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CONNECT Centre for Future Networks

IPIC BRINGING PHOTONICS TO LIFE

Access network evolution: convergence, virtualisation and intelligent control for 5G and beyond

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CONNECT and IPIC research centres

OSA 5G webinar series, 24th May 2021

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Science Foundation Ireland For what's next

Summary

- Classical broadband evolution: From DSL to FTTH

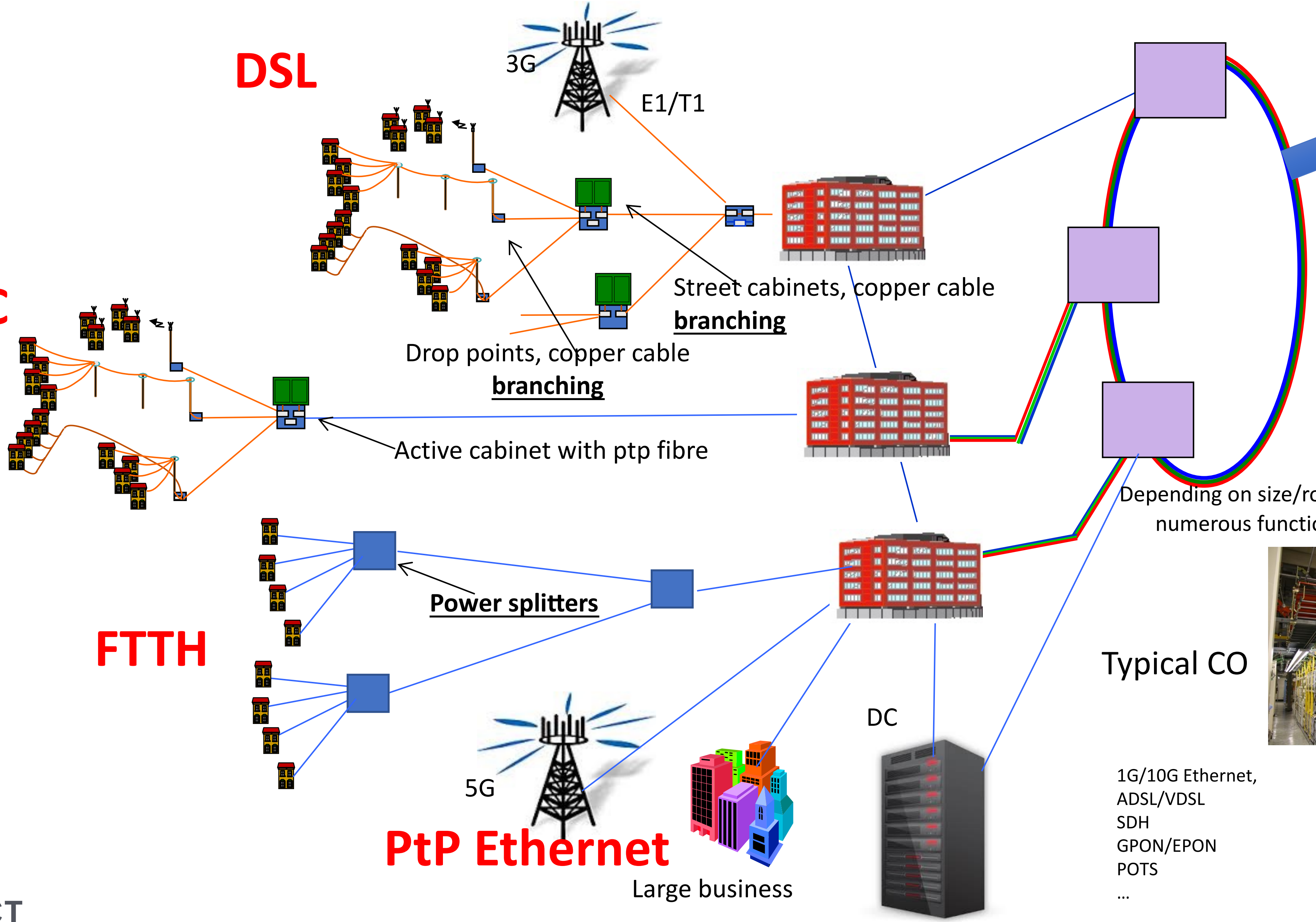
- From generic broadband service to 5G and beyond

  - SDN and virtualisation
    - From SDR to ORAN
    - PON virtualisation

  - Network convergence
    - Wireless-PON convergence
    - PON capacity evolution
    - Adding edge computing
    - Extending to metro

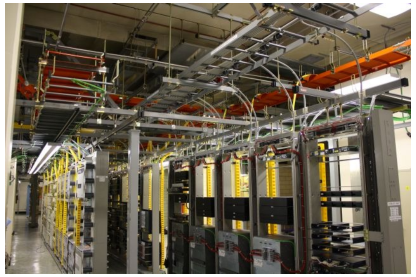
  - Open and intelligent systems
    - Open optical systems
    - Mininet-Optical
    - Testbed experimentation

Classical broadband evolution: From DSL to FTTH



N. Afraz, F. Slyne, H. Gill and M. Ruffini. **Evolution of Access Network Sharing and Its Role in 5G Networks**. Applied Sciences. 2019; 9(21):4566

Typical CO



1G/10G Ethernet,
ADSL/VDSL
SDH
GPON/EPON
POTS
…

BRAS, PE Router
SGSN/GGSN (Mobile)
DPI
DSLAM
Carrier-grade NAT
MPLS
…

Capacity increase

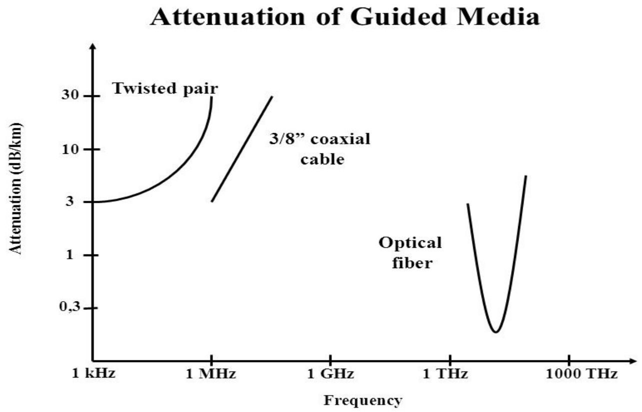
Shannon–Hartley theorem

$$C = B \cdot log_2\left(1 + \frac{S}{N}\right)$$

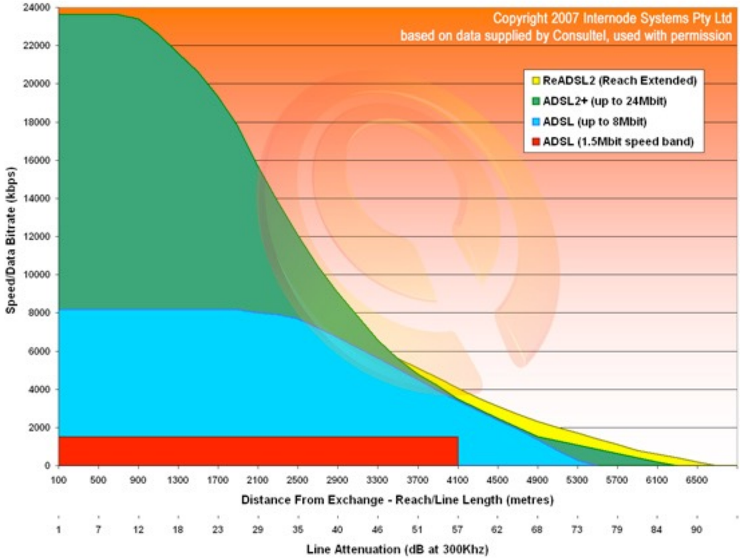
C = capacity [b/s]
B = bandwidth [Hz]
S/N = Signal to noise ratio [linear]

How to increase Bandwidth and SNR:

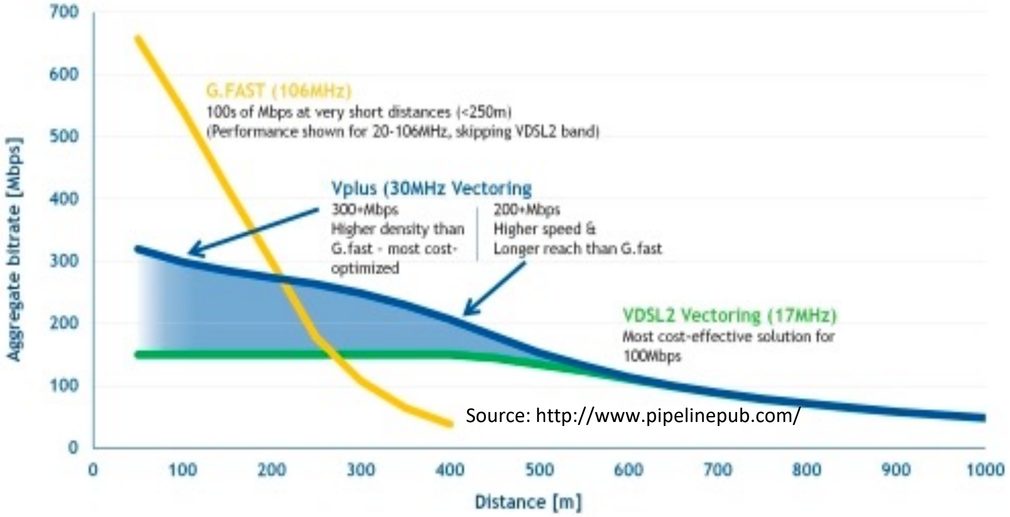
- Reduce copper distance, as loss increases at high frequency (thus reducing signal power and ability to use higher bandwidths)
- Introduce noise cancellation in copper (i.e., vectoring) to improve SNR (for cross-talk)
- Use fibre, whose loss is low and independent of frequency within a given band (also the transmission line does not generate noise)



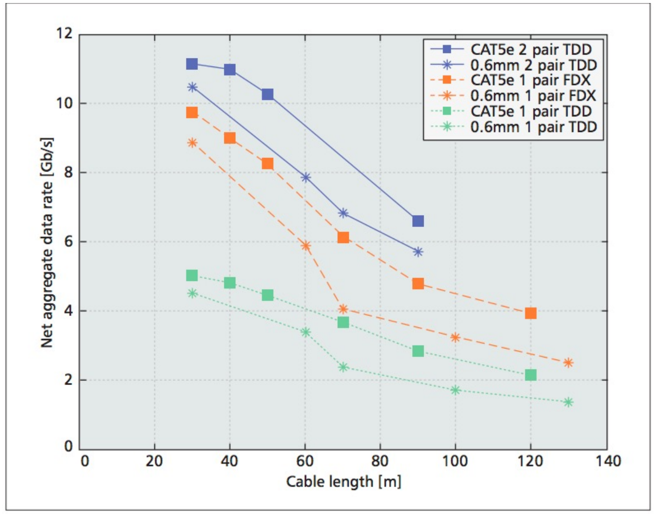
ADSL



VDSL - G.FAST

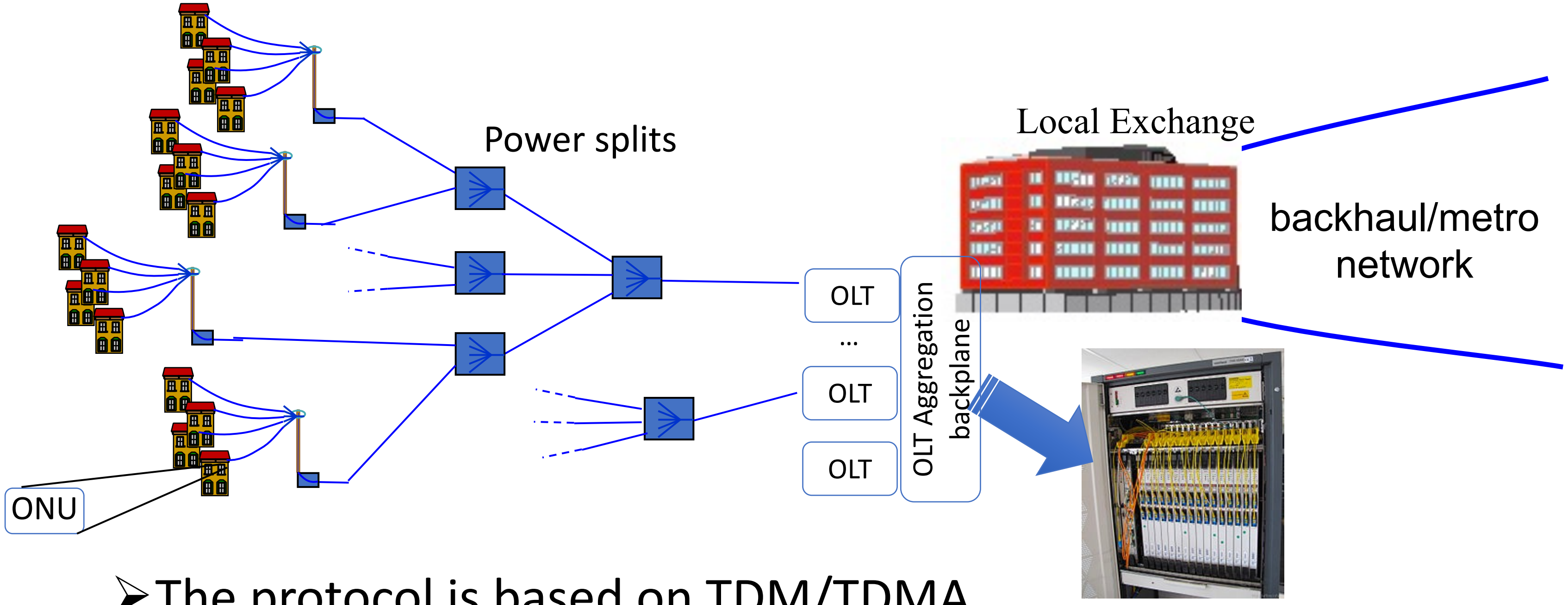


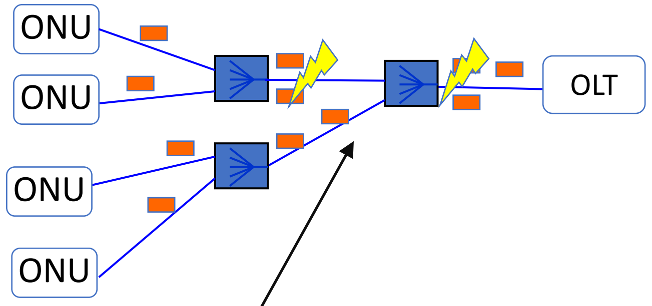
XG.FAST



Time Division Multiplexing PON (TDM-PON)

- There are both IEEE (EPON and 10GEPON) and ITU-T (GPON, XG-PON, XGS-PON) for FTTH
- IEEE PON standards are typically used in Asia, while ITU-T is used in Europe and US.



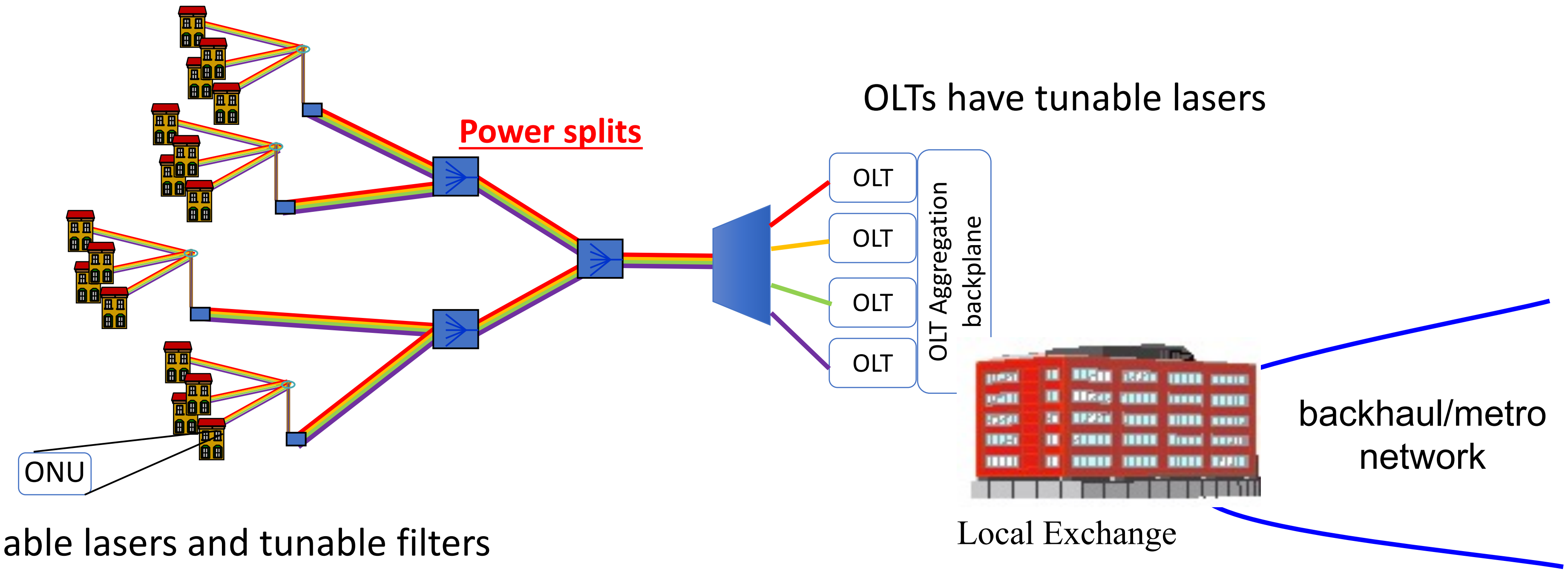


- The protocol is based on TDM/TDMA
- Downstream the OLT broadcasts data to every ONU, and each ONU filters out the data destined to it.
- Upstream is different as all data will converge into the same link to the OLT

  ➔ A MAC needs to be implemented for the upstream transmission

Time/Wavelength Division Multiplexing PON (TWDM-PON)

- The concept is the same as the TDM-PON, but now multiple wavelengths are used over the fibre

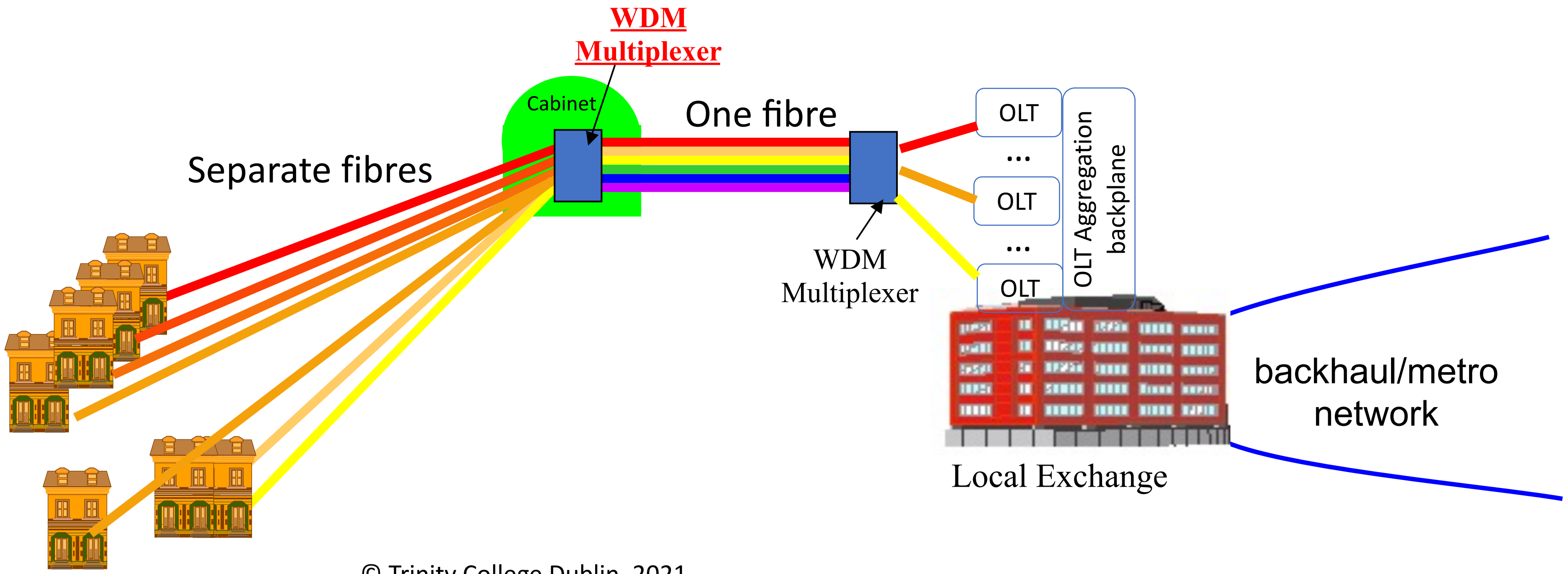


ONUs have tunable lasers and tunable filters

- ONUs can tune laser and receiving filter to select a different OLT
  - For example if one OLT is congested, ONUs can be moved to a different OLT
  - Or one ONU can be linked to a dedicated OLT (logical PtP) for the time required to complete a service (e.g., 10G bandwidth-on-demand - BoD)
  - **Passive splitters and tunable end point is the most flexible solution as it can offer very different capacity, on demand, to different type of users**

Adding wavelengths through WDM multiplexers

- In WDM-PON each user is served by a separate wavelength channel and a WDM splitter is placed in the cabinet to separate the wavelengths into different fibres
- Logically it is a point-to-point connection as each user is served by a different wavelength channel
- The channel would normally use 1GE or 10GE
- The issue is that a wavelength is fixed to a destination, so there is little room for more arbitrary capacity allocation
- Also, not exploiting statistical multiplexing gains that is typical in access networks



PON Standards

	Standard	Year	Typical Rate DS/US [Gb/s]	Power budget [dB]	Split ratio	Logical/ Differential/ Fibre reach	DS Wavelength	US Wavelength
ITU-T	GPON G.984	2008	2.5/1.25	21-31	Max 64, typical 32	60/20/10-20 km	1480-1500	1260-1360
ITU-T	XG-PON G.987	2012	10/2.5	29-31	Max 256, Typical 64	60/40/10-40 km	1575-1580	1260-1280
ITU-T	XGS-PON G.9807	2016	10/10	--	128	--/--/--	--	--
ITU-T	NG-PON2 G.989	2015	10/10 x 4 PON + 10/10 x 4 PtP	29-35	Max 256, Typical 64	60/40/20-40	1596-1603	1524-1544
IEEE	EPON 802.3ah	2004	1.25/1.25	20-33	Typical 32	--/10/10-20	1480-1500	1260-1360
IEEE	10G-EPON 802.3av	2009	10/1.25-10	20-33	Typical 32	--/10/10-20	1575-1580	1260-1280

- IEEE P802.3ca recently published 25G and 50G PON (the latter based on two wavelength channels).

- ITU-T recently published 25G and also looking at 50G (using NRZ)
  - G.9804.1. providing the requirements https://www.itu.int/rec/dologin_pub.asp?lang=e&id=T-REC-G.9804.1-201911-I!!PDF-E&type=items
  - G.hsp.X series of working groups/standards – i.e., G.hsp.50Gpmd (now G.9804.3) for single channel 50G operations

- Research is ongoing for higher rates of 100G and beyond (how to tackle dispersion, the lower power budget, always considering cost constraints of access networks)

D. Zhang, et al Progress of ITU-T higher speed passive optical network (50G-PON) standardization. JOCN , vol. 12, no. 10, October 2020.

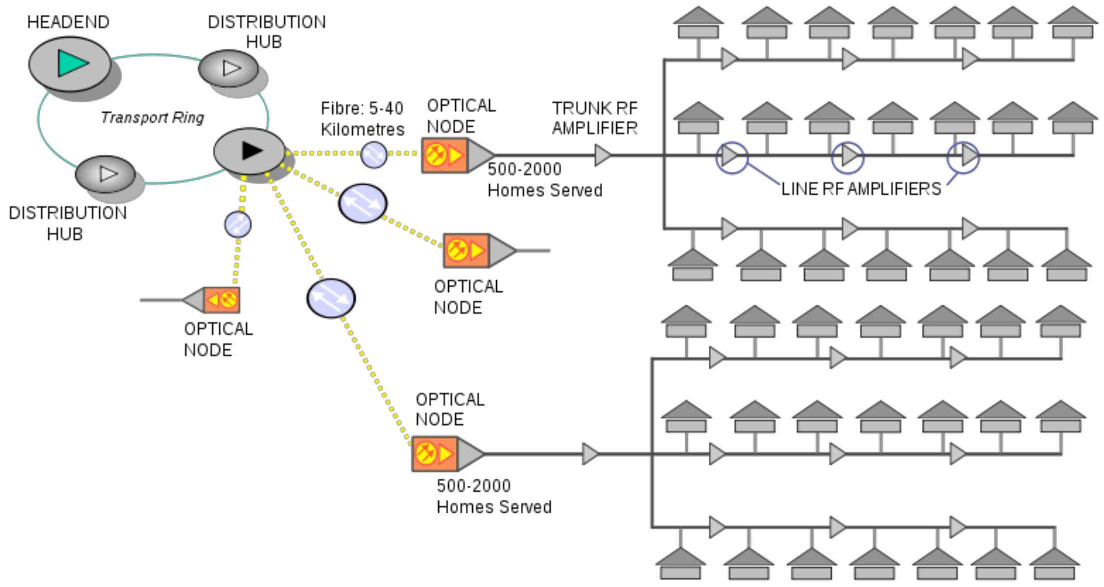
Don’t forget DOCSIS!

- **<u>This is a copper technology. But it utilizes a coaxial cable instead of a twisted copper pair!</u>**

- The cable network is different from the telephone network, as cable in not point-to-point, but is shared among a number of houses.

- The standard for cable broadband is called DOCSIS (Data Over Cable Service Interface Specification).

- Different version of DOCSIS have been released over time, providing higher speed, but also requiring a shorter cable loop (i.e., the fibre termination was progressively brought closer to the homes)



DOCSIS PHY

Version	Year	Max DS channels	DS ch width [MHz]	DS Modulation	DS rate [Mb/s]	Max US channels	US ch width [MHz]	US Modulation	US rates [Mb/s]
1.0	1997	1	6	64/256 QAM	42.88	1	0.2-3.2	QPSK/ 16QAM	10.24
2.0	2001	1	6	64/256 QAM	42.88	1	6.4	QPSK/ 8-128QAM	30.72
3.0	2006	32	6	64/256 QAM	1372.16	8	6.4	QPSK/ 8-128QAM	245.76
3.1	2013	2-5	25/50KHz OFDM 192MHz block	64-4096QAM	10 Gb/s	2	25/50KHz OFDMA 96MHz block	QPSK/ 8-4096QAM	1,000

- The European version EuroDOCSIS has different channel bandwidth (8MHz instead of 6 for the 1.0 to 3.0 versions)

- The full-duplex DOCSIS 3.1 (renamed DOCSIS 4.0 provides symmetric 10Gb/s and uses up to 1.8GHz of bandwidth in the cable)

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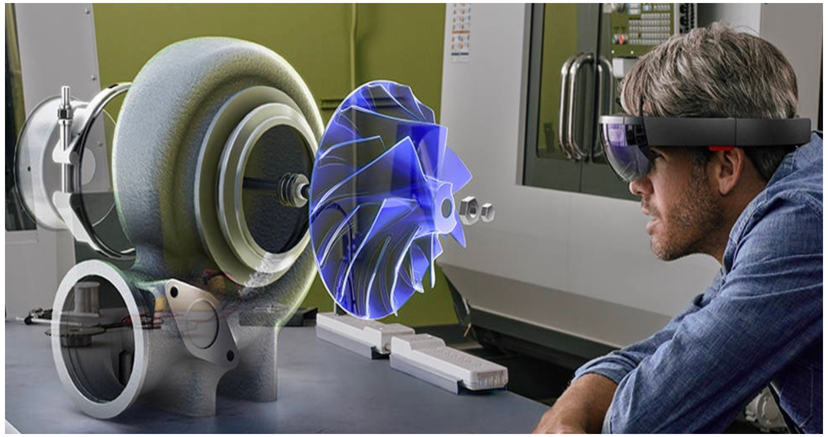
From generic broadband service to 5G and beyond

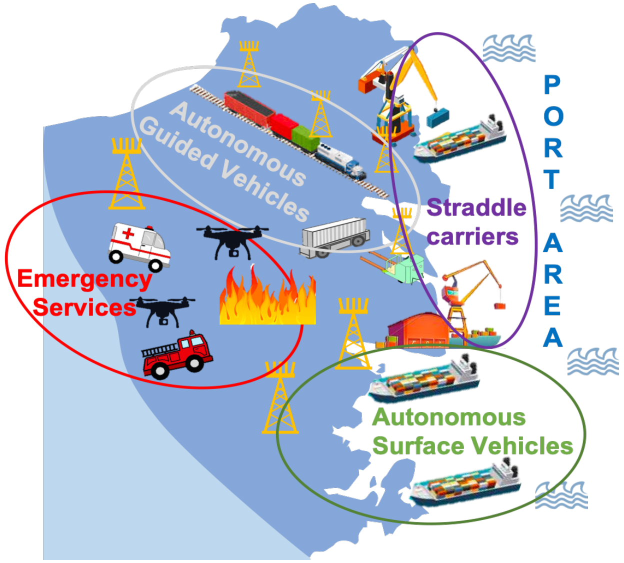
- Much of FTTH deployment as focused on residential and small business services.
- Broadband speed is important, but today's FTTH and DOCSIS seem satisfactory for the foreseeable future.
- However, one of the key vision for 5G was to go beyond generic increase in capacity -> 6G will only exacerbate that
- Especially high-performance and reliable network is something that was never there before.. That's where you want to look for new use cases

TRINITY COLLEGE DUBLIN

New value in new applications: how to attract them?

- Private networks will likely play a leading role in this area
- Attract *new* users/businesses by providing new *unprecedented* features:





- Likely to be driven by Industry 4.0
- Innovation is required also in user devices (e.g., AR/VR goggles, etc.)

- Till the day we'll be fully immersed in the digital world…

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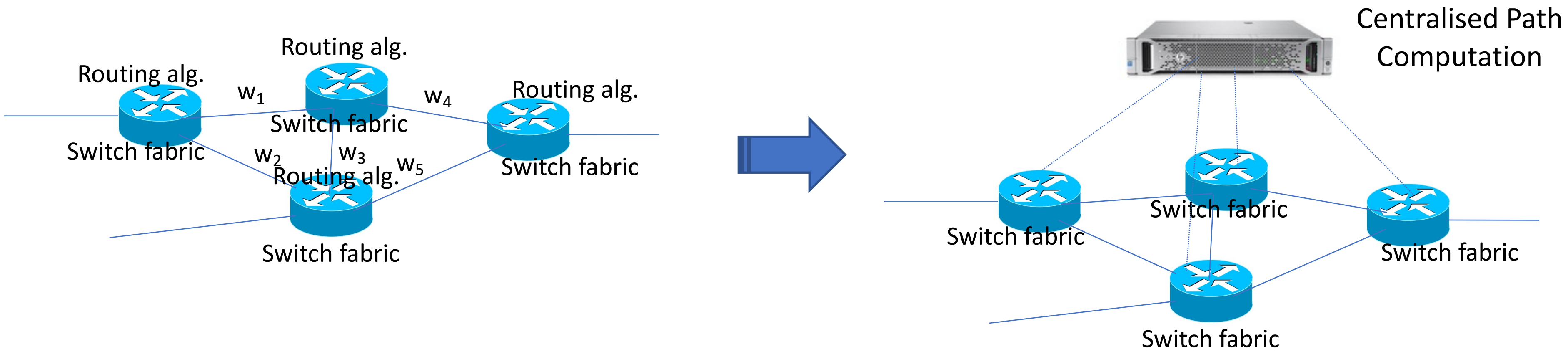
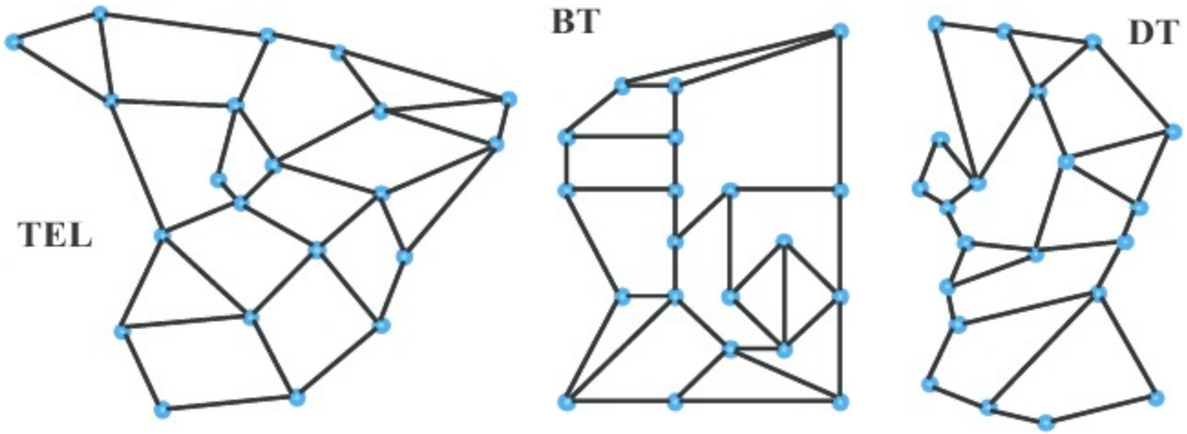
Software Defined Networks

- Move from a system where routers run independent (but converging algorithms) to a system where all routes are decided by a central entity



- Advantages:
  - More flexibility in deciding routes
  - The system opens up and facilitates development of integrated software

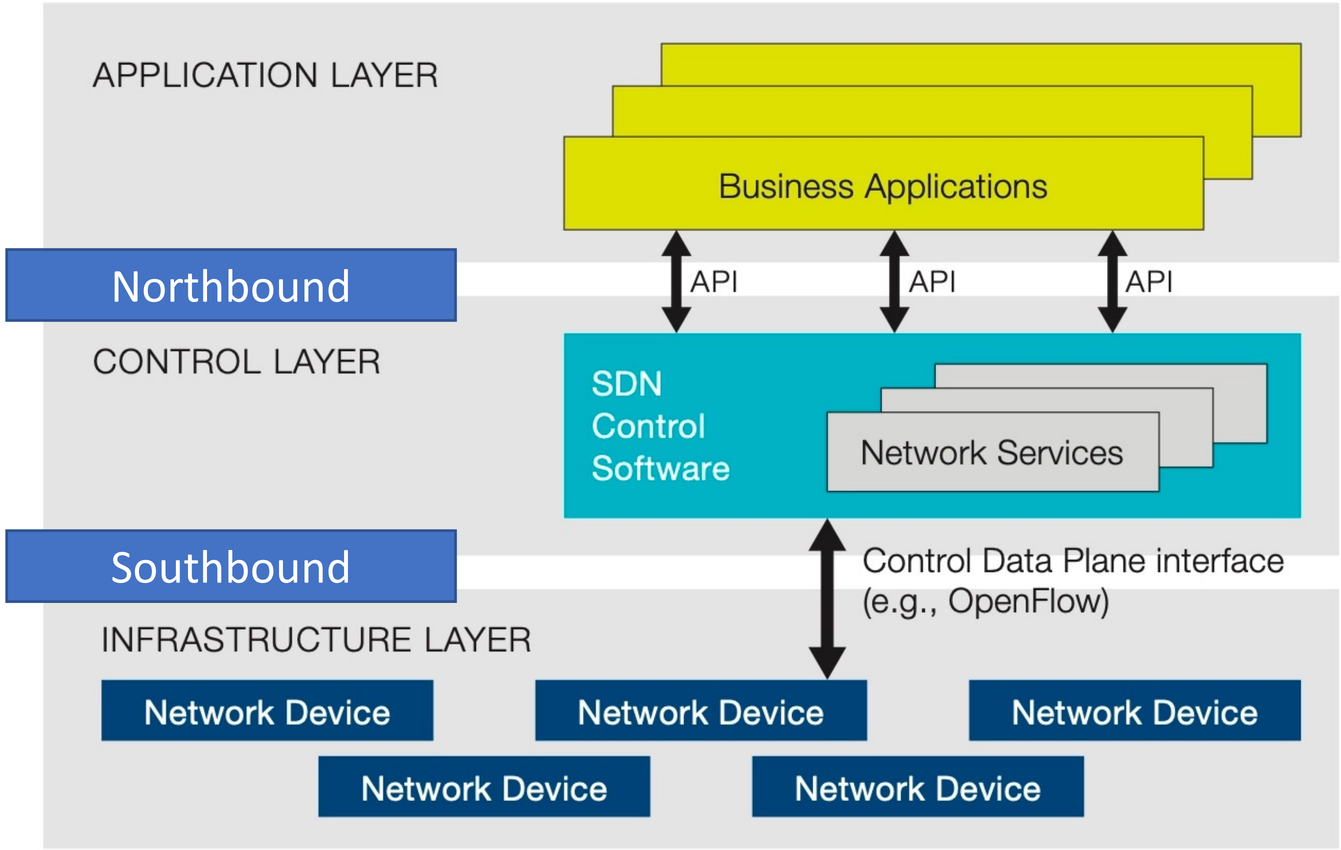


An SDN architecture

- The control plane (controller) becomes the Operating System for the network.

- Programmability requires well defined and standardized interfaces:
  - Southbound interface to send instructions to network devices (think of hardware drivers)
  - Northbound APIs are used by applications (e.g., the entity setting up a service) to express their intent

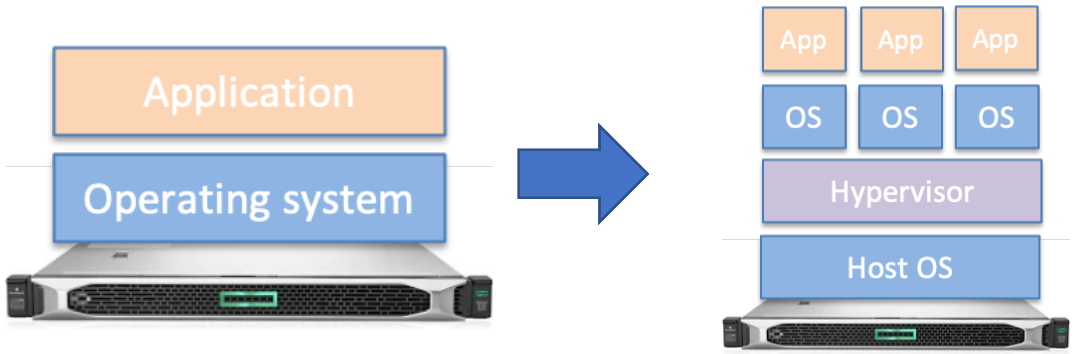
- The controller transforms abstract, high-level intents into physical layer commands



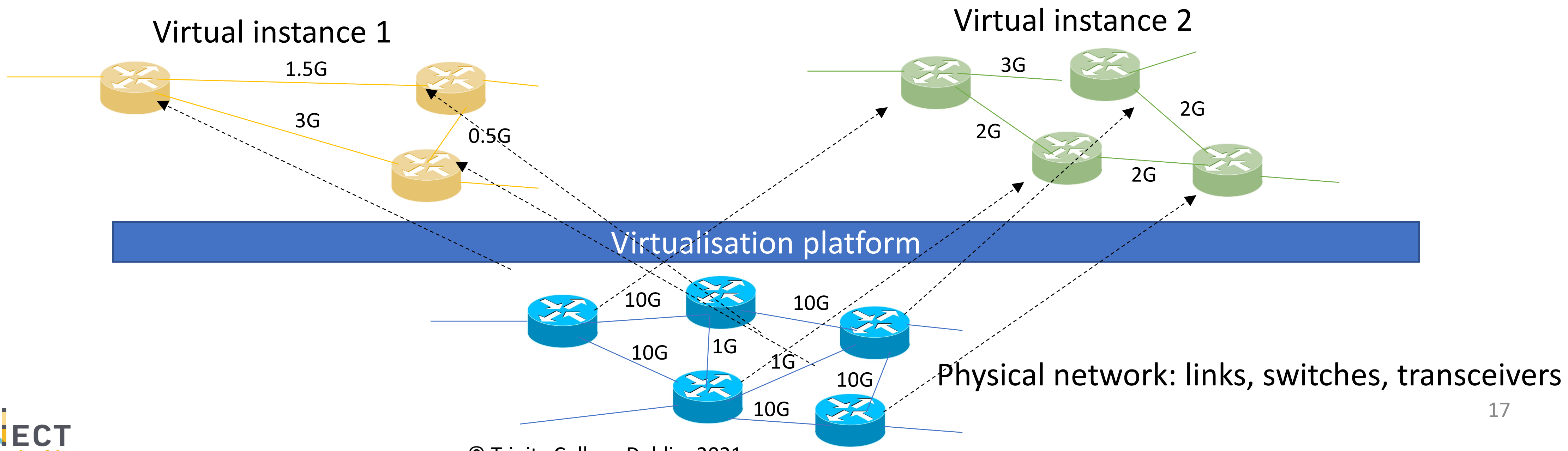
Virtualisation

Virtualisation gives the illusion of obtaining control of a physical entity or resource.

Server virtualisation

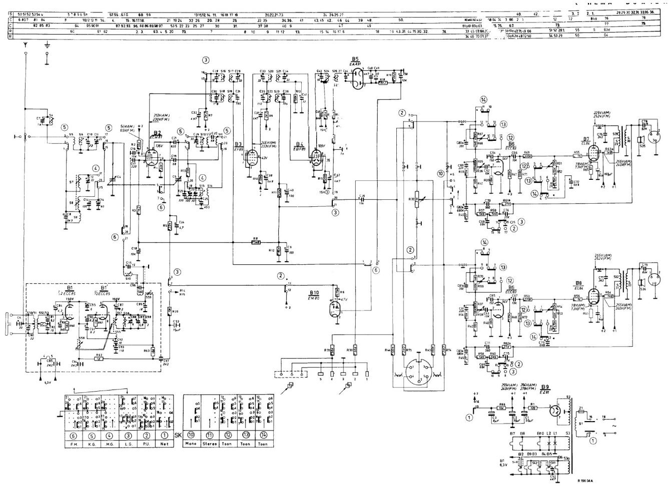


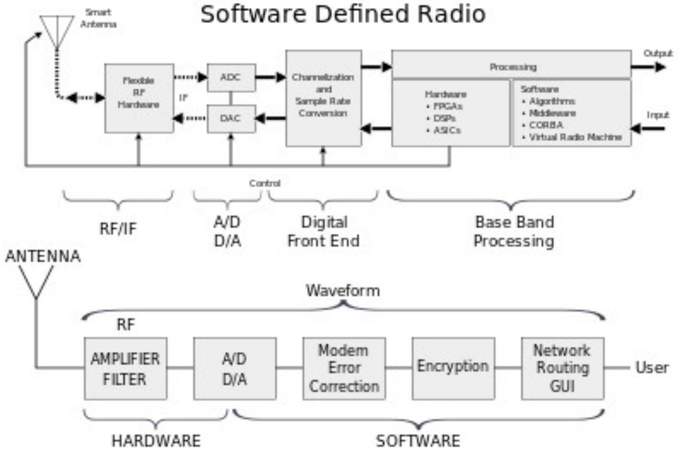
Network virtualisation



From virtualisation to network function virtualization (NFV)

- ➢NFV moves functions from dedicated hardware to software running on commodity servers
- ➢Software Defined Radio is an early example: GNU radio

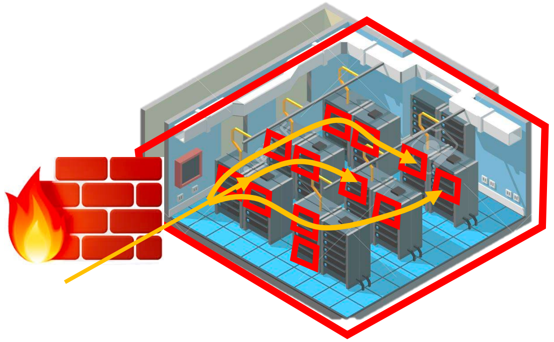




- ➢Advantages:
  - ➢flexibility of adapting transmission format to environment and application
  - ➢coordination with other radios (either distributed or centralized)
  - ➢Integration with other software components…

Network functions

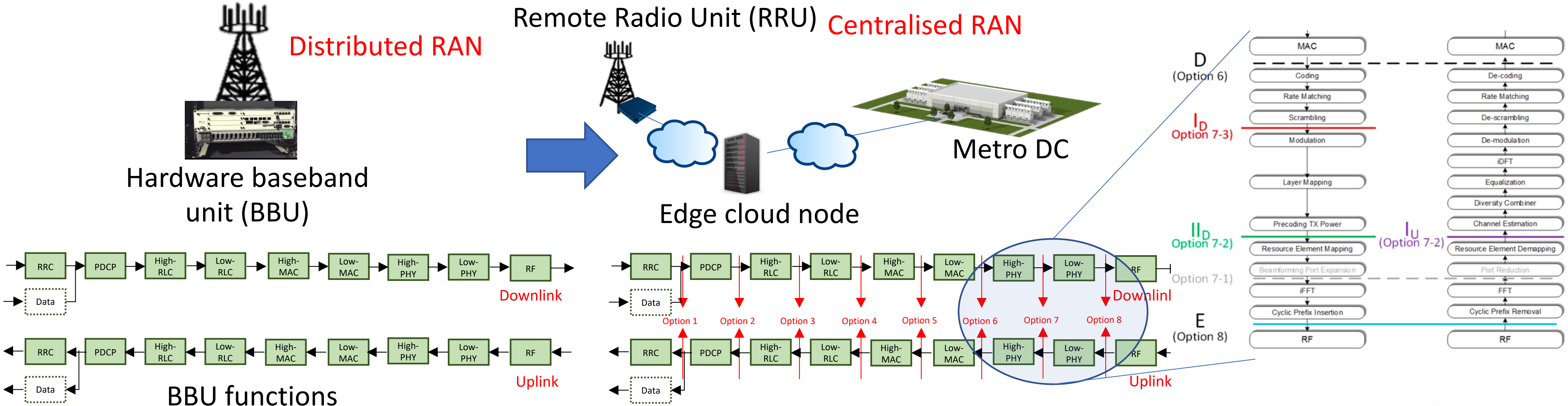
- The NFV concept applies to several other telco functions:
  - Firewall: in VMware NSX it’s integrated in each VM, for better customization, flexibility, security.



- In general all functions that require packet processing and switching are good candidates:
  - Service Gateway (vSG): e.g., route the request to the specific service provider
  - Broadband Network Gateway (vBNG o vBRAS): aggregates incoming access connections, enforces QoS, provides layer 3 (IP) connectivity
  - Customer Premises Equipment (vCPE): operates routers, firewalls, VPNs, NAT

SDR in today's telcos

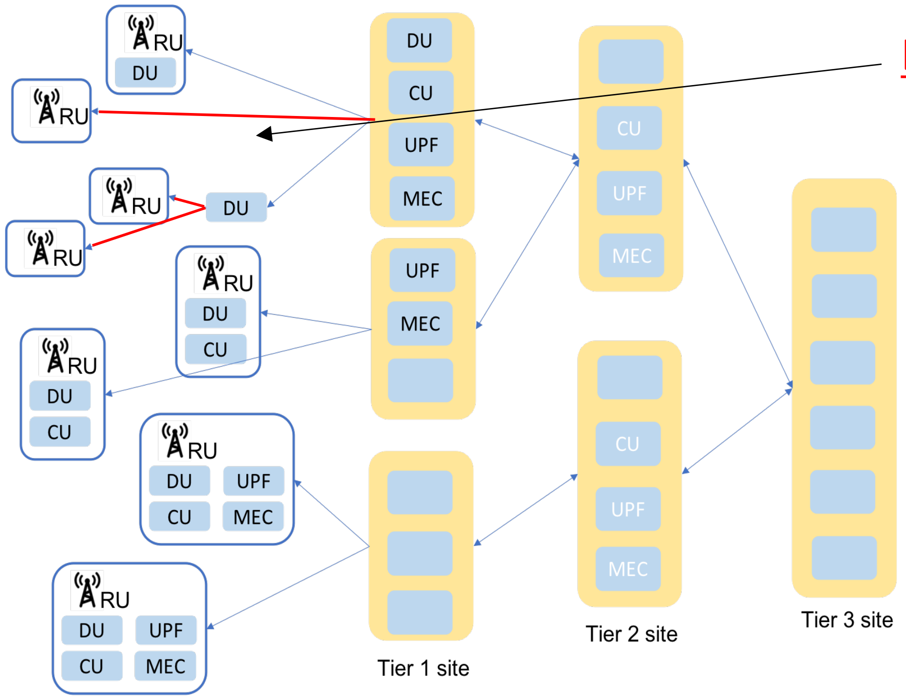
- SDR today stronger than ever:
  - C-RAN based on SDR → srsLTE, Amarisoft, Flexran, OpenAirInterface, OpenLTE, or the implementations based on GNU radio,…
  - Enabling flexibility in resource allocation, statistical multiplexing,…
  - Also, integration with other elements for convergence with other technologies, joint orchestration,…



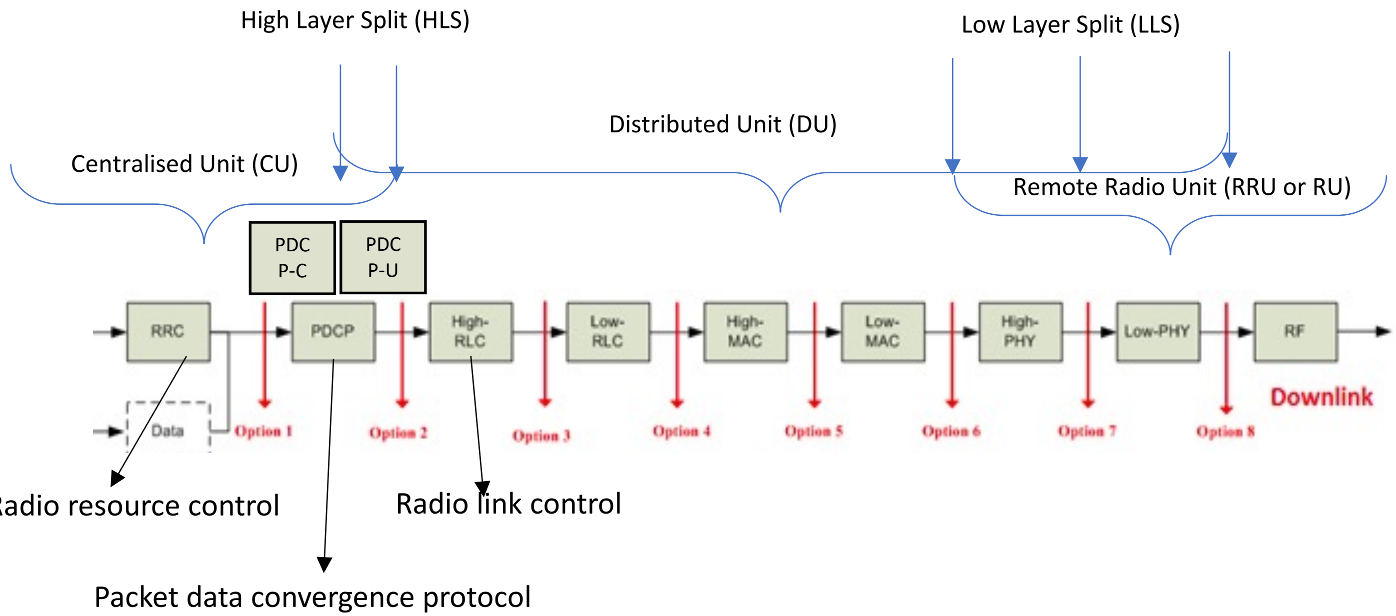
Source: Next Generation Mobile Network (NGMN) alliance. NGMN Overview on 5G RAN Functional Decomposition. Feb., 2018

Physical disaggregation of the mobile network

- 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



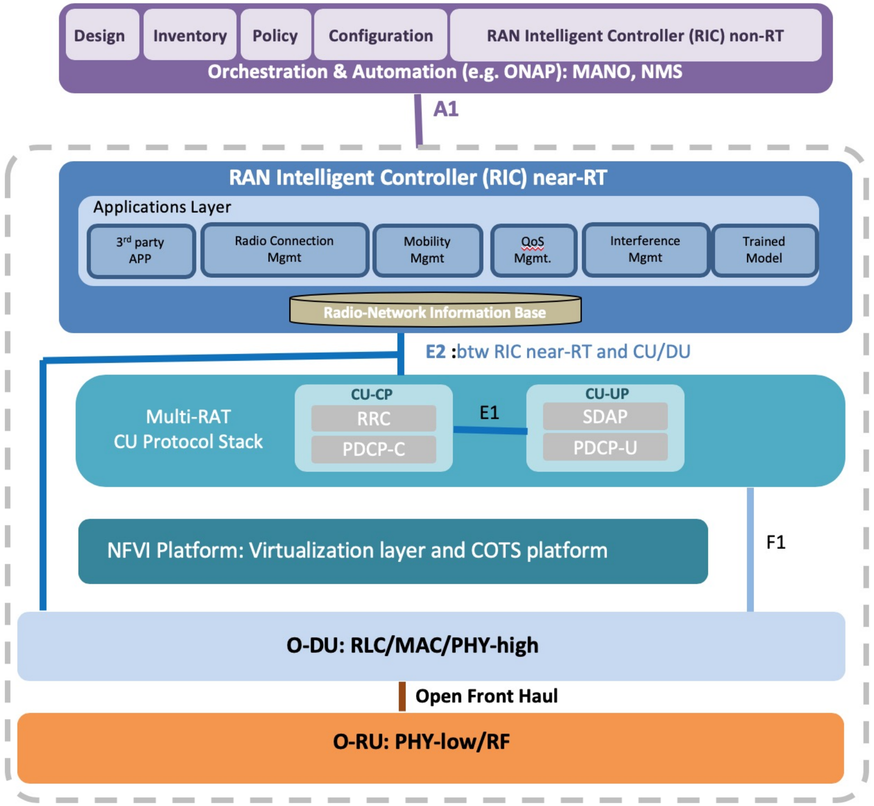
C= control plane; U=user plane

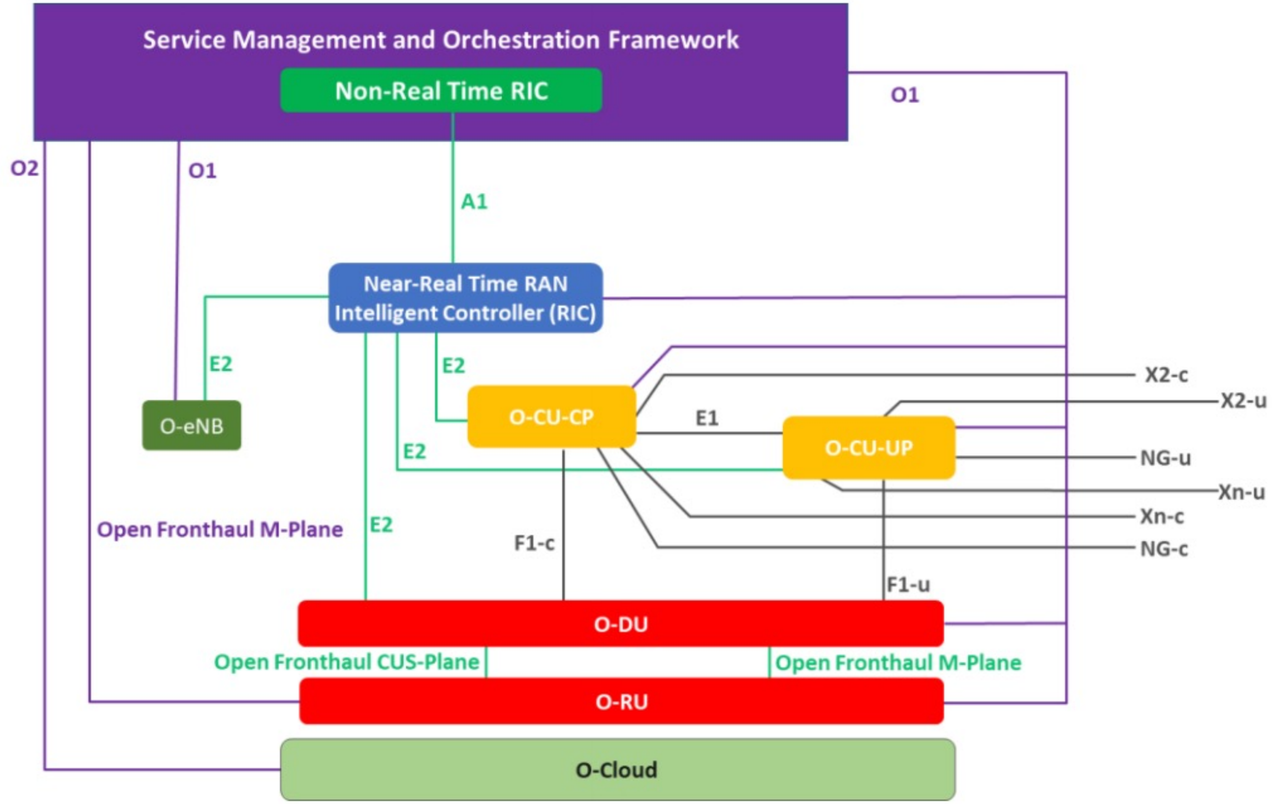
UPF Location	Tier 1	Tier 2	Tier 3
Relative number of sites	1000	100	10
Transport latency (1-way)	0.6 ms	1.2 ms	4.2 ms
Estimated 5G latency (RTT)	9.2 ms [eMBB]	10.4 ms [eMBB]	16.4 ms [eMBB]
	2.2 ms [URLLC]	3.4 ms [URLLC]	9.4 ms [URLLC]

Source: NGMN

O-RAN

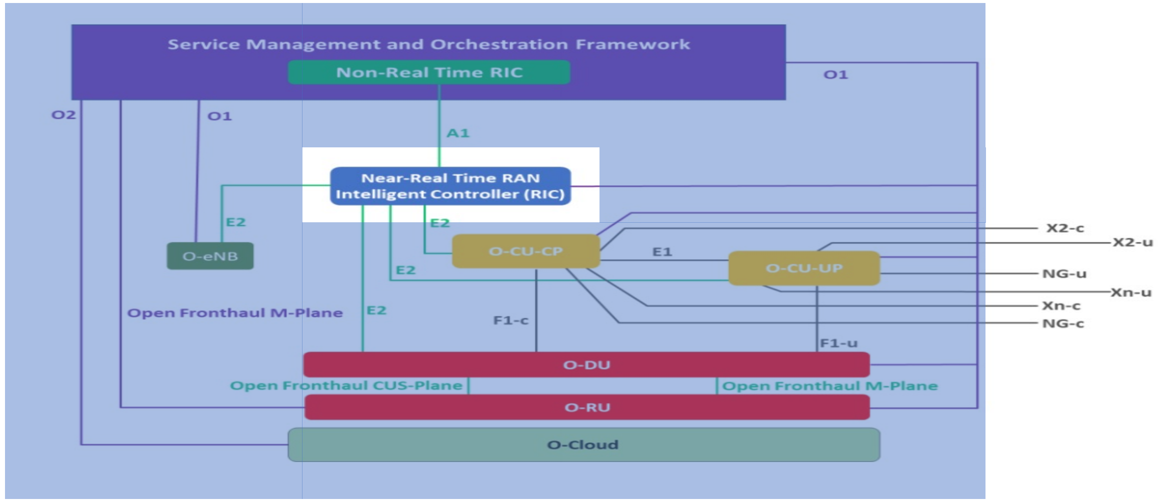
- ➢ Split 7.2 being standardised, so you can go and buy an RU and then install the rest as opensource software
- ➢ O-RAN is providing standardisation of several interfaces, so the system can be fully open





Role of opensource

- Entry barrier: if I'm interested in developing one element (say the Radio Intelligent Controller - RIC), I need the full system for performance testing,…

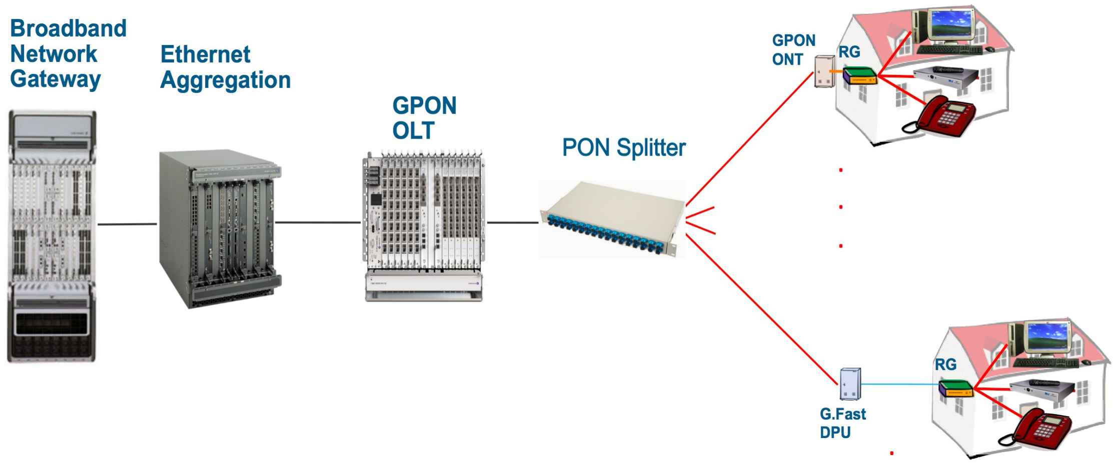


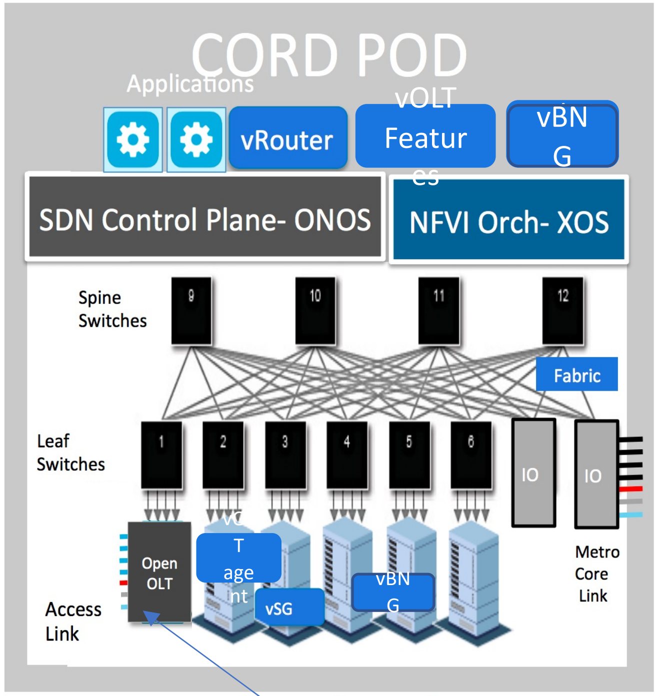
- <u>Open source implementation of the standard components is important!</u>
  RAN: OAI, SRS; Core: OAI, Magma, Open5GS...

- OpenSource is a means for faster products development.. We want to focus on real value (network automation, intelligent control, etc..) and spin off!

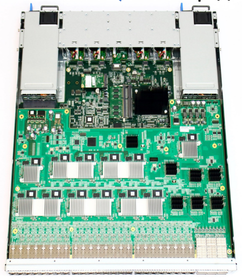
Central Office Virtualisation

➢Getting SDN and NFV into the central office:





Commodity Hardware
Source: http://opencord.org/



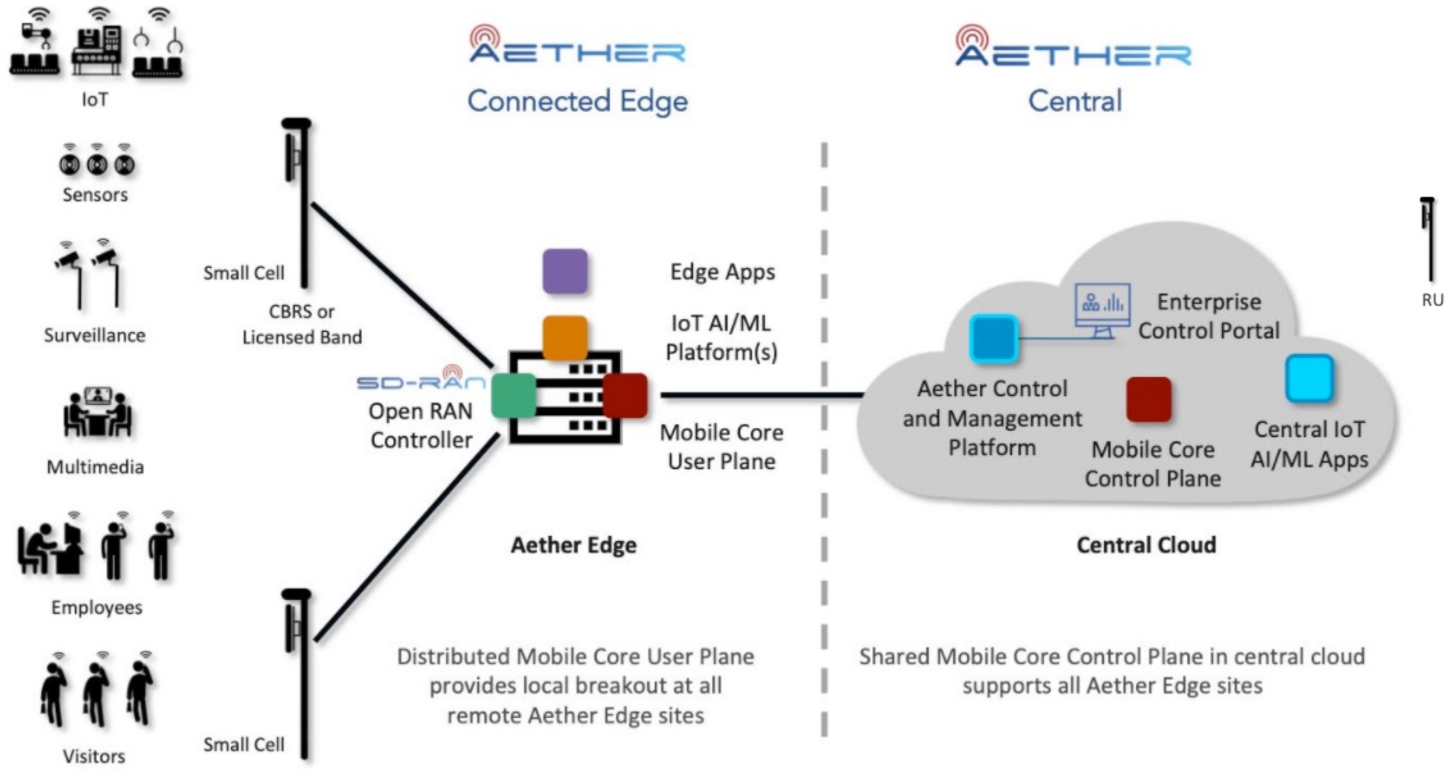
➢Latest architecture called "SDN Enabled Broadband Access (SEBA)"

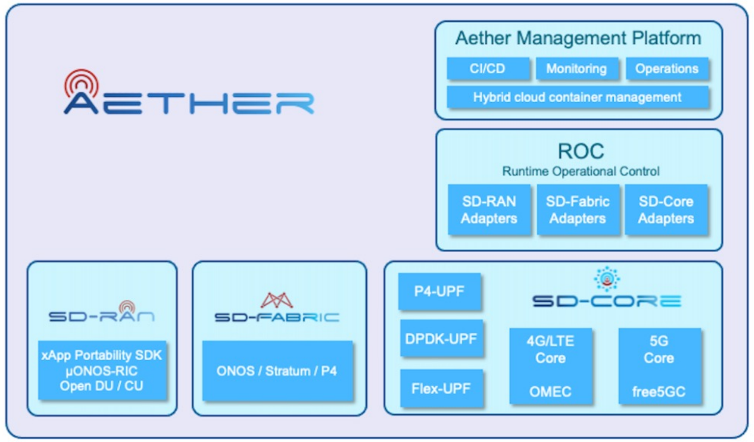
➢Being trialed by several operators world-wide

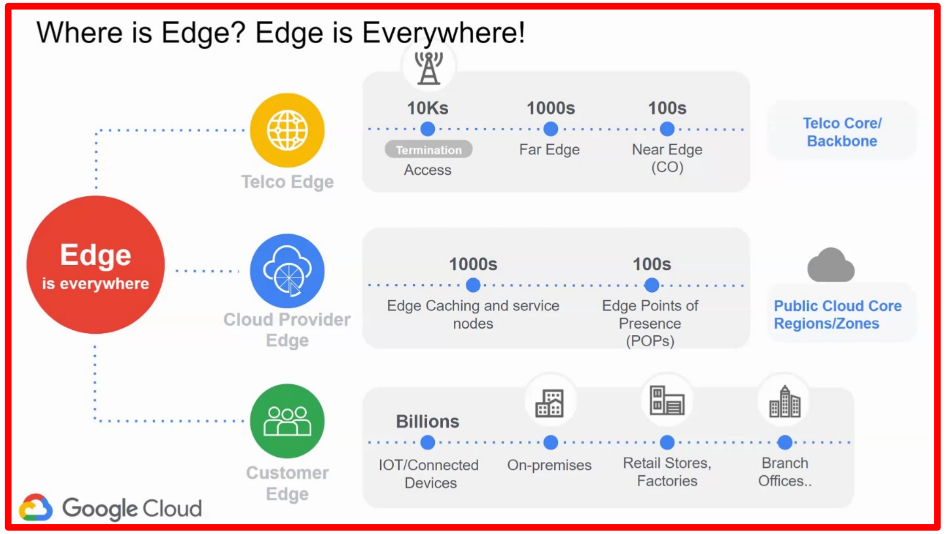
➢E.g., AT&T recently carried out trials on XGS-PON using OLT white boxes

Now also including edge cloud…

We see here also a movement from the public network (central office) towards more dedicated (private) solutions







Source https://aetherproject.org/platform/

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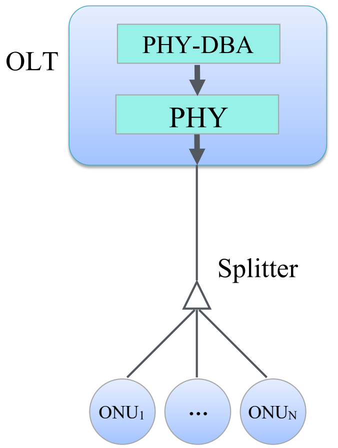
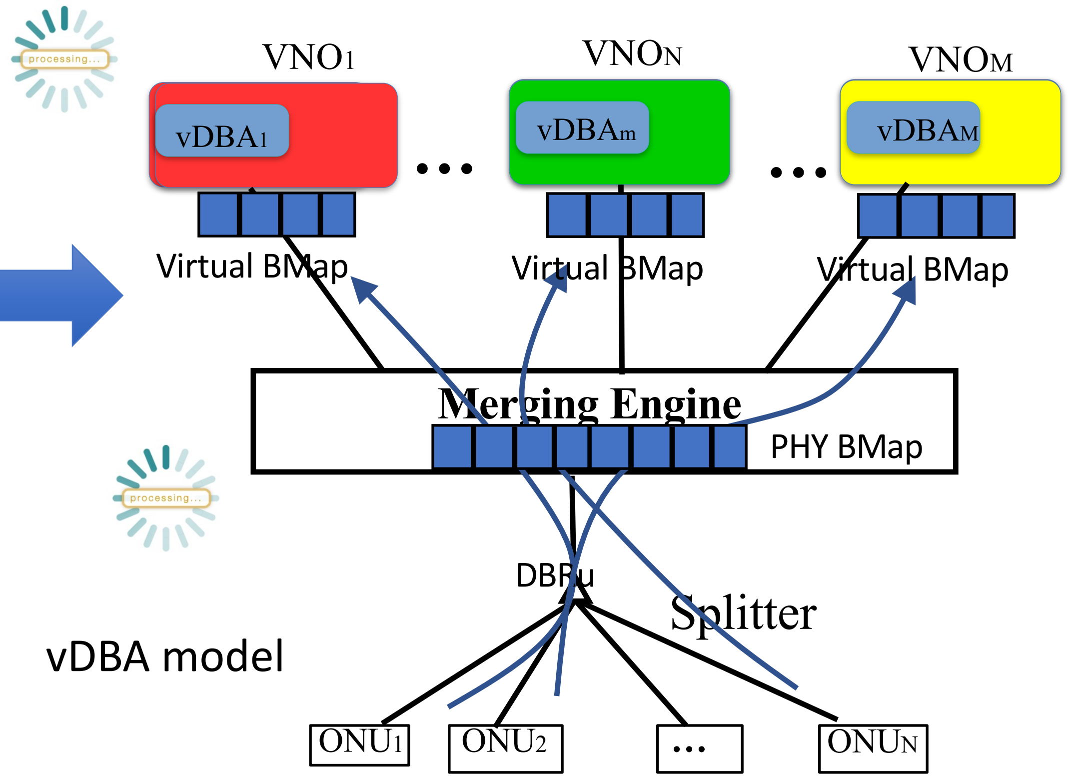
Full disaggregation of the OLT with upstream frame slicing

- Going well beyond the CORD/SEBA concept as the entire MAC is also virtualised
- The DBA is virtualized into multiple instances to enable multi tenant and service operation



Current physical DBA model

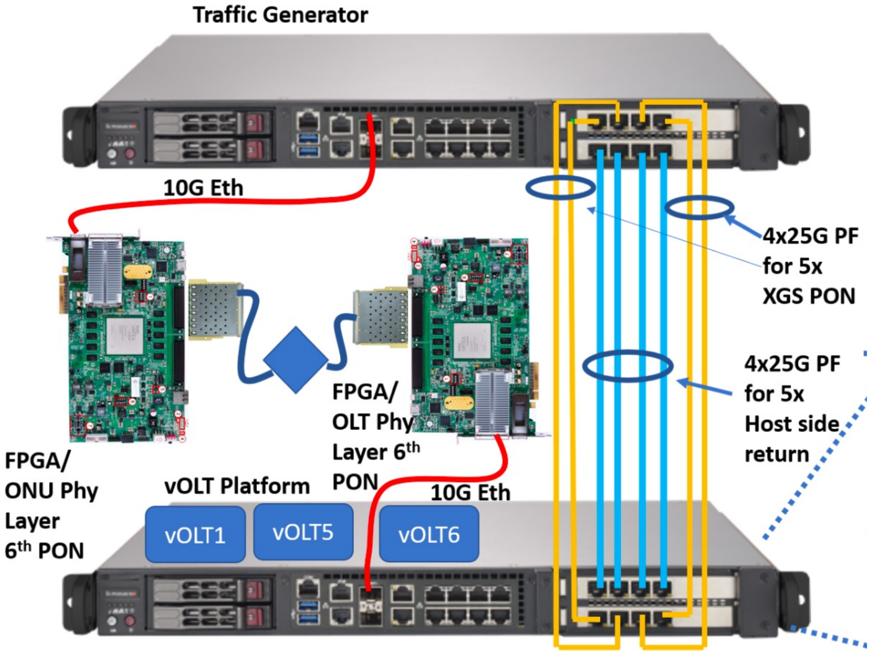


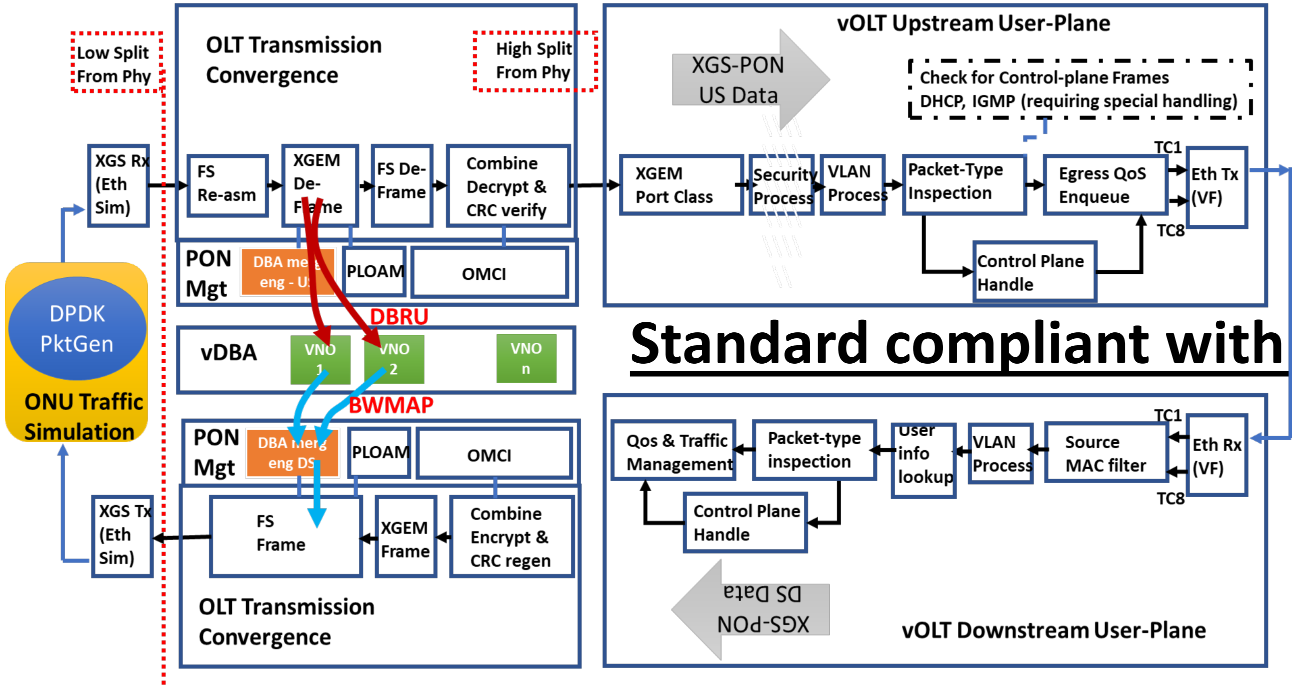
vDBA model

- 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)"

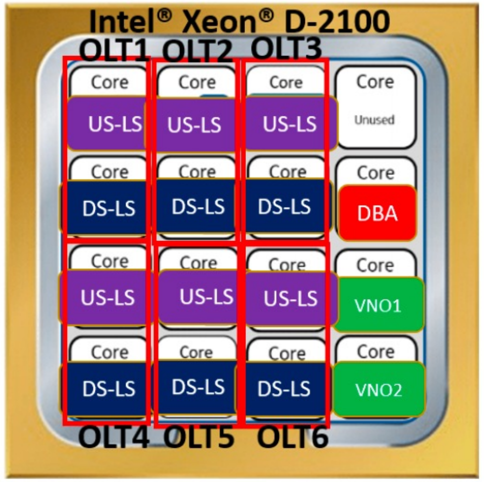
Amr Elrasad, Nima Afraz, and Marco Ruffini, Virtual Dynamic Bandwidth Allocation Enabling True PON Multi-Tenancy. OFC, paper M3I.3, March 2017
M. Ruffini, et al. The Virtual DBA: Virtualizing Passive Optical Networks to Enable Multi-Service Operation in True Multi-Tenant Environments. JOCN, No.4, Vol.12, April 2020.

The virtual PON in practice





Standard compliant with XGS-PON



Results for low level split on Xeon D-2100
Everything turned on, including FEC, encryption…

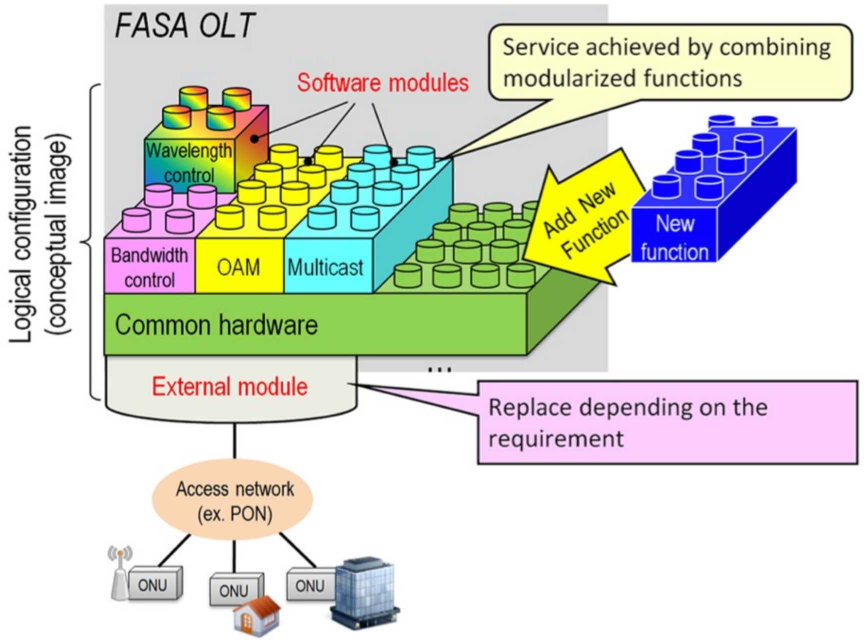
F. Slyne et al., Experimental Demonstration of multiple Disaggregated OLTs with Virtualised Multi Tenant DBA, over General Purpose Processor. OFC 2020.

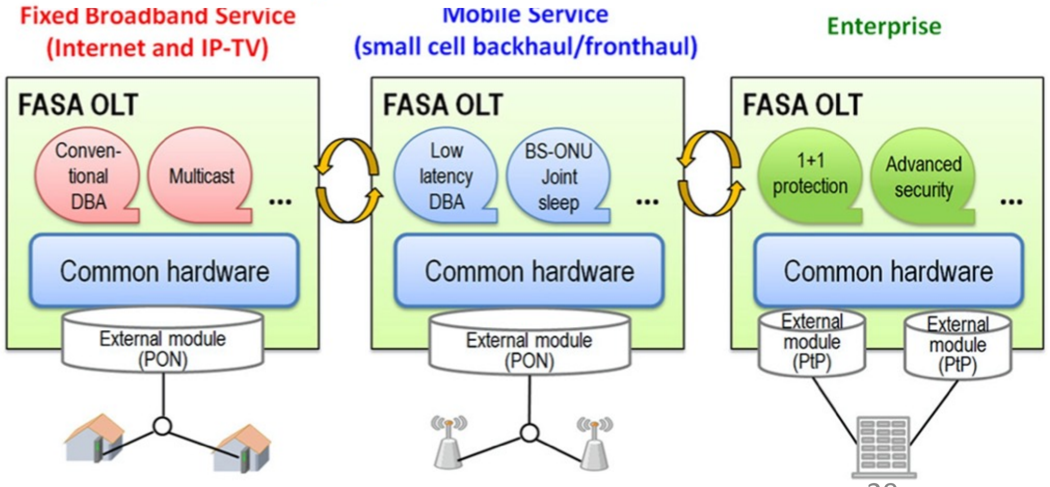
NTT’s Flexible Access System Architecture (FASA)

- ➢Disaggregate the OLT, using software functions

- ➢The DBA is also software, so it can be modified, depending on the application

Included in BBF TR-402 standard “PON Abstraction Interface for Time-critical Applications”





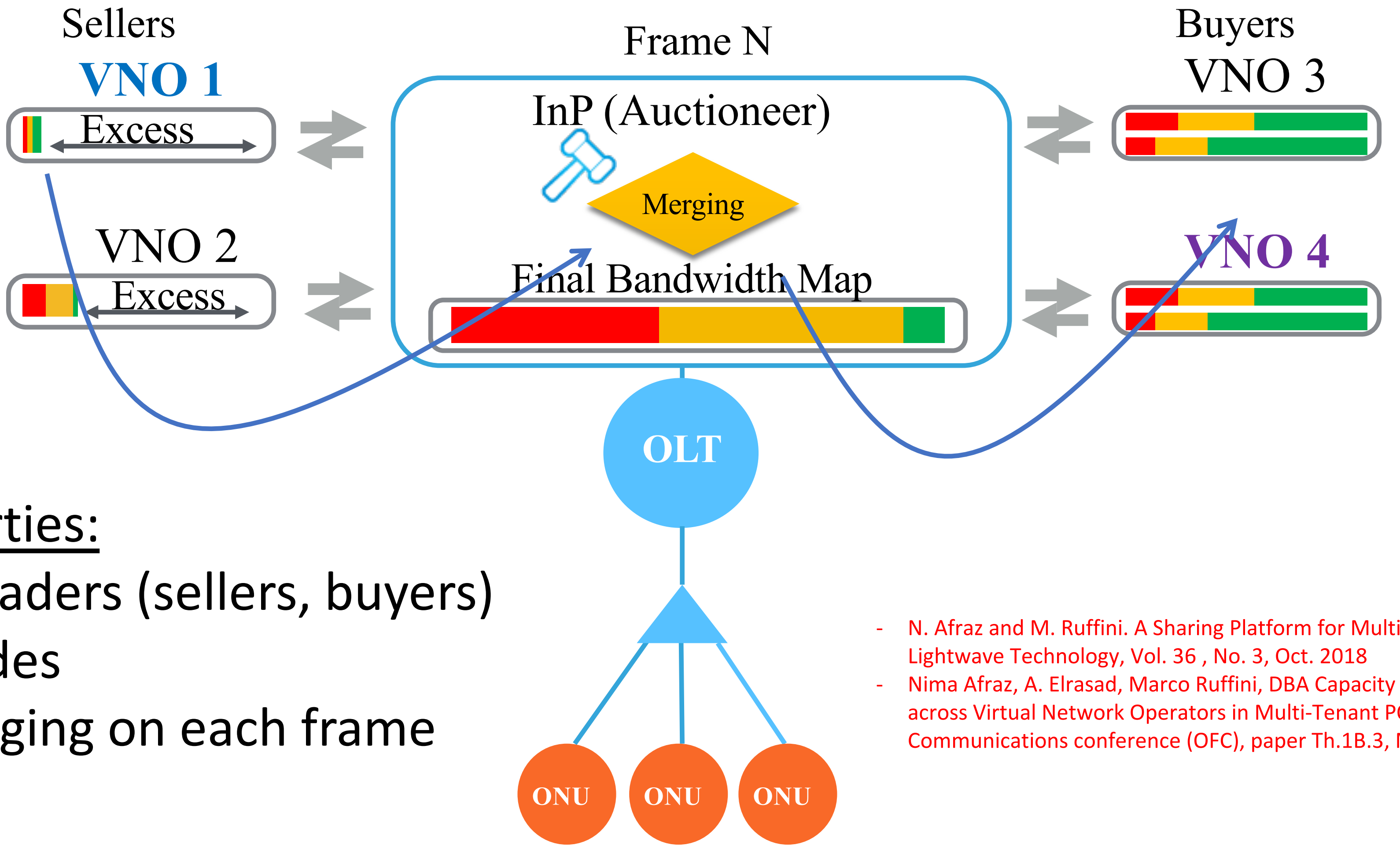
[June-Ichi Kani et al., Flexible Access System Architecture (FASA) to Support Diverse Requirements and Agile Service Creation. JLT, April 2018.]

Things you can do with a virtualized architecture…

Why would competing VNOs not claim usage of their full capacity, every frame?

…thus killing PON bandwidth sharing advantage? *(VNOs are in charge now)*

VNOs with excess capacity can sell it in the market



VNO with excess demand can buy it from the market

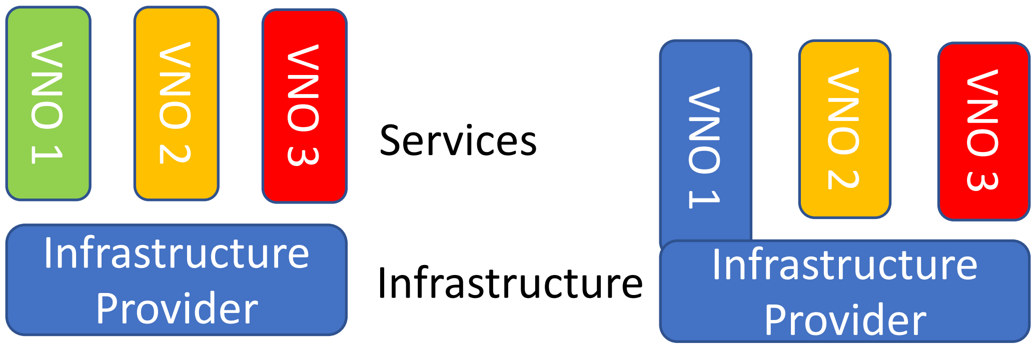
- <u>Market properties:</u>
  - Multiple traders (sellers, buyers) on both sides
  - Roles changing on each frame

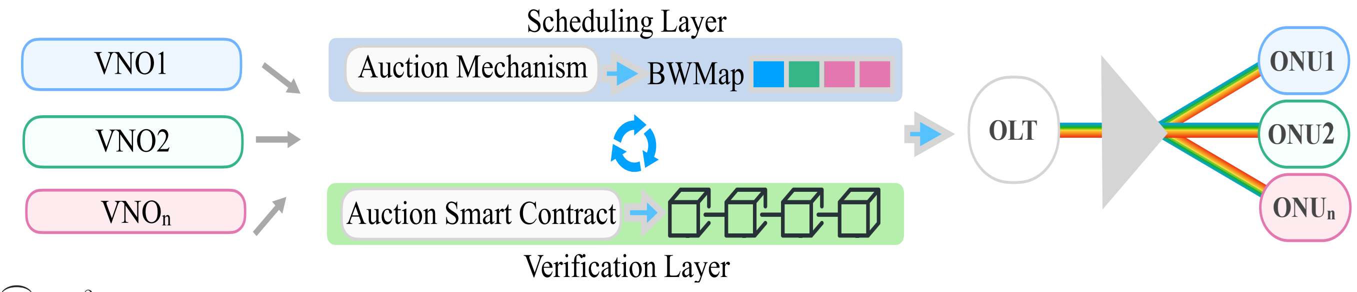
- N. Afraz and M. Ruffini. A Sharing Platform for Multi-Tenant PONs. IEEE/OSA Journal of Lightwave Technology, Vol. 36 , No. 3, Oct. 2018
- Nima Afraz, A. Elrasad, Marco Ruffini, DBA Capacity Auctions to Enhance Resource Sharing across Virtual Network Operators in Multi-Tenant PONs. Proc. of Optical Fibre Communications conference (OFC), paper Th.1B.3, March 2018

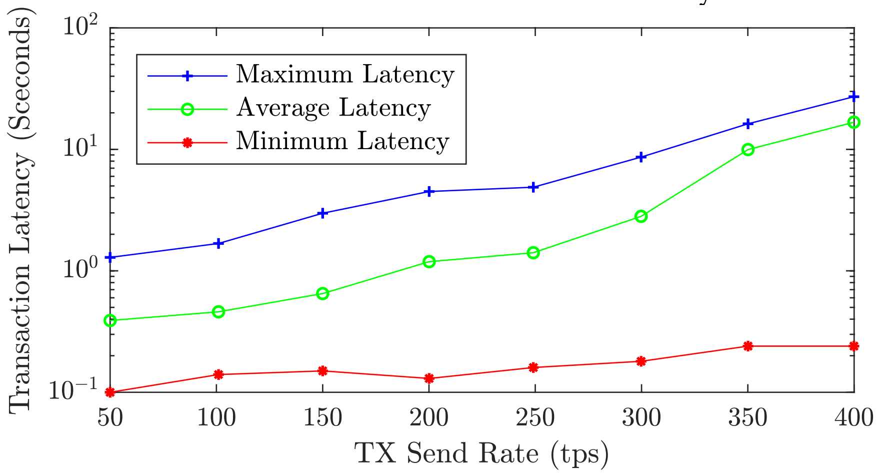
Distributed solution based on Blockchain

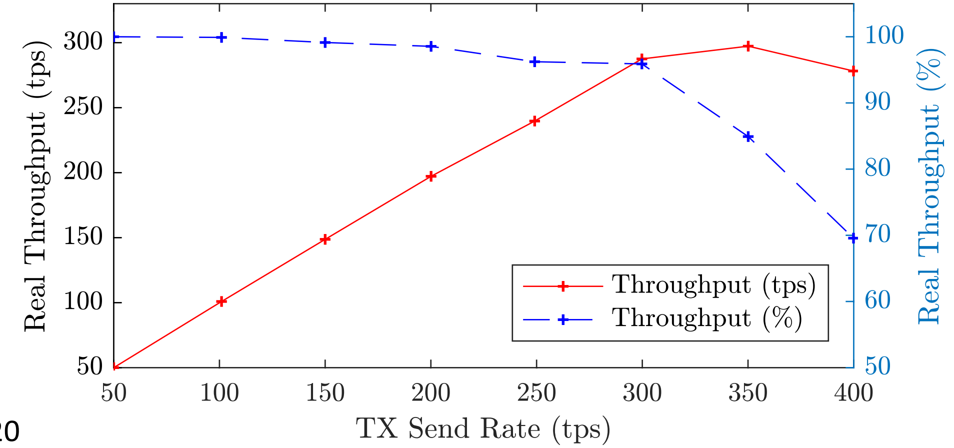
Ideal case

More typical









- Fault Tolerant distributed record-keeping
  - Distributed ledger technology
- Manipulation-proof distributed Auction
  - Smart contract technology
- We make use of the Hyperledger fabric, which deals with private Blockchain

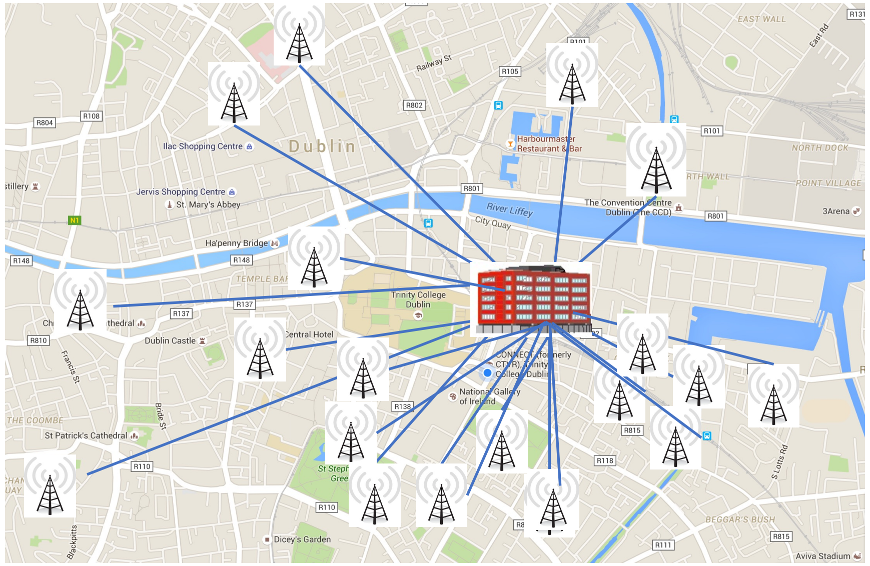
- N. Afraz, M. Ruffini. 5G Network Slice Brokering: A Distributed Blockchain-based Market. IEEE EuCNC, June 2020
- N. Afraz and M. Ruffini. A Distributed Bilateral Resource Market Mechanism for Future Telecommunications Networks. Proc. of IEEE Globecom, December 2019

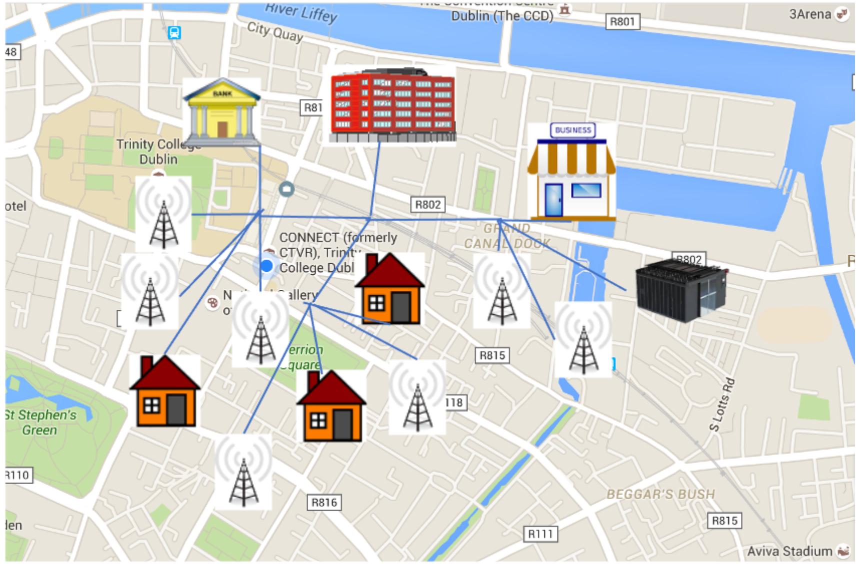
Summary

- Classical broadband evolution: From DSL to FTTH
- **From generic broadband service to 5G and beyond**
  - SDN and virtualisation
    - From SDR to ORAN
    - PON virtualisation
  - Network convergence
    - Wireless-PON convergence
    - PON capacity evolution
    - Adding edge computing
    - Extending to metro
  - Open and intelligent systems
    - Open optical systems
    - Mininet-Optical
    - Testbed experimentation

How can this technology help with convergence?

- We mentioned that access networks are also key to support 5G, especially the small cell densification aspect.
- As of today, the availability (and cost) of fibre is the main impediment to small cell deployment/densification

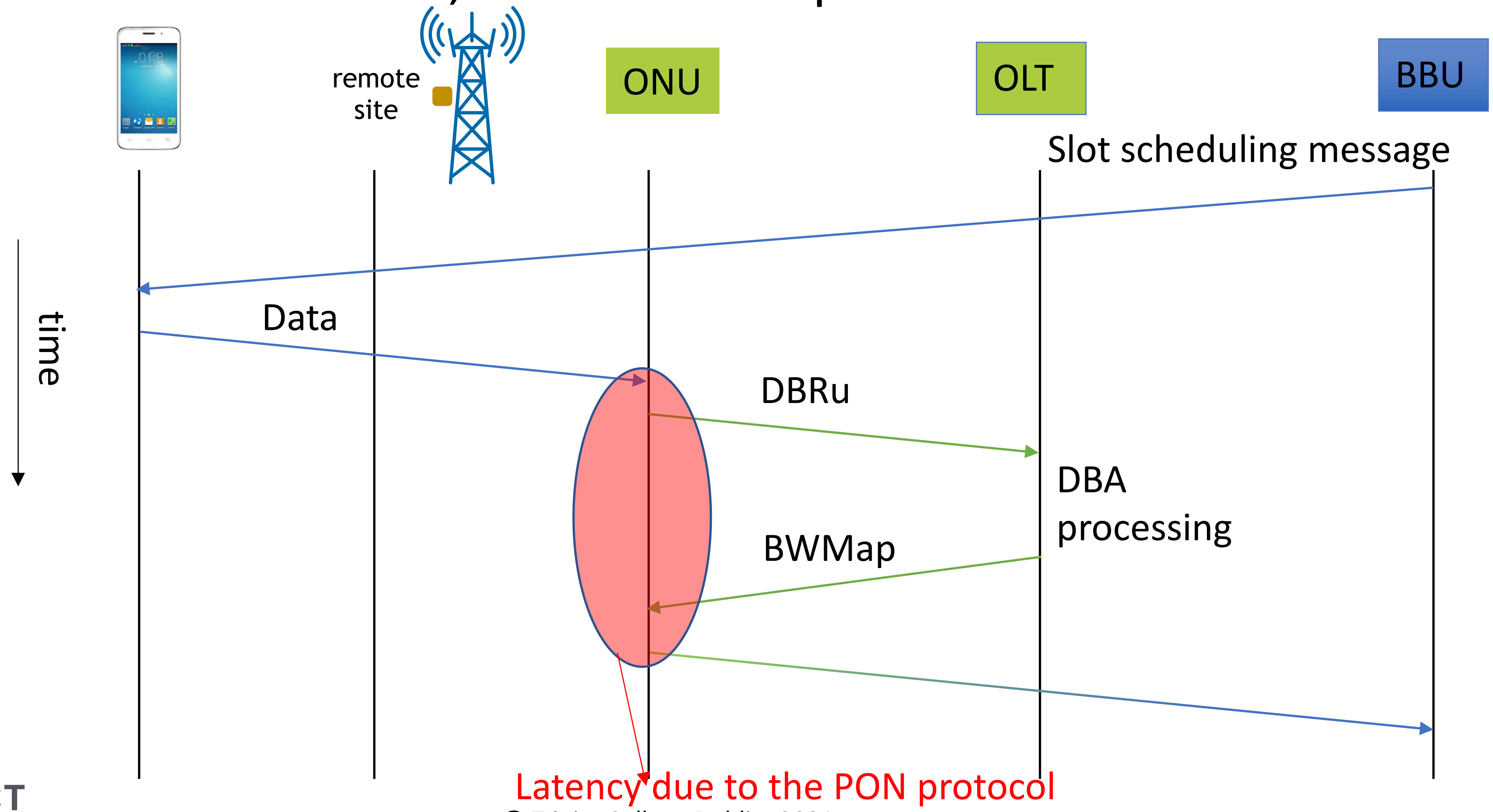




- PONs can provide a low-cost access point
  - It can also match the statistical multiplexing aspect of small cells
  - smaller coverage areas (small cells) have much higher load fluctuation
- There are however some issues to fix
  - Latency and jitter in the upstream (due to the multipoint-to-point MAC protocol - DBA)
  - Capacity (Small cells, especially in LoI Layer Split, consume high capacity)

The BDA latency issue in C-RAN

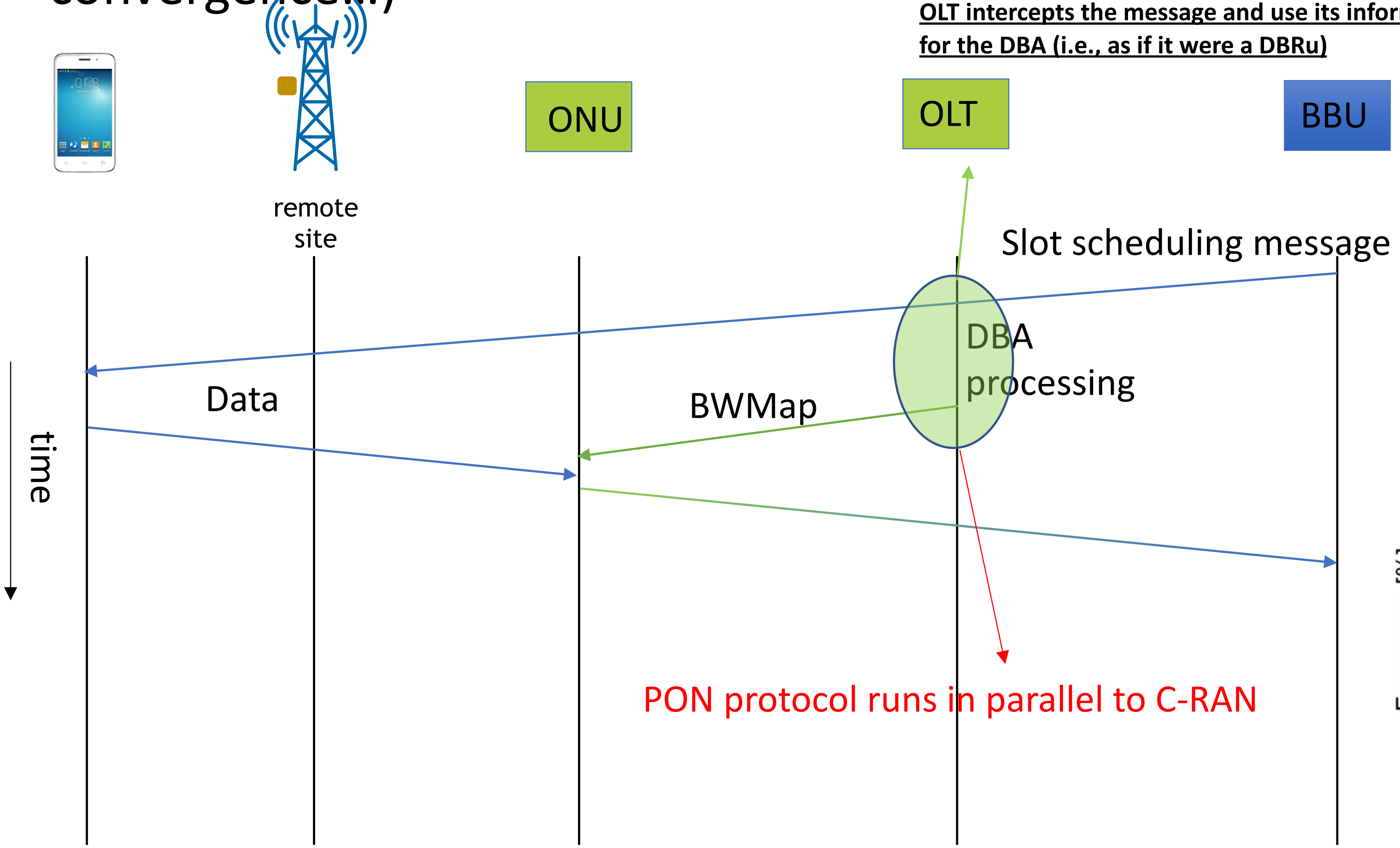
- PON and C-RAN both need to run their own upstream MAC protocol.
- Typically they work independently, (in sequence), so incoming packets get queued at the ONUs, until the PON protocol enables transmission.



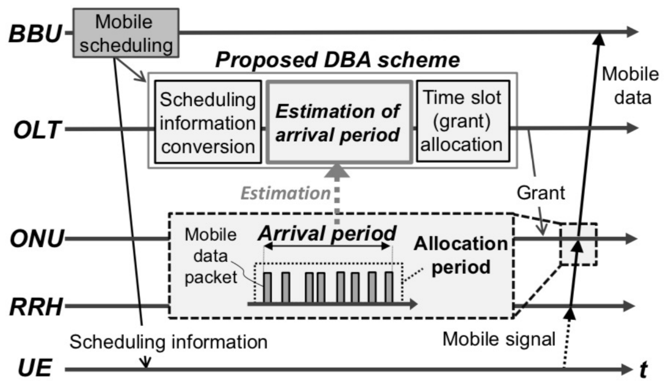
Cooperative DBA Solution (now called Cooperative Transport Interface - CTI)

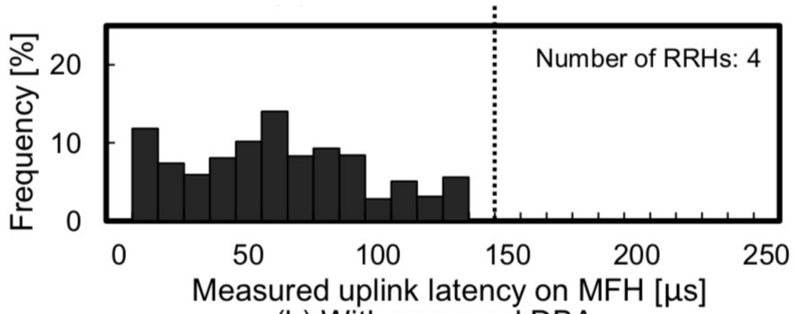
- Synchronise BBU scheduling and OLT DBA (this is optical/wireless convergence…)

OLT intercepts the message and use its information for the DBA (i.e., as if it were a DBRu)



Standardised in ITU-T G.989.3Am1





(b) With proposed DBA

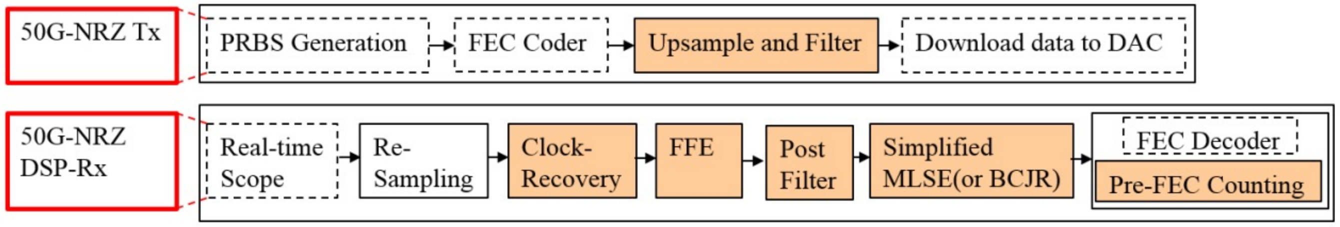
Source: H. Uzawa, et al. Practical Mobile-DBA Scheme Considering Data Arrival Period for 5G Mobile Fronthaul with TDM-PON. ECOC 2017.

Capacity: towards higher rate PONs

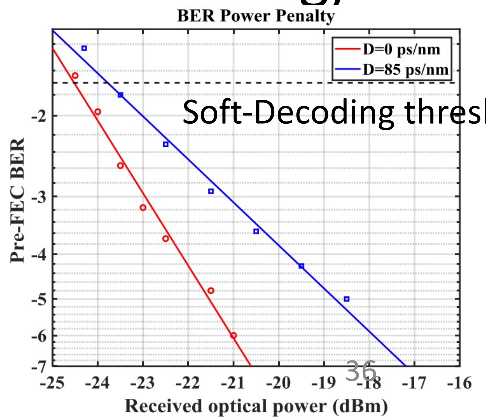
- Evolution from Data centre standards (e.g., the 25Gx4 of the 100GE)
- PAM-4 would enable 50G on 25GBaud, but receiver penalty of 8-9dB too high for PONs
  - ➔ NRZ is preferred choice
- 50G APD difficult to produce at low cost point
  - Use of 25G APD receivers with Electrical Duo Binary – EDB (reduces the bandwidth of an NRZ signal)
- DSP for equalization required to counteract low bandwidth of receiver
- Chromatic dispersion is also a problem (the requirement is of 1dB penalty over 20km distance) ➔ 74 ps/nm
  - EBD can just meet this requirement

D. van Veen, V. Houtsma, Strategies for economical next-generation 50G and 100G passive optical networks. JOCN, Jan. 2020

- Example work using DSP for Clock recovery, equalization, LDPC (soft or hard decoding)



Enables 20 km transmission distance

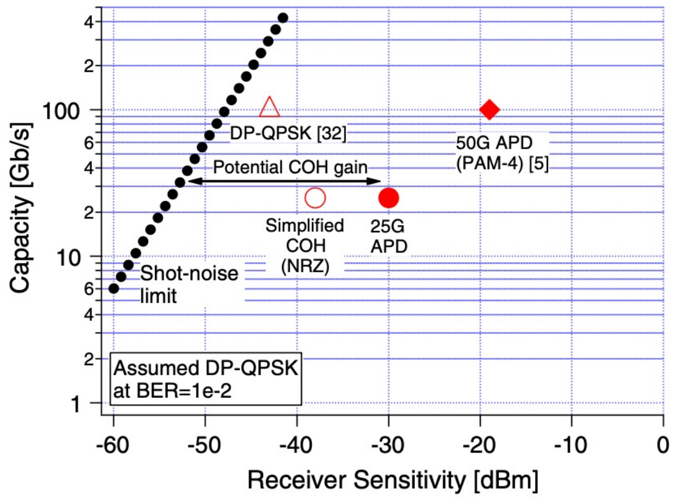


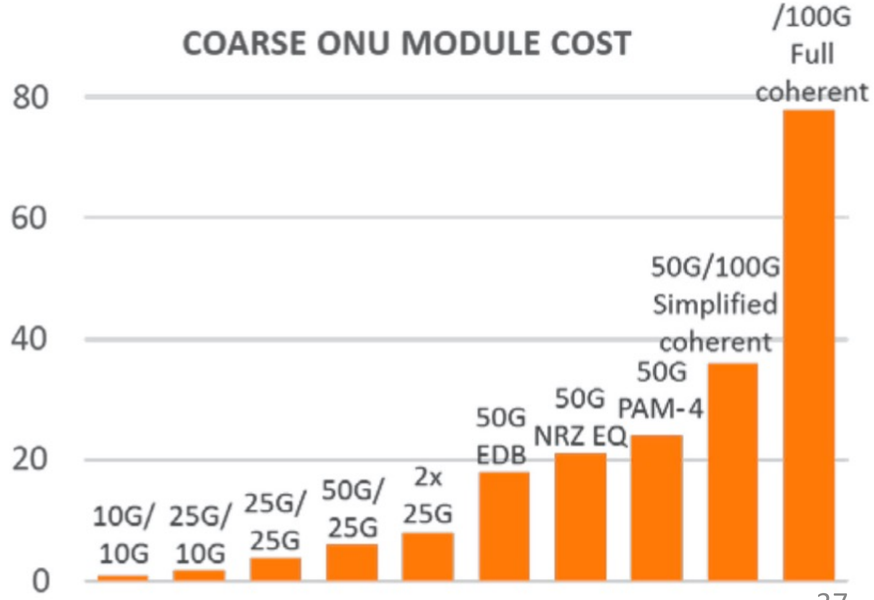
M. Tao et al., Improved Dispersion Tolerance for 50G-PON Downstream Transmission via Receiver-Side Equalization. OFC 2019

What about 100G?

- Single channel on direct detection very difficult due to severe chromatic dispersion and power budget
- Use of multiple wavelengths is an option and that will need to be used, but each channel should still deliver as much capacity as possible.
- However, one big question is whether coherent technology could be used.
  - Cost has decreased over time and now we see coherent in the metro (about <$10k for a 200G Tx/Rx)
- Advantages:
  - Use of 25Gbaud technology, with higher modulation formats
  - Compensate dispersion (and overall equalization) through DSP
  - Improve in power budget due to increase in sensitivity
  - Faster receiver tuning

D. van Veen, V. Houtsma, Strategies for economical next-generation 50G and 100G passive optical networks. JOCN, Jan. 2020

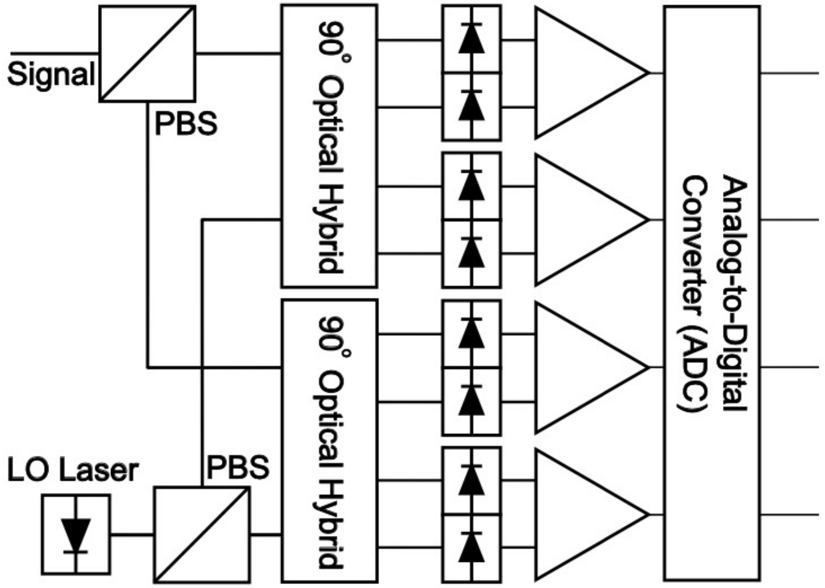




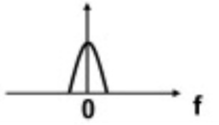
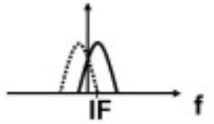
Coherent PON technology

Cost driven by the coherent receiver:

- 2 x polarization beam splitters (for polarization diversity)
- 2 x 90^{o} optical hybrids (for phase diversity)
- 4 x balanced photodetectors
- 4 x analog-to-digital converters (ADC)
- 1 x local oscillator laser (LO).



Full coherent receiver

Heterodyne	Homodyne	Intradyne
Analog optical PLL + DSP (frequency - stabilized LO)	Analog optical PLL + DSP (frequency - stabilized LO)	Digital phase compensation + DSP (free -running LO)
High multiplicity	High multiplicity	Low multiplicity
		

Optical Fiber Telecommunications Systems and Networks A. 6th Edition, 2013

Concept of coherent reception: local oscillator beats coherently with signal to extract phase information

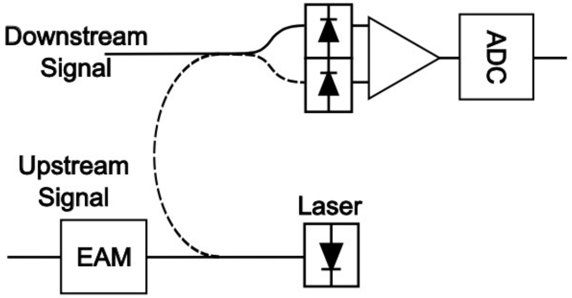
- Homodyne: LO same frequency as signal and LO is frequency stabilized
- Heterodyne: LO at different frequency of LO signal and LO is frequency stabilized
- Intradyne: LO same frequency as signal but LO is free running. Phase error is compensated for digitally

D Lavery et al., Opportunities for Optical Access Network Transceivers Beyond OOK, JOCN, Feb. 2019.

Reduce cost of coherent receivers

For access networks, the idea is to reduce cost by <u>simplifying the receiver</u>:

- Use polarization insensitive architectures to remove the 90º optical hybrid
- Quasi-coherent detection: use LO to improve sensitivity, but only detect envelope (not suitable for higher-order modulation formats)
- Use the same laser for LO and for upstream transmission
- Reduce complexity of the ADC (lower resolution)

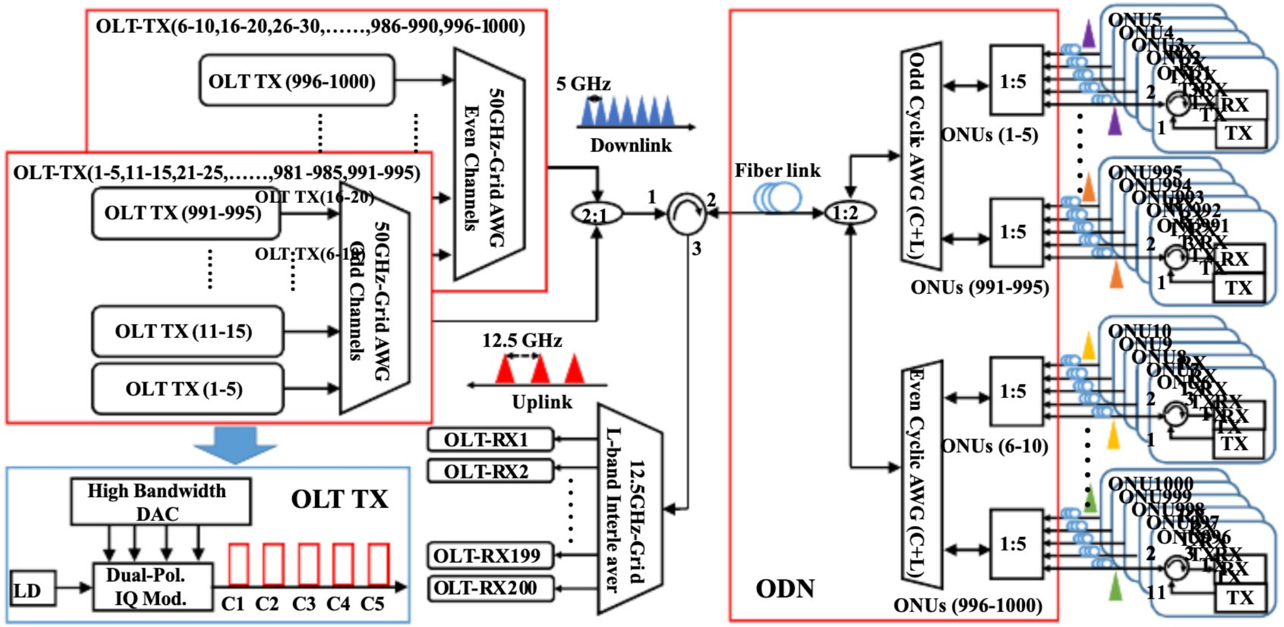


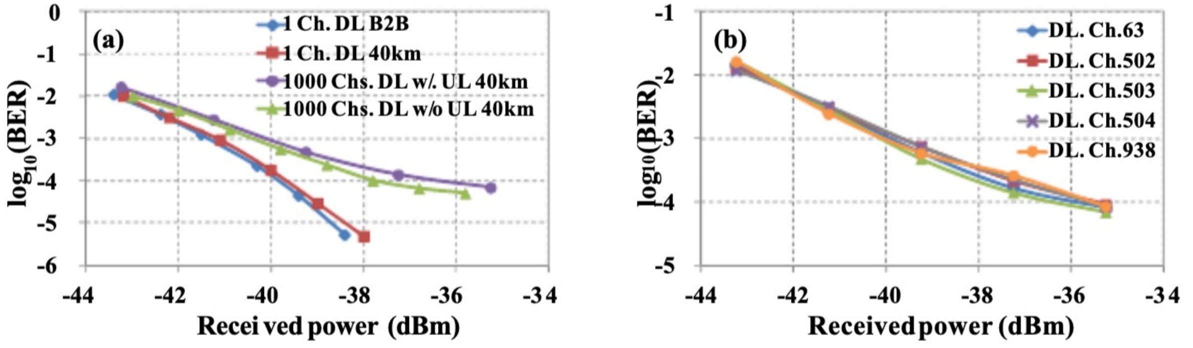
However, they suffer from reduced sensitivity, higher bandwidth and still require expensive LO.

A different approach is to maintain the complexity of the receiver (with all its benefits), but reduce the number of electronic/digital components.
Take advantage of photonic circuit integration (exploit integration of silicon and III-V).

D Lavery et al., Opportunities for Optical Access Network Transceivers Beyond OOK, JOCN, Feb. 2019.

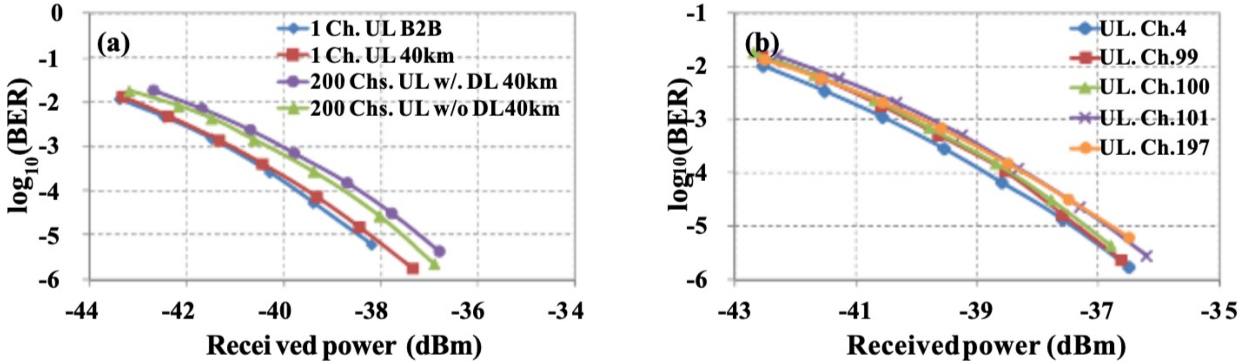
UDWDM-PON





Downstream performance

- 1000 individual wavelength channels downstream
  - DP-QPSK, 5GHz spacing 10Gb/s, C band, 28dB
  - PS-QPSK, 7.5Gb/s, 30 dB
- 200 channels upstream with TDM
  - 12.5GHz spacing, DP-QPSK, 10 Gb/s, L band



Upstream performance

Real-time bidirectional coherent ultra-dense TWDM-PON for 1000 ONUs. J. LI et al., Optics Express, Sept. 2018.

How can this technology help with convergence?

- Coherent and multi-wavelength (tunable) are expensive (consider low popularity of NG-PON2 for the multi-wavelength aspect)…

- … but here we are not talking about residential services, but business 5G (i.e., fronthaul).
  - A $1-2K ONU is a fraction of a small cell deployment
  - In any case much cheaper option than ptp fibre leasing..
  - PtP wavelength over PON also being considered, but TWDM can be more flexible and take advantage of statistical multiplexing

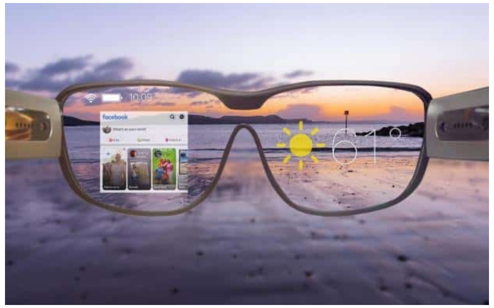
- A new issue arising with inclusion of edge computing (MEC nodes), as it modifies the requirements on the access topology

High performance VR today

- There is a large amount of computation, for which you need either external support… (cabled device)

- Or can do without PC and cable, sacrificing some performance

- <u>Or wait for this…</u>



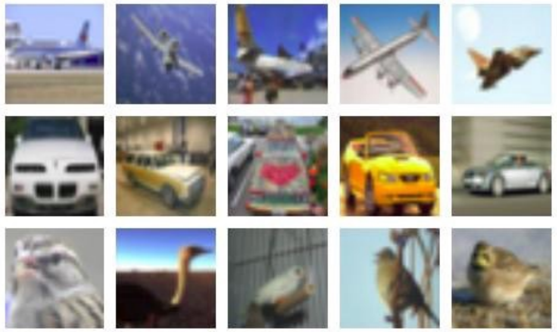
Object recognition

<u>…and offload your computation elsewhere</u>

Offloading to the edge

There is much research happening now on removing heavy computation altogether, i.e. offloading computation to the edge.

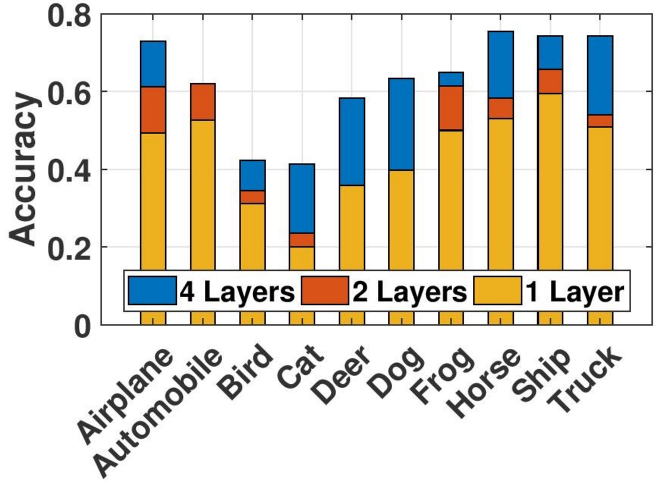
- ➢Example of object recognition



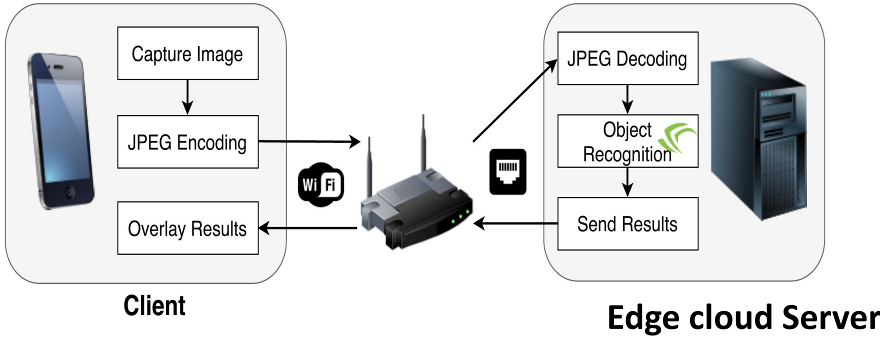
VS

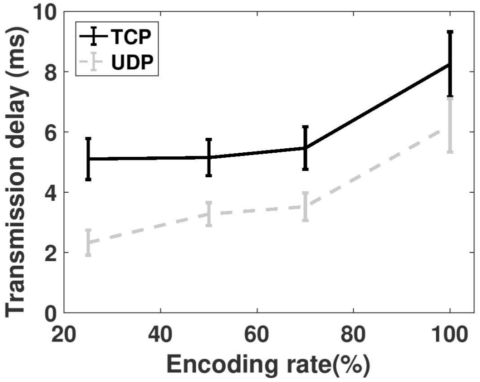
laptop

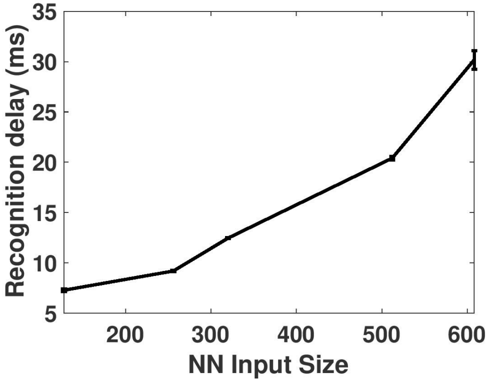
Average time: 2.537 s vs. 0.191



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







Average Precision

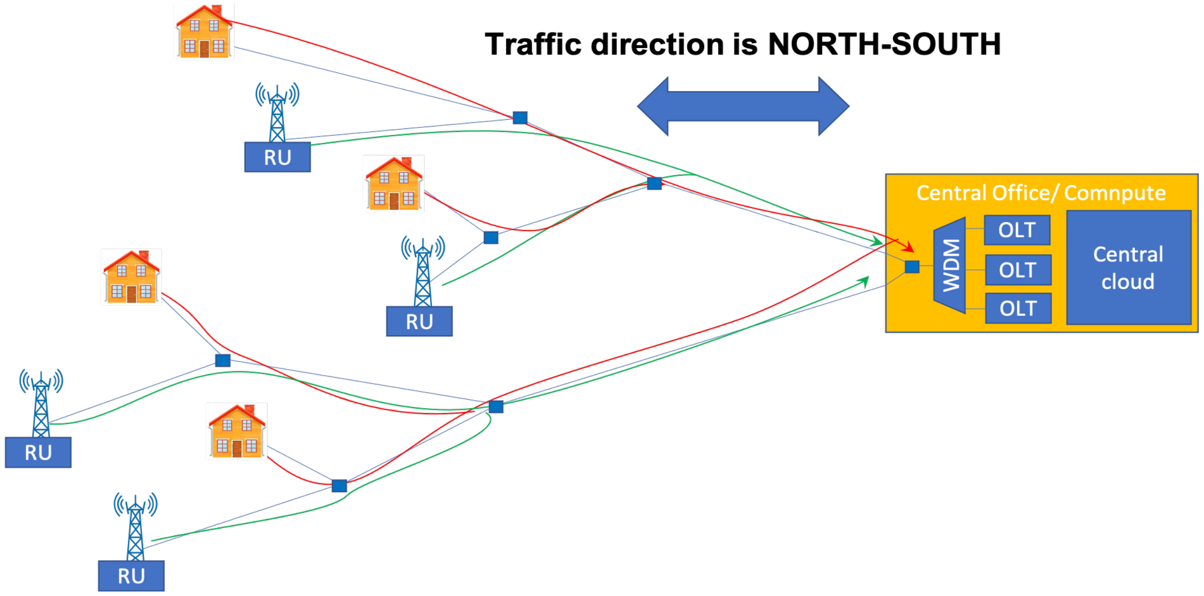
NN Input Size \ Encoding rate (%)	25	50	75	100
608	0.41	0.47	0.5	0.52
512	0.43	0.48	0.5	0.52
320	0.42	0.44	0.45	0.45
256	0.38	0.4	0.4	0.4
128	0.12	0.12	0.12	0.12

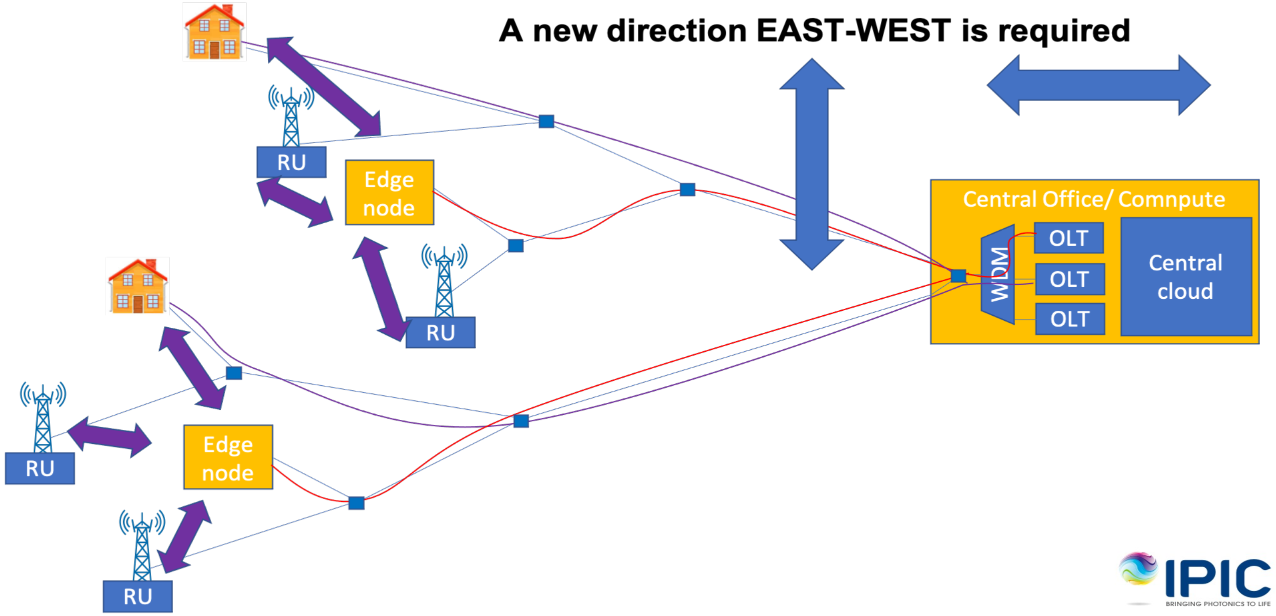
Encoding rate (%)

A. Galanopoulos, et al. Measurement-driven Analysis of an Edge-Assisted Object Recognition System, in proc. of IEEE ICC, 2020

The edge connectivity problem

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





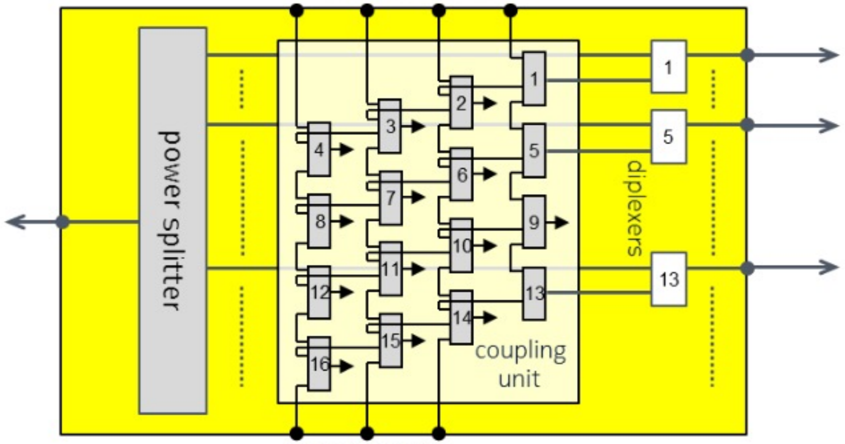
- ➢For lower latency there are MEC nodes… that's why they were invented
- ➢But traffic to edge nodes requires handling of direct end points communications (EAST-WEST)
- ➢<u>This is also crucial for mobile functional split</u>

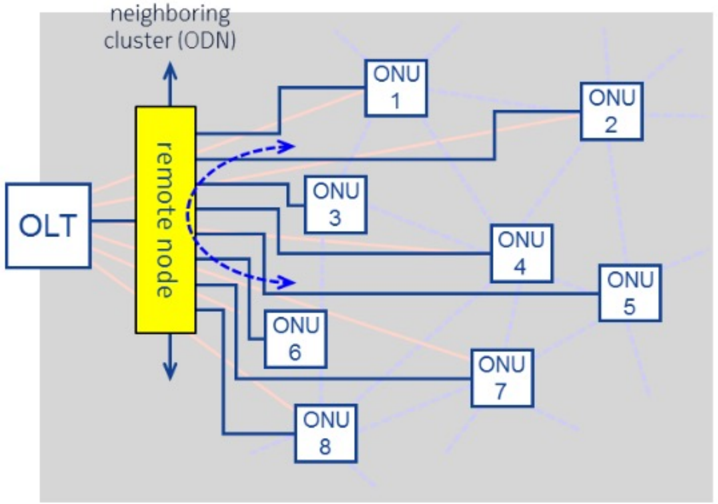
CONNECT Networks of the Future

PON-based solutions

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

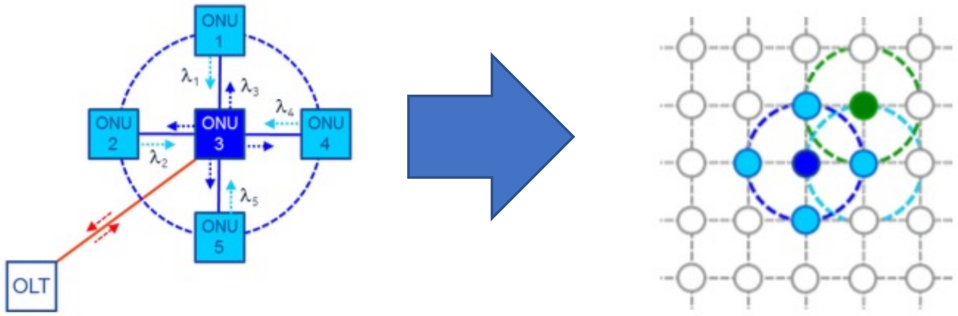
PON solutions:





Fully passive solution

Th. Pfeiffer, “Converged heterogeneous optical metro-access networks,” ECOC 2010, paper Tu.5.B.1



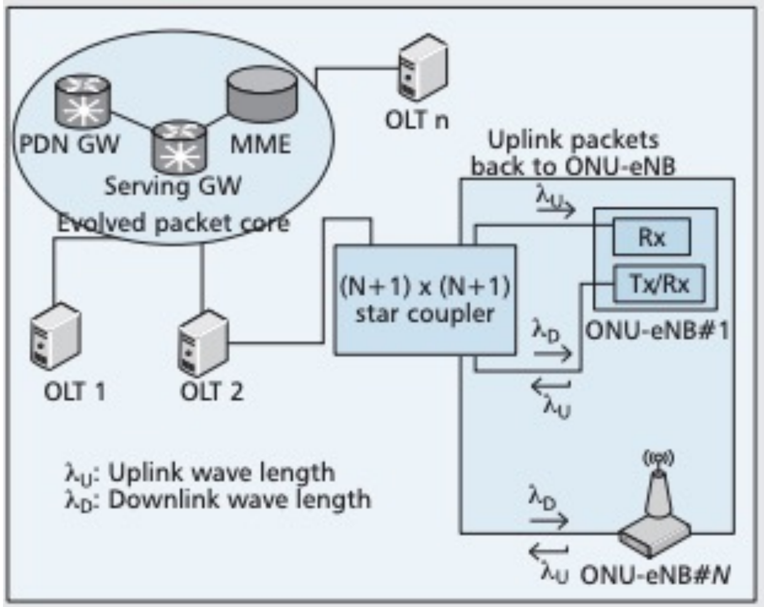
Less flexibility in direct links, more suitable for macro to small cell communications

PON-based solutions

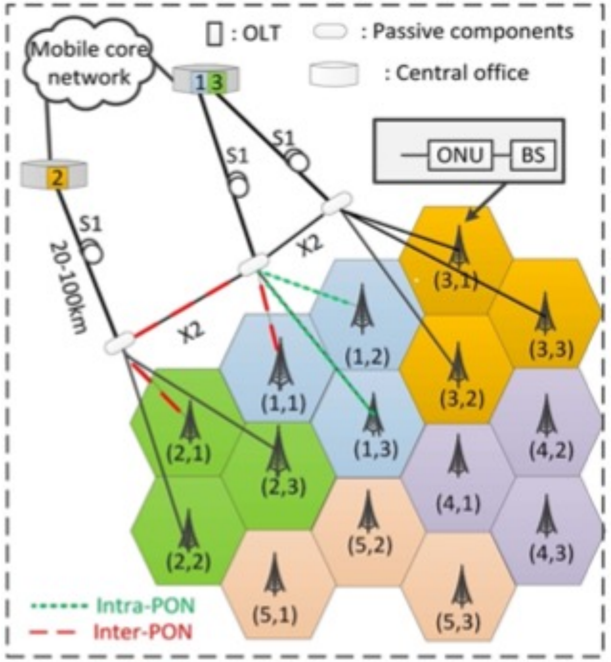
Use of passive star coupler

Focused on mobile base station connectivity.

Fully passive solution, but limited scalability



C. Ranaweera, E. Wong, C. Lim, and A. Nirmalathas, "Next generation optical-wireless converged network architectures," IEEE Network 26, 22–27 (2012).



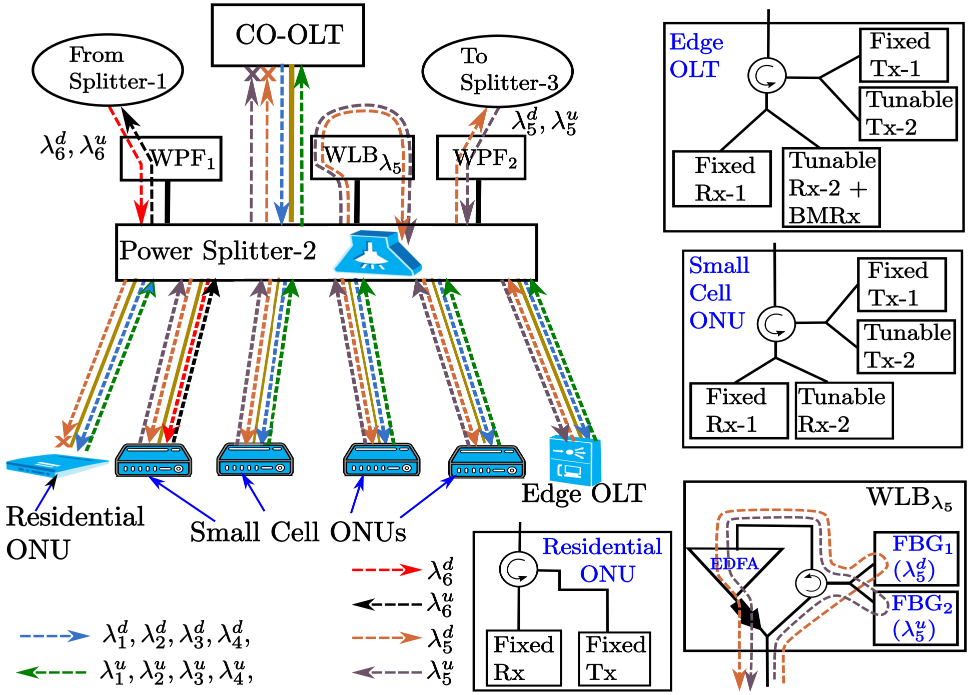
J. Li and J. Chen, "Passive optical network based mobile backhaul enabling ultra-low latency for communications among base stations," IEEE/OSA Journal of Optical Communications and Networking 9, 855– 863 (2017).

Passive solution: use of additional fibre to link splitters on same stage,

Difficult to reuse wavelengths, so some scalability issues.

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.



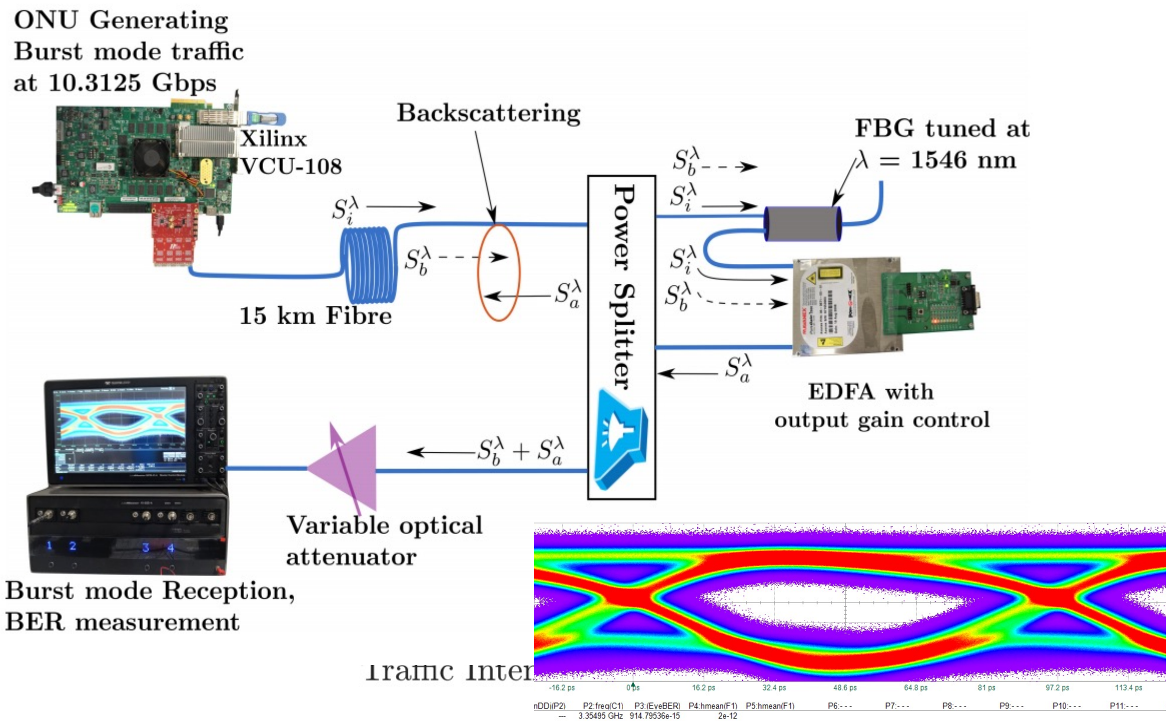
- ➢ Example use of Fibre Bragg Gratings
- ➢ Power loss going through splitter, but OK for last stage.
- ➢ Higher stage splitter might need amplifier integrated with FBG.

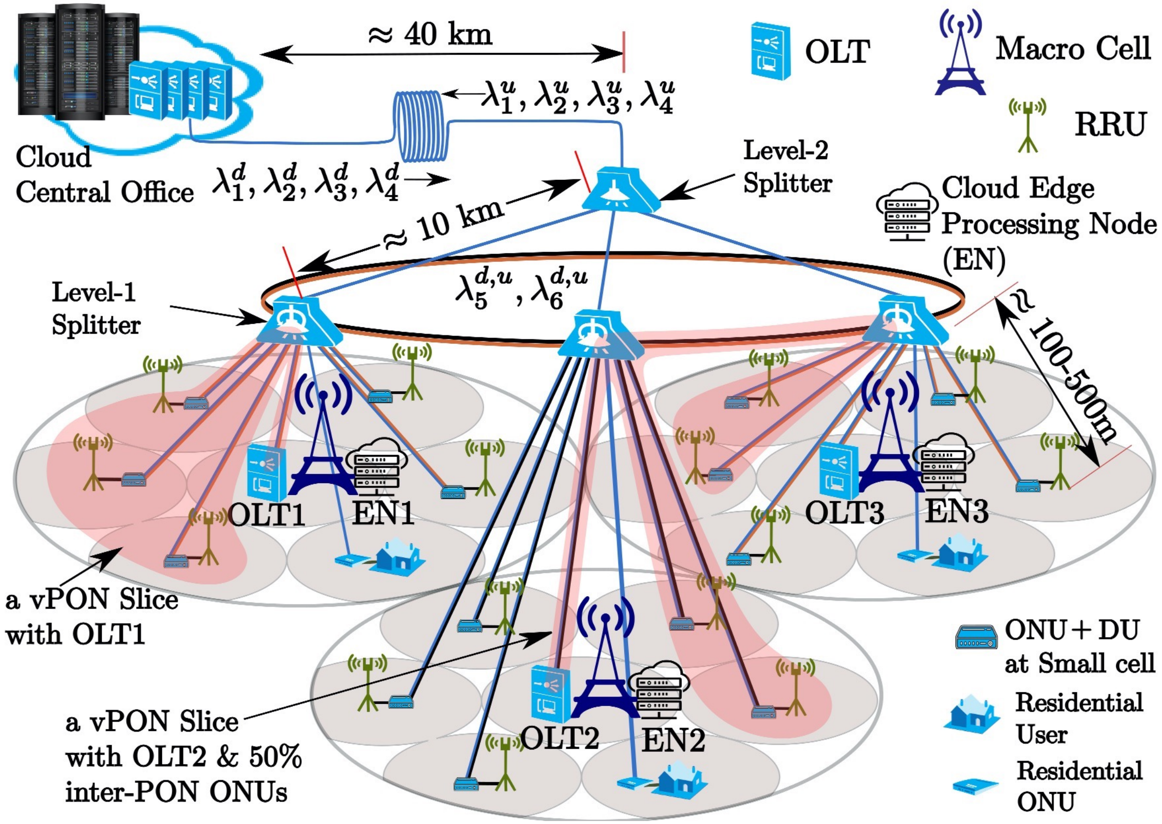
<u>Other technologies could be investigated…</u>
<u>e.g., power/wavelength re-configurable splitters</u>

- 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.
- ➢<u>The MEC node can be located anywhere (at any PON end point)</u>



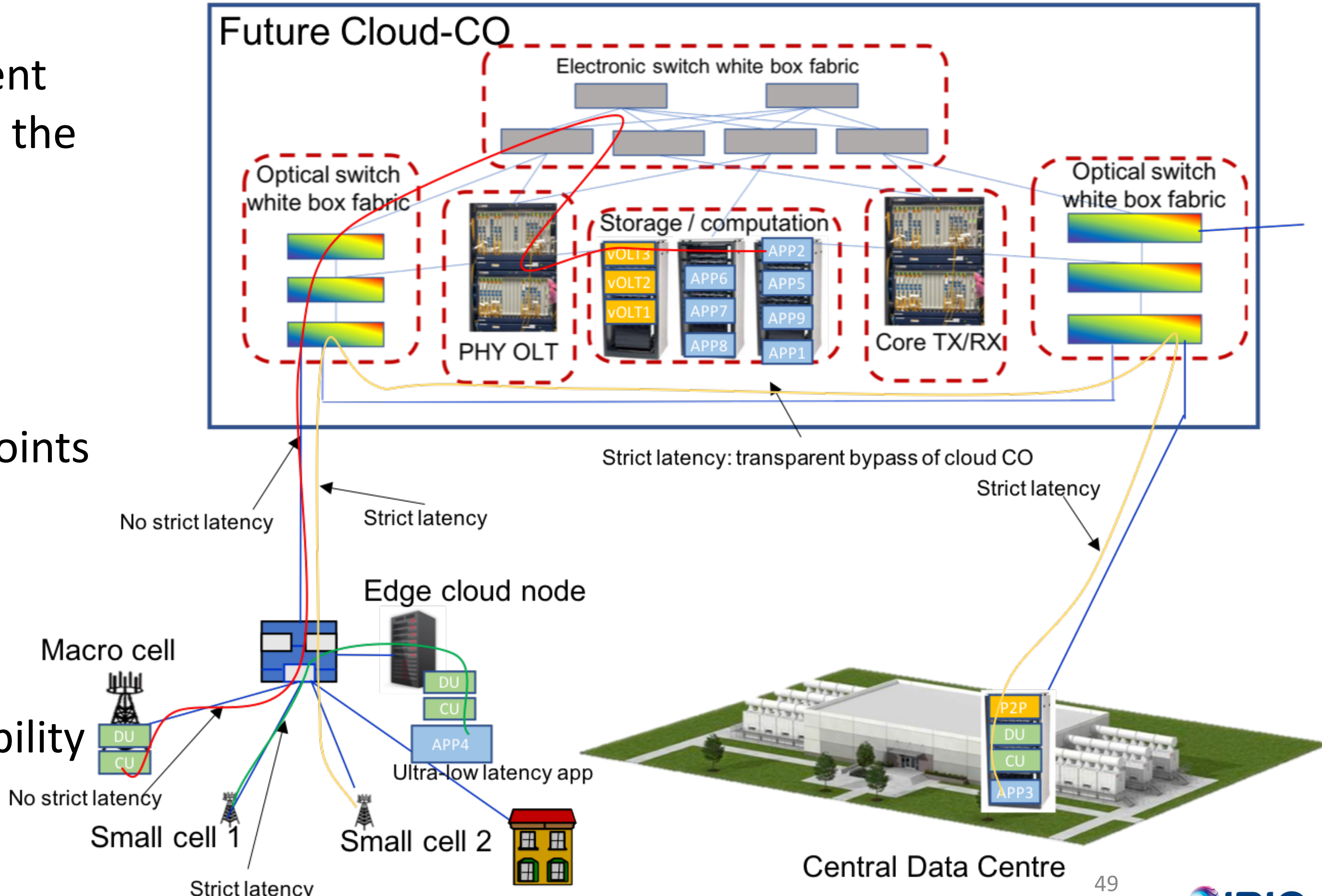


Largely unaffected by signal reflections

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



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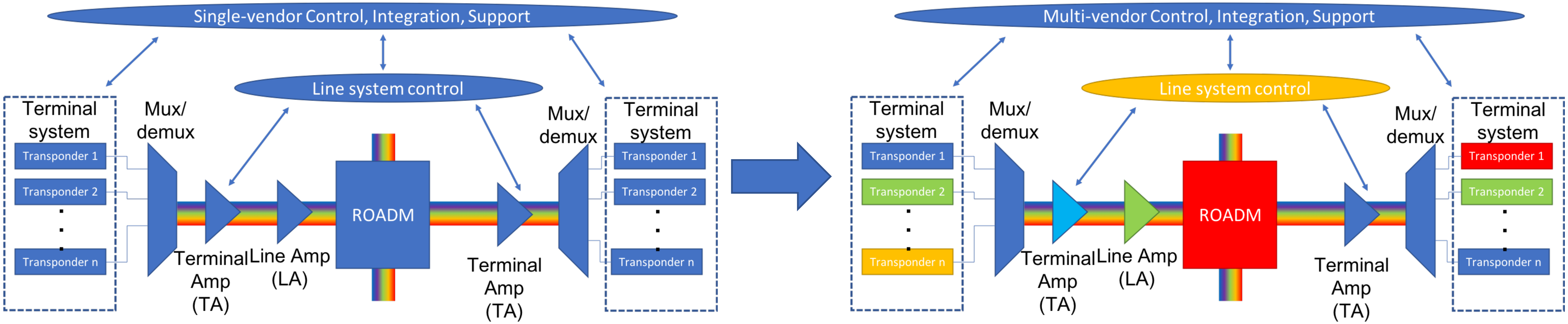
    - Wireless-PON convergence
    - PON capacity evolution
    - Adding edge computing
    - Extending to metro
  - Open and intelligent systems
    - Open optical systems
    - Mininet-Optical
    - Testbed experimentation

What is an open optical network?

- With CORD, etc. the NFV paradigm was pushed down to the MAC layer of optical technologies (e.g., in PON with the VOLTHA)..
- ..and for wireless technologies down to the physical layer (software radio implementation of LTE)
- The optical layer has also started the disaggregation process:

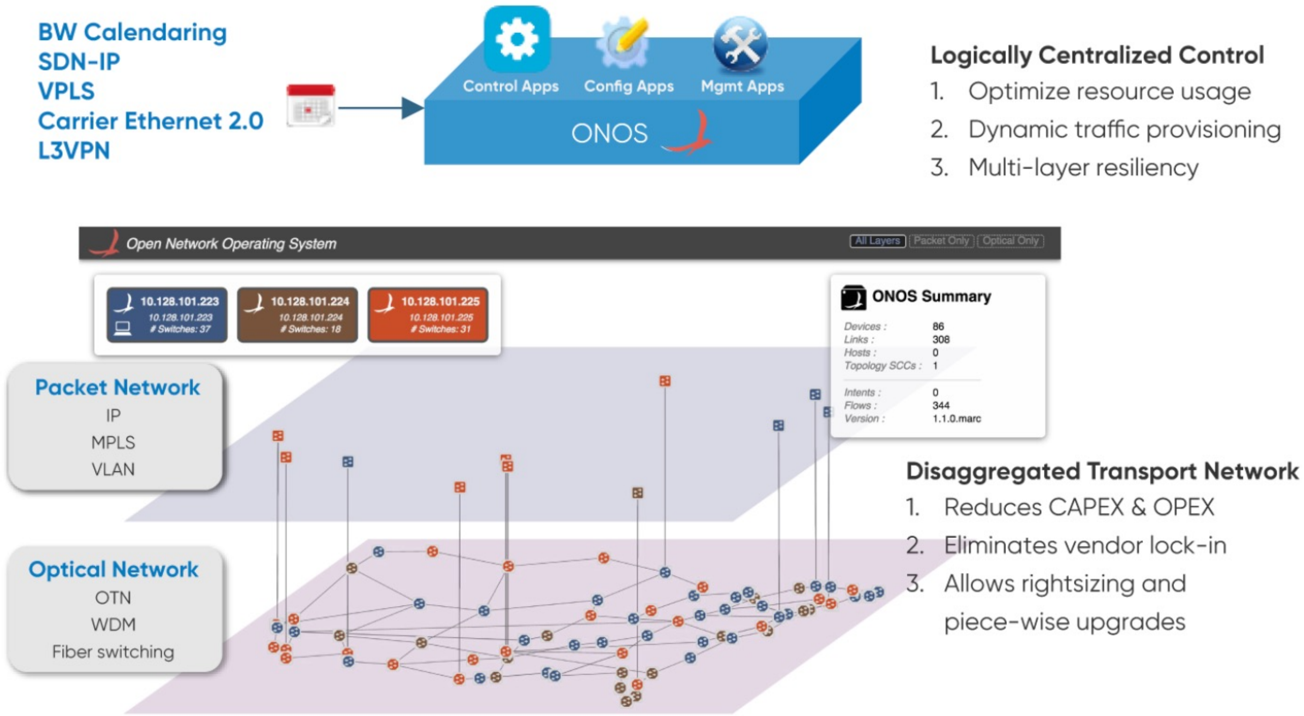


- What it means:
  - Mix and match transponders, amplifiers, ROADMs, control loops, optical control plane …

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**



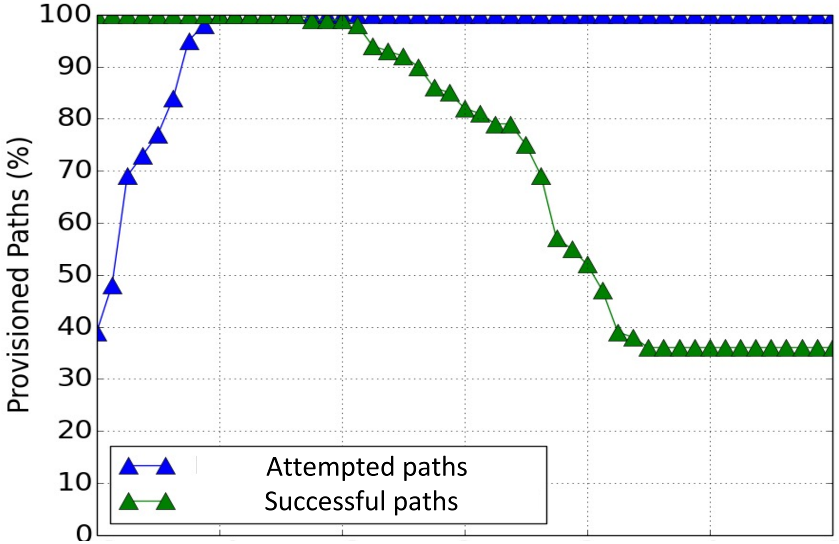
Challenges:

- 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

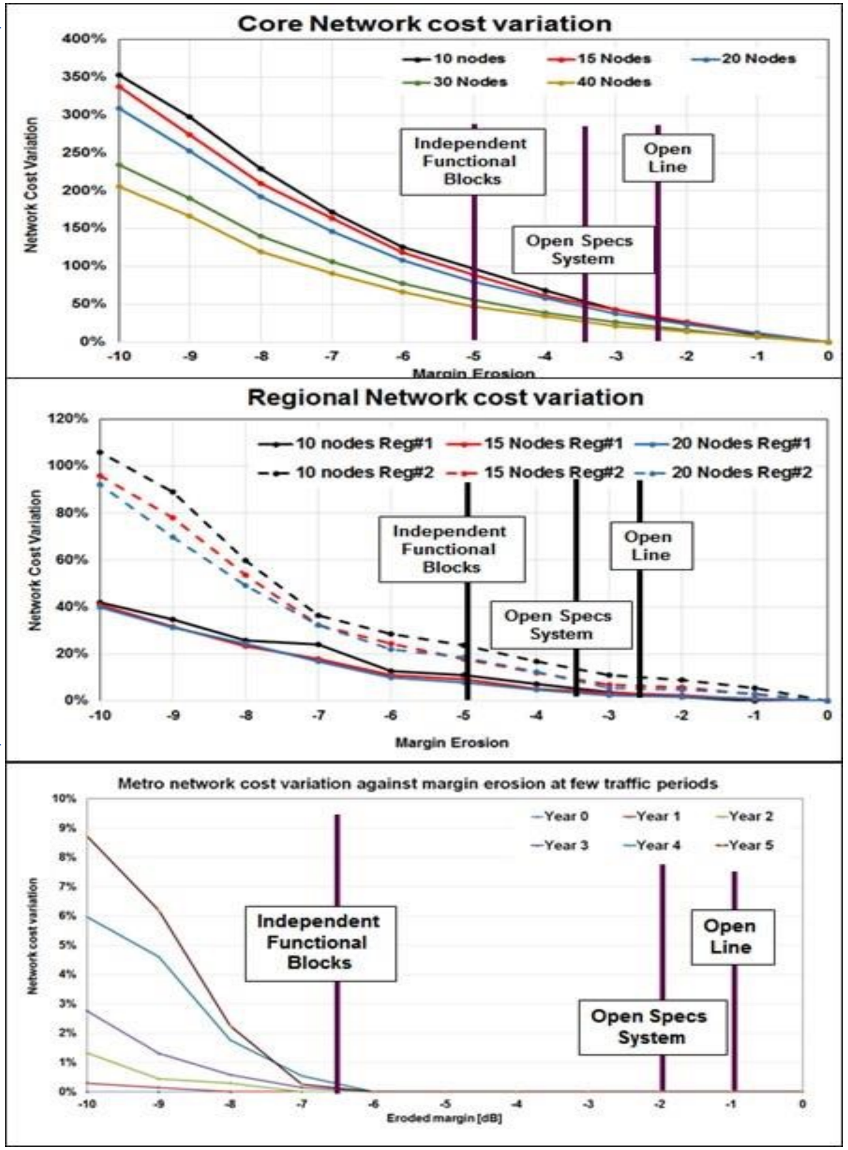
More aggressive

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

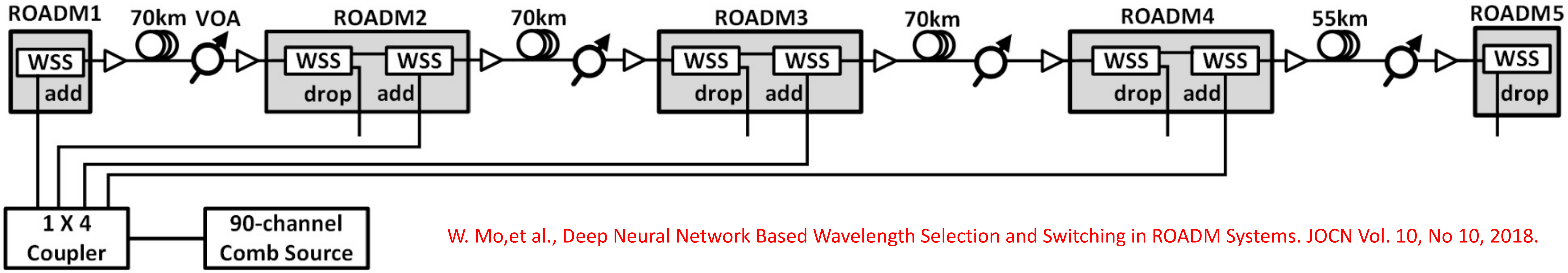
Effect on metro though is negligible, as the metro has larger margins



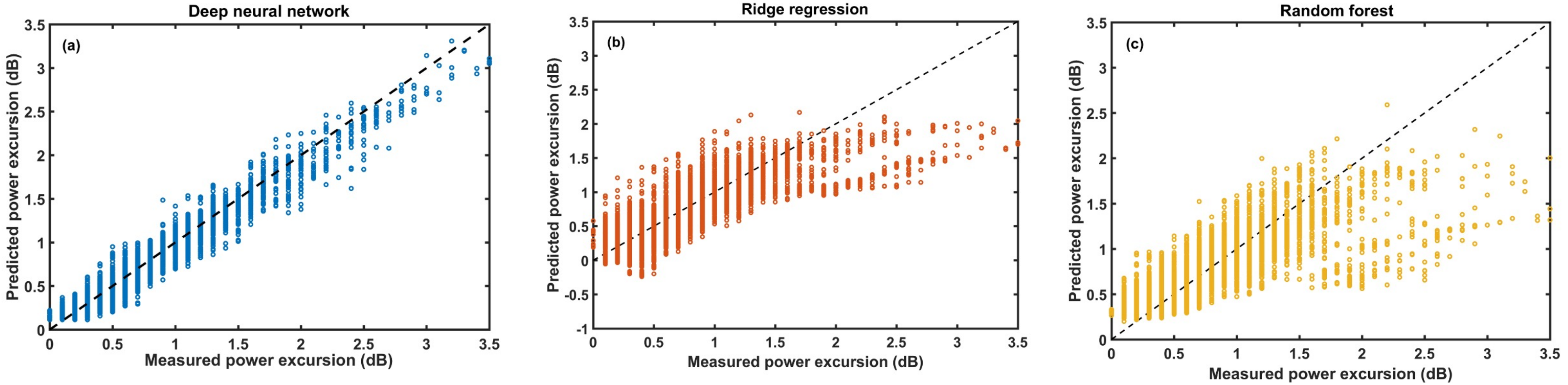
Source: M. Bleanger, M, O'Sullivan and P, Littlewood. Margin requirement of disaggregating the DWDM transport system and its consequence on application economics. M1E.2, OFC '18

CONNECT Networks of the Future

Deep Learning Shown Effective for Predicting Optical Signal Powers



W. Mo,et al., Deep Neural Network Based Wavelength Selection and Switching in ROADM Systems. JOCN Vol. 10, No 10, 2018.

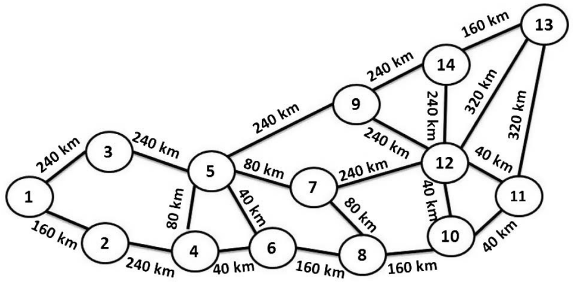


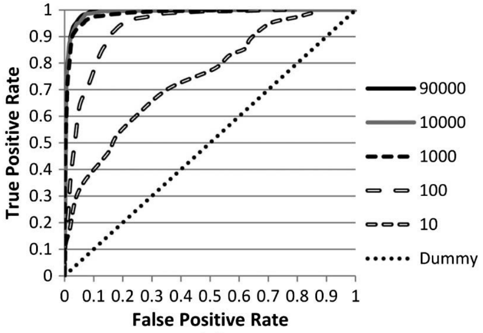
Deep learning (left) shown to accurately predict optical signal power which is main determinant of signal quality, based on the channel configuration alone.

More ML

QoT prediction using random forest ML algorithm

Dependency on training set size

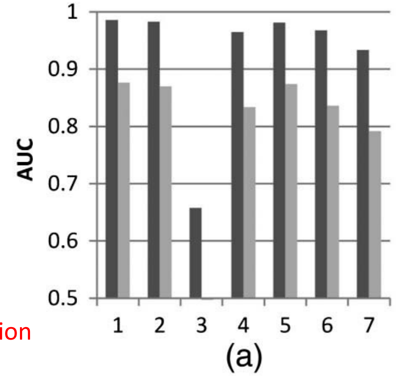




Relevance of different features

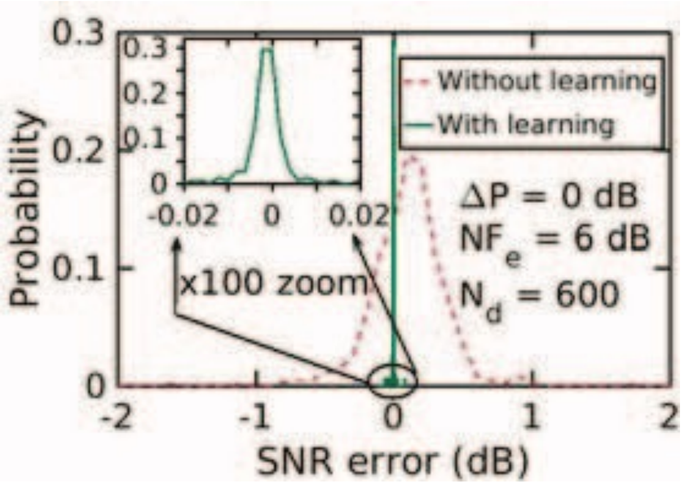
CONSIDERED FEATURE SUBSETS

	S1	S2	S3	S4	S5	S6	S7
Number of links	✓	✓	✓	✓			
Lightpath length	✓	✓	✓	✓	✓	✓	
Length of longest link	✓	✓	✓	✓			
Traffic volume	✓	✓	✓		✓		✓
Modulation format	✓	✓		✓	✓	✓	✓
Guardband, modulation format, and traffic volume of nearest left and right neighbor	✓						



Source: C. Rottondi, et al. Machine-learning method for quality of transmission prediction of unestablished lightpaths. JOCN Vol. 10, No. 2, Feb. 2018

Using gradient descent on input parameters of QoT tool to reduce uncertainty on margins.



Source: E. Seve, et al. Learning process for reducing uncertainties on network parameters and design margins. OFC 2017.

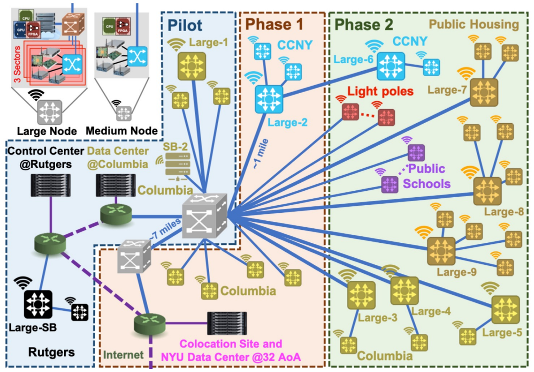
- There are still issues:
  - Scalability for large network systems need to be addressed, black box ML not a good option
  - Data collection, storage and sharing is still the main problem

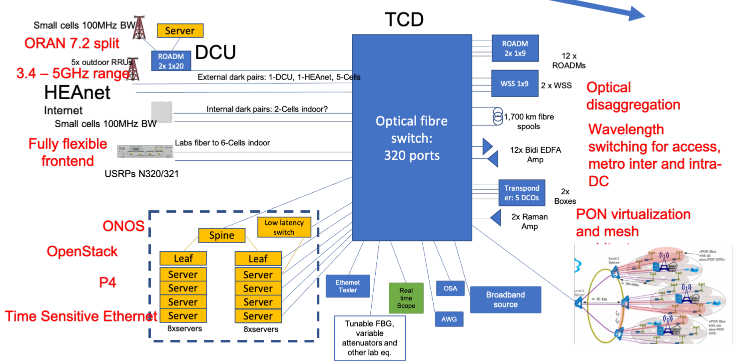
How do I test my control plane / algorithms?

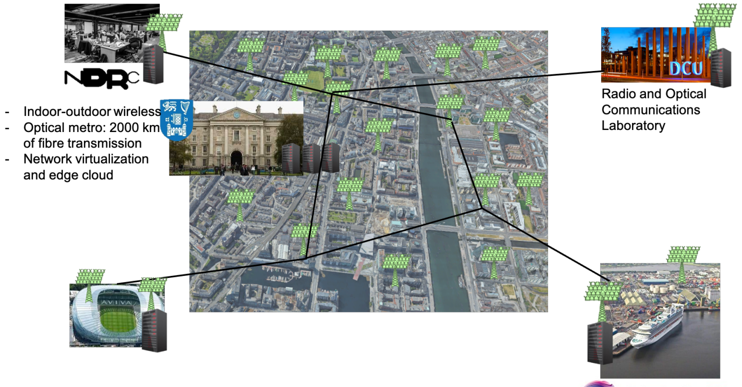
Real network infrastructure is best!... but

1) Only available to operators (or large vendor/ service provider)
   - ➢Private network, only usable by owner
   - ➢If large scale, then part of production network, so very limited research/test
   - ➢If dedicated just for experiments then it’s typically of limited size

2) I can use public (academic) experimental academic infrastructure
   - i.e., **COSMOS (NY-US), OpenIreland (Dublin)**
   - Limited to a couple of thousand km and around 10 ROADMs







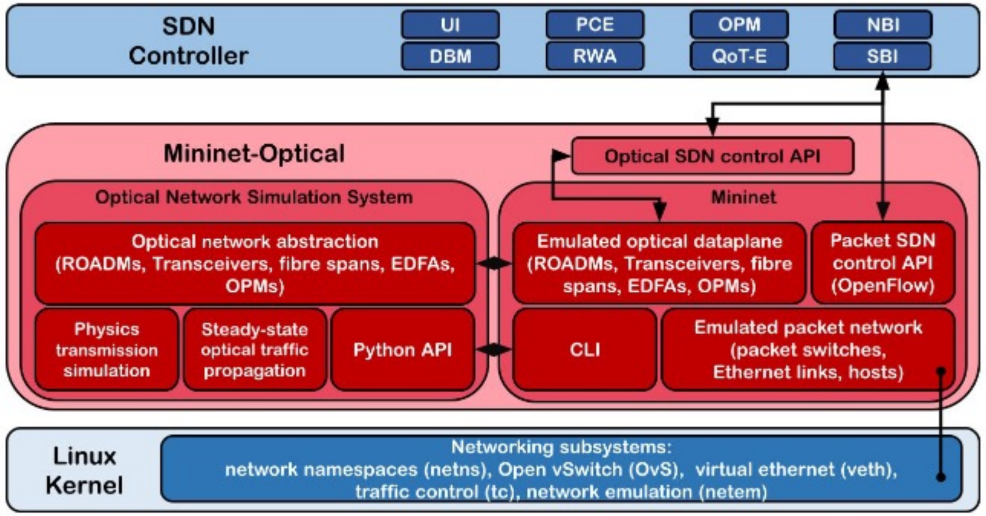
CONNECT Networks of the Future

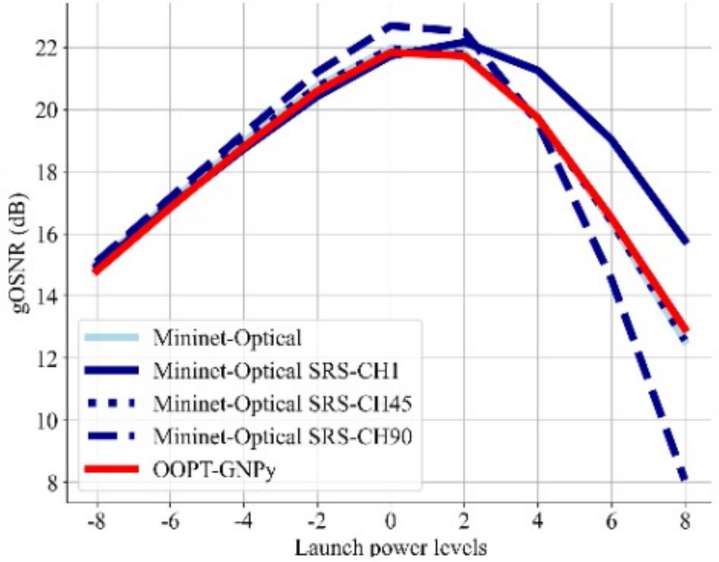
IPIC

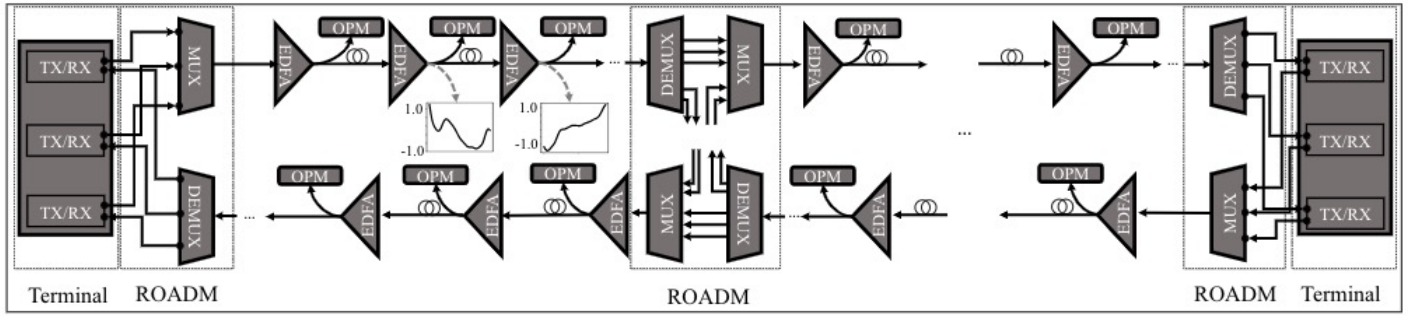
Mininet becomes Optical!

- We have created **Mininet-Optical**: an SDN emulator that uses Mininet and additional physical layer optical simulation to emulate optical devices, such as ROADMs, amplifiers, transceivers, fibre propagation (including nonlinearities), etc.

- Now you can test an SDN control plane also on optical devices (i.e., ONOS) on large scale networks

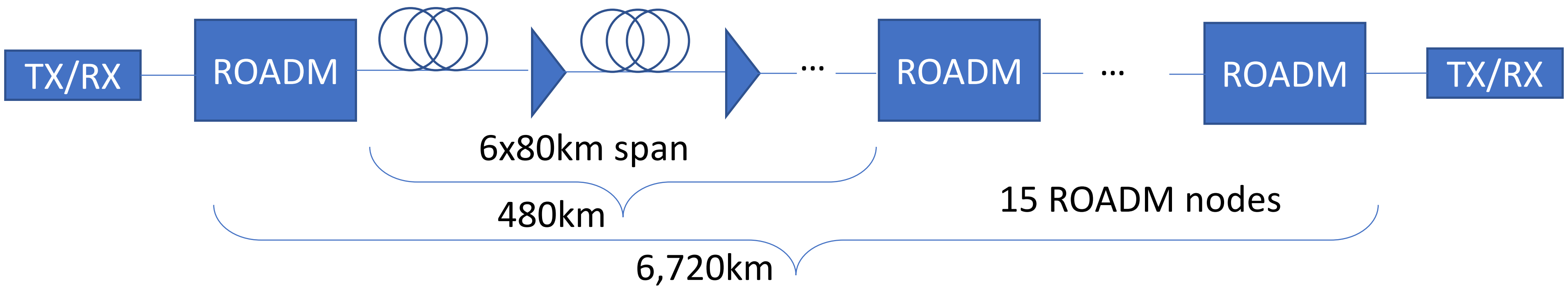






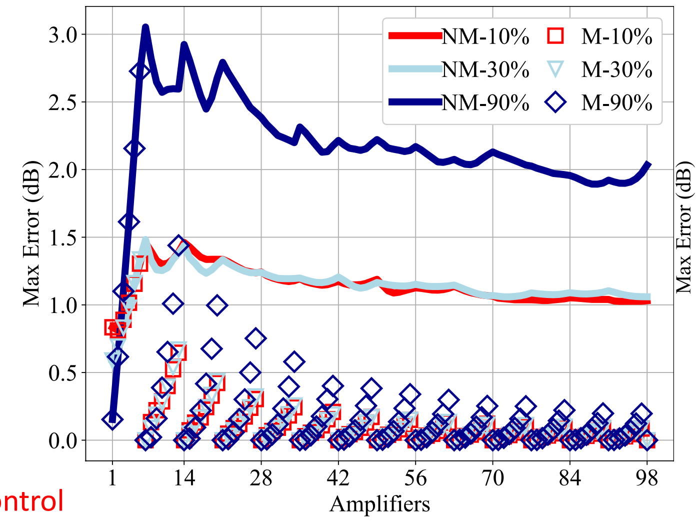
- B. Lantz, et al. SDN-controlled Dynamic Front-haul Provisioning, Emulated on Hardware and Virtual COSMOS Optical x-Haul Testbeds. To appear in OFC, June 2021.
- A. Diaz-Montiel, A. Bhardwaj, B. Lantz, J. Yu, A.N. Quraishy, D. Kilper and M. Ruffini. Real-Time Control Plane Operations for gOSNR QoT Estimation through OSNR Monitoring. To appear in OFC 2021.

Example of operation: Use OPM to improve controller's QoT estimation

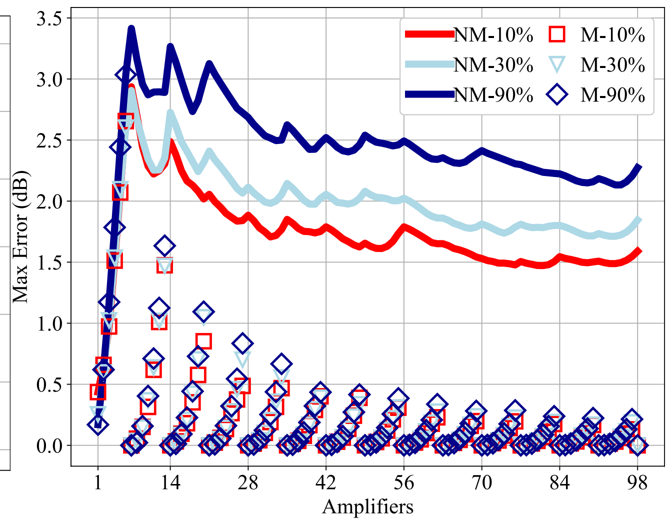


- Loading channels on a 90-wavelength transmission system.
- The <u>unknown EDFA wavelength dependent gain</u> causes errors on the QoT estimation algorithm.
- The controller can use OPM to correct the estimation error

- Controller's QoT estimation considers nonlinear effects and EDFA noise, but not the wavelength-dependent gain
- The estimation error on the worst channel can be up to 3 dB.
- <u>Adding monitoring every 7 amplifiers can reset the estimation error, keeping it below 1 dB for most of the path</u>



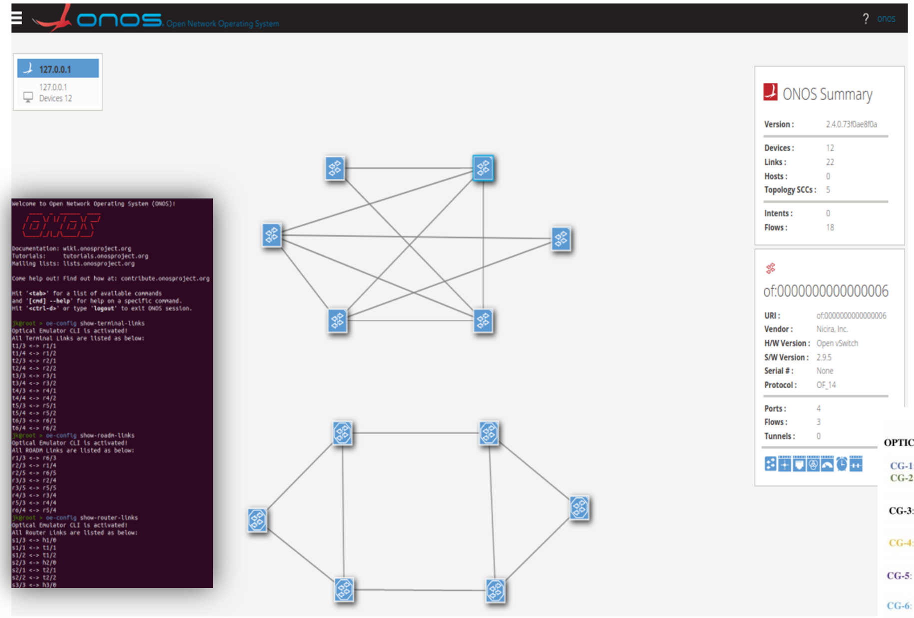
Sequential channel loading



Random channel loading

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.

Example of operation: SDN controller operating failure recovery



- Creating system of 6 ROADM nodes and in line amplifiers
- ONOS monitoring OSNR at given points (OPMs)
- Simulating EDFA failure: sudden reduction of OSNR across group pf channels
- ONOS operating failure recovery through traffic rerouting

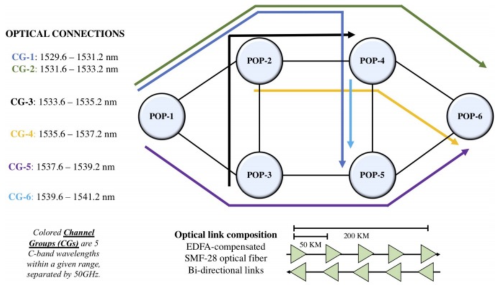
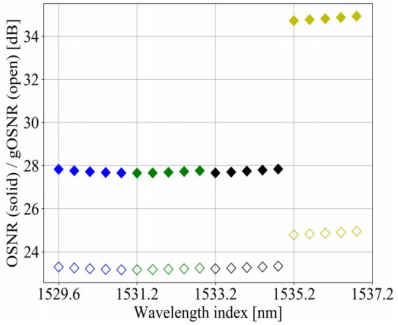


Fig. 3: Controller monitors OSNR (solid) and gOSNR (open) of all channels entering POP-4 (via POP-2) during the initial transmission



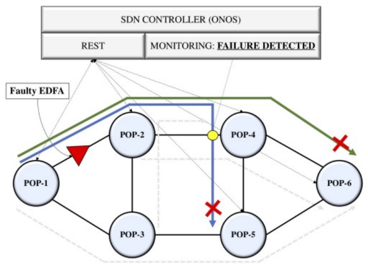
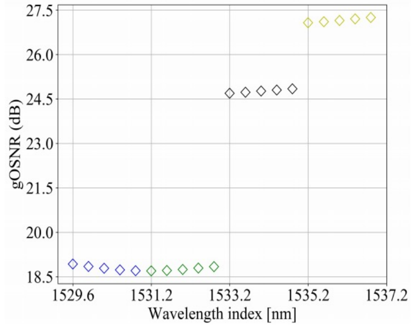


Fig. 4: Faulty EDFA degrades CG-1 and CG-2; controller observes low monitored gOSNR for signals entering POP-4 (via POP-2)



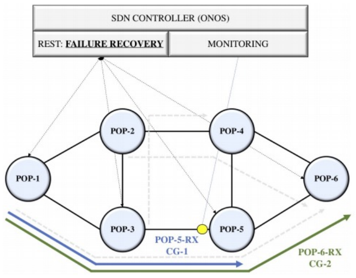
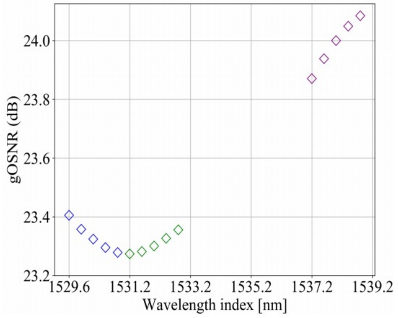


Fig. 5: Controller re-routes CG-1 and CG-2, resulting in high monitored gOSNR for signals entering POP-5 (via POP-3)



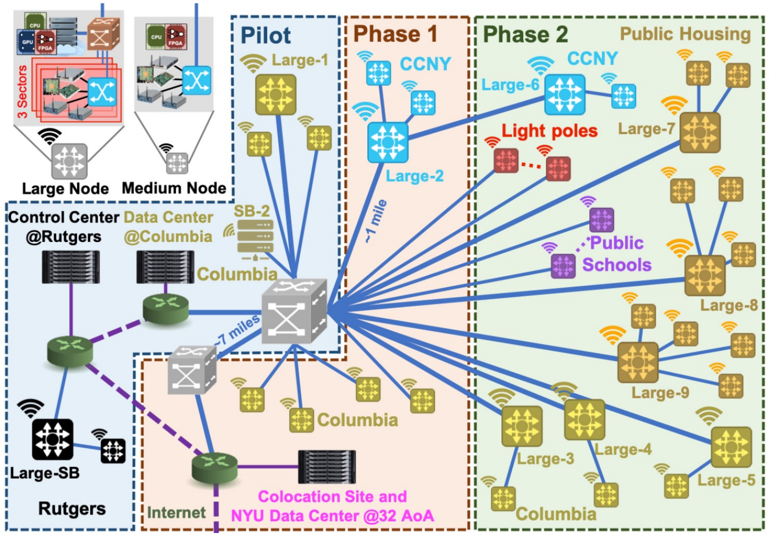
Bob Lantz, Alan A. Díaz-Montiel, Jiakai Yu, Christian Rios, Marco Ruffini, Dan Kilper. Demonstration of Software-Defined Packet-Optical Network Emulation with Mininet-Optical and ONOS. OFC 2020.

Mininet-optical in support of testbed infrastructure

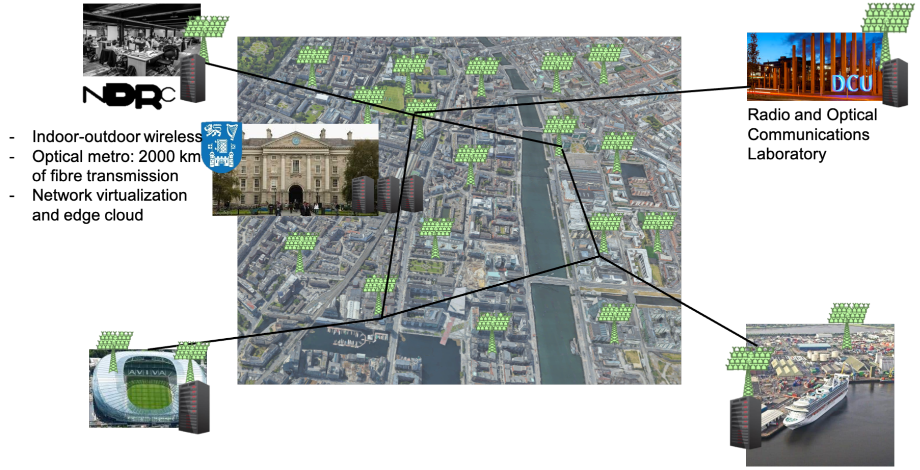
Emulation platforms like Mininet-Optical are complementary to testbed

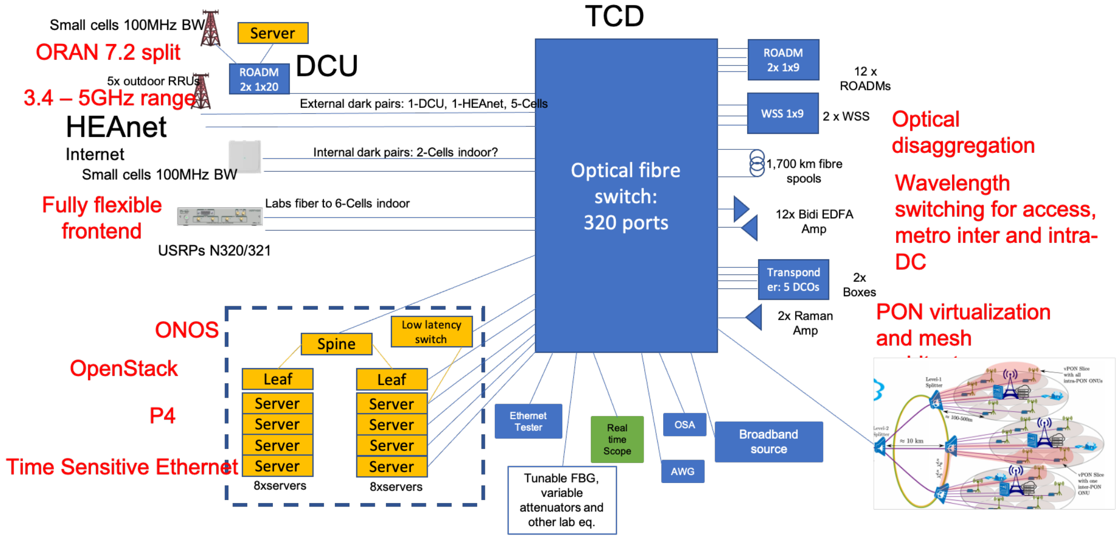
1. Provide a ”sandbox” for testing control plane application in “home” environment before migrating to testbed
2. Testing control planes over much larger topologies
3. ==> Emulation and testbed can be used side-by-side to develop and test both accuracy and scalability of control planes for disaggregated optical networks!

COSMOS (US)



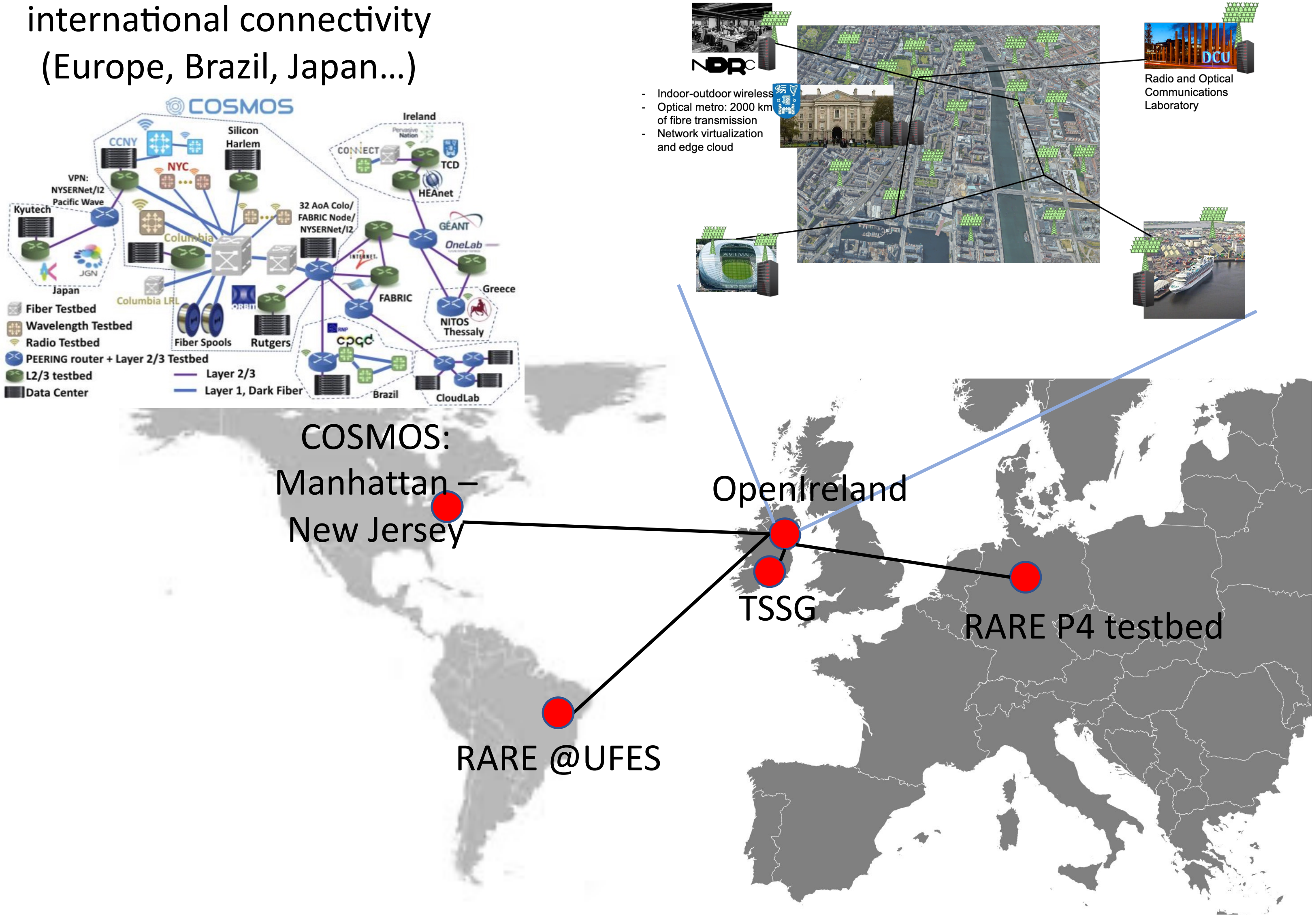
OpenIreland (Dublin)





Worldwide reach of our testbeds

COSMIC: COSMOS international connectivity (Europe, Brazil, Japan…)



OpenIreland offers fully reconfigurable topology including:

- Metro transmission (ROADMs, Coherent transponders, amplified links ~2000km, channel loading)
- SDR Wireless, including laboratory USRPs and OpenRAN indoor and outdoor small cells)
- Edge computing and networking (including P4, etc.)

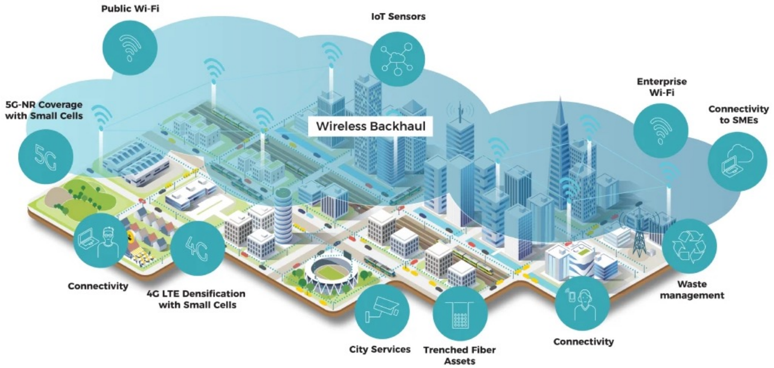
- **Key feature: only based on open systems and open source!**

CONNECT Networks of the Future

Takeaway message

- Ubiquitous fibre connectivity with flexible topology will be instrumental for the growth of 5G and beyond
  - PON can provide low-cost access, but more work required for low latency, mesh topology, etc.
  - … and more study required for seamless integration into city environment

<u>TIP - Connected City Infrastructure</u>, chaired by CONNECT and Dublin City Council



- Open systems are key to boost flexibility through programmability!
  - Open Source is key to enable wide access to technology for research and testing
  - … together with availability of open testbeds and emulation tools

- What's next? Time to start putting more emphasis on quantum communications??

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Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

CONNECT Centre for Future Networks

IPIC BRINGING PHOTONICS TO LIFE

Thank you

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CONNECT and IPIC research centres

OSA 5G webinar series, 24th May 2021

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