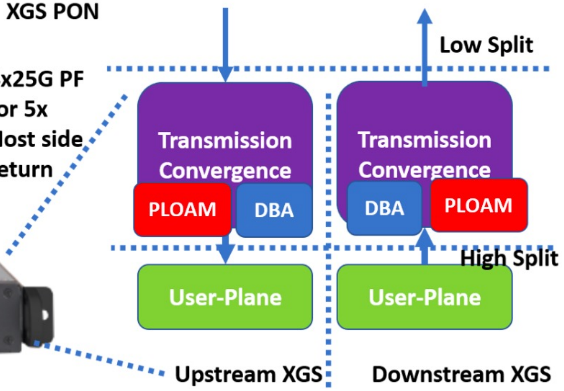
<u>The DBA is in GPP software in both cases</u>

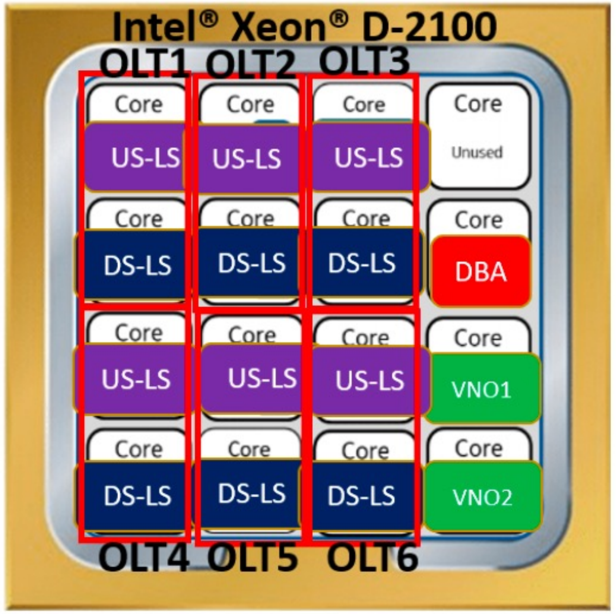


The virtual PON in practice



Fully Standard compliant with XGS-PON



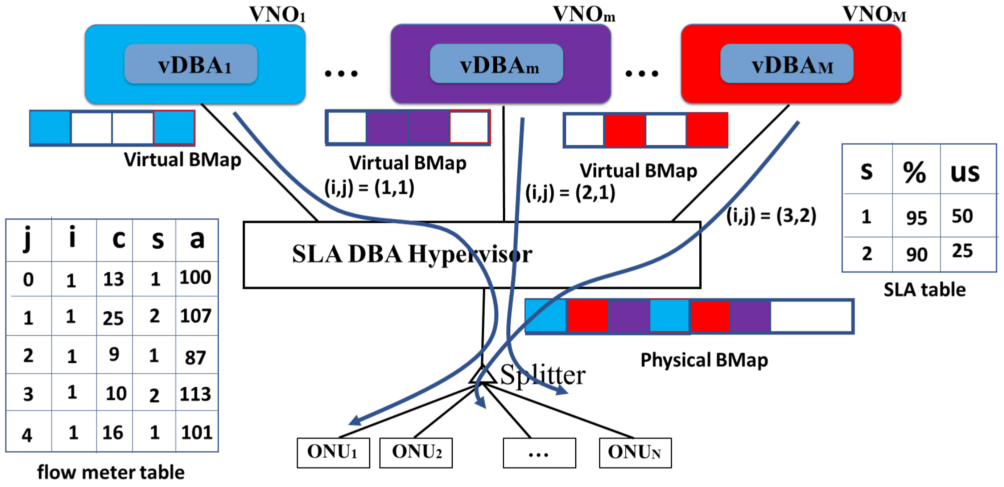


Very interesting for synching DBA across multiple wavelengths!
… and coordination with C-RAN, etc.

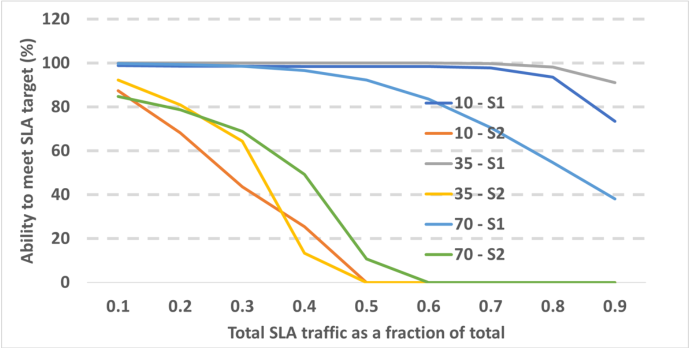
F. Slyne et al., Experimental Demonstration of multiple Disaggregated OLTs with Virtualised Multi Tenant DBA, over General Purpose Processor. OFC 2020.

Example of scheduler for SLA optimisation

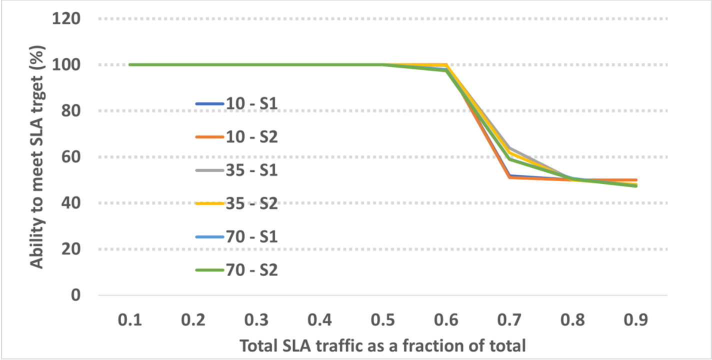
- Prioritisation and queue management is based on relative importance: who goes first.
- While OK at data plane, it shouldn't be the high-level decision!
  - How to decide priority: 95% of packets within 100 us vs 99% of packets within 200 us?
- Algorithm for prioritization based on probability of SLA breach
- It's stateful, so algorithm optimization is essential!



Baseline: priority based

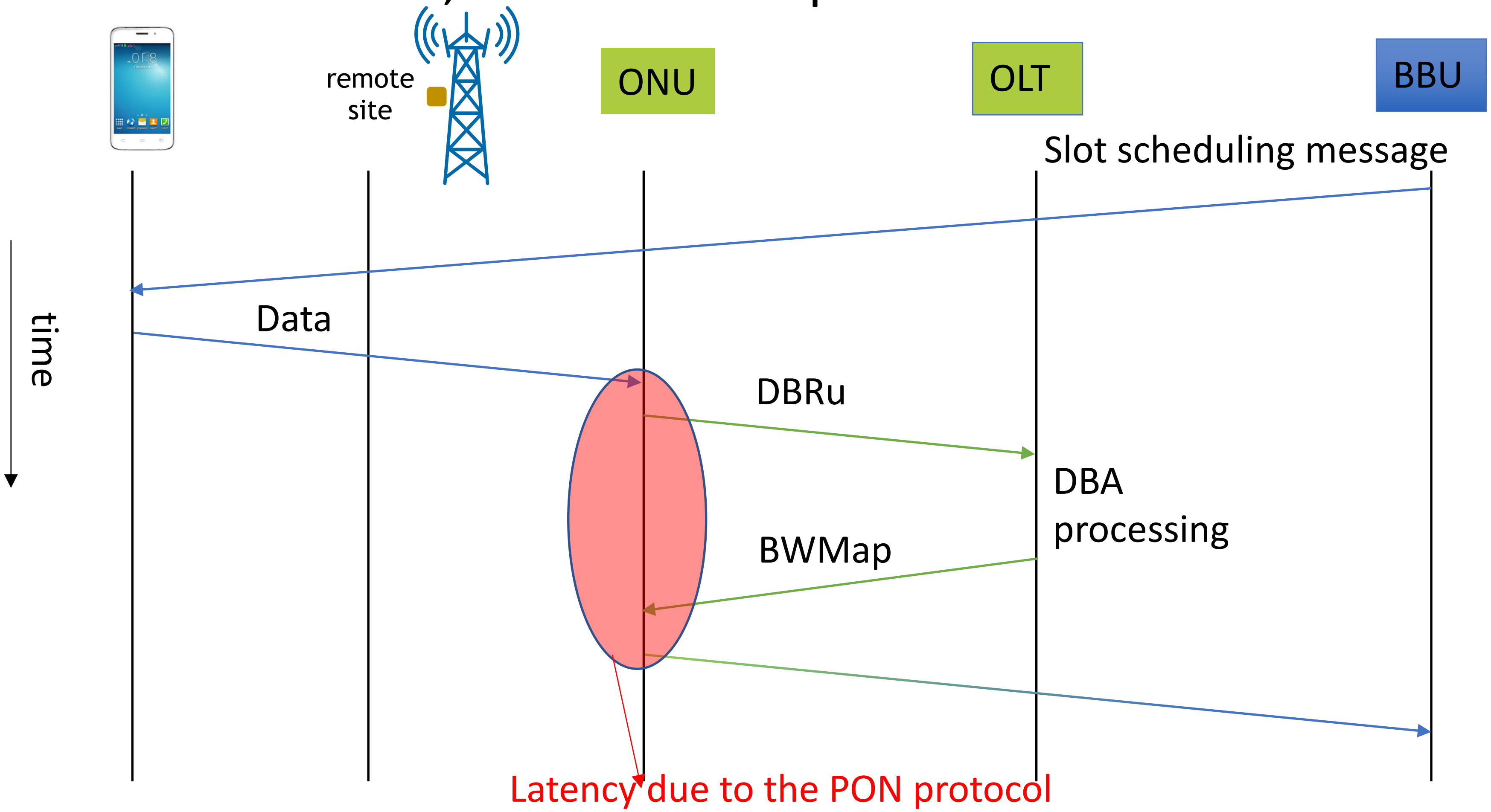


Proposed: priority based



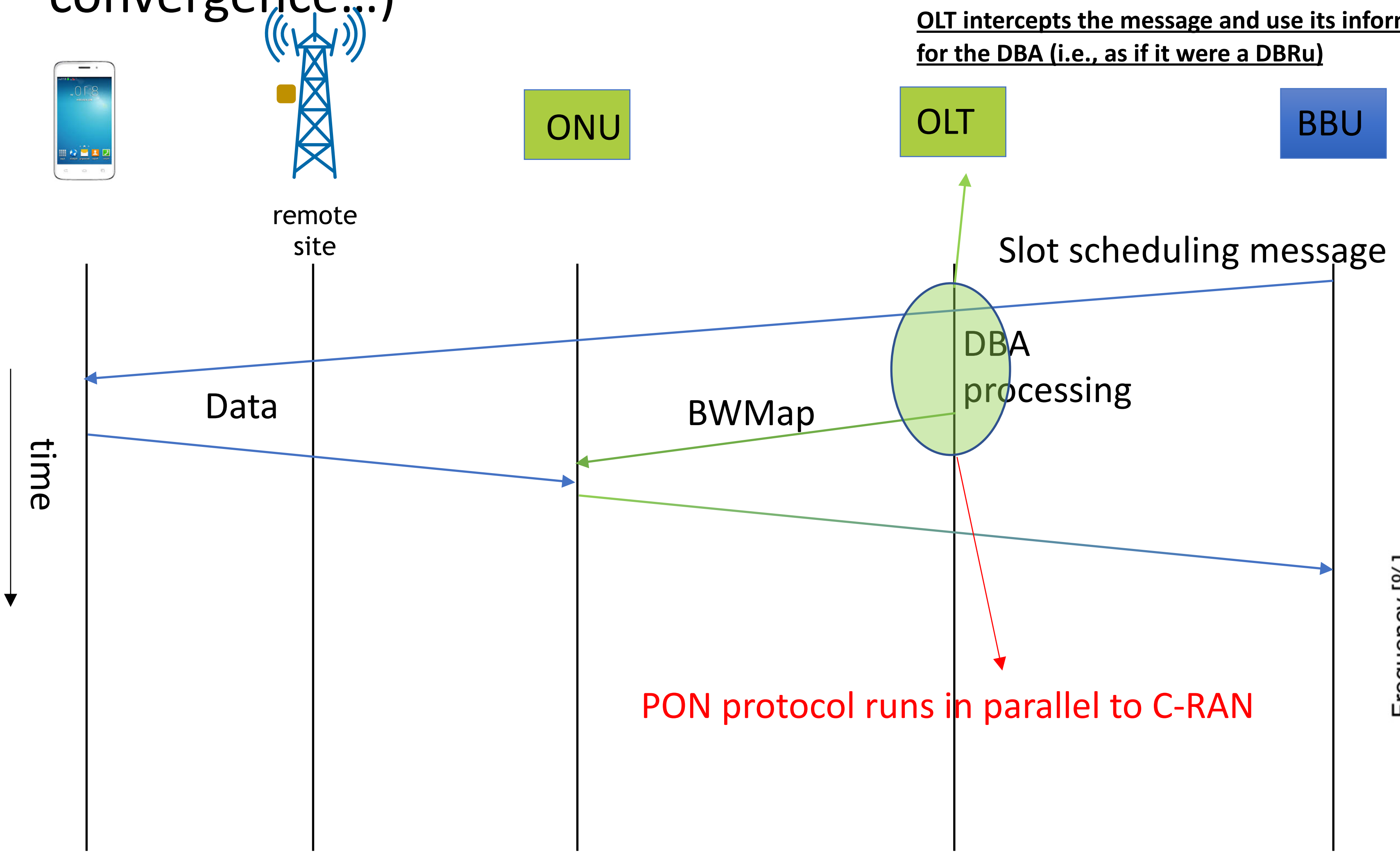
The BDA latency issue in C-RAN

- PON and C-RAN both need to run their own upstream MAC protocol.
- Typically they work independently, (in sequence), so incoming packets get queued at the ONUs, until the PON protocol enables transmission.

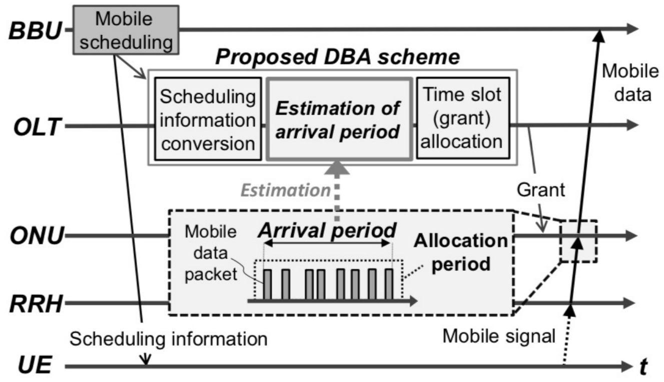


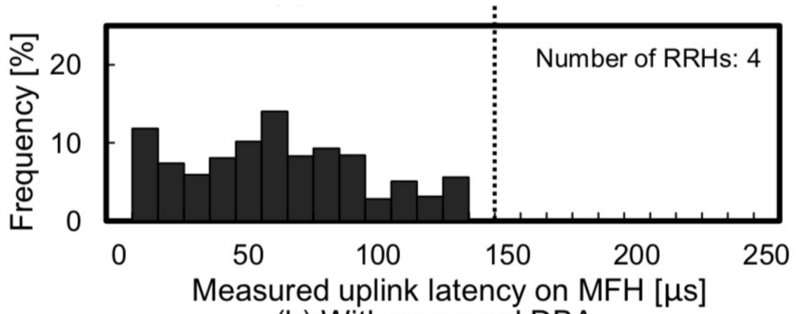
Cooperative DBA Solution (now called Cooperative Transport Interface - CTI)

- Synchronise BBU scheduling and OLT DBA (this is optical/wireless convergence…)



Standardised in ITU-T G.989.3Am1



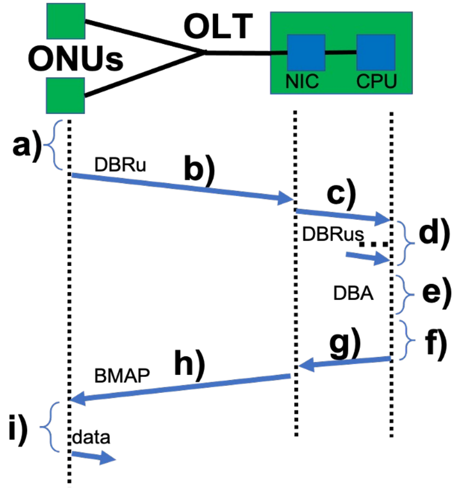


(b) With proposed DBA

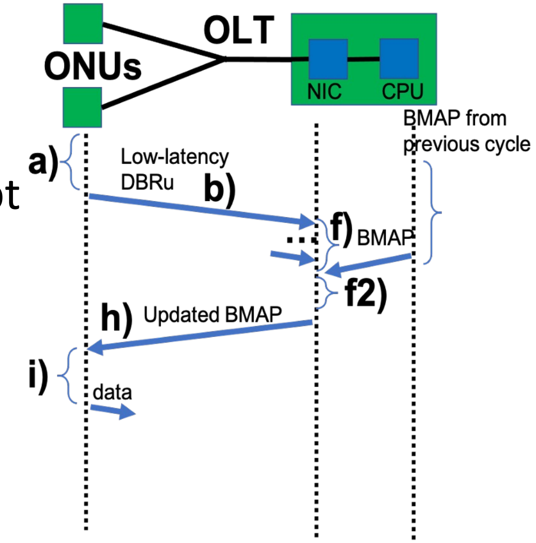
Source: H. Uzawa, et al. Practical Mobile-DBA Scheme Considering Data Arrival Period for 5G Mobile Fronthaul with TDM-PON. ECOC 2017.

Low latency for unpredictable traffic

Standard DBA process

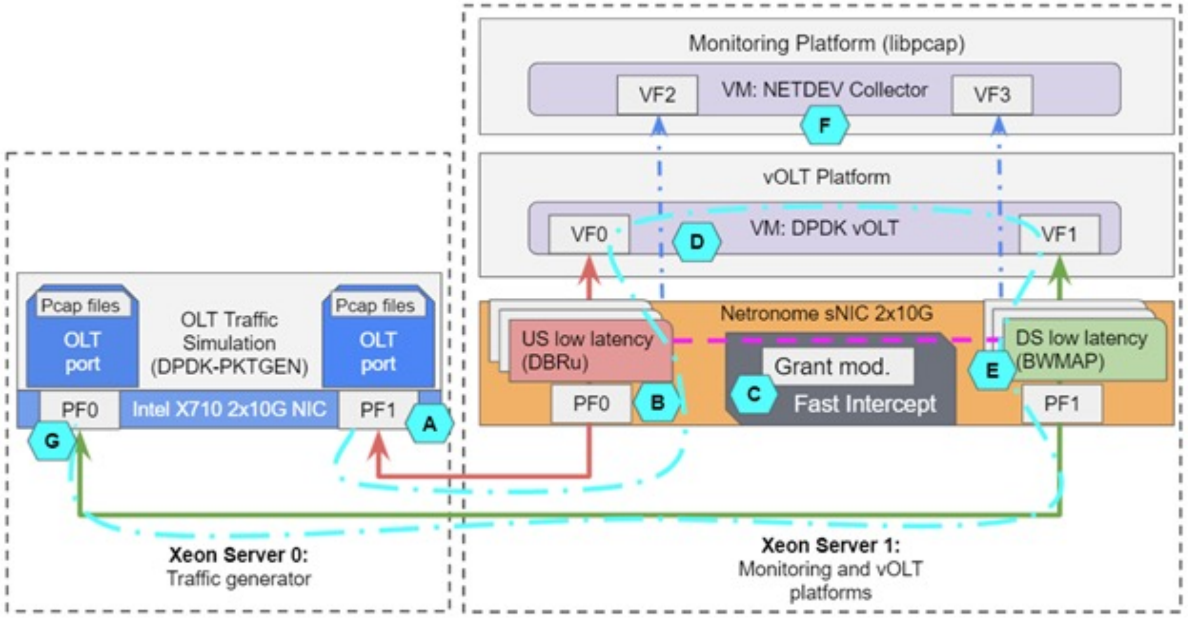


Fast intercept process



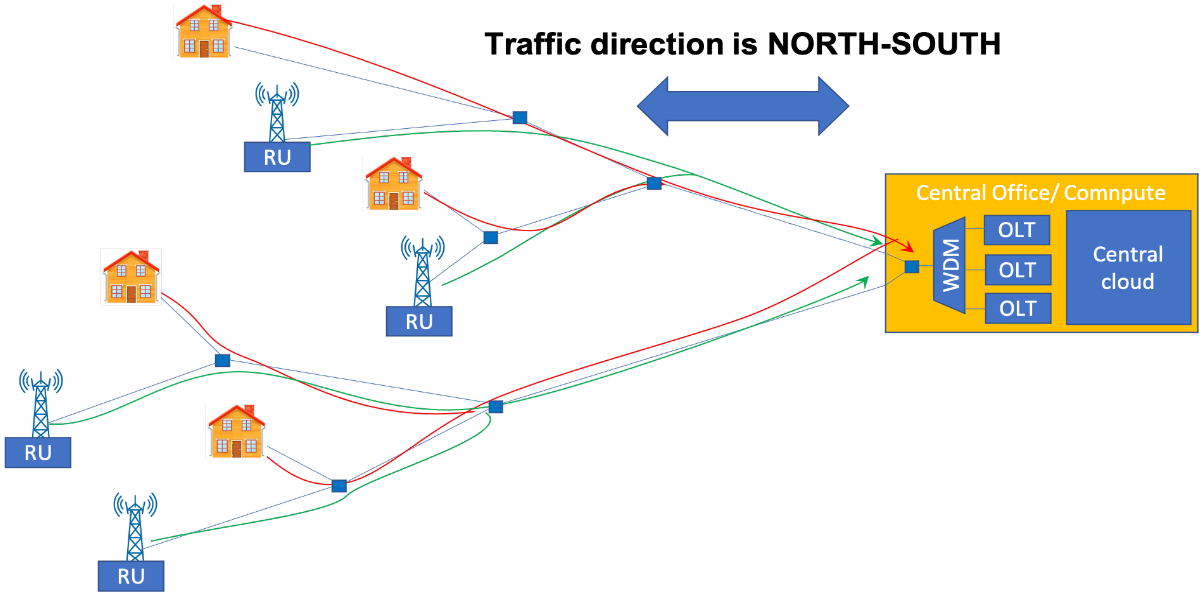
a. ONU waits for the opportunity for the DBRu
b. DBRu propagates through the fibre.
c. Information from phy to virtual process.
d. DBA process waits a time window to receive DBRus.
e. OLT runs the DBA algorithm.
f. BWMAP added to the next downstream frame.
g. BWMAP travels from virtual process to phy.
h. BWMAP propagates through the fibre.
i. ONU transmit the data at its allocated time.

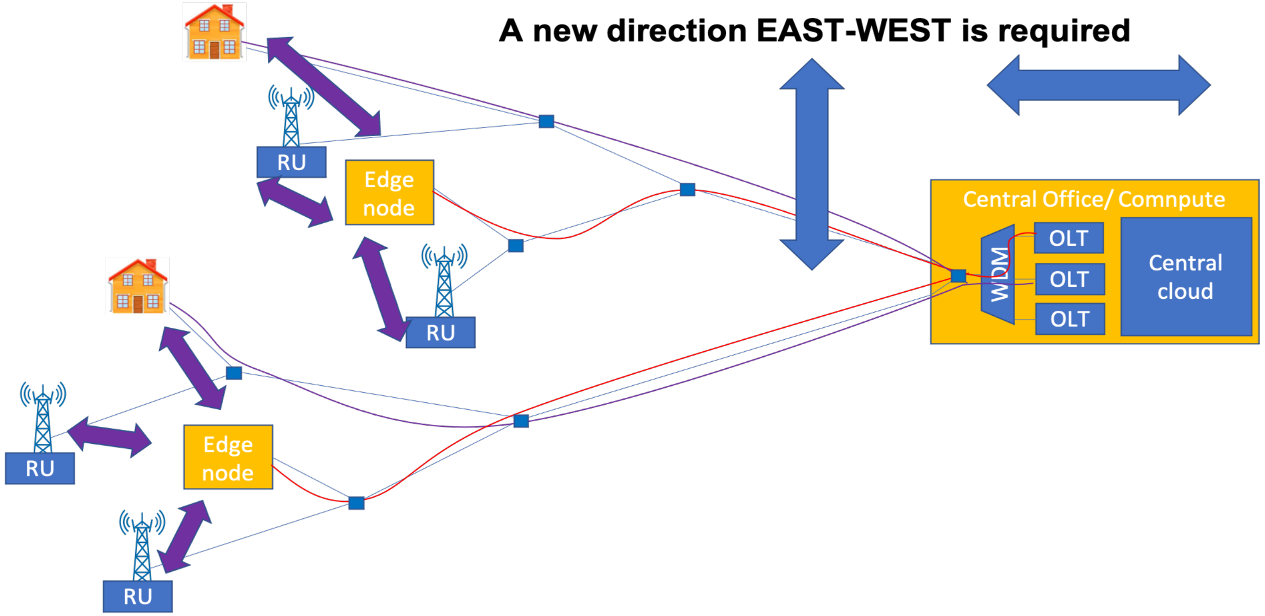
- Standard DBA best latency =~ **418.5µs** (virtual implementation)
- Fast intercept avg latency =~ **237 µs** (~ 43% faster)



The edge connectivity problem

- ➢PONs can carry the info back to the central office and can work for many applications

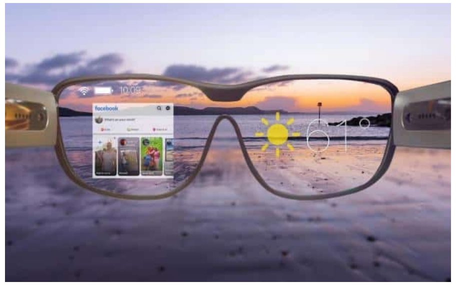


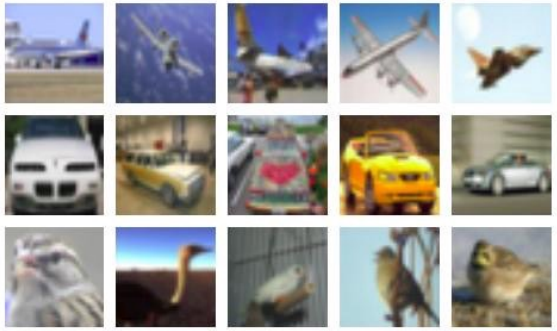


- ➢For lower latency there are MEC nodes… that's why they were invented
- ➢But traffic to edge nodes requires handling of direct end points communications (EAST-WEST)
- ➢This is also crucial for mobile functional split

High performance VR today

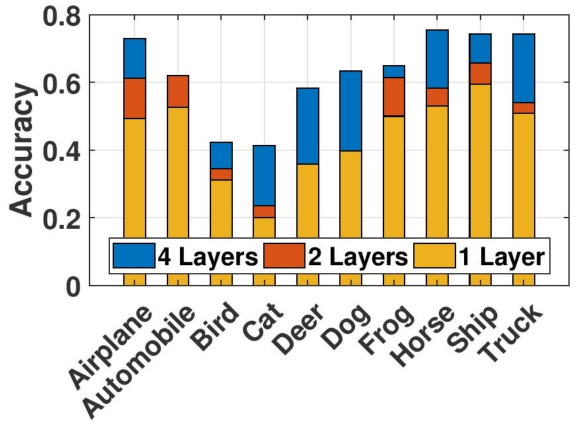
Object recognition





VS

laptop



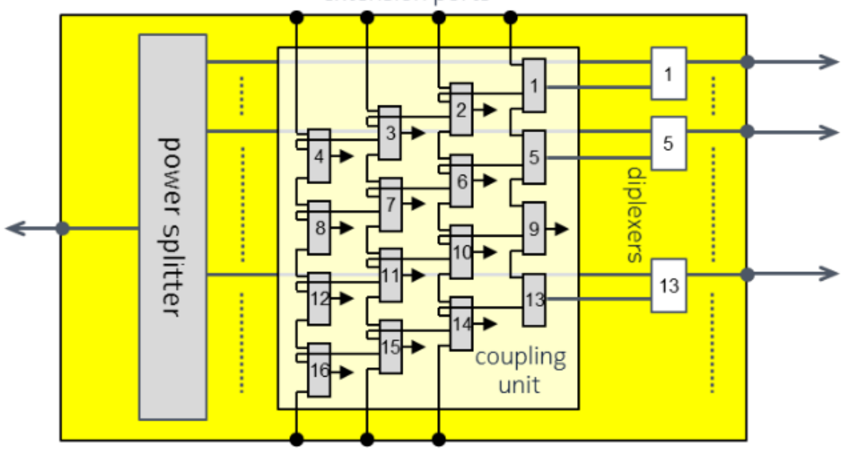
Average time: 2.537 s vs. 0.191

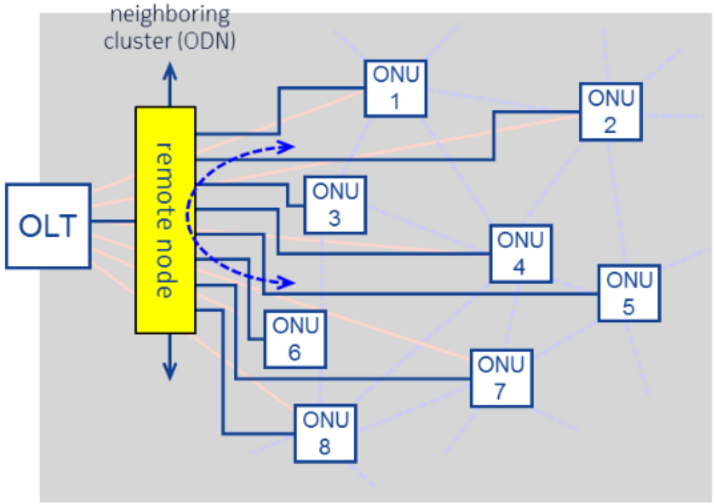
A. Galanopoulos, et al. Improving IoT Analytics through Selective Edge Execution, in proc. of IEEE ICC, 2020

PON-based solutions

Using active networks, with Ethernet switches at every splitter not a preferred option… so

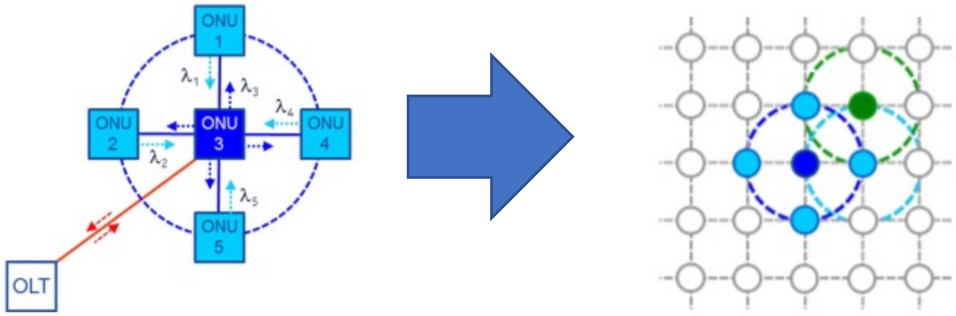
PON solutions:





Fully passive solution

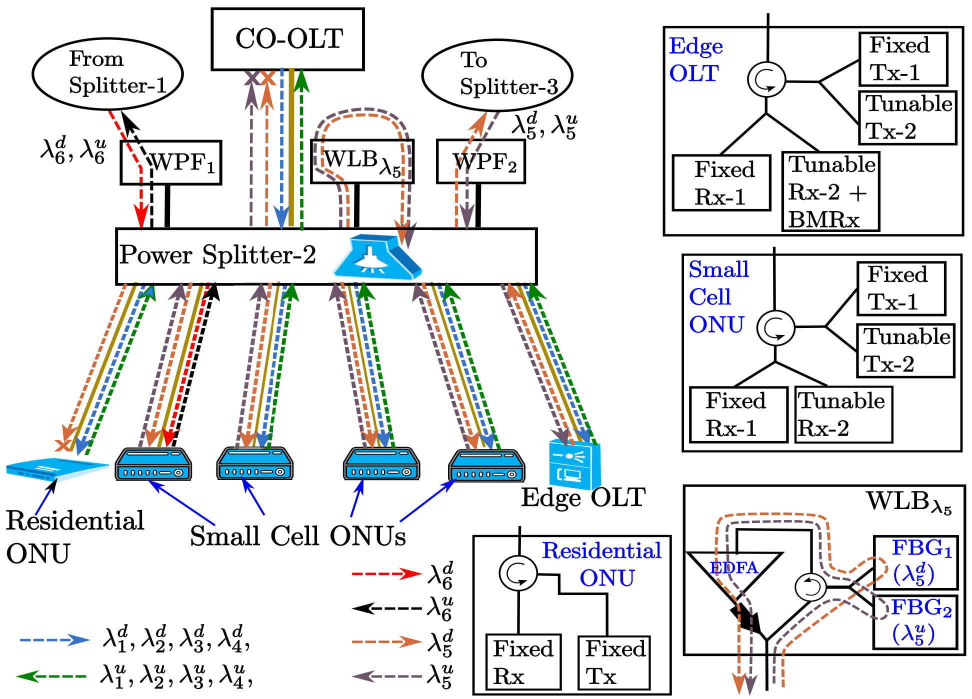
Th. Pfeiffer, “PON going beyond FTTH,” JOCN Jan. 2022.



Less flexibility in direct links, more suitable for macro to small cell communications

Actively controlled components

- ➢ Fully passive components are great but limit scalability.
- ➢ Proposing use of actively controlled component (i.e., tunable optical reflectors) can help improve scalability and control over slices.



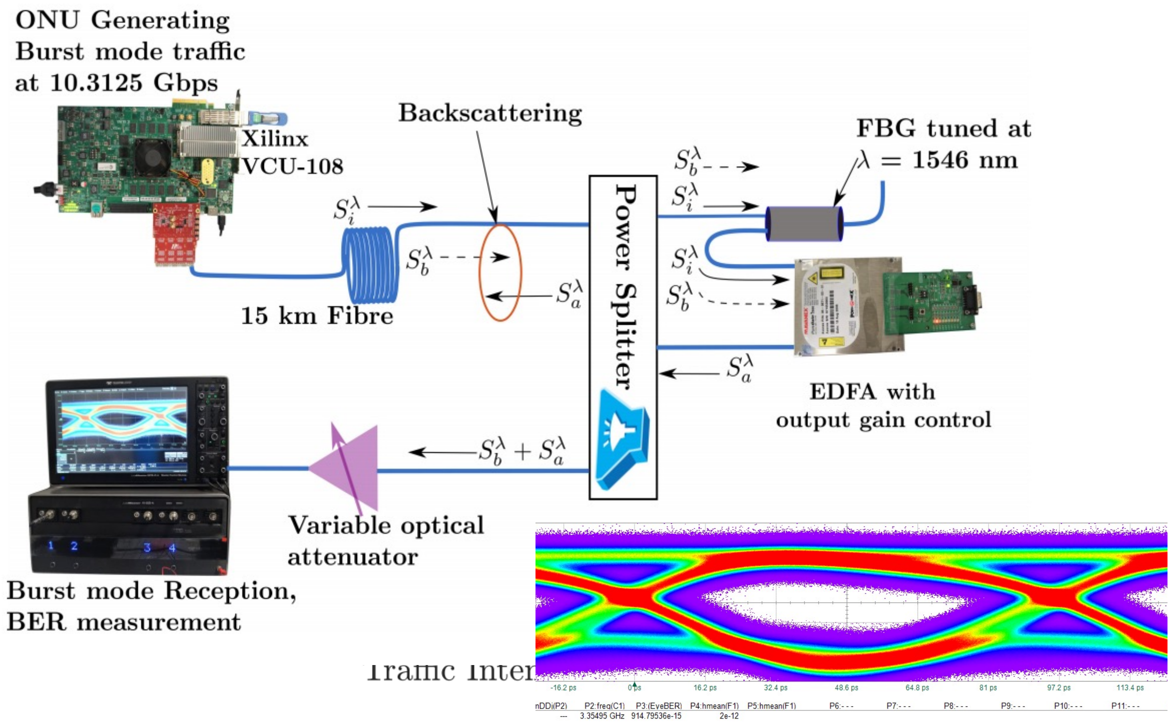
- ➢ Example use of Fibre Bragg Gratings
- ➢ Power loss going through splitter, but OK for last stage.
- ➢ Higher stage splitter might need amplifier integrated with FBG.

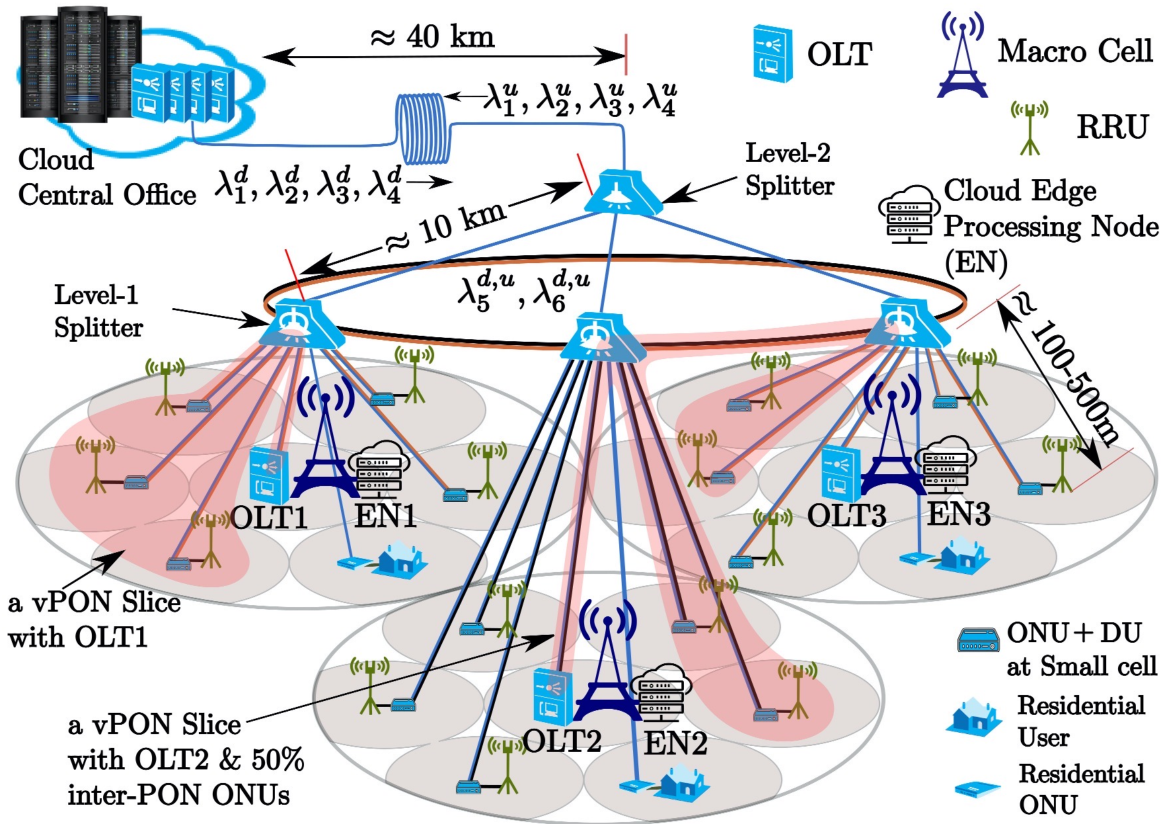
<u>Other technologies could be investigated…</u>
<u>e.g., power/wavelength re-configurable splitters</u>

- S. Das, M. Ruffini. PON Virtualisation with EAST-WEST Communications for Low-Latency Converged Multi-Access Edge Computing (MEC). OSA Optical Fiber Communications Conference (OFC), March 2020

Virtualisation aspects

- The core aspect is our virtualization technology (virtual DBA)
- Creation of dynamic slices with different group of end points.
- The MEC node can be located anywhere (at any PON end point)



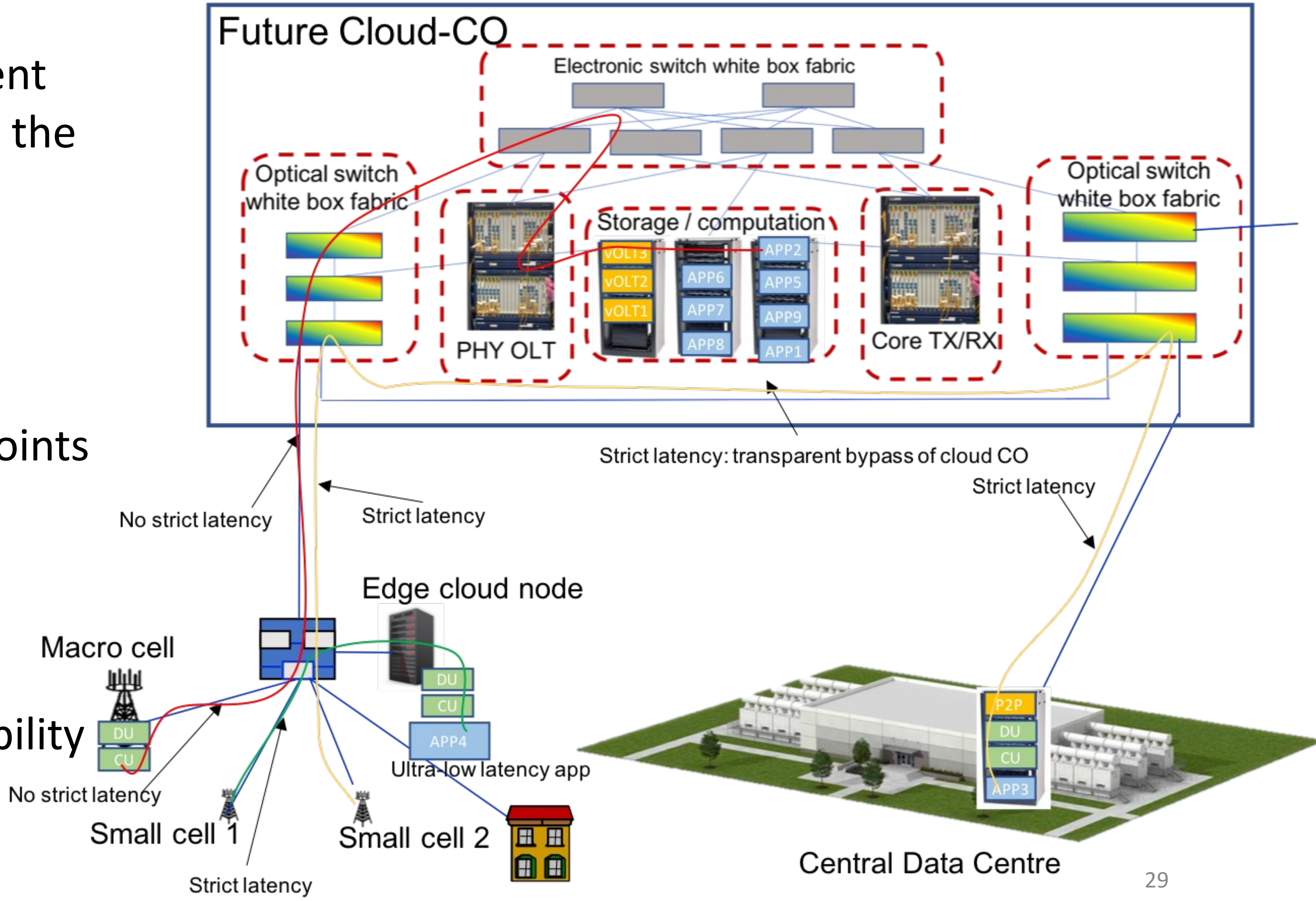


Largely unaffected by signal reflections

S. Das, F. Slyne, A. Kaszubowska and M. Ruffini. Virtualised EAST-WEST PON Architecture Supporting Low-Latency communication for Mobile Functional-Split Based on Multi-Access Edge Computing. OSA Journal of Optical Communications and Networking, No 10, Vol 12, October 2020

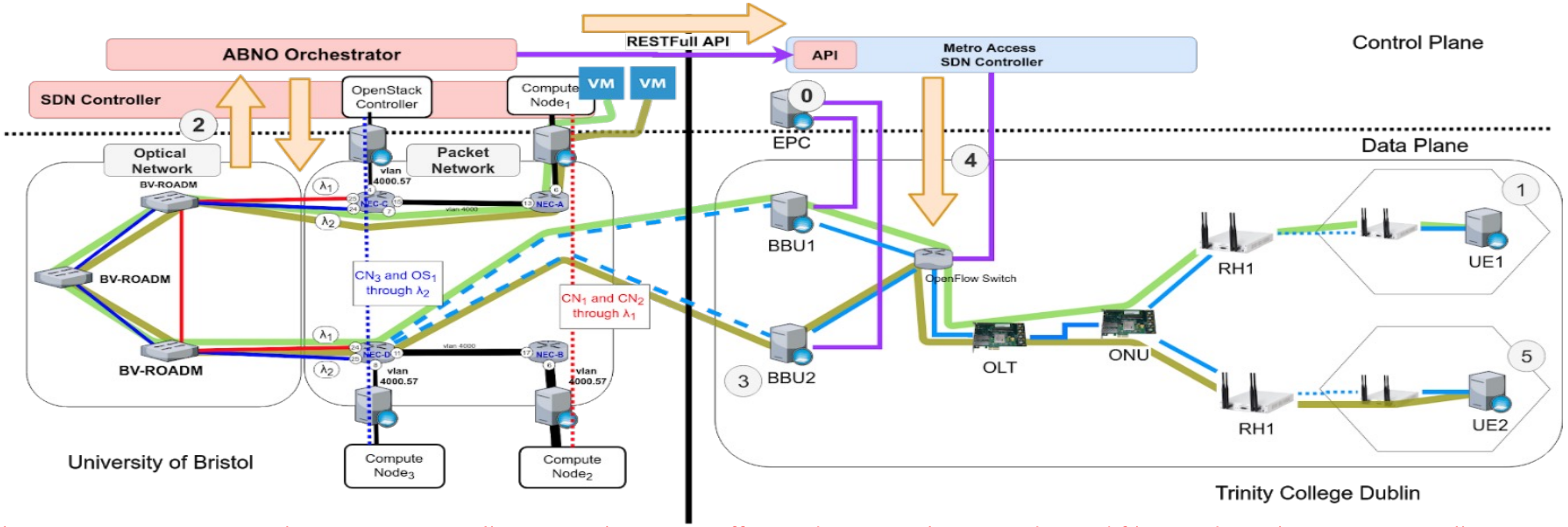
Extension to metro network

- Orchestration of transparent optical connections across the access and metro
- Flexibility in orchestrating computing (edge, CO and central)
- Flexibility in serving end points (cells and fixed users)
- Need for open optical networks for full programmability and flexibility



Demonstration of optical-wireless convergence

- Optical core network connected to servers representing content providers (UnivBris)
- Wireless edge network with fronthaul operating over fibre access PON (TCD)
- SDN system controlling:
  - optical core path and computing resources (UnivBris);
  - liaise with TCD controller for configuring TCD access network: adaptation between the BBU, the RRH and the PON enabling spectrum reuse across multiple adjacent cells.



F. Slyne, R.S. Guimaraes, Y. Zhang, M. Martinello, R. Nejabati, M. Ruffini and L.A. DaSilva. Coordinated fibre and wireless spectrum allocation in SDN-controlled wireless-optical-cloud converged architecture. Proc. of European Conference on Optical Communications – ECOC, September 2019

https://www.dropbox.com/s/tvp6il8dbol60em/ECOC%202019%20OW%20Demo.avi?dl=0

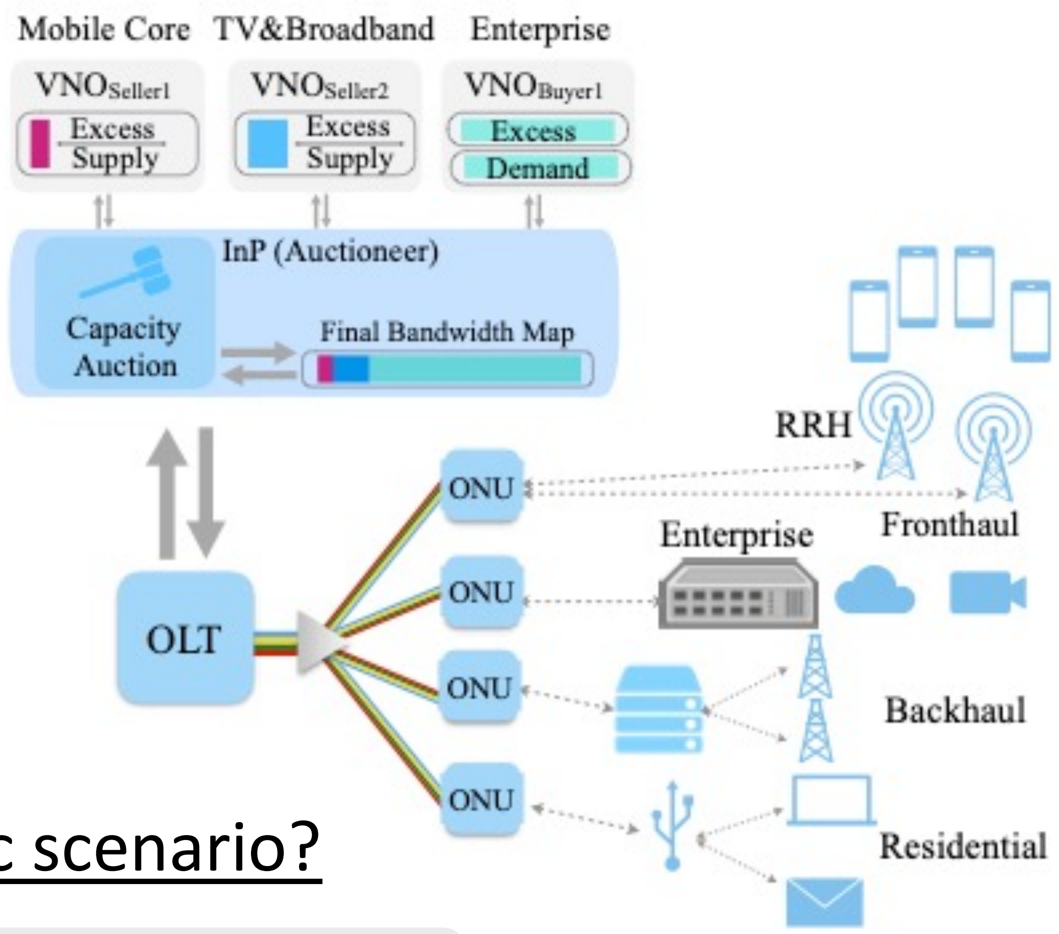
Multi-Tenant PON Market

Incentive Solution:

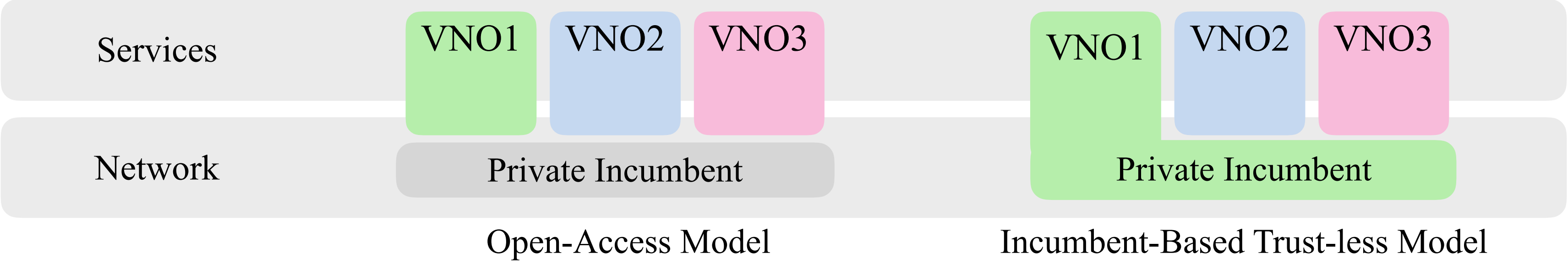
- Monetary Compensation for Excess Bandwidth

Market features:

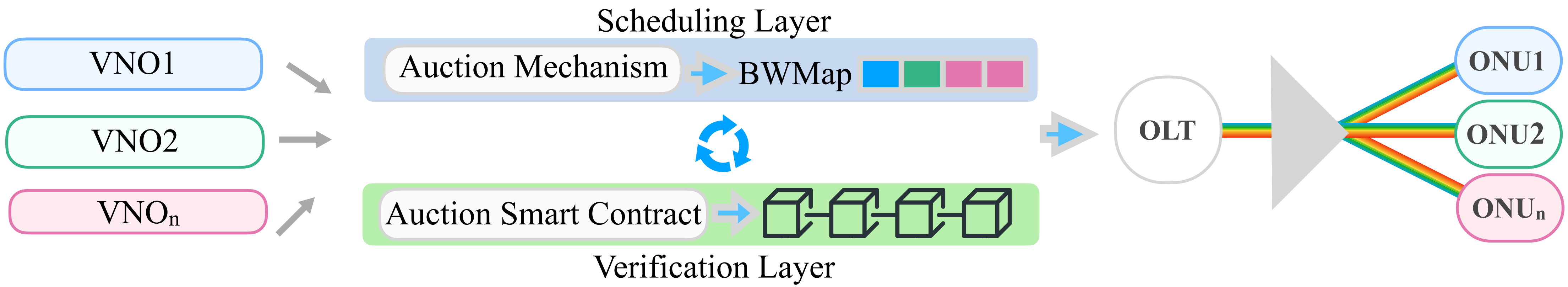
- Multiple traders (sellers, buyers) on both sides
- Multiple Identical frame units to trade
- Roles change in each frame

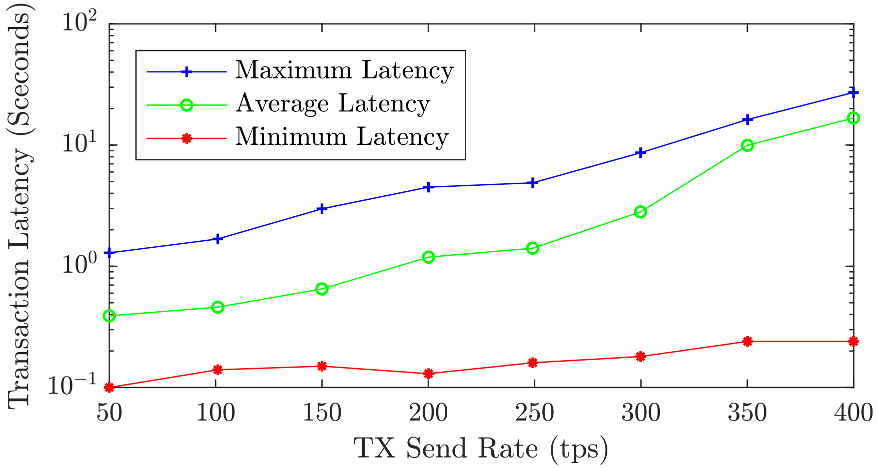


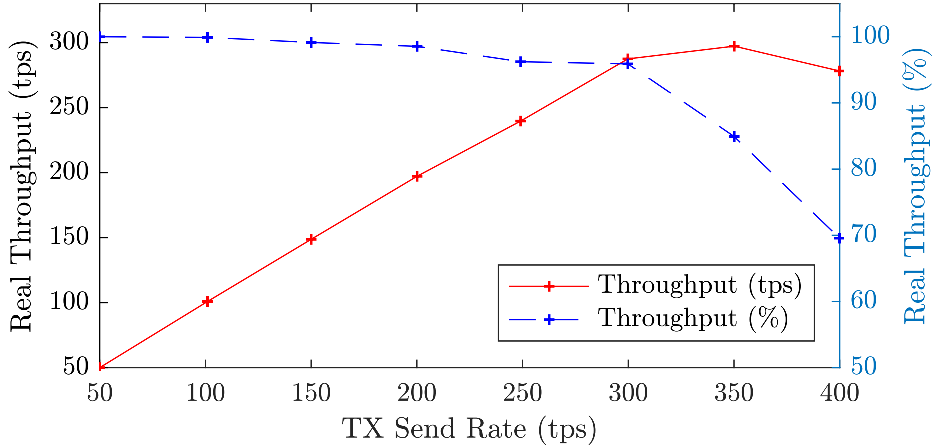
<u>How do you solve a more realistic scenario?</u>



Blockchain as verification mechanism







- N. Afraz and M. Ruffini. A Distributed Bilateral Resource Market Mechanism for Future Telecommunications Networks. Proc. of IEEE Globecom 2019.
- N. Afraz, M. Ruffini. 5G Network Slice Brokering: A Distributed Blockchain-based Market. IEEE EuCNC, June 2020

Summary of the talk

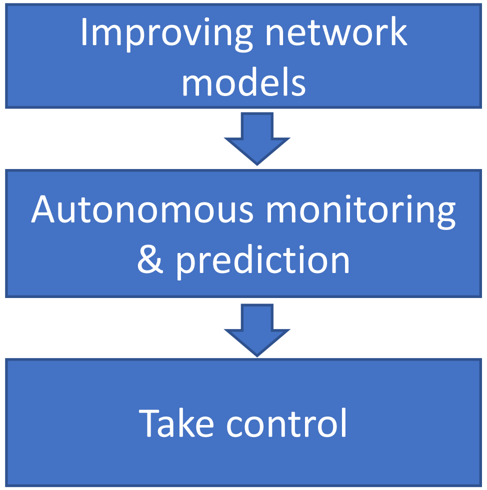
- Open networking trends
  - Opening mobile base stations
  - Opening the optical transmission layer
  - Opening the central office (access network)

- Linking to our work on PON virtualization (Aka what you can do once it’s in software)
  - Scheduler virtualization and software-based PON
  - Low-latency design
  - Support for MEC / deep edge computing
  - Optical-Wireless convergence
  - Fine-granularity multi-tenancy & blockchain

- Next step and digital twinning
  - Digital twinning an optical network
  - Key role of open testbeds: COSMOS and OpenIreland

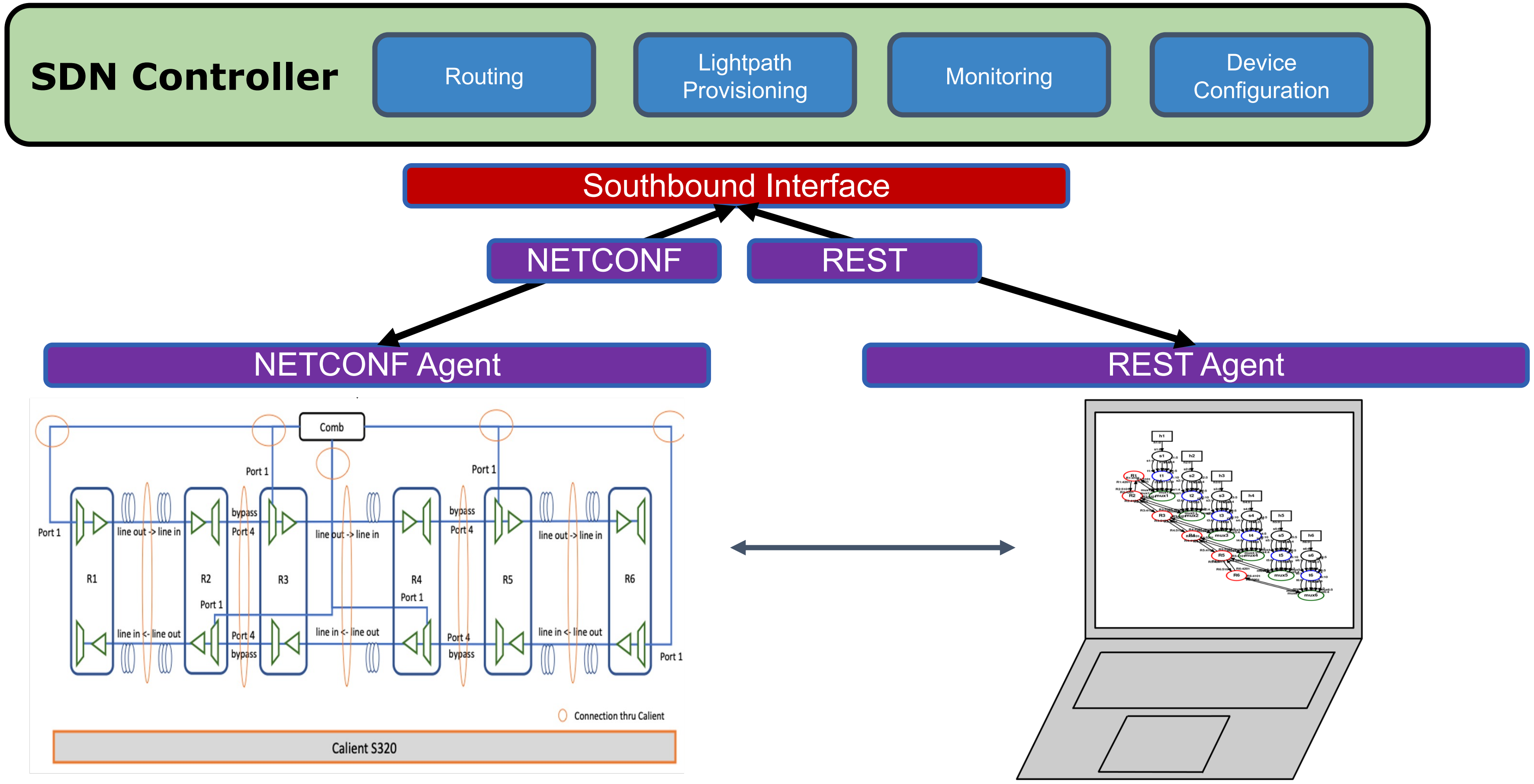
Next steps towards digital twinning

- What is a digital twin is a good topic of discussion:
- Emulation of specific aspects of its twin network (i.e., doesn't need to replicate all layers)
- Live interaction between emulated and real network:
    - Use real input/output data from network to improve models across an increasing number of states/scenarios
    - Predict network states that can lead to anomaly (malfunctions or simple SLA breach): <u>*Decide when to monitor what*</u>
    - Ultimate goal is that of autonomous decision making and trusting the twin to fully manage the networks



- A testbed is essential to enable this type of research
- An open testbed enables research and collaboration on these topics across academic and industrial partners

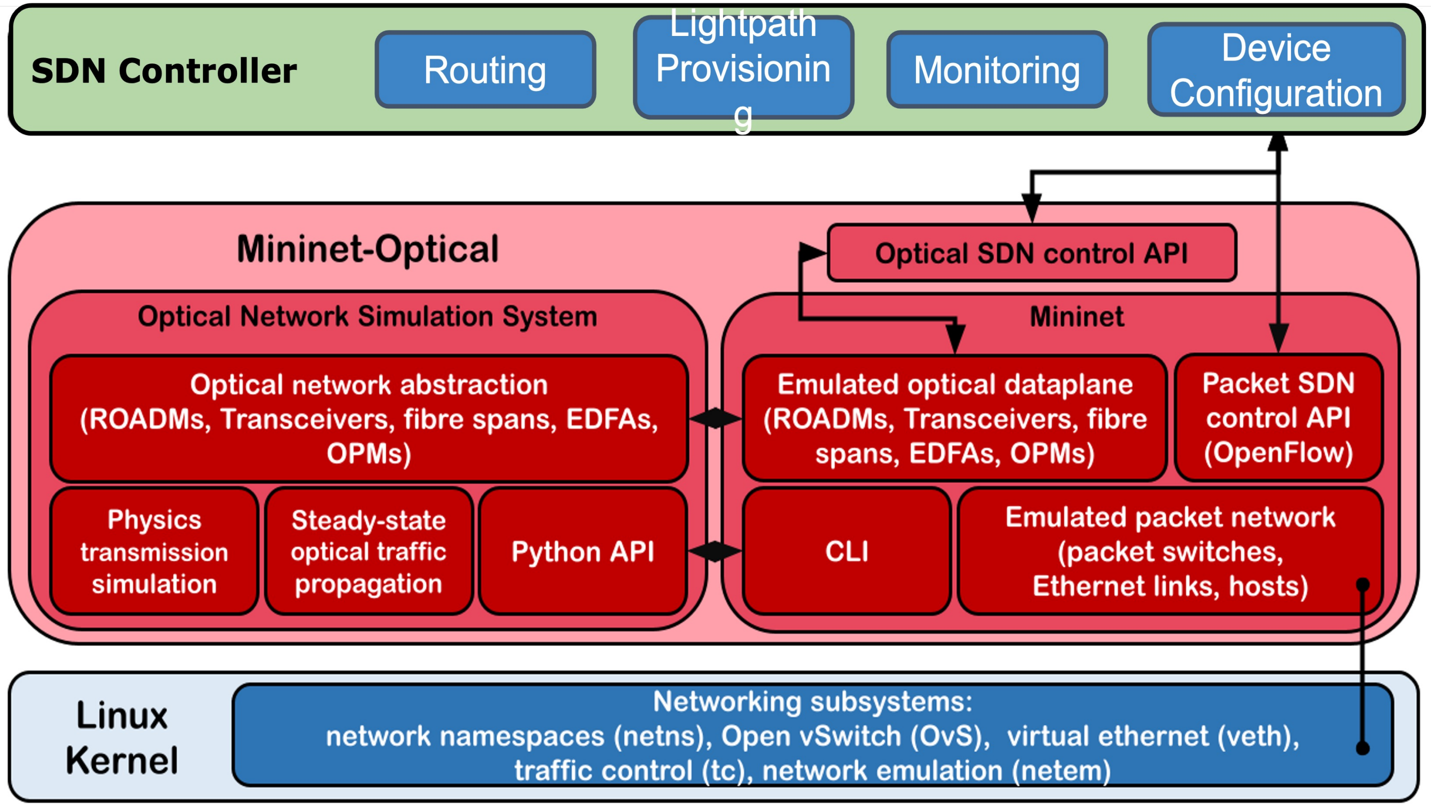
Building a digital twin for Open Access testbeds



Hardware network on testbed

Virtual network in Mininet-Optical

Experimentation through open source software: Mininet-Optical



- A. Diaz-Montiel, B. Lantz, J. Yu, D. Kilper and M. Ruffini. Real-Time QoT Estimation through SDN Control Plane Monitoring Evaluated in Mininet-Optical. IEEE Photonics Technology Letters, April 2021.
- A. Diaz-Montiel, A. Bhardwaj, B. Lantz, J. Yu, A.N. Quraishy, D. Kilper and M. Ruffini. Real-Time Control Plane Operations for gOSNR QoT Estimation through OSNR Monitoring. OSA Optical Fiber Communications Conference (OFC), June 2021
- B. Lantz, A. Diaz-Montiel, J. Yu, C. Rios, M. Ruffini and D. Kilper. Demonstration of Software-Defined Packet-Optical Network Emulation with Mininet-Optical and ONOS. OSA Optical Fiber Communications Conference (OFC), March 2020

Node types:

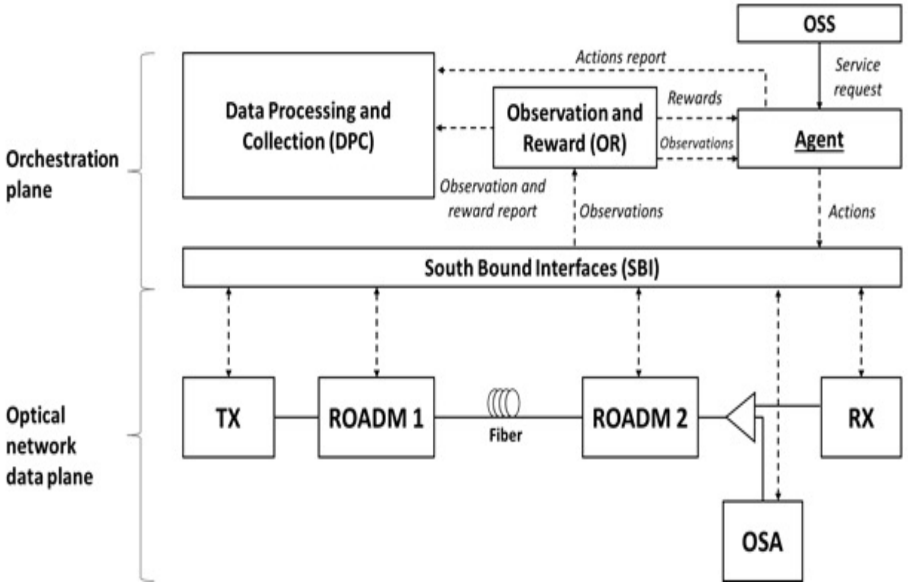
- Transponders: modulation, baud rate, power, wavelength, BER from gOSNR
- ROADMs: insertion loss, variable attenuation, wavelength routing, booster/preamp
- EDFA: linear gain, wavelength dependent gain, ASE, automatic gain control mode
- Fibre length: attenuation, dispersion, SRS, nonlinear impairments through the GN model
- Performance monitors to emulate different types: power, OSNR, gOSNR,…

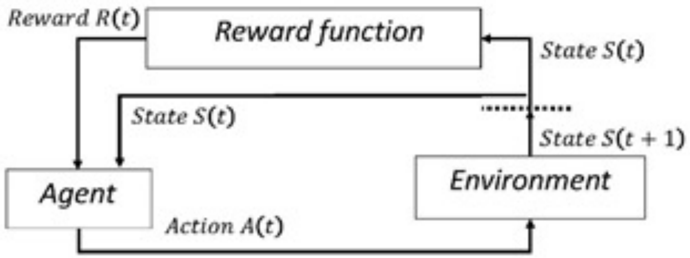
```
def build( self, txCount=4 ):
        "Build our network topo"
        h1, h2 = self.addHost('h1'), self.addHost('h2')
        transceivers = [('t%d' %t, 0*dBm, 'C')
                        for t in range(1, txCount+1) ]
        t1, t2 = [ self.addSwitch( name, cls=Terminal,
                                   transceivers=transceivers )
                   for name in ('t1', 't2') ]
        self.ethLink( h1, t1 )
        self.ethLink( h2, t2 )
        boost = ( 'boost', dict(target_gain=1.0) )
        spans = [ 50.0, ( 'amp1', dict(target_gain=50*.22) ),
                  50.0, ( 'amp2', dict(target_gain=50*.22) ) ]
        self.wdmLink( t1, t2, boost=boost, spans=spans)
```

Sampe use case: Building a QoT estimation algorithm

Control plane algorithm development and test based on simulation:

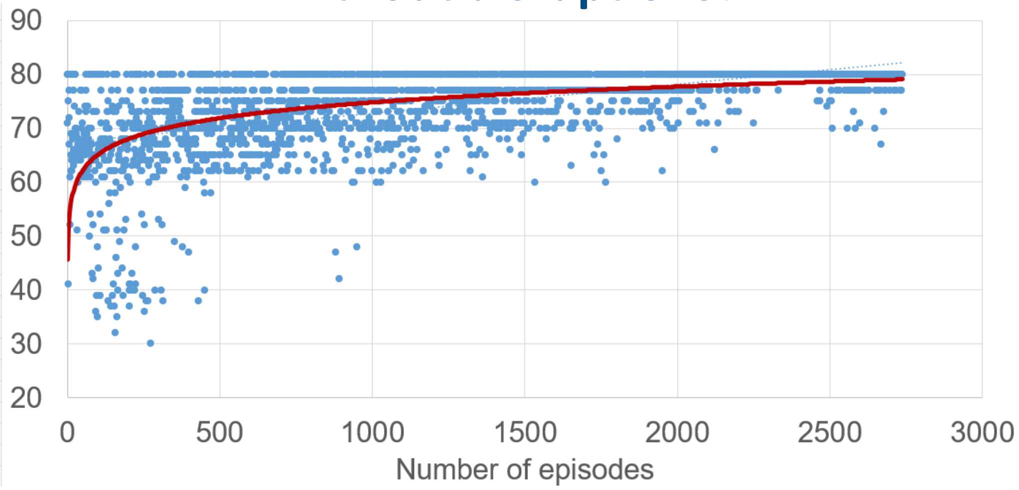
- Online learning through agent that loads the optical spectrum with optical channel and measures OSRN variation
- Through multiple iterations the agent improves strategy for channel selection





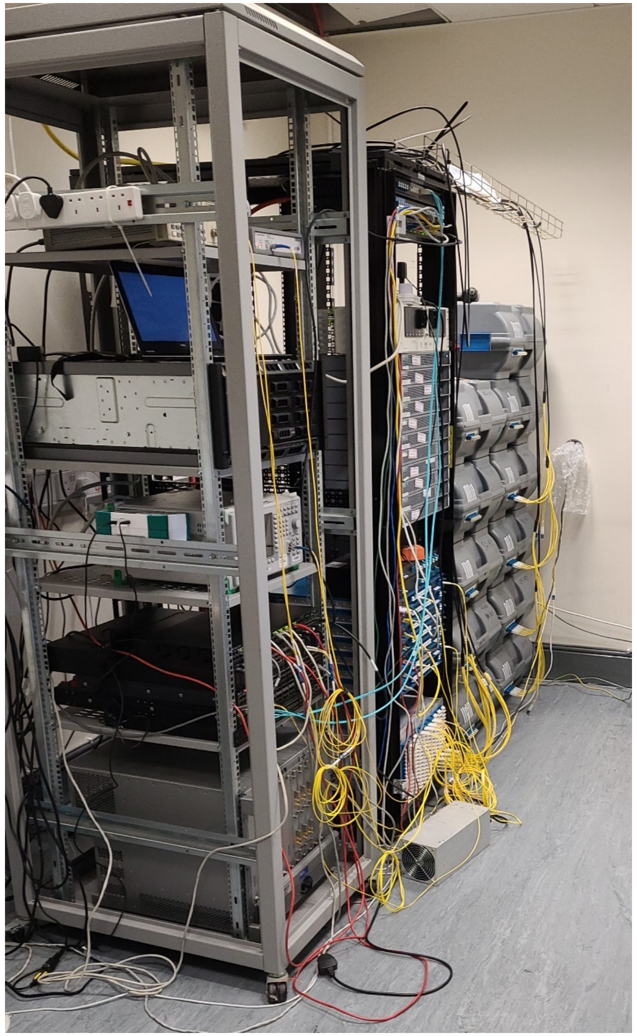
Work carried out by Politecnico di Milano optical group

How many channels are allocated without disruptions?



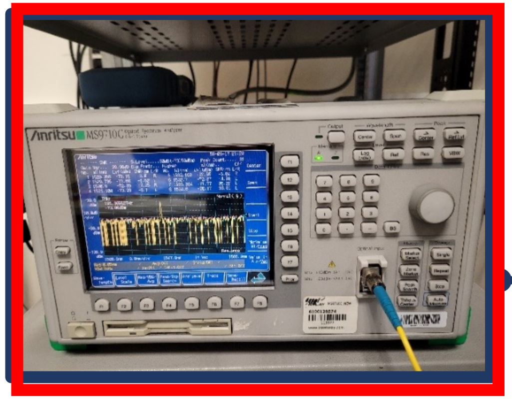
Use of simulated data plane

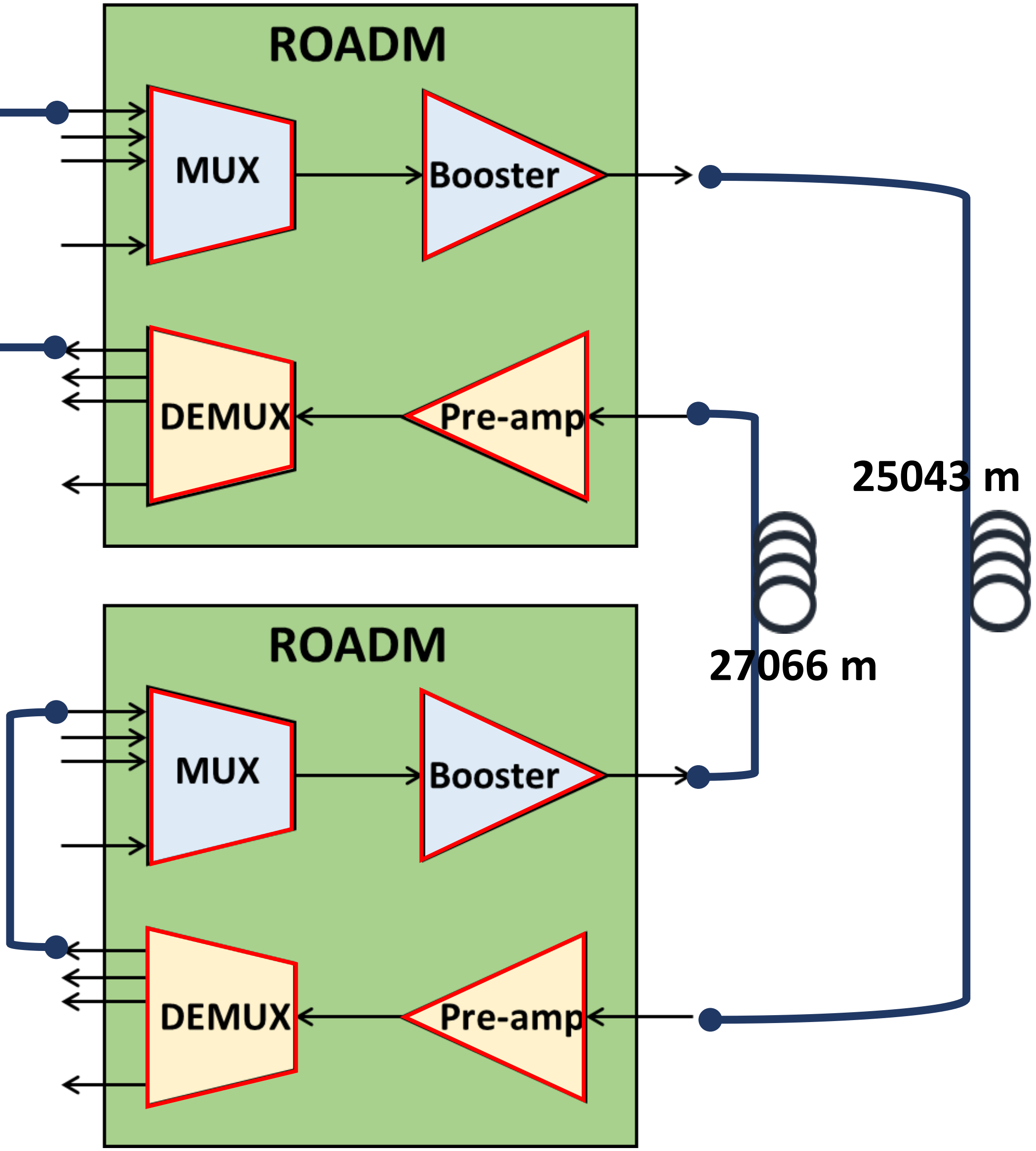
Moving into the testbed



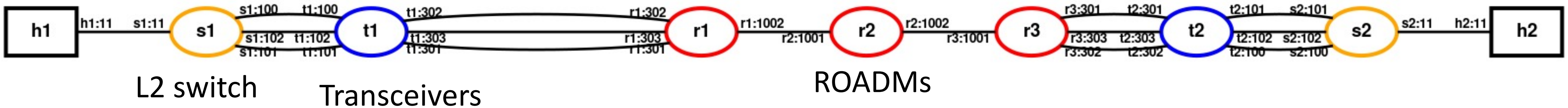
Channel generation: ASE noise spectrally shaped into channels by ROADM WSS

OSA





… towards seamless switching between Network & Emulation



Testbed control plane vs Digital twin control plane

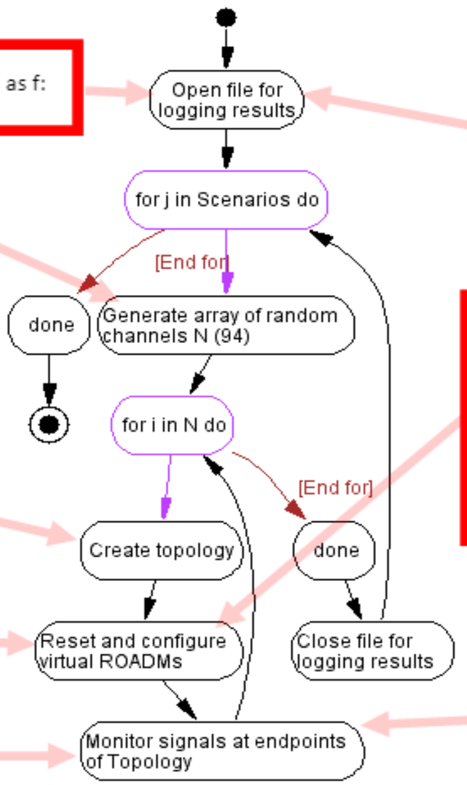
```
with open('data_collection/sample_channels_4.txt', 'w') as f:
    f.write("%s\n" % channels)
```

```
channels = utils.generateRandom(94)
agents.runner_parallel_agents(channels, 'close')
```

Physical Topology Configured already

```
agents.runner_parallel_agents([i], 'open')
```

```
item_a = obs.check_first_signal_level(item_a)
```



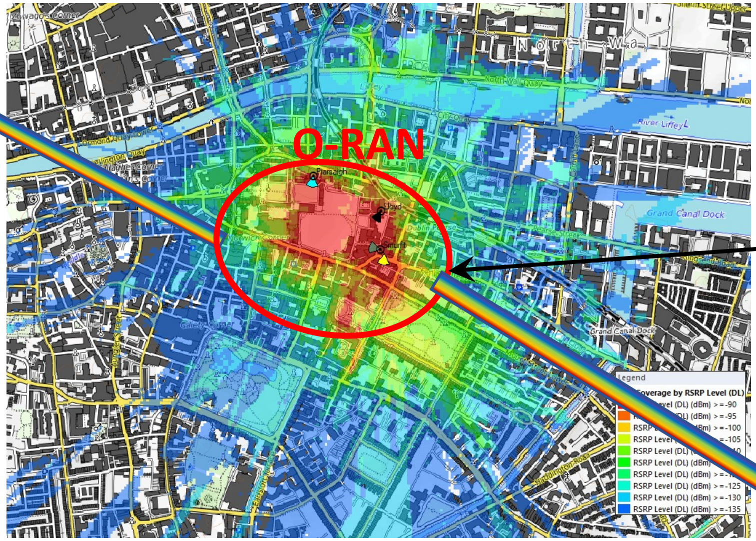

```
# URL for REST server
url="localhost:8080"; t1=$url; t2=$url; r1=$url; r2=$url; r3=$url
curl="curl -s"

echo "* Resetting terminal"
$curl "$t1/reset?node=t1"
$curl "$t2/reset?node=t2"
```

```
for ch in $(seq 1 $numCh); do
    echo "* Configuring ROADM to forward ch$ch from t1 to t2"
    port=$((300 + ${chArray[ch-1]}))
    $curl "$r1/connect?node=r1&port1=$port&port2=1002&channels=${chArray[ch-1]}"
    $curl "$r2/connect?node=r2&port1=1001&port2=1002&channels=${chArray[ch-1]}"
    $curl "$r3/connect?node=r3&port1=1001&port2=$port&channels=${chArray[ch-1]}"
done
```

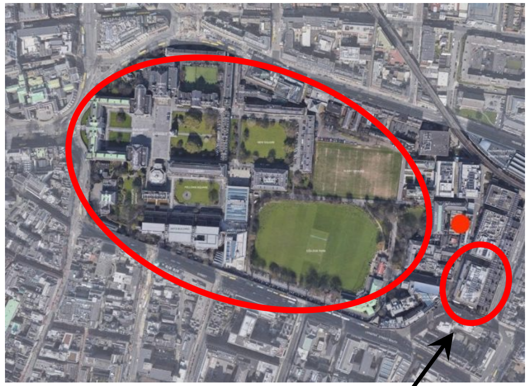
```
for tname in t1 t2; do
    url=${!tname}
    echo "* $tname"
    $curl "$url/monitor?monitor=$tname-monitor"
    echo " " >> testResult.txt
    $curl "$url/monitor?monitor=$tname-monitor" >> testResult.tx
done
```

Open Ireland: Ireland's Open Networking Testbed



www.openireland.eu

Based in Trinity College campus

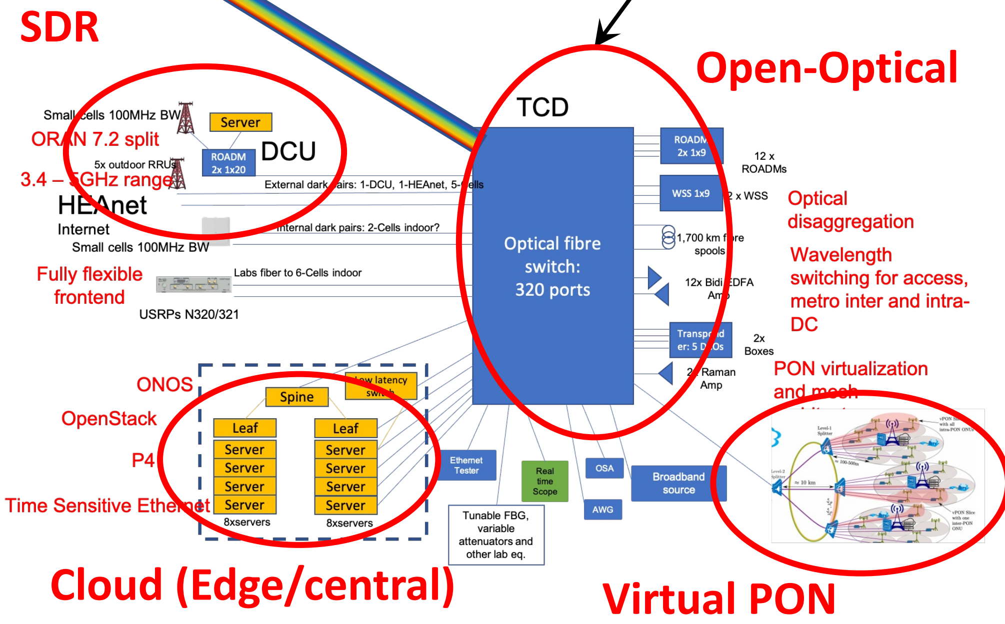


O-RAN

CONNECT research centre building

Reconfigurable and **Lego-like** topology reconfiguration with following blocks:

- 1,700km fibre, **SDN ROADMs**, **amplifiers and coherent Tx** (Cassini), virtual PON, OSA, etc.
- **5G O-RAN** (outdoor and indoor); **OpenSource 5G** (OAI and SRS)
- **Edge cloud**, L2 switching, P4 programmability



Run an experiment:

- Use optical fibre switch to put together a suitable physical topology of such blocks
- Load your image into servers for data plane (5G-SDR, Virtual PON, etc..)
- Load your SDN control plane and run experiment (execute commands, read network parameters, train ML algorithm, etc.)

ComReg 100MHz spectrum license

Existing 3.6 GHz for 5G | **Upper 4 GHz band for 5G**

Region	Guard Band	A-Lot		B-Lots					
Borders Midlands & West South West East South East Dublin City and Suburbs Cork City and Suburbs Galway City and Suburbs Limerick City and Suburbs Waterford City and Suburbs		Airspan	State Services	Vodafone	Imagine	Airspan	Meteor	Three	CONNECT
Frequency Range (MHz)		3410 - 3435	3410 - 3475	3475 - 3580	3560 - 3620	3580 - 3615	3615 - 3700	3700 - 3800	3850 - 3950

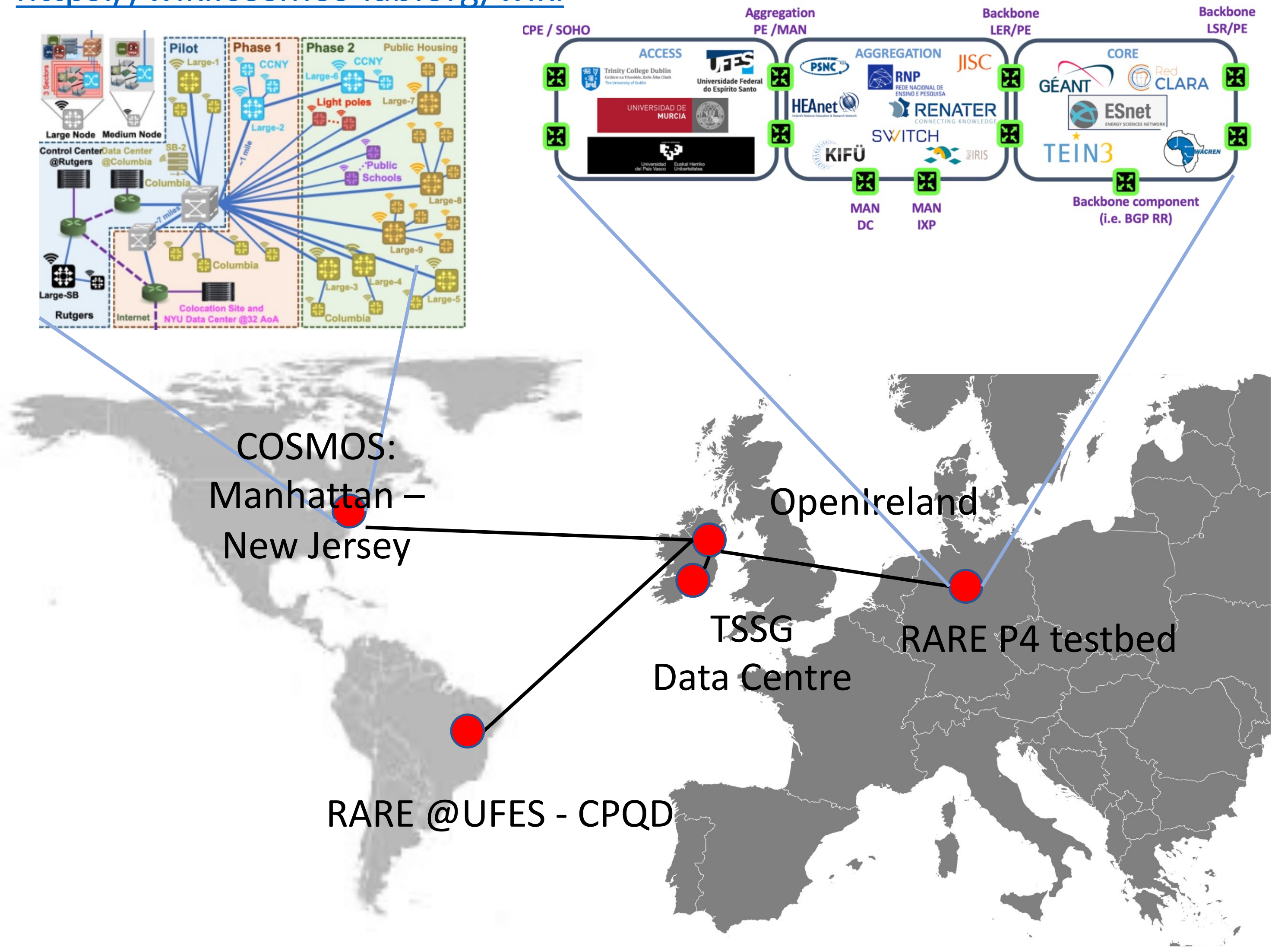
Upper N77 band: 3.8 – 4.2 GHZ

- 5G spectrum enables experimentation with commercial devices (smartphones and future AR, smart cities, etc)

- Use AI to solve complex network interference optimization problems based on real data
- Put together interesting 5G demos, such as smart intersection…

Worldwide reach… and further plans

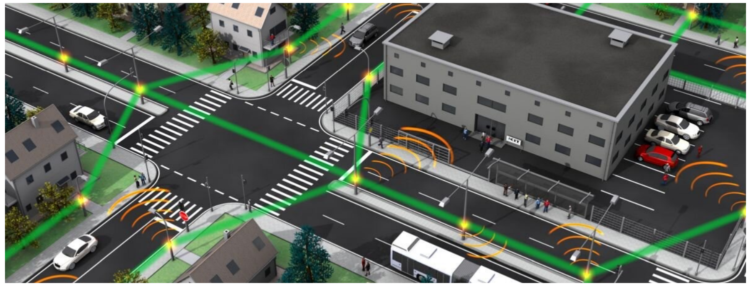
https://wiki.cosmos-lab.org/wiki



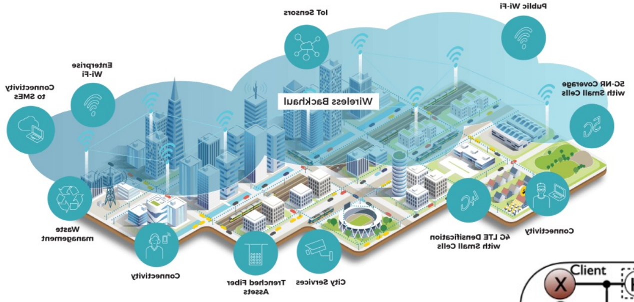
Foundation testbed in CONNECT2

Starting point for further exploration:

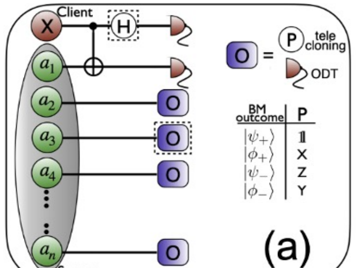
⇒ ***mmWave and THz experimentation***



⇒ ***Connected City Infrastructure***

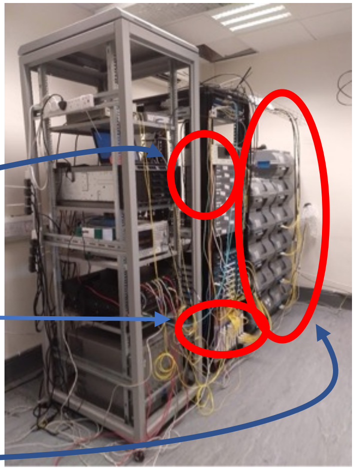


⇒ ***Quantum Internet***

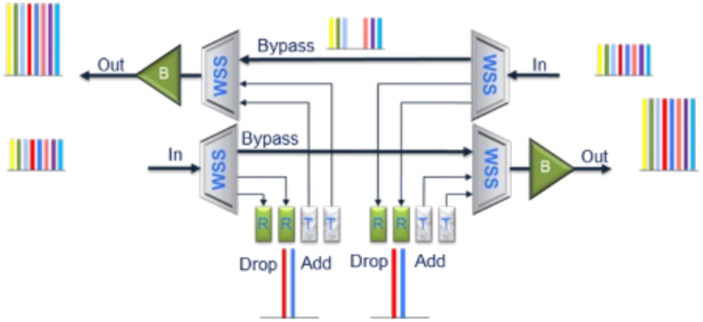


Optical devices

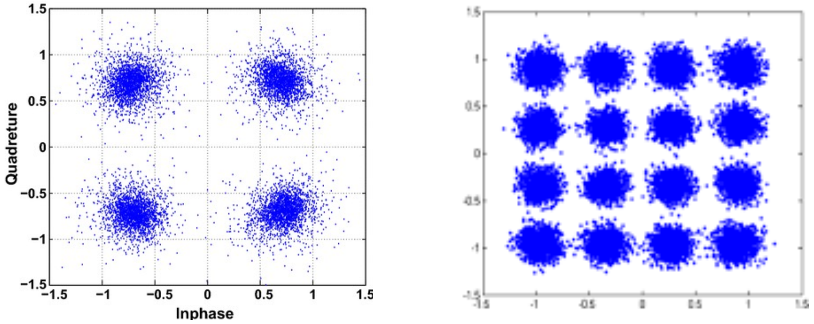
- Large count fibre switch: allows creating any physical fibre topology and interconnect
  - Connect any fibre to any other fibre, measure power
- 1,700 km fibre, power splitters, etc.
- 11 x Inline optical amplifiers



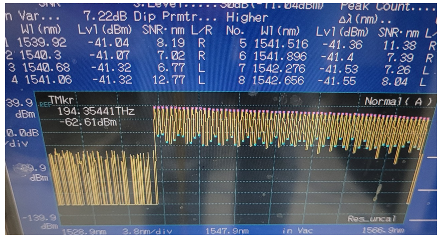
- 11 x ROADMs (lumentum graybox): allow switching of optical wavelength channels across
  - Actions: add/drop channel (set filters), set amplification params, variable attenuation, measure power at wavelengths and ports



- 8 x coherent transceivers: allow long distance transmission and software-defined modulation format (DP-QPSK – 100Gb/s, 1,200 km; DP-16QAM – 200Gb/s, 600km)
  - Actions: set wavelength, power, modulation, FEC,… measure power, BER (deduct OSNR), constellation



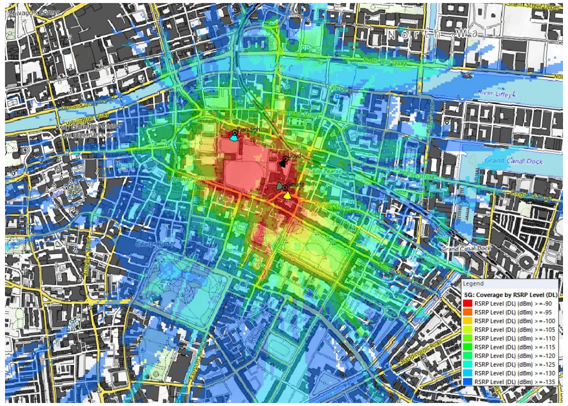
- 1 x Comb generator: spectrally shape (filter) random photons to emulate data channels of a given spectral width.
  - Generate arbitrary number of channel at given power



Wireless devices

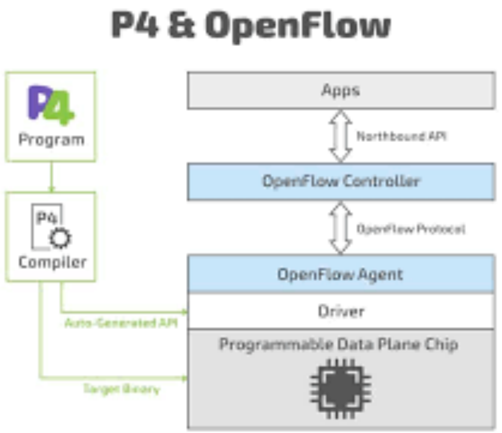
- USRPs:
  - 8 x X310, 8 x B210
    - Implement radio part for open source SDR (OAI, SRS), in non standalone and standalone
      - Currently getting 100Mb/s out of standalone OAI
    - Implement 7.2 split (upcoming) – with functions in USRP FPGA
  - In addition to many other existing USRPs

- Commercial O-RAN based on 7.2 split
  - 2 x Indoor units – 100MHz, 4x4 MIMO, 24 dBm per port
  - 4 x Outdoor units – 100MHz, 4x4 MIMO, 37 dBm per port* (4GHz band restricted to 30 dBm total EIRP)
  - Accelleran (DU) – CU and RIC



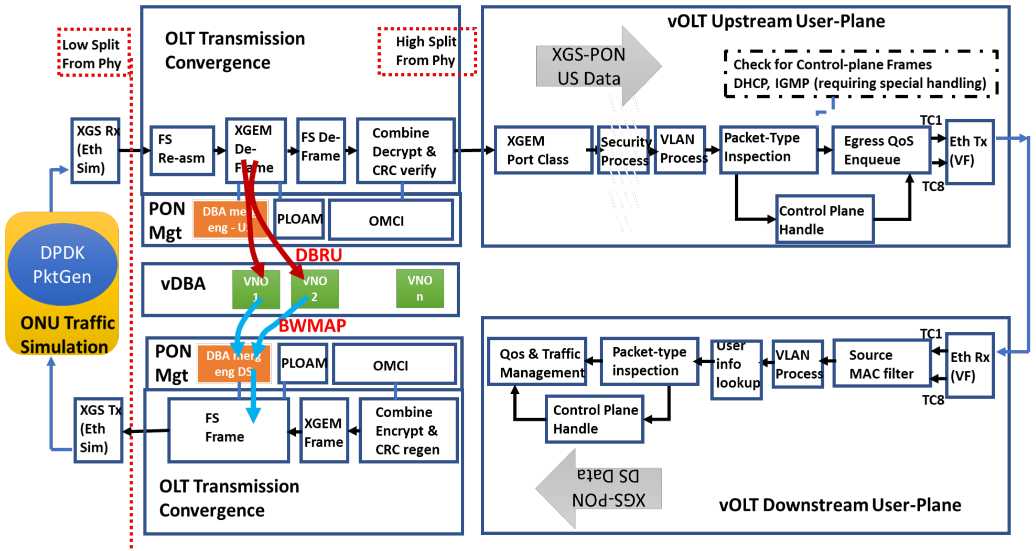
L2 and above infrastructure

- Servers:
  - 6 x high performance (data plane switching, virtual network functions, SDR, DU/CU/RIC)
  - 3 x Network virtualization services



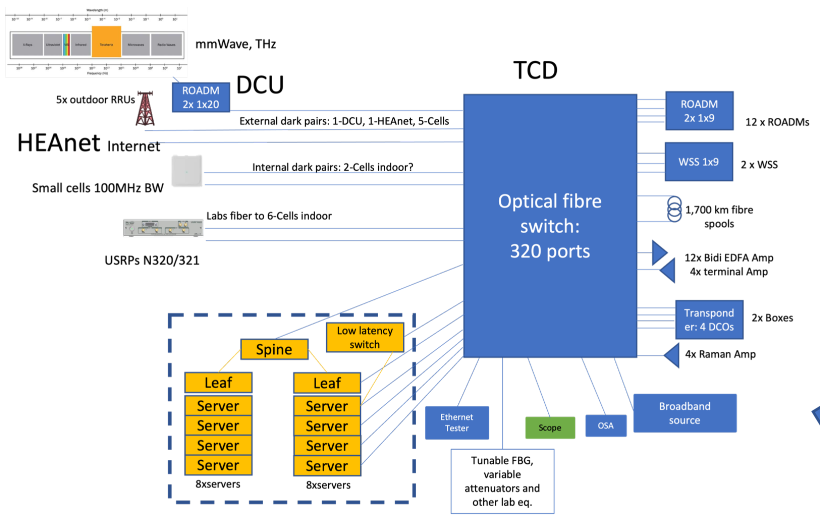
- Switches:
  - P4-enabled SDN switch (programmable data plane)
  - SDN enabled Low latency L2 switch
  - Management switches

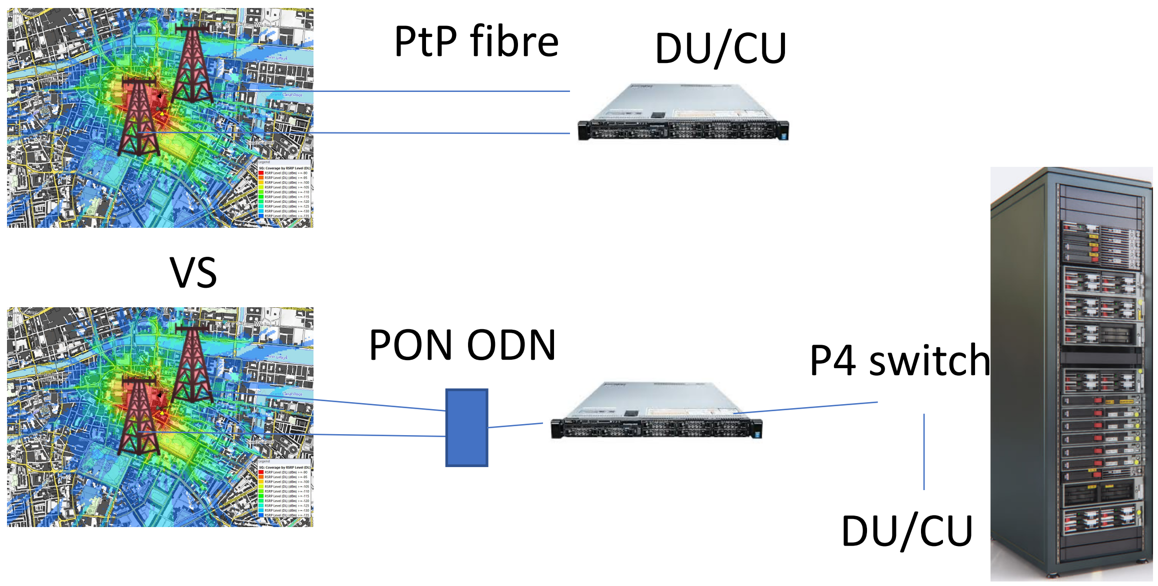
- Virtual PON:
  - Full virtualized Passive Optical Network
  - Standard compliant XGS (10G symmetric) PON
  - Additional TCD IP of virtual DBA (scheduler virtualization)



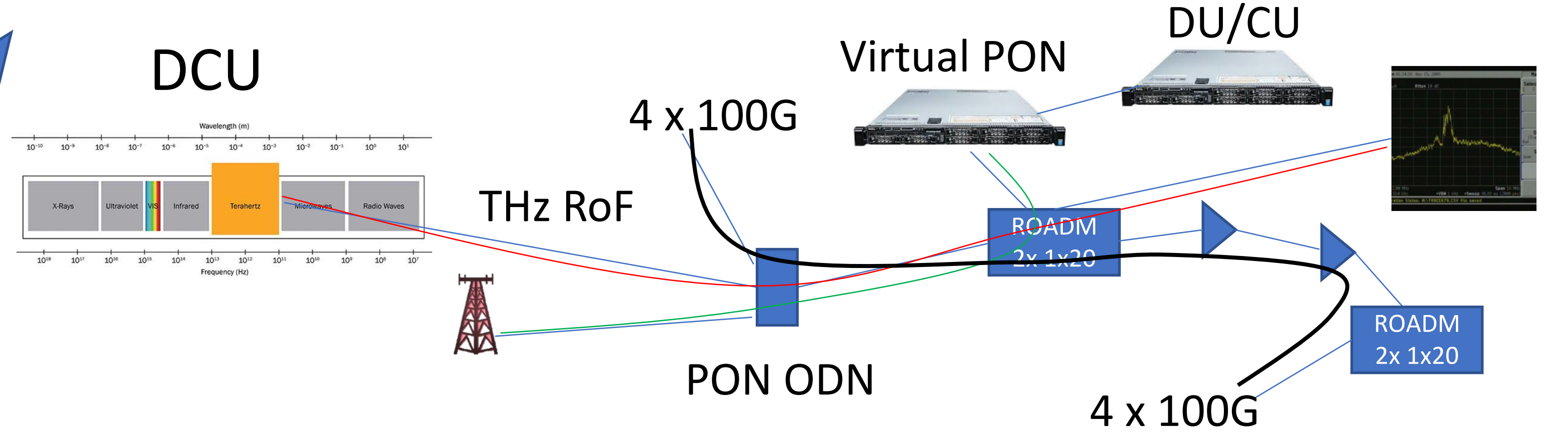
The power of topological reconfiguration

- Use case 1: Compare different O-RAN fronthaul, for meeting basic requirements, effect on performance for advanced RIC-based coordination



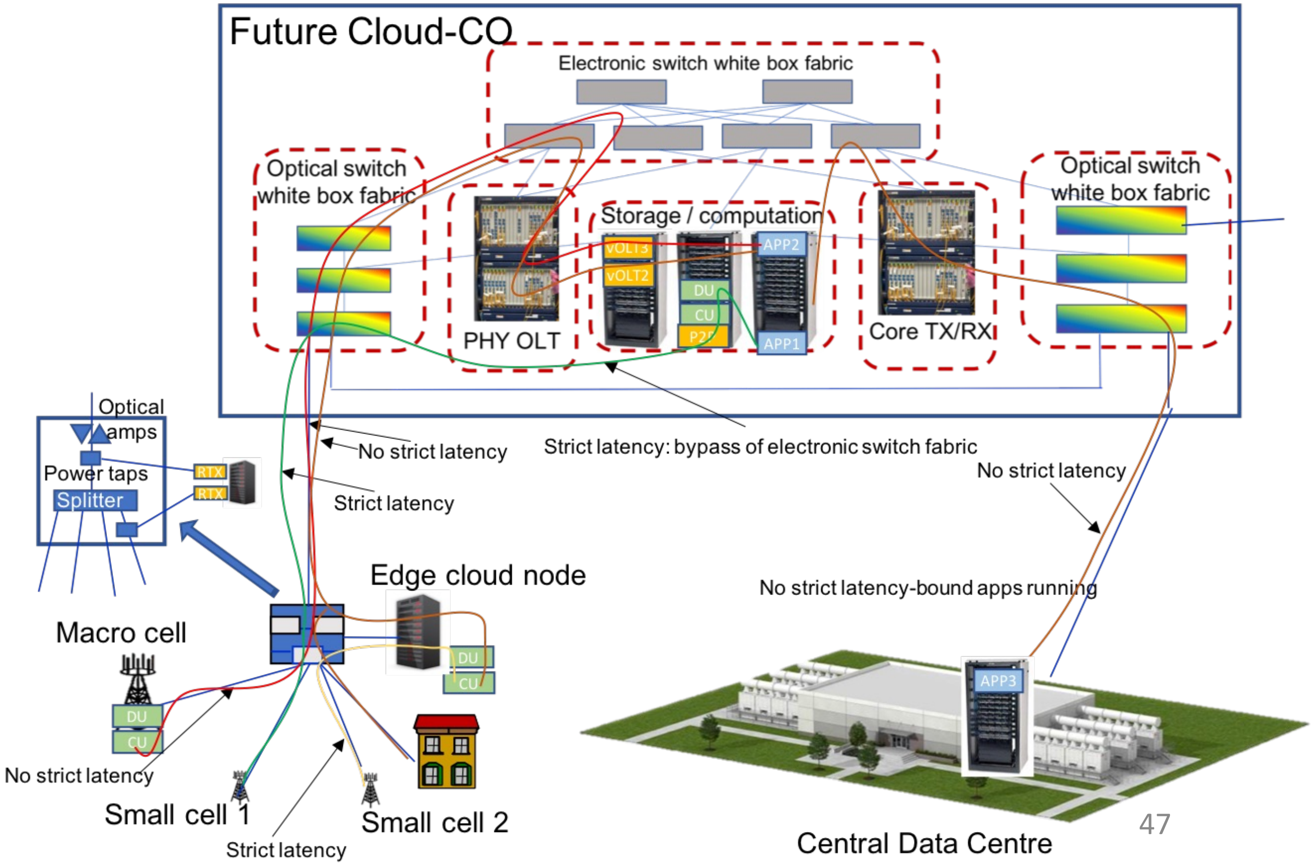


- Use case 2: Examine coexistence of different transmission formats analogue, digital RoF for support of 6G dense mmWave, THz

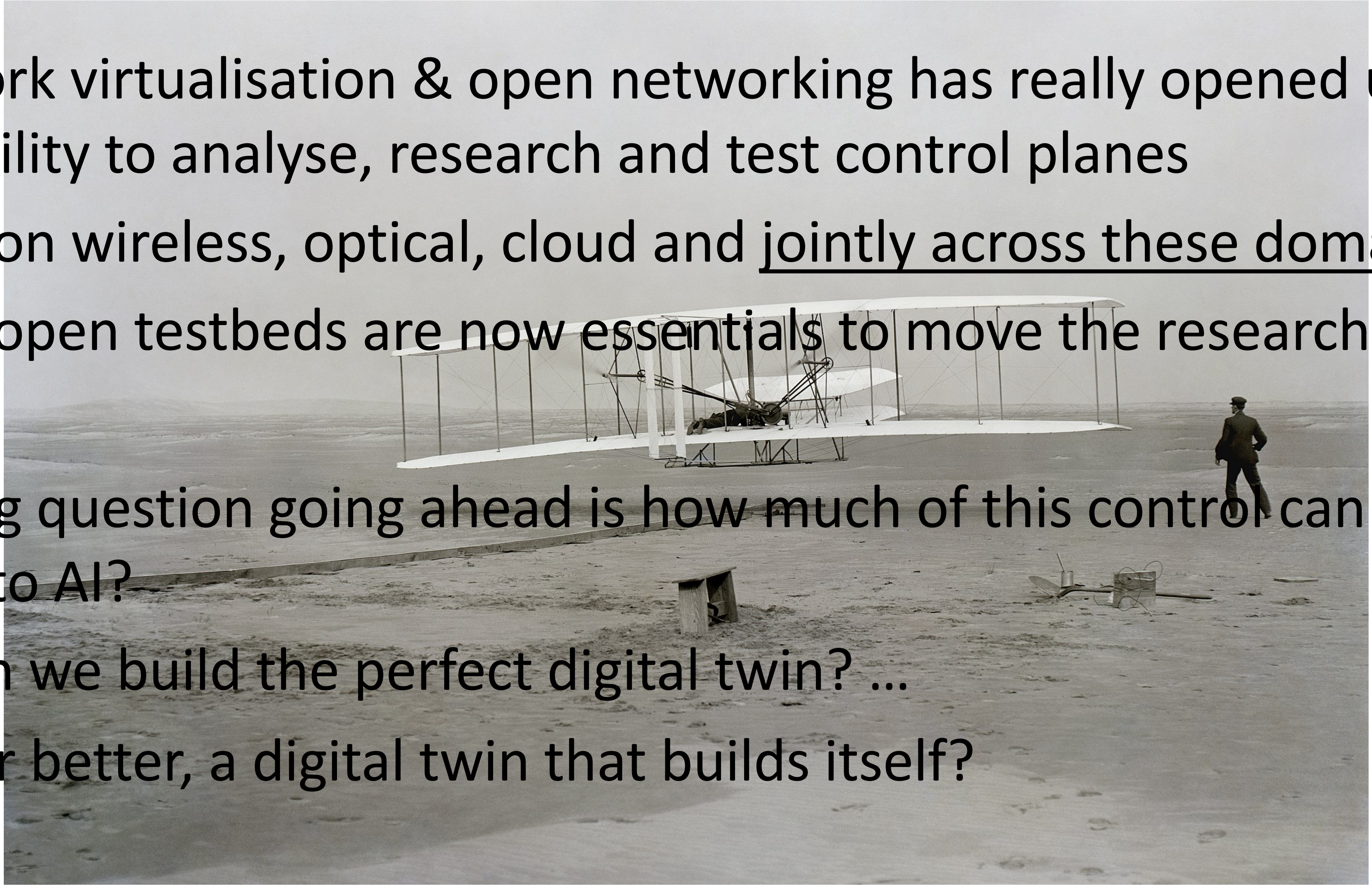


Conclusions

- Disaggregation is happening everywhere in the network:
  - Standardisation is moving forward: ORAN, BroadBand Forum (BBF)…
- We have great physical layer technology that can provide much optical layer flexibility:
  - switching: flexgrid ROADMs, micro-ring resonator technology,…
  - transmission: coherent moving towards the access to provide higher power budget and wavelength flexibility



Conclusions



Network virtualisation & open networking has really opened up the possibility to analyse, research and test control planes

- ➔ on wireless, optical, cloud and jointly across these domains
- ➔ open testbeds are now essentials to move the research ahead

The big question going ahead is how much of this control can be given to AI?

➔ Can we build the perfect digital twin? …

➔… or better, a digital twin that builds itself?

CONNECT Centre for Future Networks

IPIC BRINGING PHOTONICS TO LIFE

Thank you

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CONNECT and IPIC research centres