A World Leading SFI Research Centre

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

CONNECT
Centre for Future Networks

Open networking: benefits, challenges, AI and the road to edge cloud

Prof. Marco Ruffini
Dept. Computer Science and Statistics, Trinity College Dublin
CONNECT and IPIC research centres

Trinity College Dublin
The University of Dublin

Ireland's European Structural and Investment Funds Programmes 2014-2020
Co-funded by the Irish Government and the European Union

European Union
European Regional Development Fund

Science Foundation Ireland sfi For what's next

IPIC
BRINGING PHOTONICS TO LIFE

Content of the talk

- Brief into to my research and research group
- The Open Networking Movement
  - From SDR to SDN and from research to production
  - Opening the optical layer: a use case for the need for AI
  - Mininet becomes optical
  - How we opened the Passive Optical Network
- The edge
  - Not just RAN… offloading the next generation of weareable computing
  - Connecting the edge
- Conclusions: putting it all together
  - Opening Ireland

CONNECT
Networks of the Future

Marco Ruffini, Ph.D. (2008)

TRINITY COLLEGE DUBLIN

https://marcoruffini.com/ Full CV available HERE

- ✓ Associate Professor and Fellow of TCD
- ✓ PI in CONNECT and IPIC; Head of the Optical Network Architecture lab
- ✓ 140 International publications, 10s patents
- ✓ €7M raised in competitive funding

- ➢ Access Network Virtualisation:
  - ➢ The Virtual DBA and Full virtual PON prototype
  - ➢ Mobile-optical-cloud convergence
  - ➢ Use of blockchain for access network sharing
  - ➢ Mesh architectures for edge cloud
- ➢ Disaggregated optical networks:
  - ➢ Mininet-Optical: network emulation for optical disaggregation
  - ➢ Machine learning for Quality of Transmission Estimation
  - ➢ Open Networking testbed for disaggregated access-metro
- ➢ Fixed-Mobile Convergence:
  - ➢ Variable Rate Fronthaul scheme for PON transport
  - ➢ SDN based integrated LTE-PON control system

CONNECT Networks of the Future

TRINITY COLLEGE DUBLIN

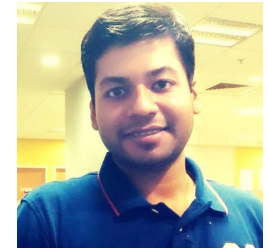
Research areas:

- Access Network Virtualisation
  - The Virtual DBA
  - Full virtual PON prototype
  - Mobile-optical-cloud convergence
  - Use of blockchain for access network sharing
  - Mesh architectures for edge cloud
- Disaggregated optical networks:
  - Mininet-Optical: network emulation tool for design and test of disaggregated optical systems
  - Use of Machine learning for Quality of Transmission Estimation
  - Open Networking testbed based on disaggregated metro and access networks
- Fixed-Mobile Convergence:
  - Variable Rate Fronthaul scheme for PON transport
  - SDN based integrated LTE-PON control system
- Access-Metro Convergence:
  - Long-Reach PONs: architecture, protection, SDN control plane, cost modelling, etc.

The Research group

PD Joining in two weeks: Sourav

PhD joining in March: Arijeet



Blockchain in telecomms

OpenRAN

Edge compute nodes

DBA virtualization for multi-tenancy

Open Networking testbed

Fixed-mobile convergence

Mesh PON access

Mininet-Optical

Dynamic spectrum for satellites

Multi-Access Edge Computing

Free space optics backhaul

Rural LR-PON deployments

SDN for optical components and disaggregated testbeds

ML for QoT estimation

Hardware programmability with P4

Content of the talk

- Brief into to my research and research group

- The Open Networking Movement
  - From SDR to SDN and from research to production
  - Opening the optical layer: a use case for the need for AI
  - Mininet becomes optical
  - How we opened the Passive Optical Network

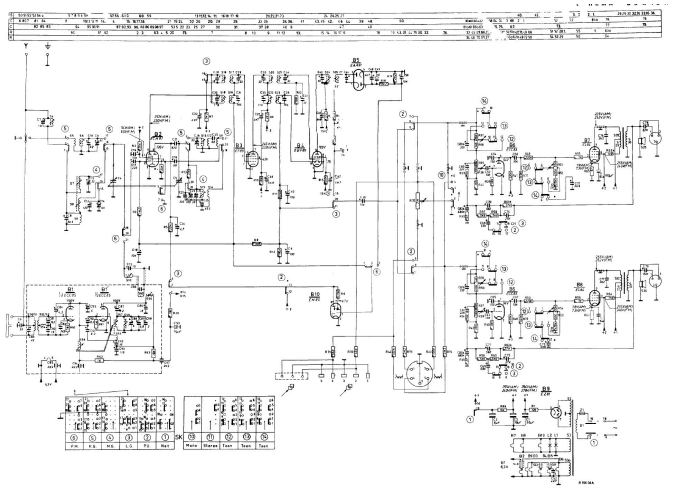
- The edge
  - Not just RAN… offloading the next generation of weareable computing
  - Connecting the edge

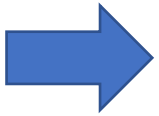
- Conclusions: putting it all together
  - Opening Ireland

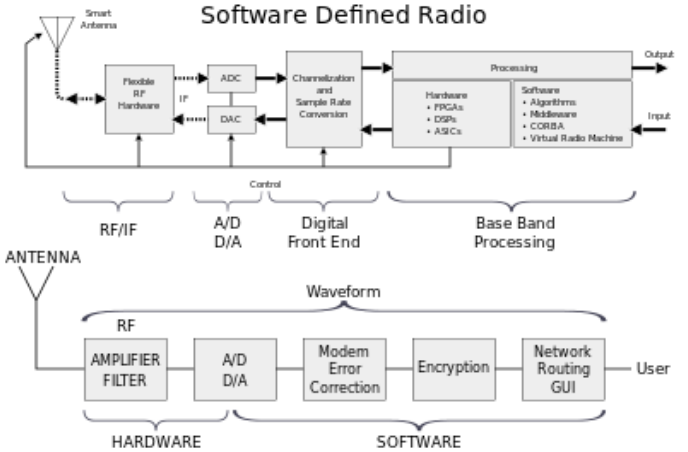
The Open Movement

- Software Defined Radio introduced in 1992 by Mitola in IEEE journal

1. Moving from hardware to software is the first step for opening up a system
   - Software can be copied, downloaded, etc. and can be worked on by anyone.

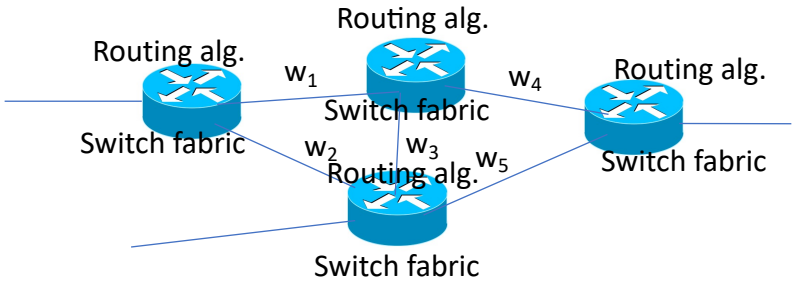


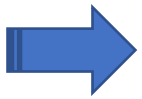


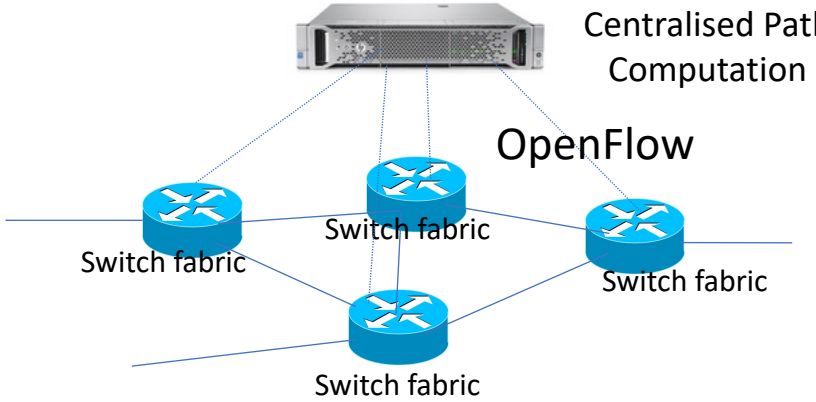


2. In 2008 we then saw the separation of control and data planes.

➔ It means providing an open interface (OpenFlow / SDN) so that the hardware and software could communicate across a distance

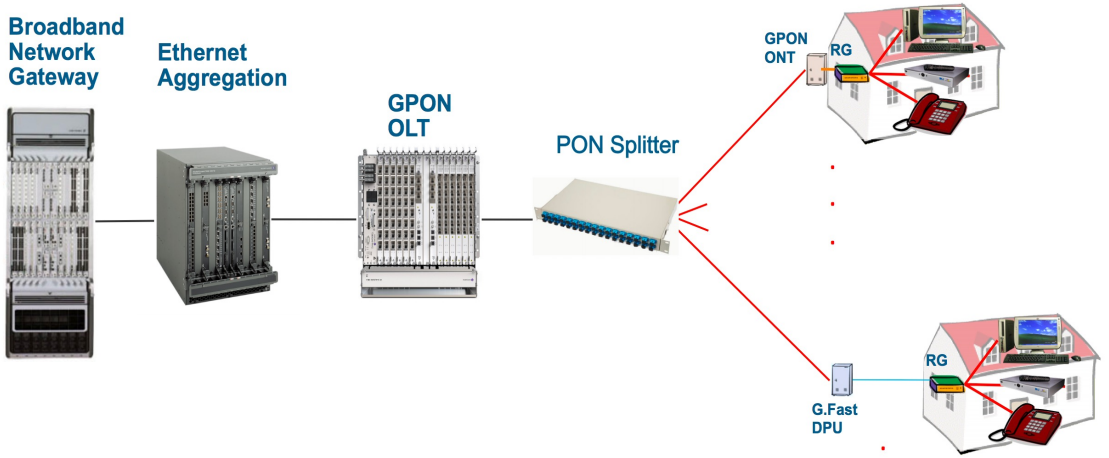


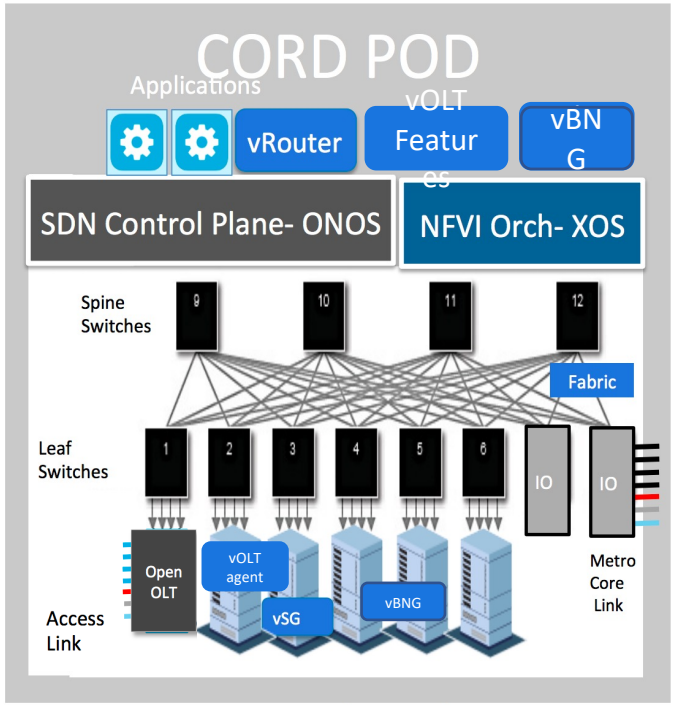




Opening the central office

- 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).



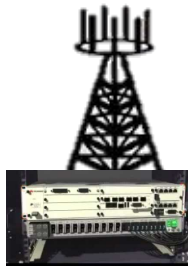


This has now evolved into the SDN-Enabled Broadband (SEBA)

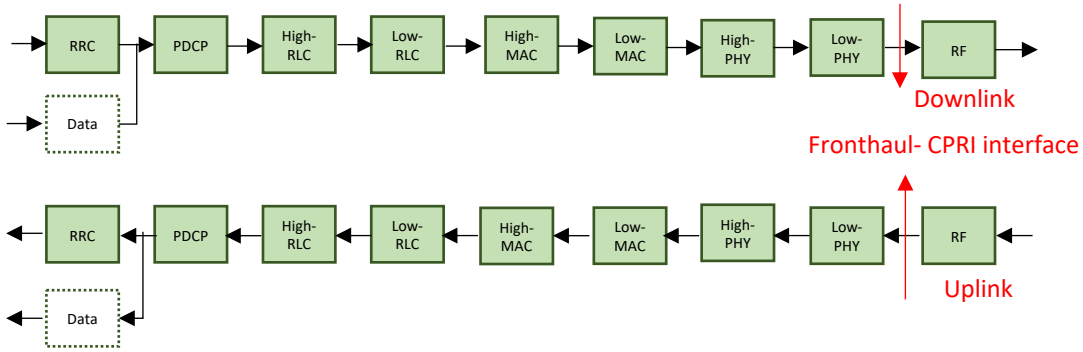
Also, other entities have defined Cloud-CO (BBF), Open Network automation Platform (ONAP),…

Opening the base station

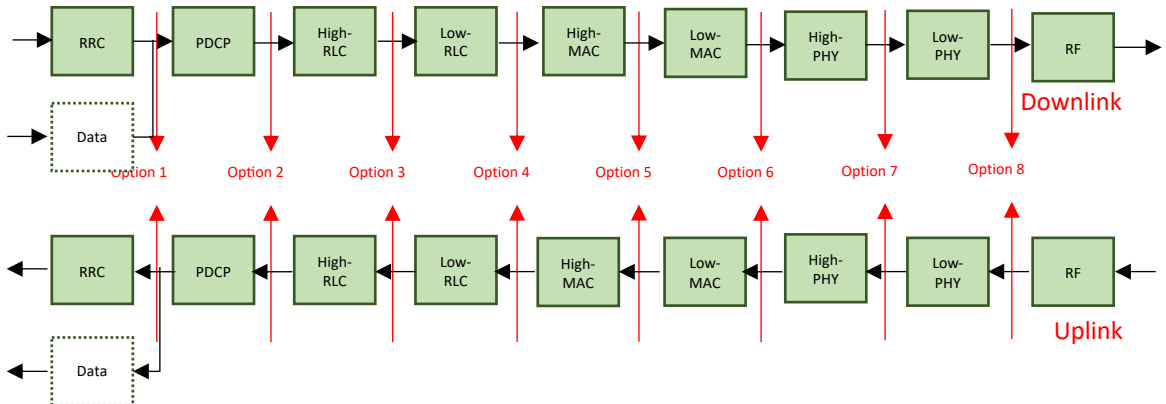
- For over 10 years we have been able to do this: run a 4G base station from a laptop



Remote unit (RU)

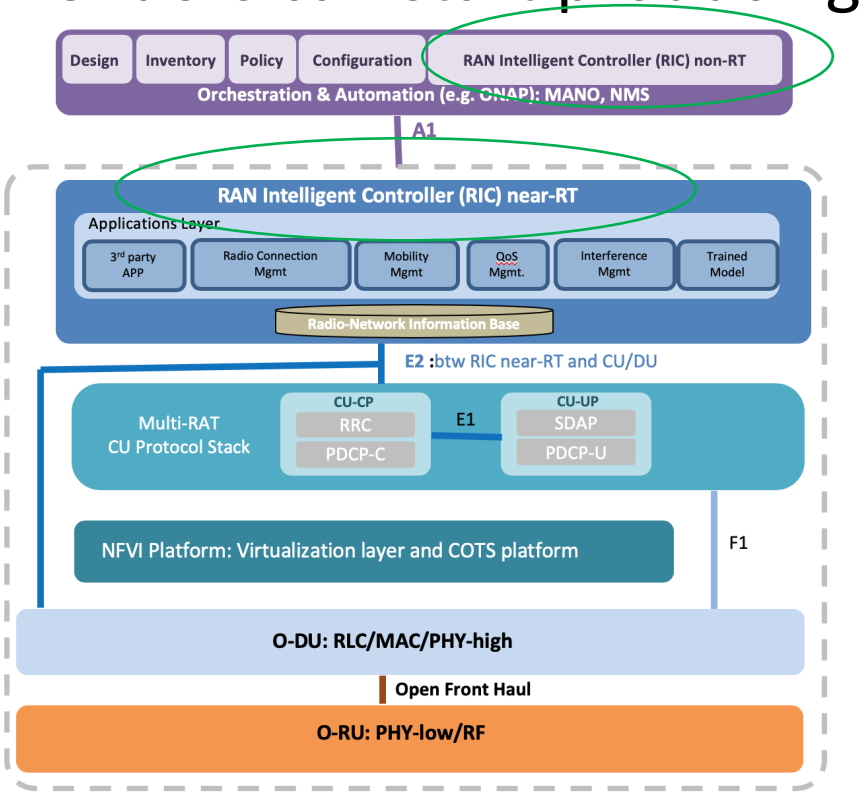


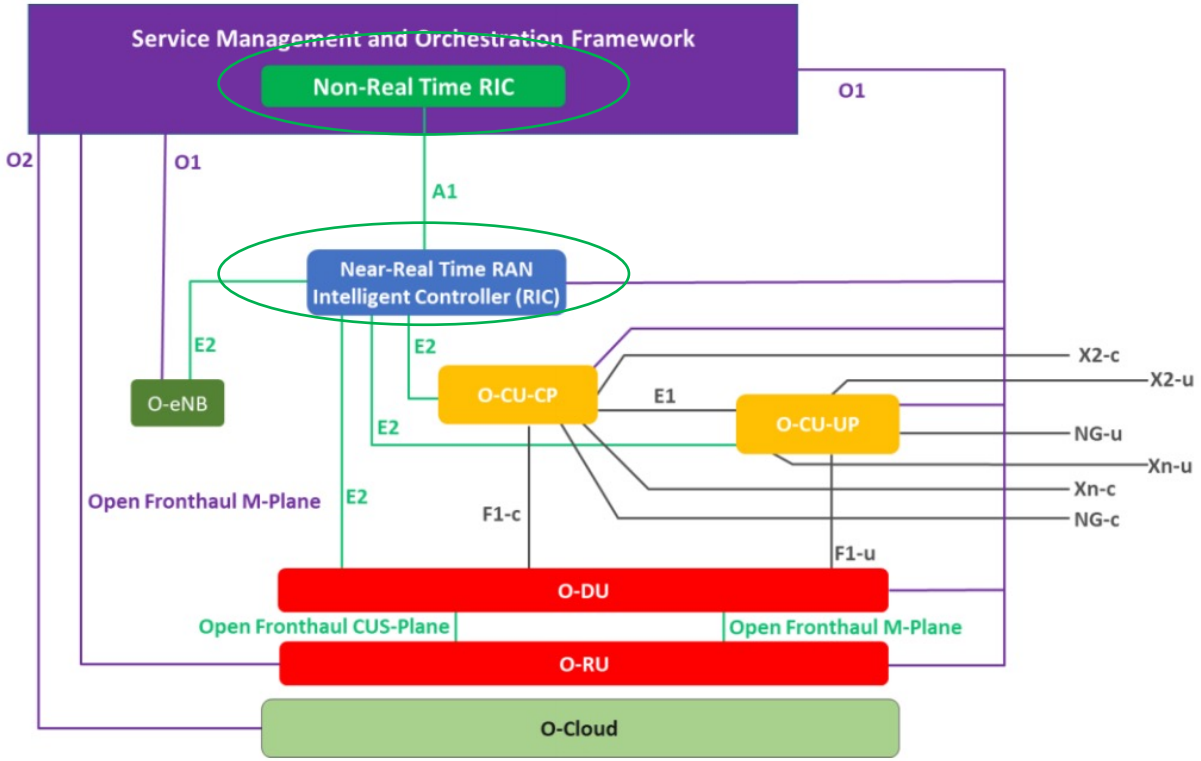
- Over that past 5 years industry fora have come together to define other split points for separating Remote Unit – RU (hardware) from the rest (Distributed Unit and Centralised Unit). Alternatives to CPRI.



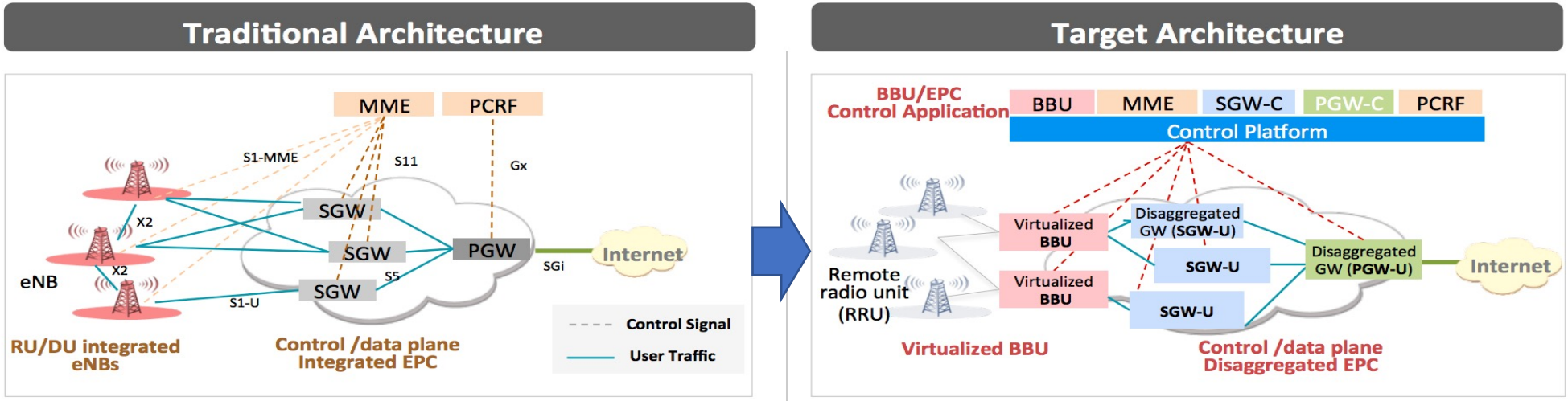
Opening the Radio Access Network – O-RAN

- Next step is to bring this concept to proper commercialization (actually replacing current large vendor base stations)
- Define one one specific split (called 7.2) and start defining interfaces so that vendors can start producing the different parts





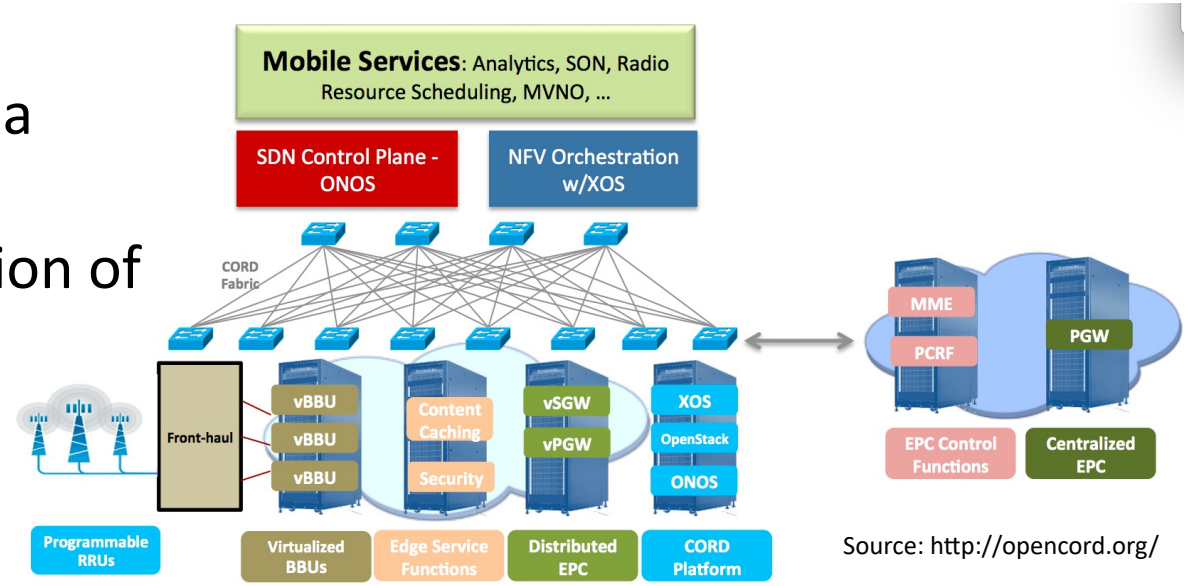
Multi-service example: Mobile-CORD



with proprietary boxes & solutions

with commodity H/W & open source/open API

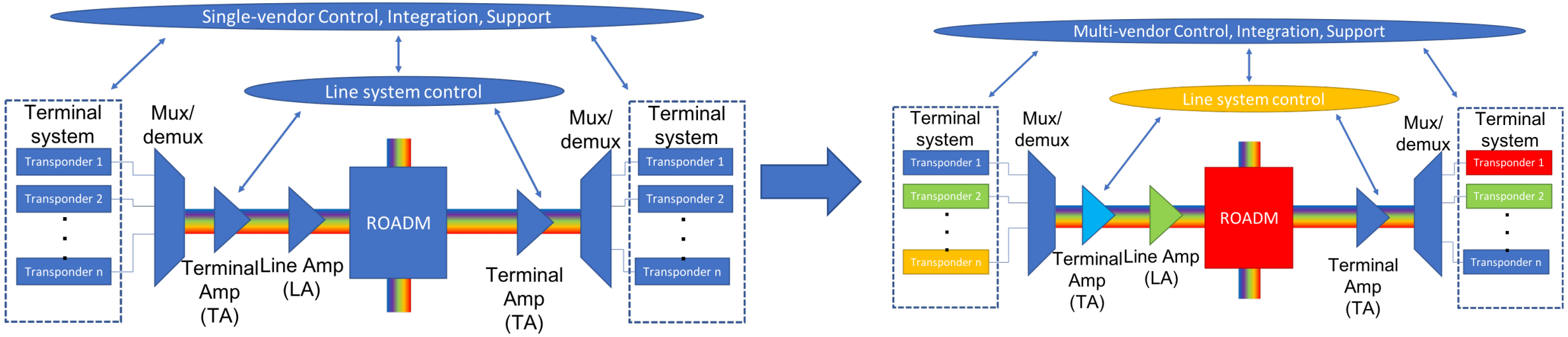
- Software and programmability a main enabler of convergence
- E.g., enables tighter orchestration of resources (see fixed/mobile)



Source: http://opencord.org/

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

- First and foremost: AVOID VENDOR LOCK-IN
  - Ability to add new features from other vendors
  - Get the best from each vendor

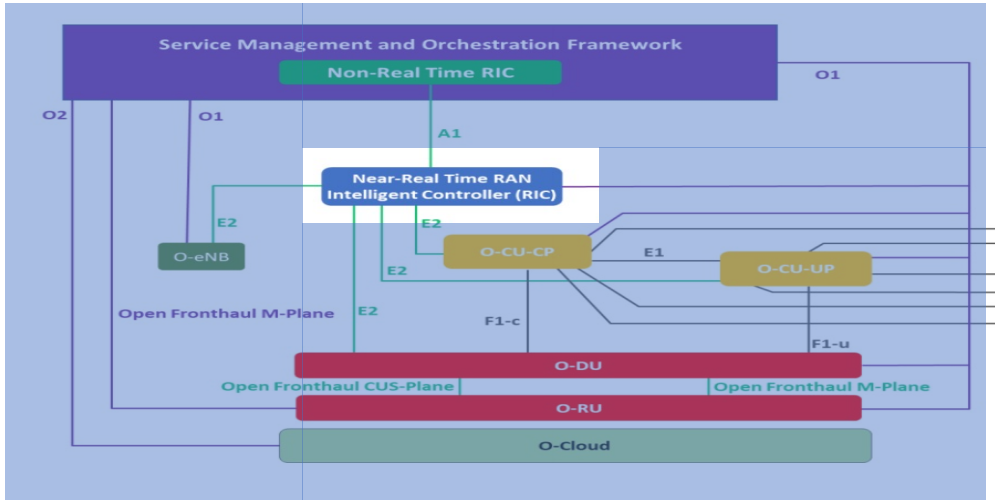
- Create a more competitive environment: lower cost, more research!
  - Enable Universities and SMEs to take part to the research INDEPENDENTLY
  - Create the environment for new startups to get to market

- First and foremost: who is going to put the system back together for the operator?
  - This is what vendors have done in the past, but if the system is made up of bits and pieces, who will deliver the working system to the vendor?
  - Risk to get back to a few large companies doing the aggregation…
  - …but maybe that's the way to go, think of Dell, etc.

- It surely gives us the possibility to do very interesting research on Real Life systems

What are key challenges to ORAN and the "OPEN" movement from a research perspective?

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

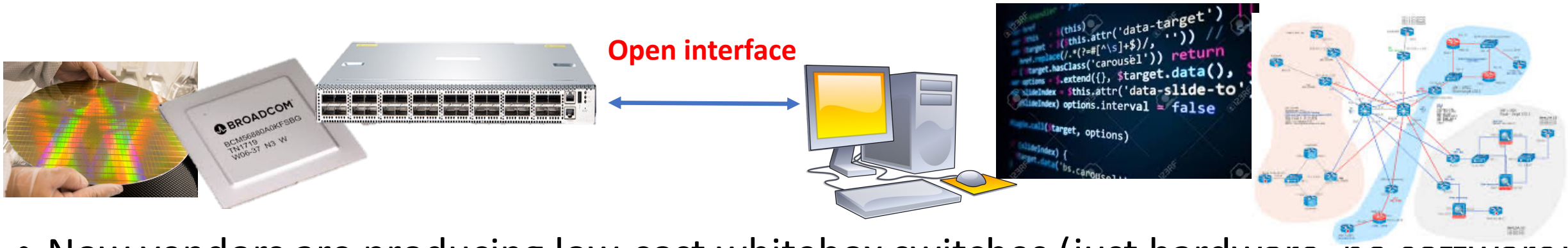


- <u>Open source implementation of the standard components is important</u>!
  Open Air Interface, SRS, Magma (Facebook),...

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

Why is Software key in OPEN networks?

- Software has been a key aspect in network devices long before moving into open systems..
  - A router is made of dumb ultra-fast silicon data plane (few vendors) and massive amount of software (intelligence, flexibility, etc)
- Open networking has created a physical separation between the silicon and the software. **And it has standardised and opened the interface between the two**.



- Now vendors are producing low-cost whitebox switches (just hardware, no software): a 3.2 Tb/s switch costs less than €7k! (the same as an entry level iMAC Pro)
- … so now we can design control plane software like any other company

… and test it quickly on a real network: brings academy and industry much closer

Content of the talk

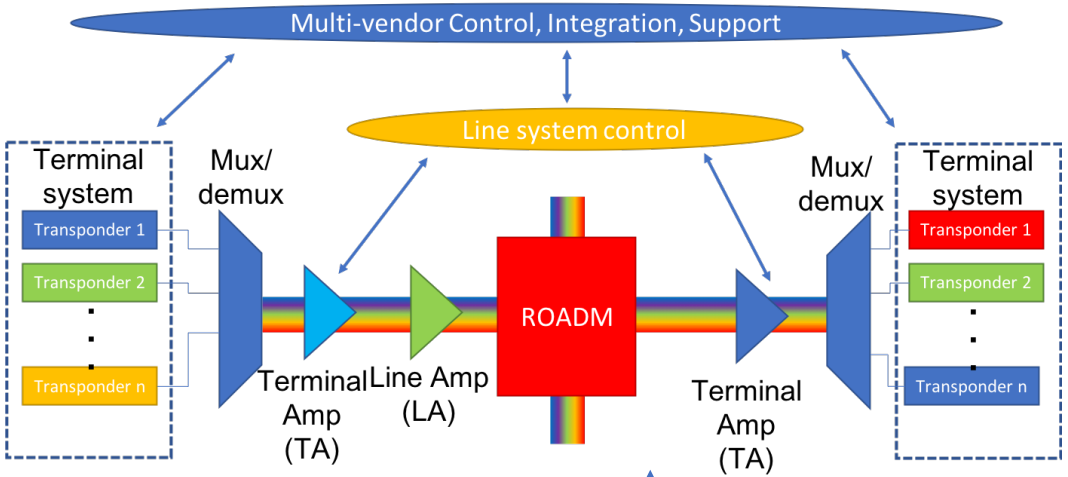
- Brief into to my research and research group
- The Open Networking Movement
  - From SDR to SDN and from research to production
  - **Opening the optical layer: a use case for the need for AI**
  - Mininet becomes optical
  - How we opened the Passive Optical Network
- The edge
  - Not just RAN… offloading the next generation of weareable computing
  - Connecting the edge
- Conclusions: putting it all together
  - Opening Ireland

Machine learning for quality of transmission estimation in optical transport networks

Consider an open system:

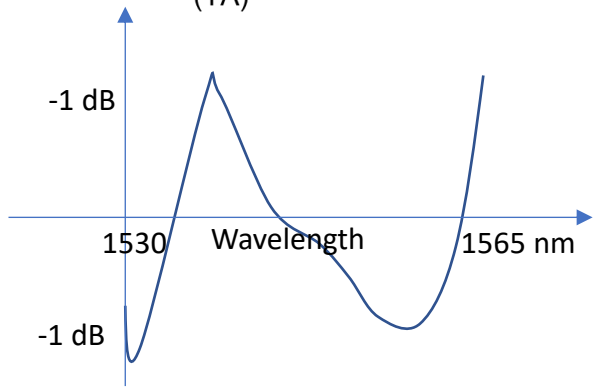
- Some impairments, such as dispersion, loss, nonlinearties can be calculate almost deterministically

- Other are device dependent…

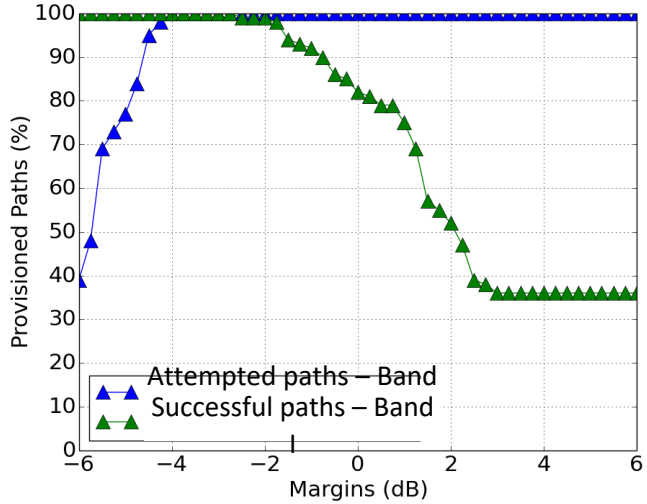


- Example: optical amplifiers have a gain that is frequency dependent and vary with operation point (i.e., cannot be approximated with one curve)
- There are tens of amplifiers in a transmission system (one every 80 km, plus two at each node), so its effect adds up
- This creates two issues:
  - The optical signal to noise ratio cannot be predicted accurately (lower amplification can create lower OSNR.
  - The system operates on gain clamping: if I add a channel, the amplifier power changes to keep the average gain constant

    ==> Adding a wavelength channel can increase/decrease the power and OSNR of all other channels



Studying the margins

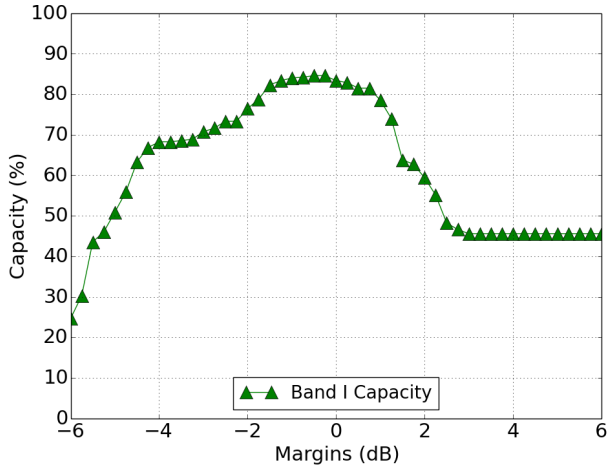


Estimation assumes flat amplifier gain

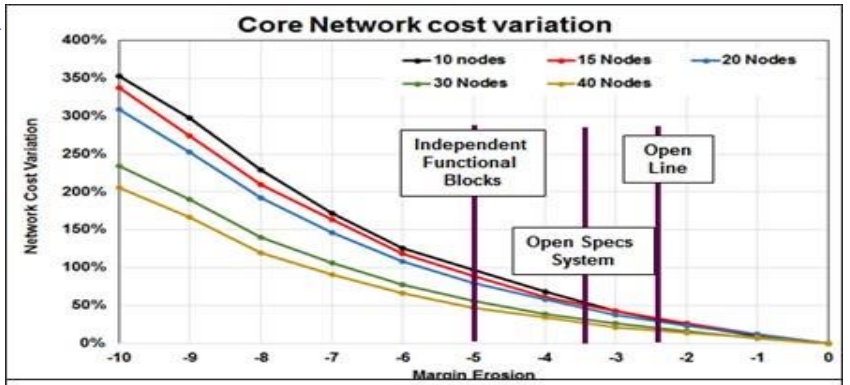
More conservative ⟷ More aggressive

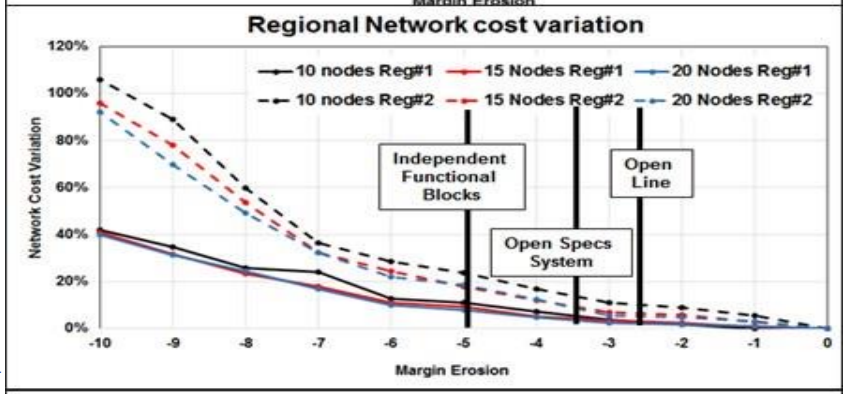
$OSNR_{est} + Margin > OSNR_{th}$

X axis: how conservative are the margins

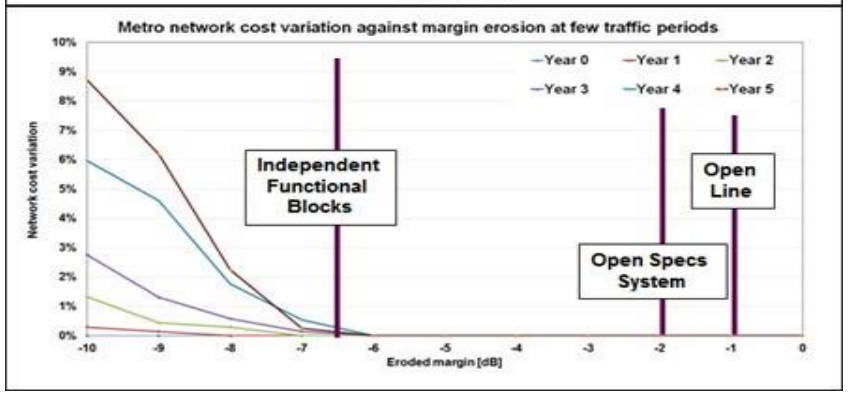


Effect on cost of core and regional network shown to be substantial due to low available margins





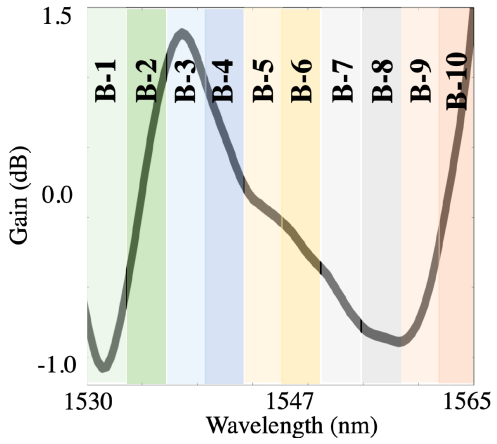
Effect on metro though is negligible, as the metro has larger margins

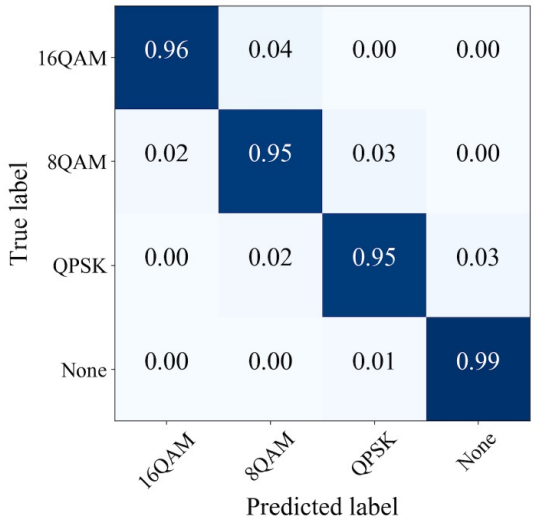


Source: M. Bleanger, M, O'Sullivan and P, Littlewood. Margin requirement of disaggregating the DWDM transport system and its consequence on application economics. M1E.2, OFC '18

Machine learning example

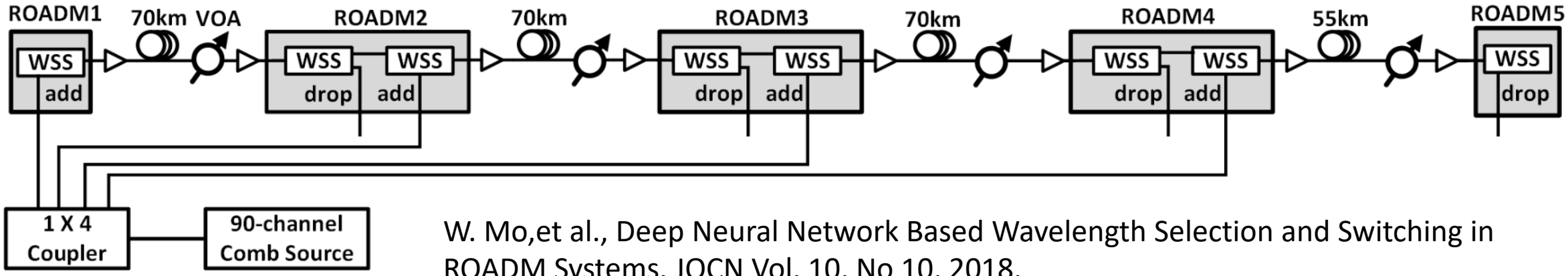
- Quality of Transmission estimation is an important research area, and ML techniques have been used to provide such estimation
- Build multi-class SVM classifier to decide what modulation is possible (e.g., related to OSNR) with features: number of nodes, fibre length, launch power, EDFA gain, plus the number of wavelength channels already loaded in each of the 10 bins below.



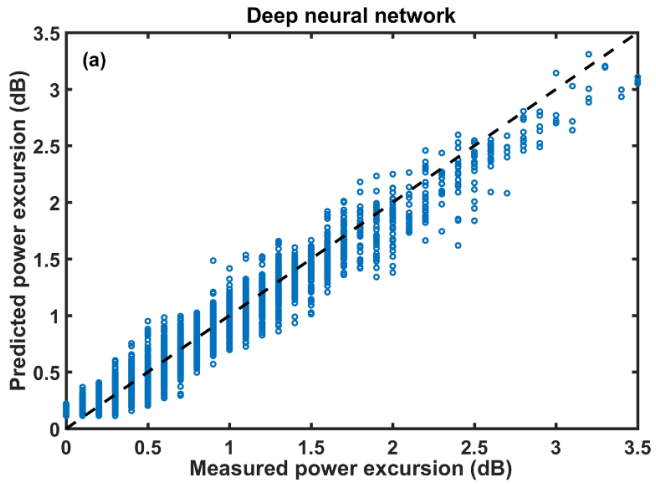


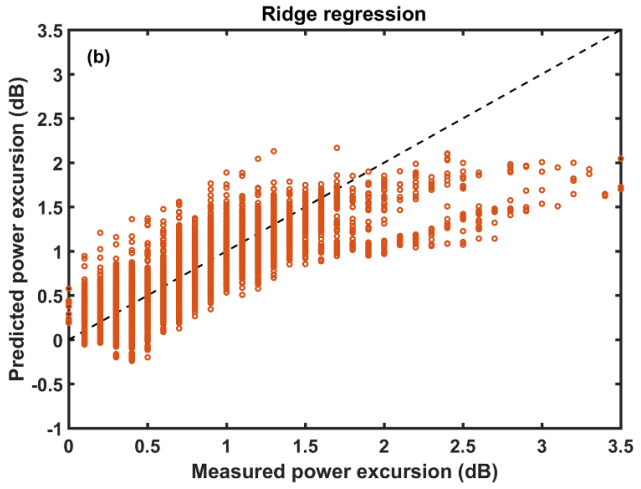
A. A. Dıaz-Montiel, S. Aladin, C. Tremblay and M. Ruffini. Active Wavelength Load as a Feature for QoTEstimation Based on Support Vector Machine. IEEE International Conference on Communications, May 2019

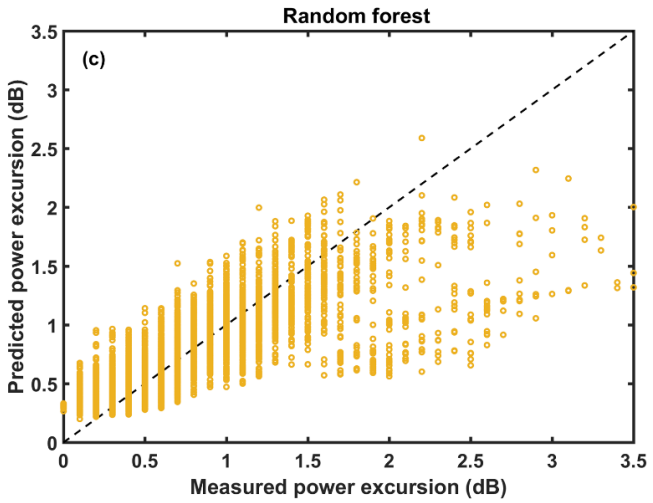
Deep Learning Shown Effective for Predicting Optical Signal Powers



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



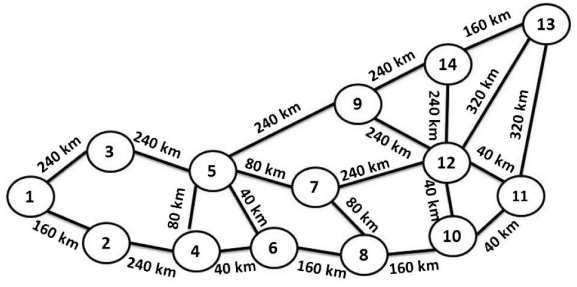




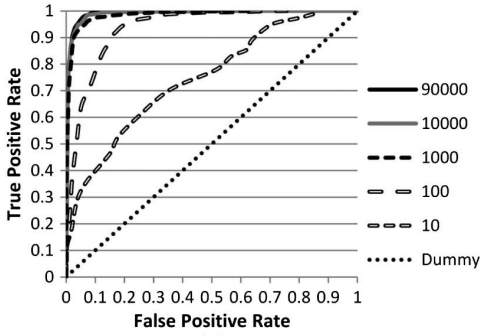
Deep learning (left) shown to accurately predict optical signal power which is main determinant of signal quality, based on the channel configuration alone.

More ML

QoT prediction using random forest ML algorithm



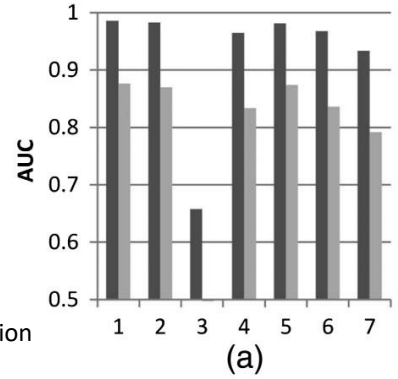
Dependency on training set size



Relevance of different features

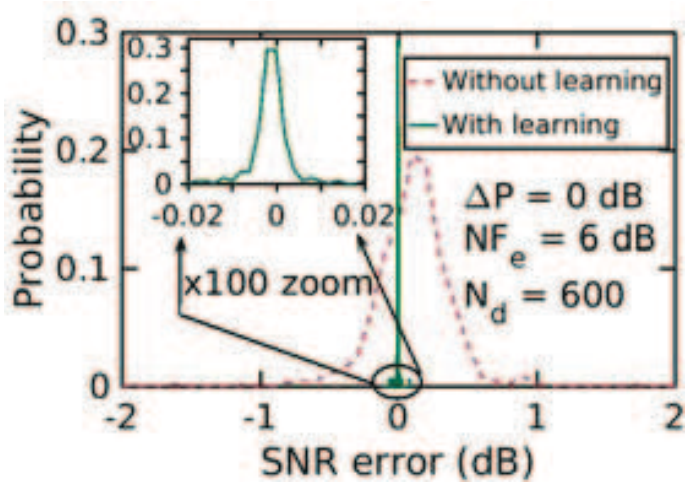
CONSIDERED FEATURE SUBSETS

	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.

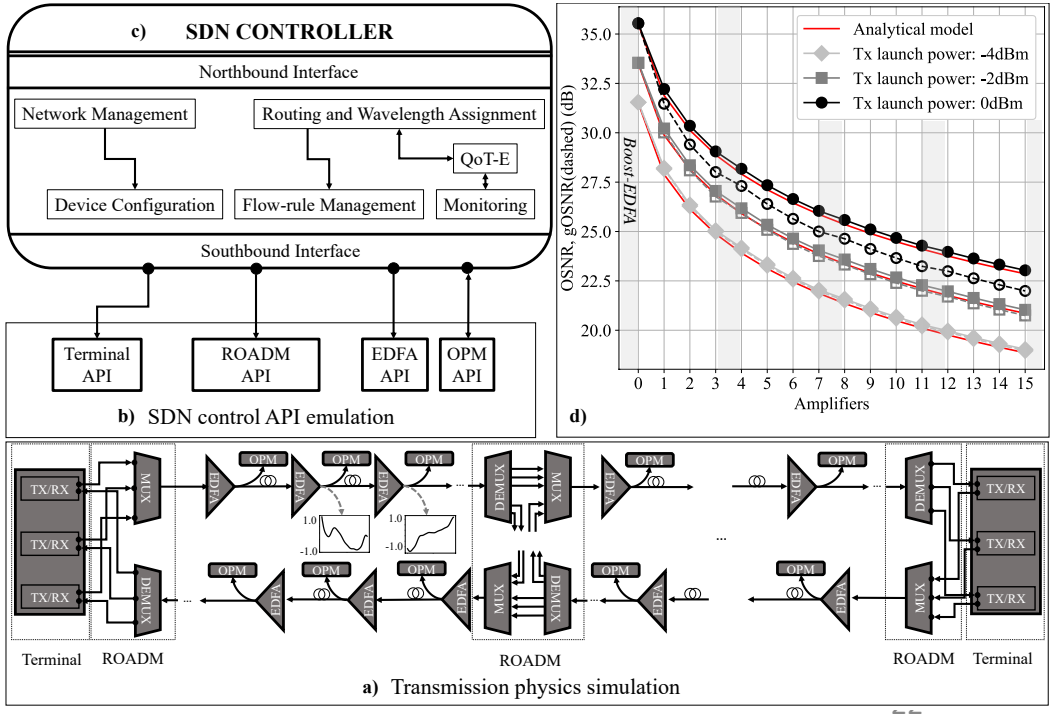


Source: E. Seve, J. Pesic, C. Delezoide, and Y. Pointurier. Learning process for reducing uncertainties on network parameters and design margins. OFC 2017.

- 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

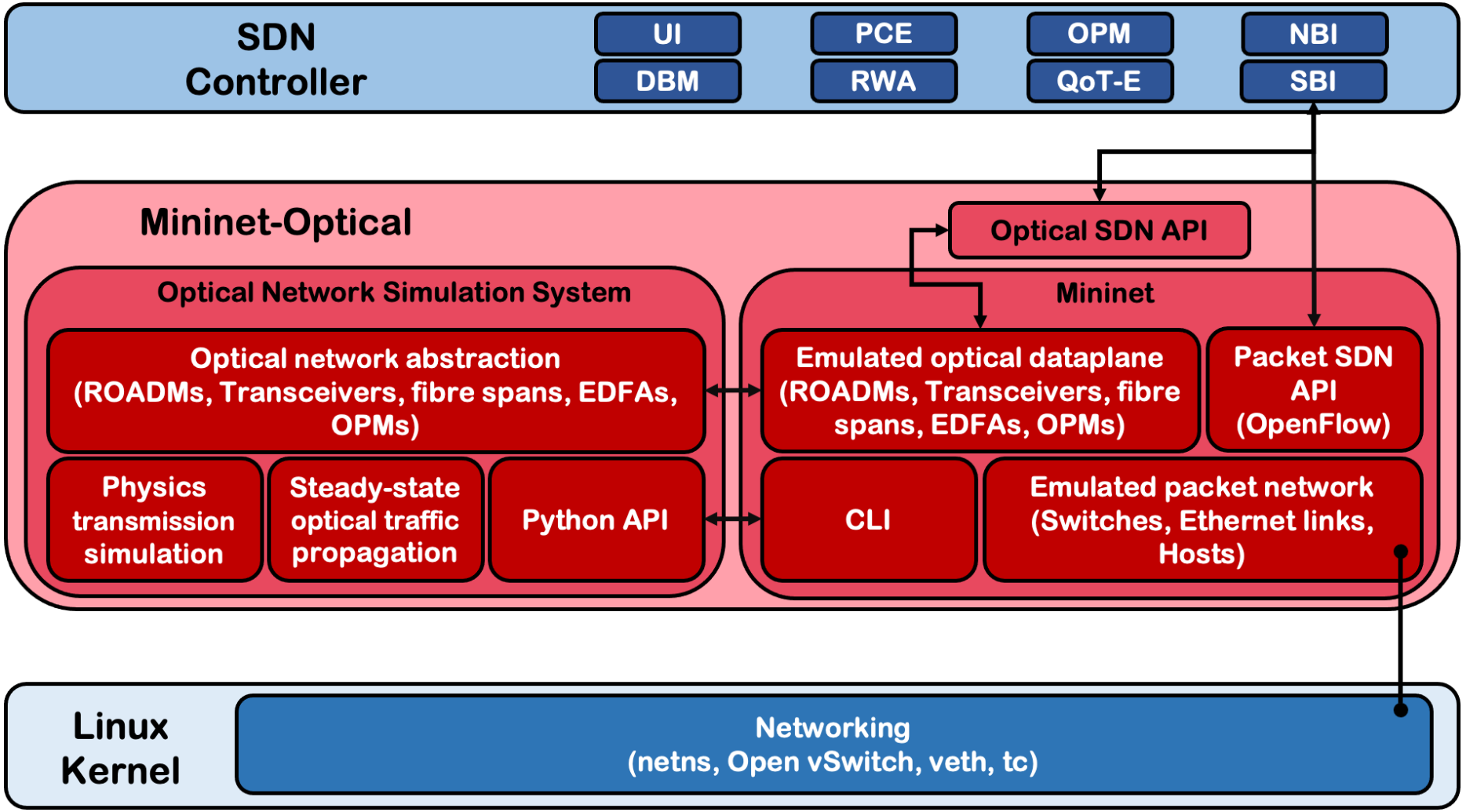
Mininet becomes Optical!

- 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-ODTN) on large scale networks



- 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
- Alan A. Díaz-Montiel, J. Yu, W. Mo, Y. Li, D.C. Kilper and M. Ruffini. Performance Analysis of QoT Estimator in SDN-Controlled ROADM Networks. Proc. of Optical Network Design and Modeling conference (ONDM), May 2018

The architectural diagram



DBM: Database Manager

UI: User Interface

PCE: Path Computing Element

RWA: Routing and Wavelength Assignment

OPM: Optical Power Monitoring

QoT-E: Quality of Transmission Estimation

NBI: North-Bound Interface

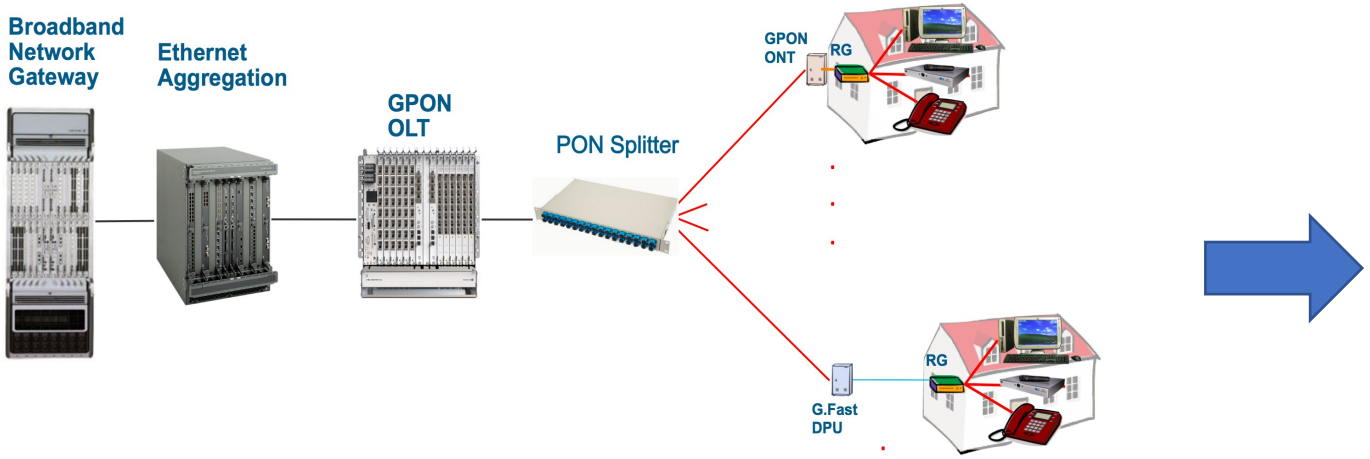
SBI: South-Bound Interface

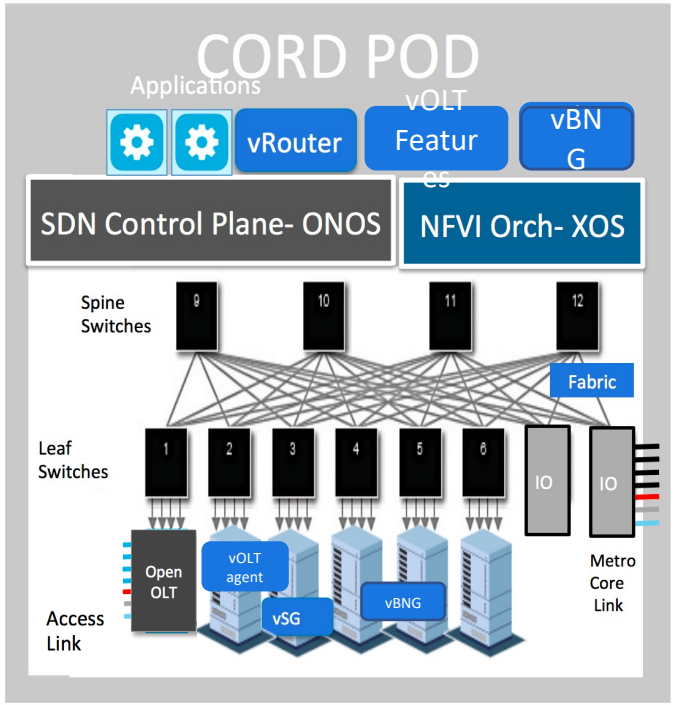
Content of the talk

- Brief into to my research and research group
- The Open Networking Movement
  - From SDR to SDN and from research to production
  - Opening the optical layer: a use case for the need for AI
  - Mininet becomes optical
  - **How we opened the Passive Optical Network**
- The edge
  - Not just RAN… offloading the next generation of weareable computing
  - Connecting the edge
- Conclusions: putting it all together
  - Opening Ireland

Remember the open 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).



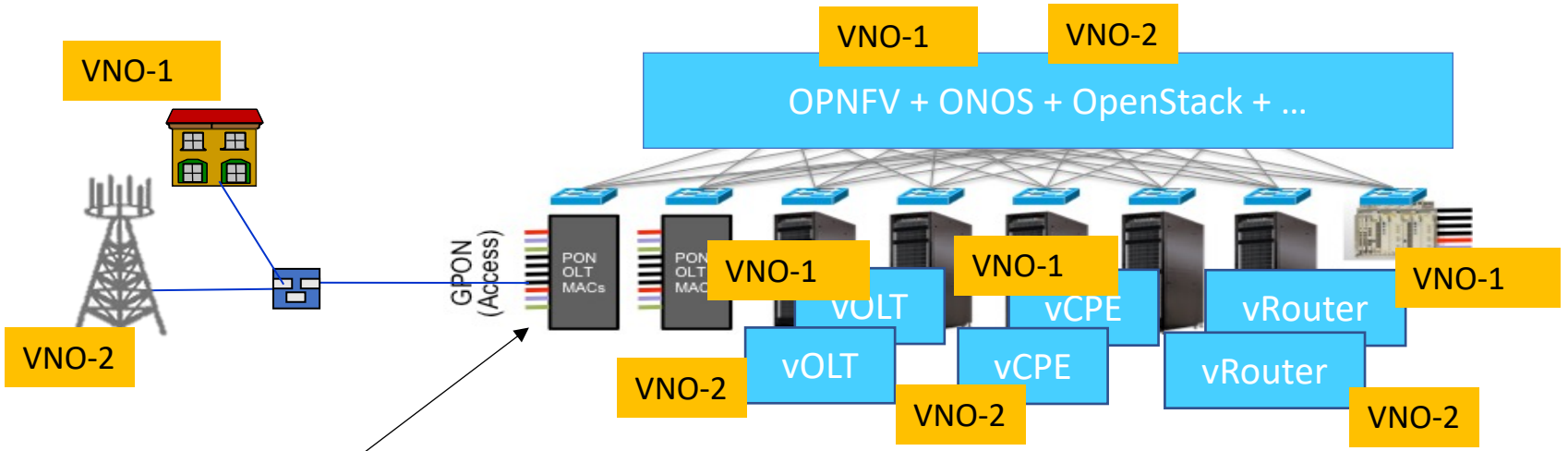


Commodity Hardware

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

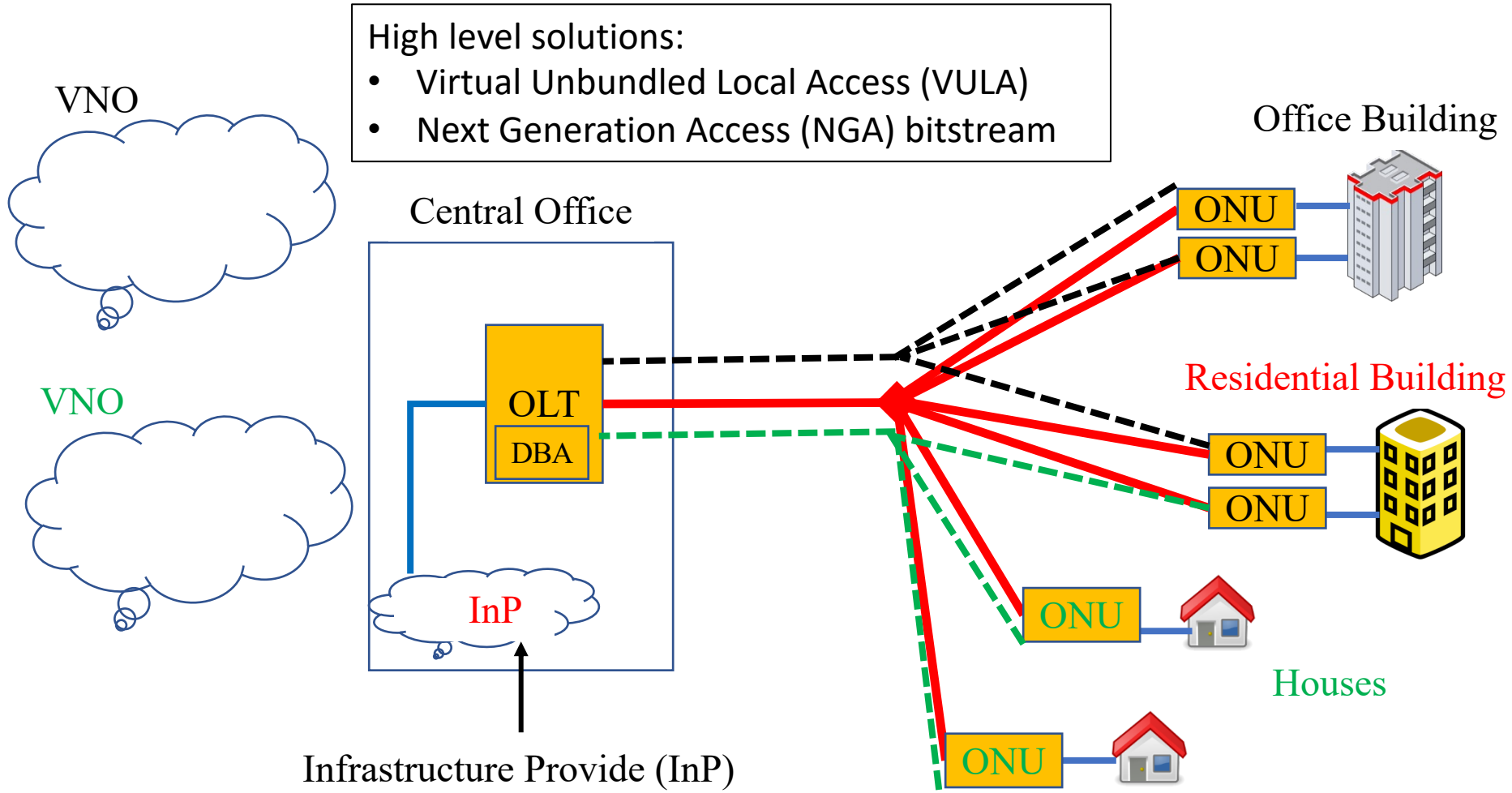
Also, other entities have defined Cloud-CO (BBF), Open Network automation Platform (ONAP),…

Is CORD virtualization enough for PONs?



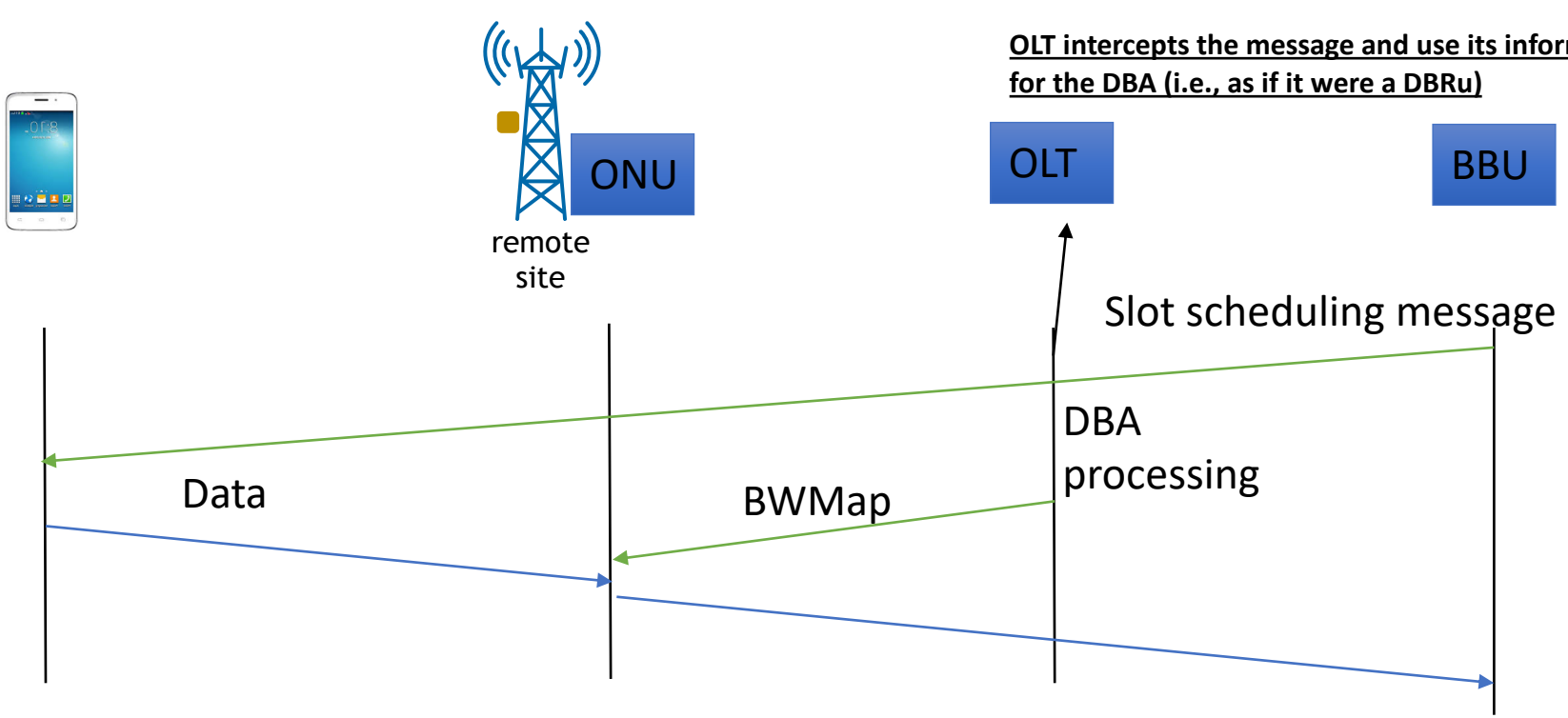
- Functions are virtualized and multiple instances can be assigned to different Virtual Network Operators (VNOs)
- … but for example Dynamic Bandwidth Allocation (DBA) is carried out in hardware

This is the current PON Multi-Tenancy

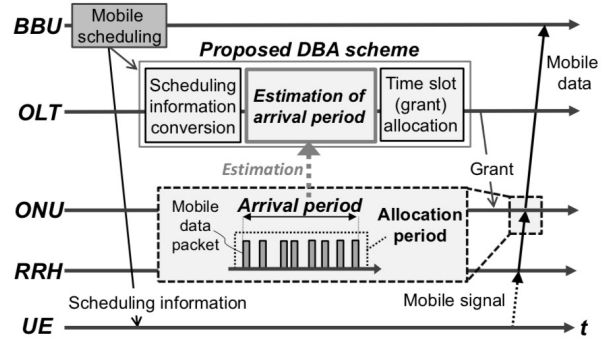


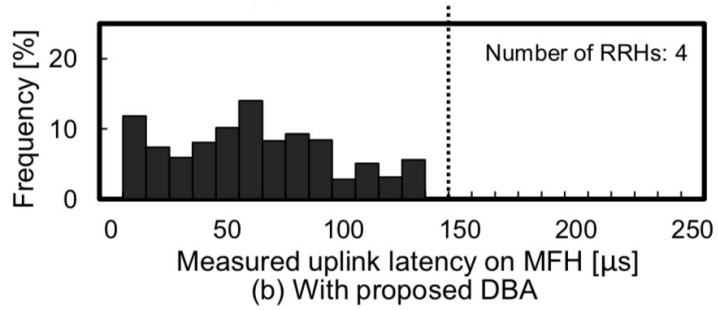
The big question: how deep to virtualize?

- CORD virtualizes the PON management and all other aggregation, routing, service layers …**BUT**… The MAC and PHY are in hardware.
- Operating a PON in low latency mode requires access to scheduling



Standardised in ITU-T G.989.3Am1

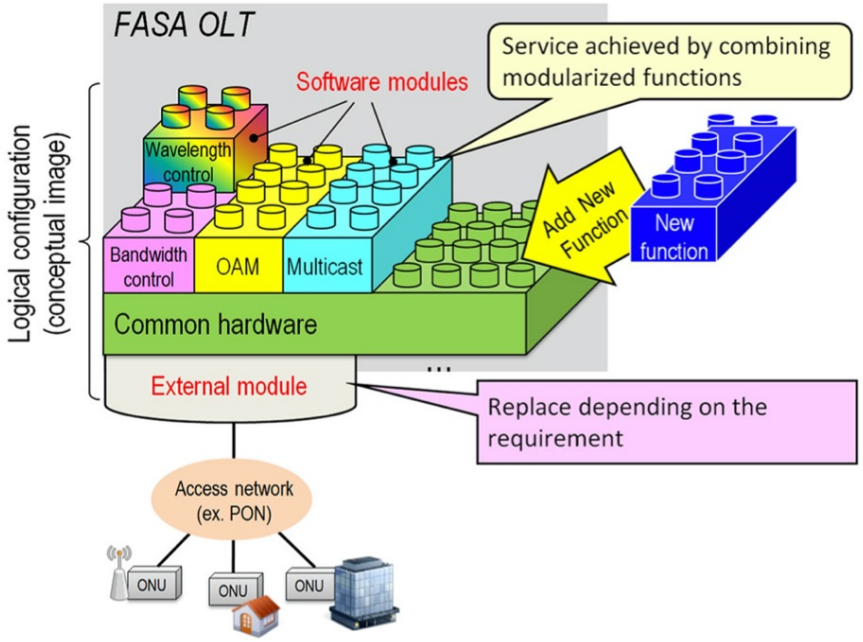




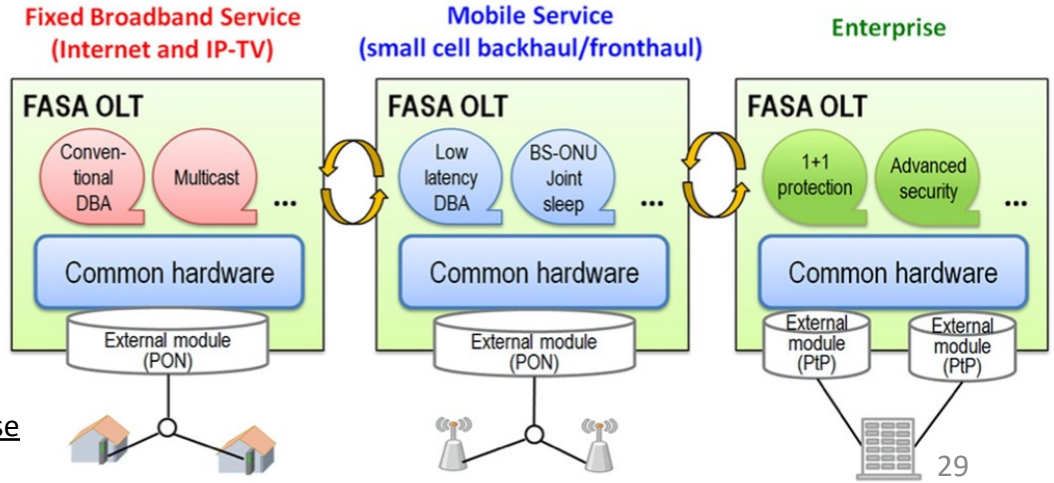
Source: H. Uzawa, et al. Practical Mobile-DBA Scheme Considering Data Arrival Period for 5G Mobile Fronthaul with TDM-PON. ECOC 2017.

NTT's Flexible Access System Architecture (FASA)

- Disaggregate the OLT, using software functions



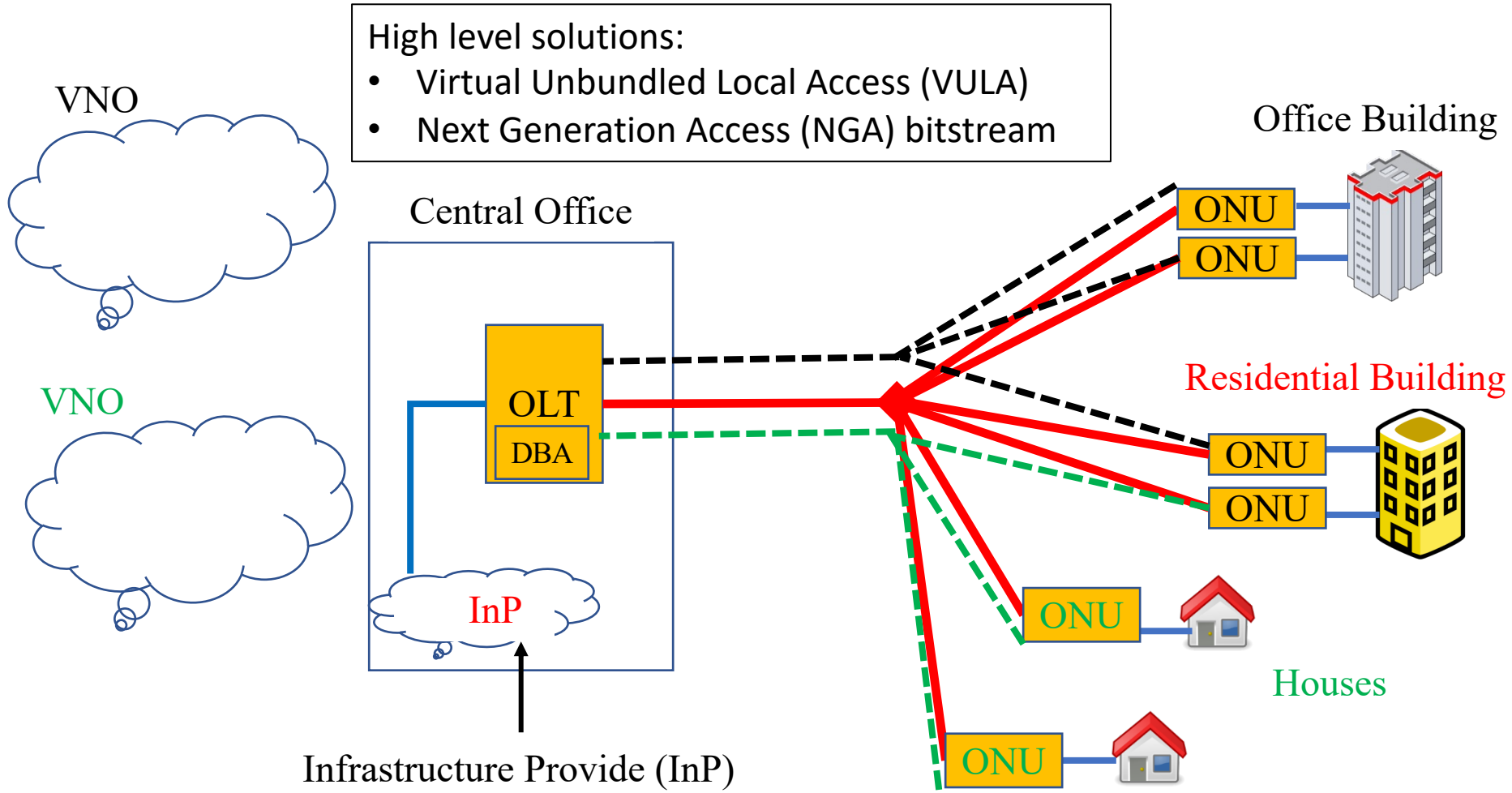
- The DBA is also software, so it can be modified, depending on the application



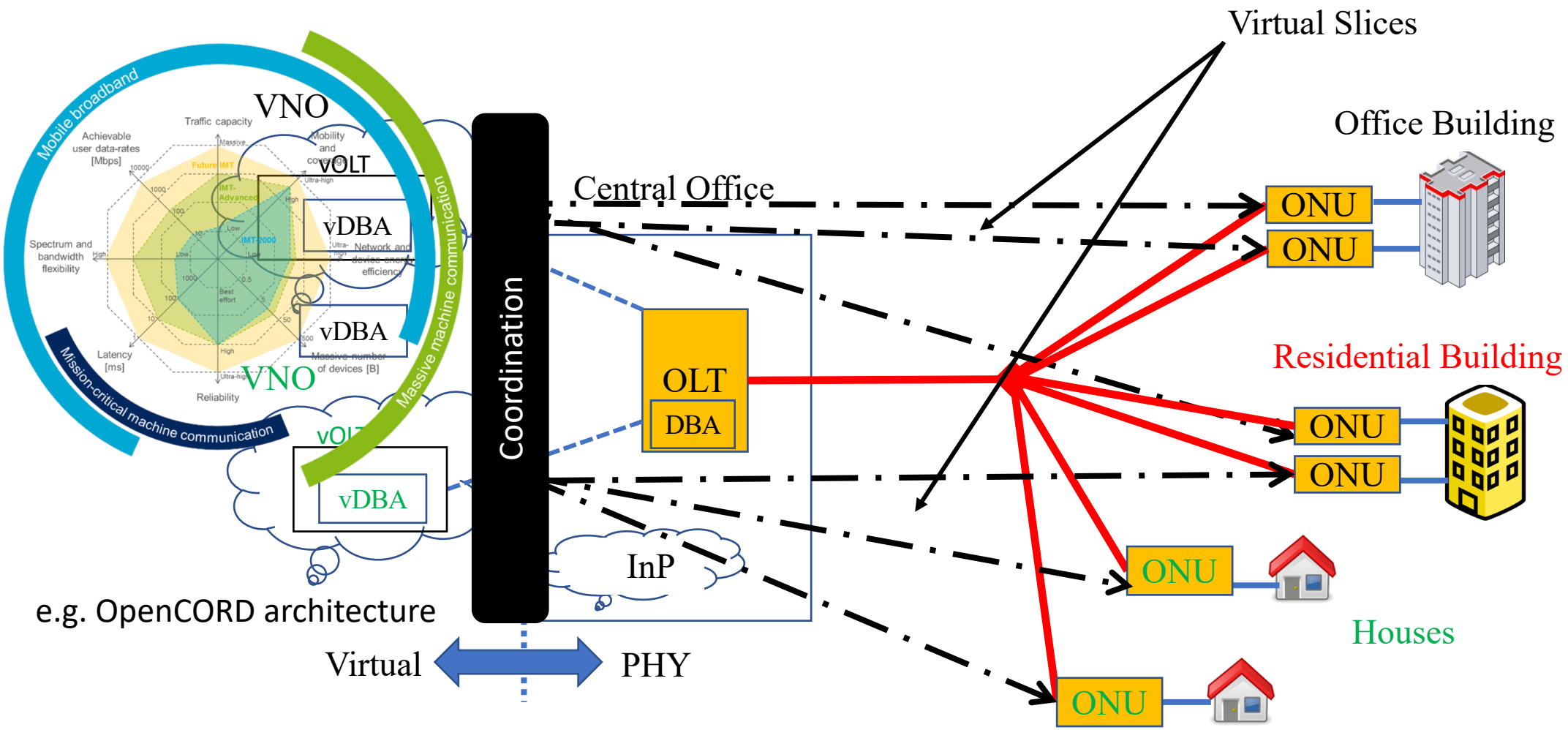
Included in BBF TR-402 standard "PON Abstraction Interface for Time-critical Applications"

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

This is the current PON Multi-Tenancy

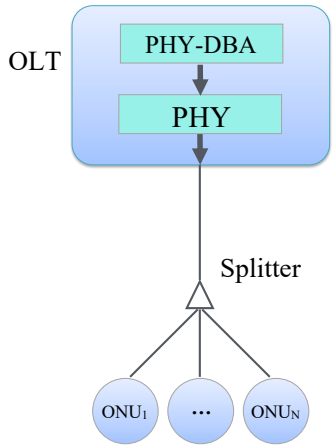


This is True PON Multi-Tenancy

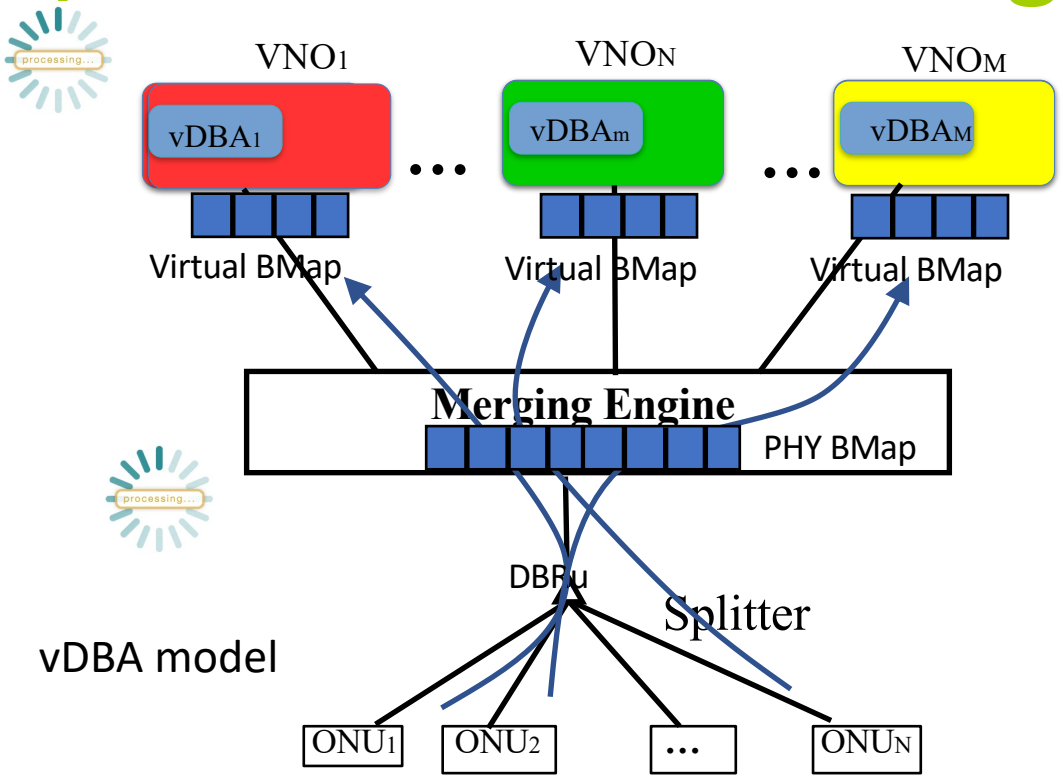


- M. Ruffini, A. Ahmadi, S. Zeb, N. Afraz and F. Slyne. **The Virtual DBA: Virtualizing Passive Optical Networks to Enable Multi-Service Operation in True Multi-Tenant - Environments.** OSA Journal of Optical Communications and Networking, No.4, Vol.12, April 2020
- M. Ruffini, F. Slyne. Moving the Network to the Cloud: the Cloud Central Office Revolution and its Implications for the Optical Layer. IEEE/OSA Journal of Lightwave Technology, Vol. 37, No 7, April 2019

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)

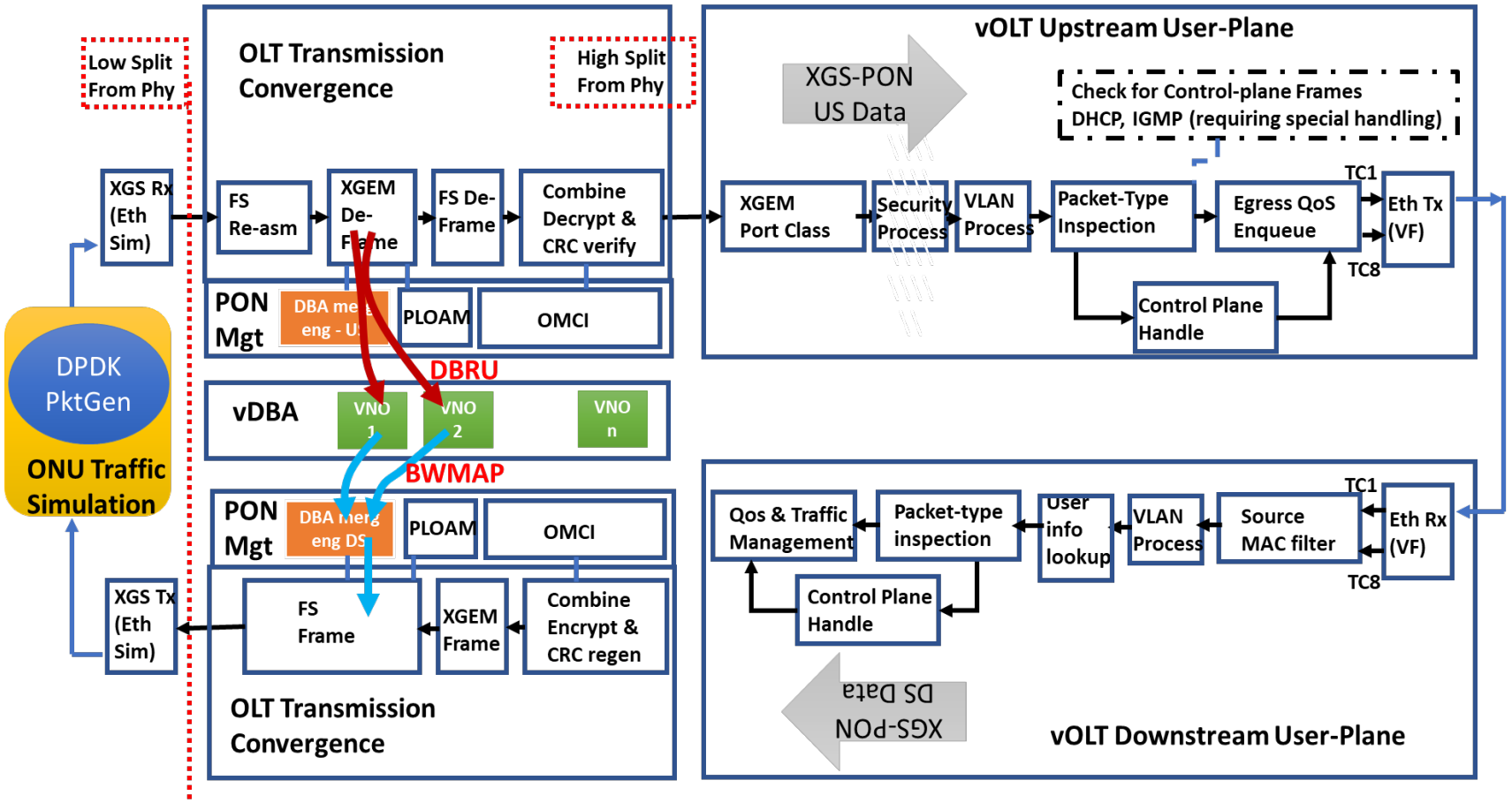
The virtual PON implementation

XGS-PON compliant protocol implemented in software

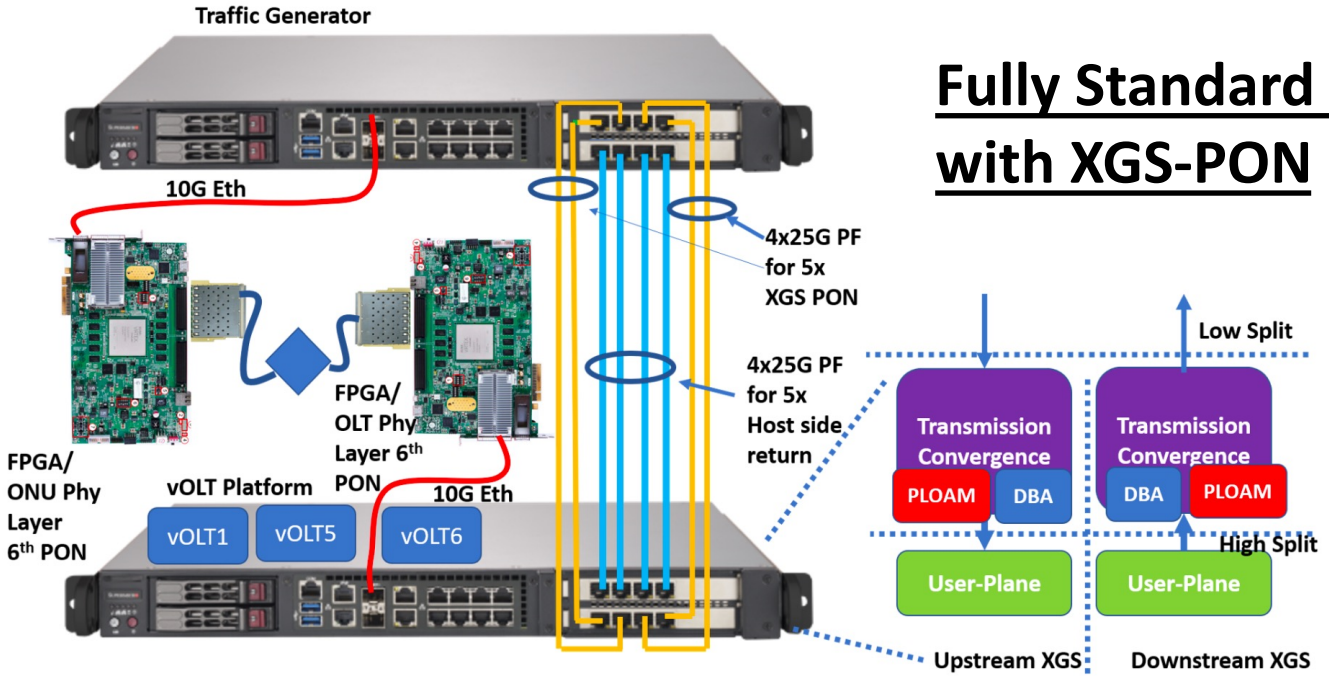
Two implementations:

- 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

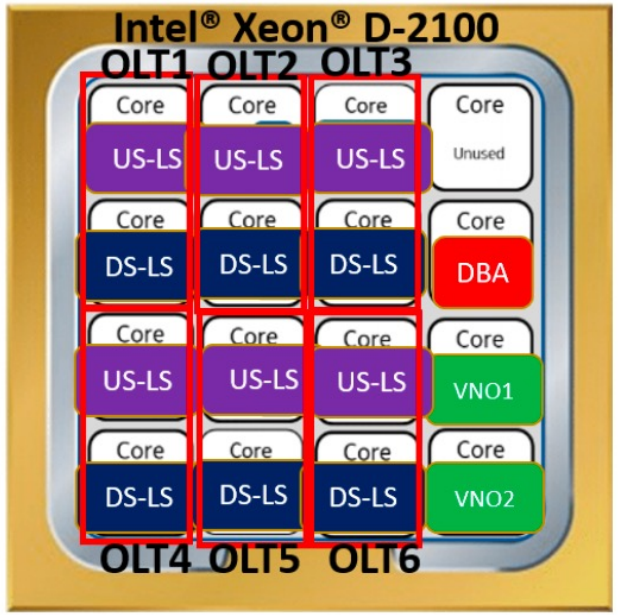
<u>The DBA is in GPP software in both cases</u>



The virtual PON performance



Fully Standard compliant with XGS-PON

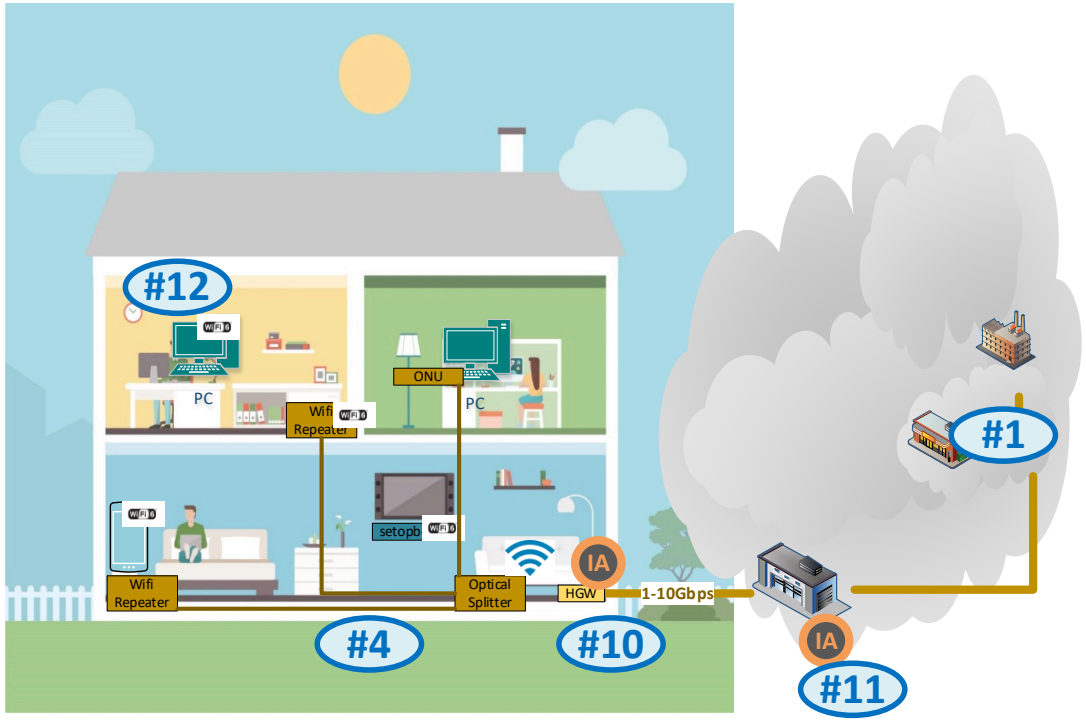


- F. Slyne et al., Experimental Demonstration of multiple Disaggregated OLTs with Virtualised Multi Tenant DBA, over General Purpose Processor. OFC 2020, Paper M3Z.11
- F. Slyne, J. Singh, R. Giller and M. Ruffini, Experimental Demonstration of DPDK Optimised VNF Implementation of Virtual DBA in a Multi-Tenant PON. Proc. of ECOC 2018

Content of the talk

- Brief into to my research and research group
- The Open Networking Movement
  - From SDR to SDN and from research to production
  - Opening the optical layer: a use case for the need for AI
  - Mininet becomes optical
  - How we opened the Passive Optical Network
- The edge
  - Not just RAN… offloading the next generation of weareable computing
  - Connecting the edge
- Conclusions: putting it all together
  - Opening Ireland

Fifth Generation Fixed Network (F5G) sample cases



Enhanced Fixed Broadband (eFBB):
- increase BW Capability

Full-Fiber Connection (FFC):
- Increase density

Guaranteed Reliable Experience (GRE):
- Increase quality

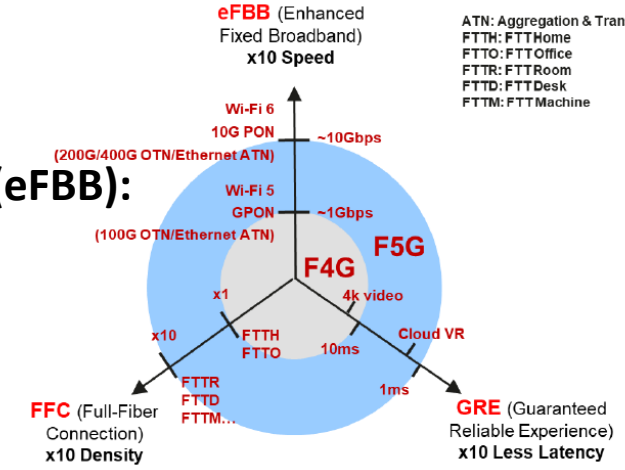


Figure 1: Features of F5G

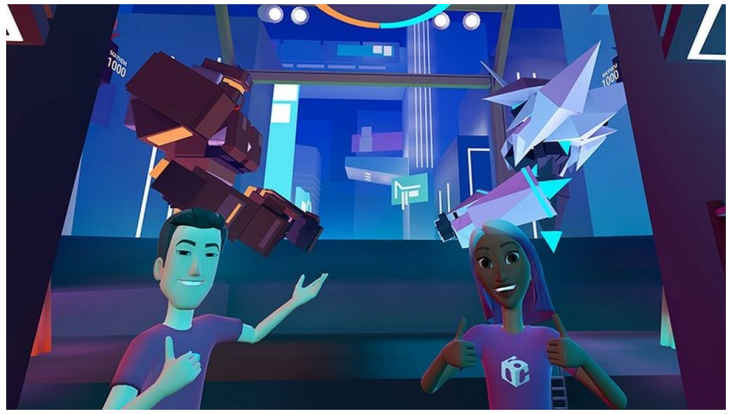
#1: Cloud Virtual Reality
#4: PON on-Promises
#10: Scenario based broadband
#11: Enhanced traffic monitoring and network control in Intelligent Access Network
#12: On Demand High Quality Transport for Real time applications

https://www.etsi.org/images/files/ETSIWhitePapers/etsi_wp_41_FSG_ed1.pdf

What are we going to run on that network?

- Immersive participation in entertainment can be a game changer…

  we are seeing great improvements in devices

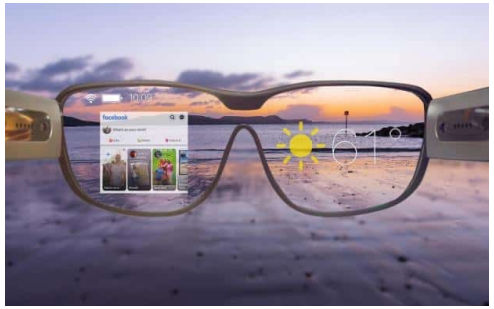


- You can create your own avatar..
  - For this one uses a phone app called in3D.. and you can export it to other apps
  - Takes 10 seconds to do it.. But **<u>all processing is done in the cloud</u>**, before getting back to you.

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>



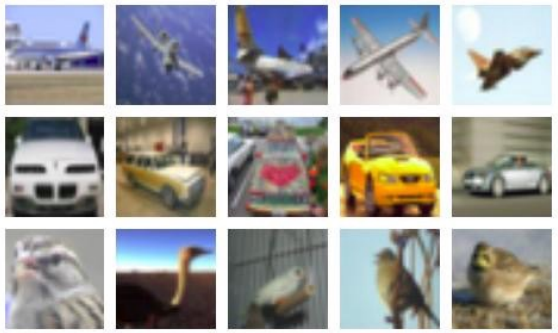
Object recognition

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

Offloading to the edge

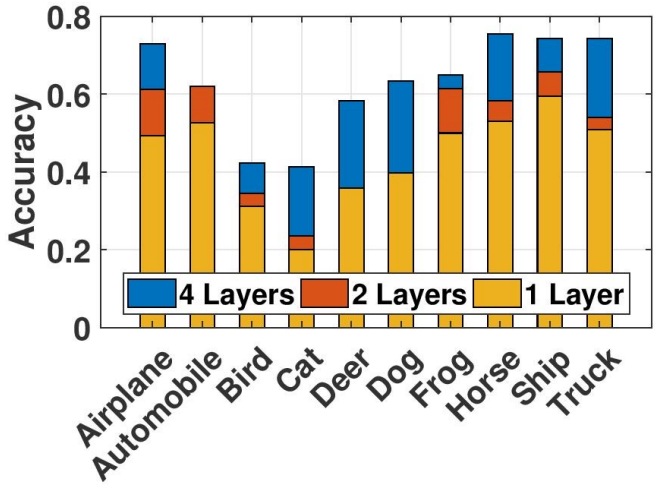
There is much research happening now on removing heavy computation altogether, i.e. offloading computation to the edge.

- Example of object recognition

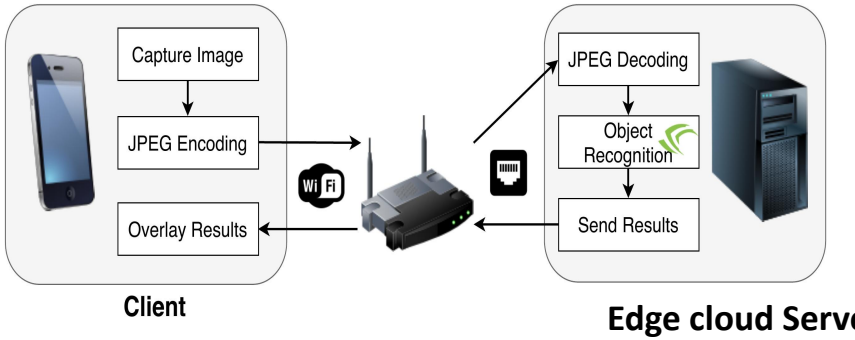


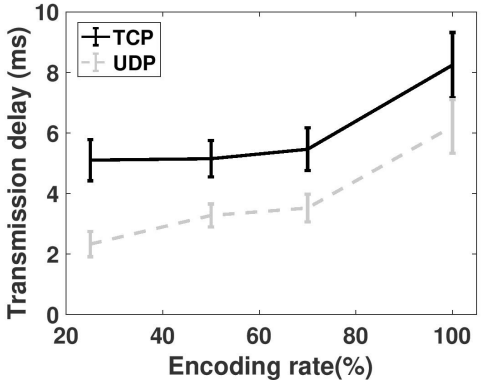
VS

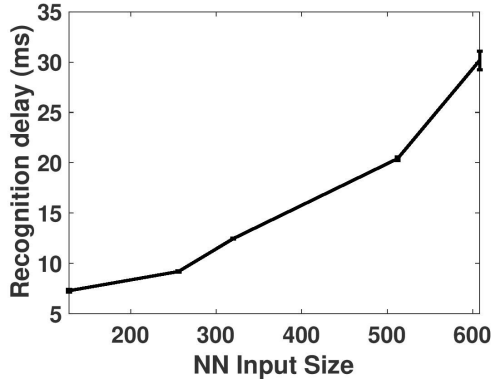
Average time: 2.537 s vs. 0.191

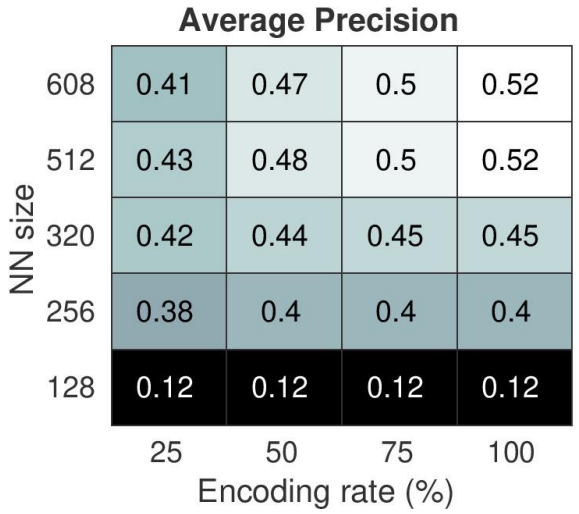


A. Galanopoulos, et al. Improving IoT Analytics through Selective Edge Execution, in proc. of IEEE ICC, 2020





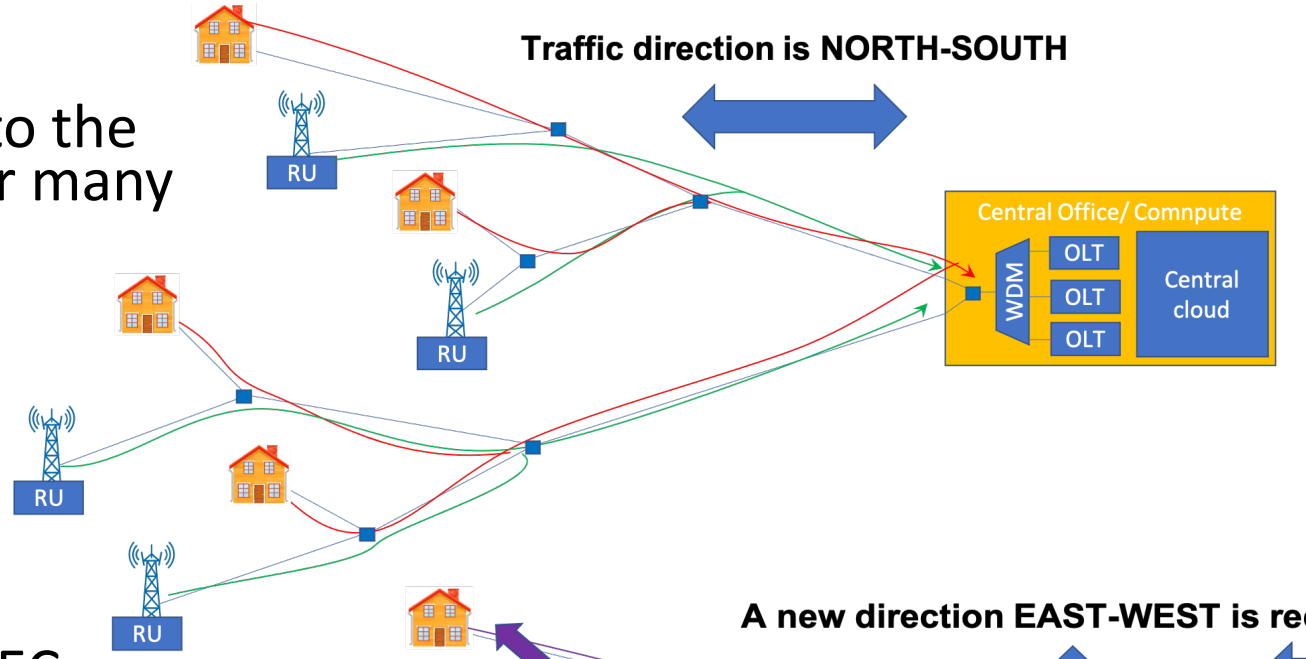




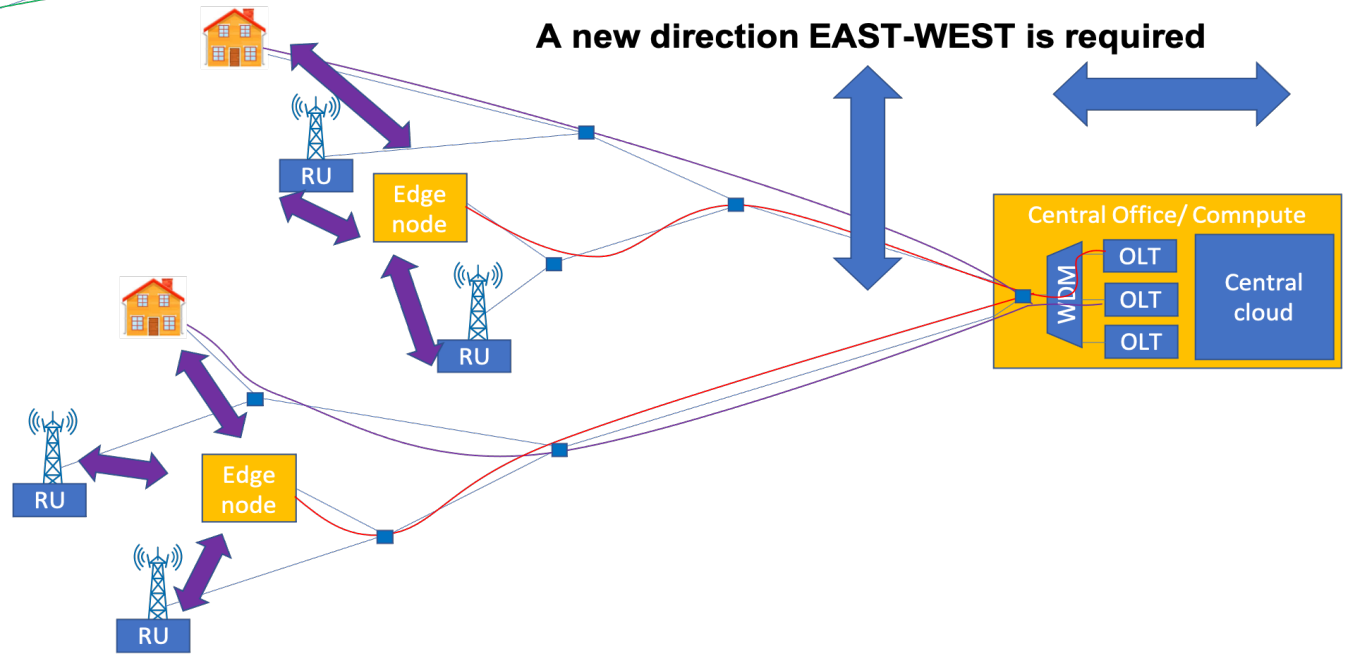
A. Galanopoulos, et al. Measurement-driven Analysis of an Edge-Assisted Object Recognition System, in proc. of IEEE ICC, 2020

The edge connectivity problem

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



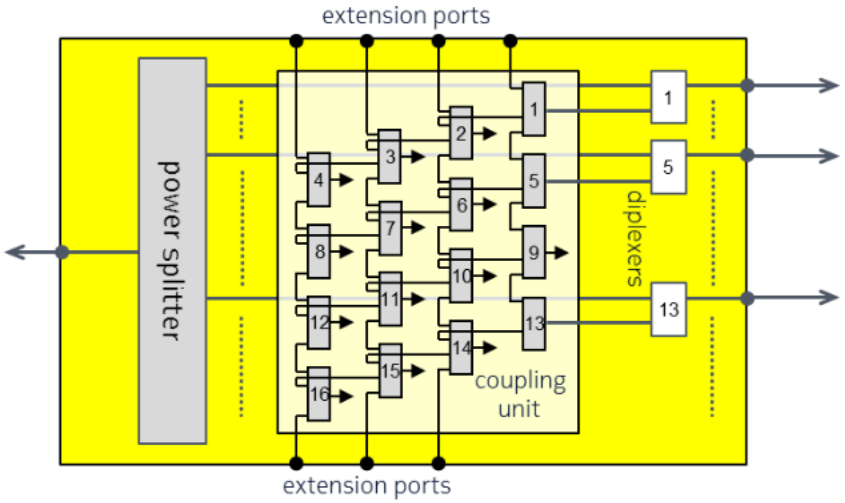
- For lower latency there are MEC nodes… that's why they were invented
- But traffic to edge nodes requires handling of direct end points communications (EAST-WEST)
- This is also crucial for mobile functional split

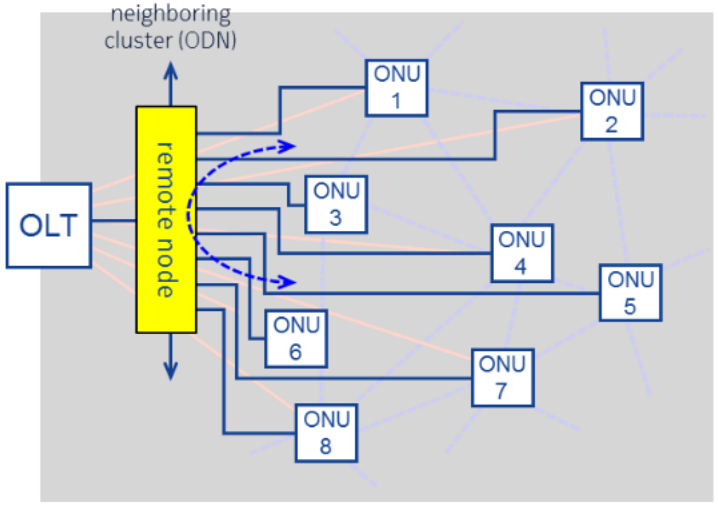


PON-based solutions

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

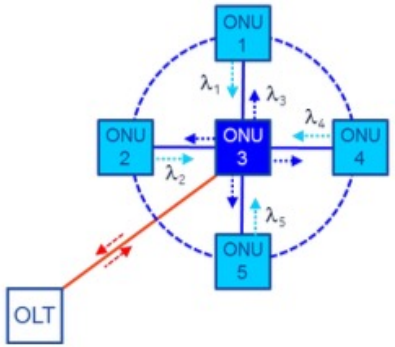
PON solutions:

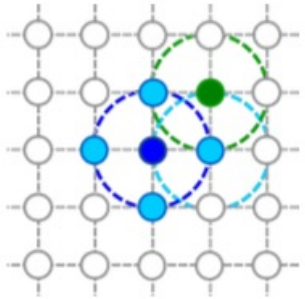




Fully passive solution

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

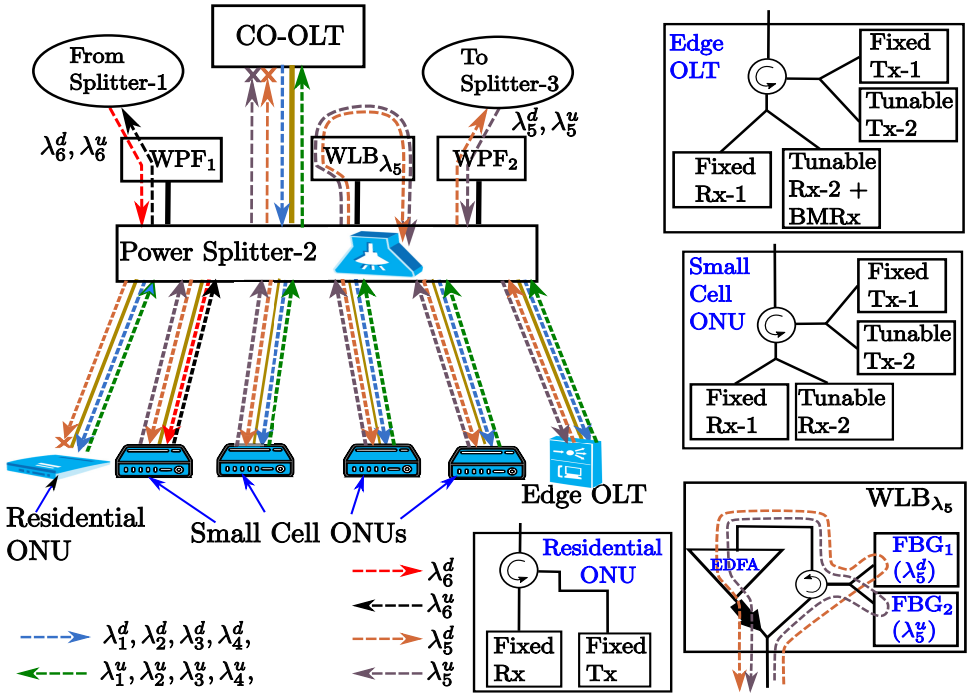




Less flexibility in direct links, more suitable for macro to small cell communications

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.



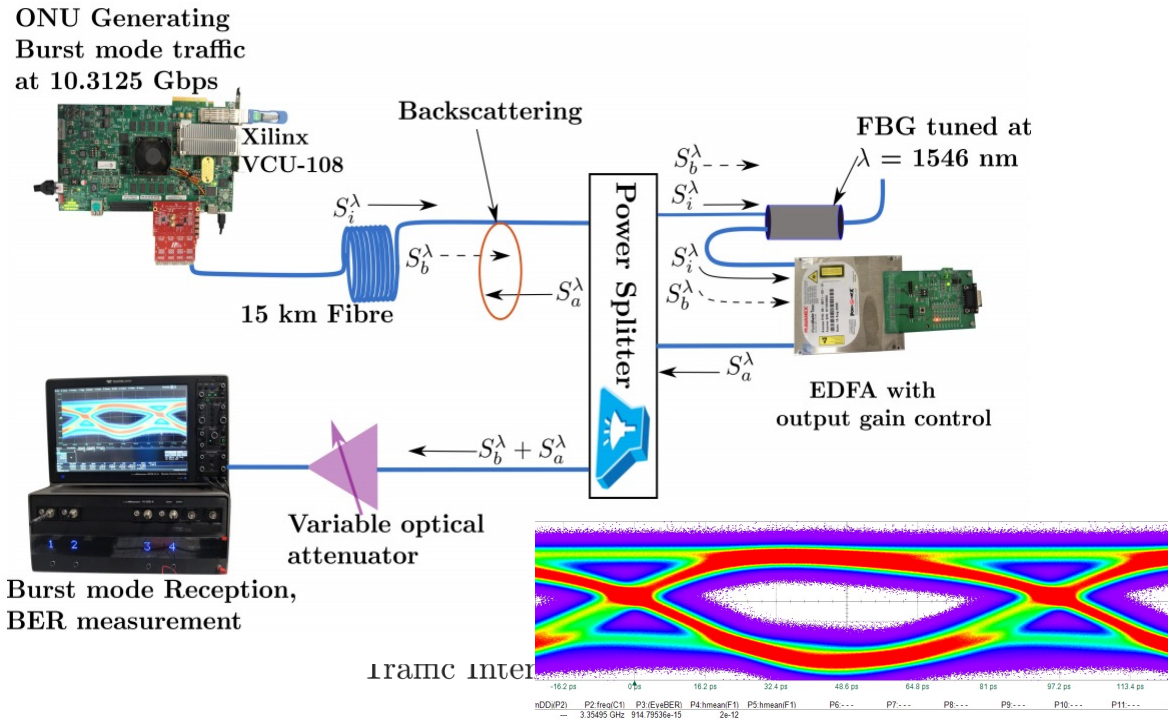
- Example use of Fibre Bragg Gratings
- Power loss going through splitter, but OK for last stage.
- Higher stage splitter might need amplifier integrated with FBG.

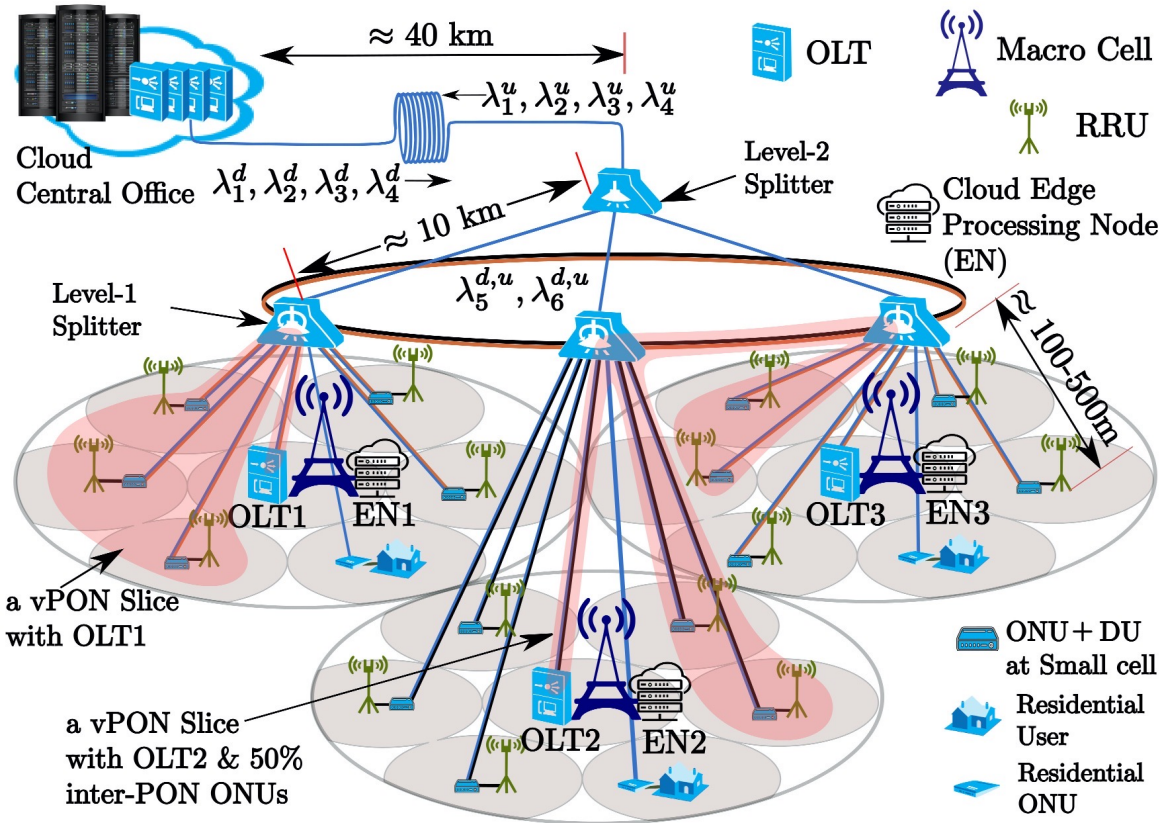
<u>Other technologies could be investigated…</u>
<u>e.g., power/wavelength re-configurable splitters</u>

- 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 dyanmci slices with different group of end points.
- Enable the use of wavelength and time domains making it independent across services (as well as tenants)





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

CONNECT Networks of the Future

Conclusions: putting it all together

TRINITY COLLEGE DUBLIN

- Open networking is a great opportunity for academic researchers…
  - … give the ability to do research at any layer and with real testbeds
  - …puts academy and industry at the same level
- It's also a good match for Machine Learning / AI technology
- Interesting challenges on:
  - Use of open networking/source across a network end-to-end
  - Technology for fast and low-cost interconnection of dense edge points
  - …
- Testbeds are more important than ever…
  - Test your solution exactly where it's meant to be used
  - Need good data for our AI (AI is only as good as your data…)

Open Ireland: Ireland's Open Networking Testbed

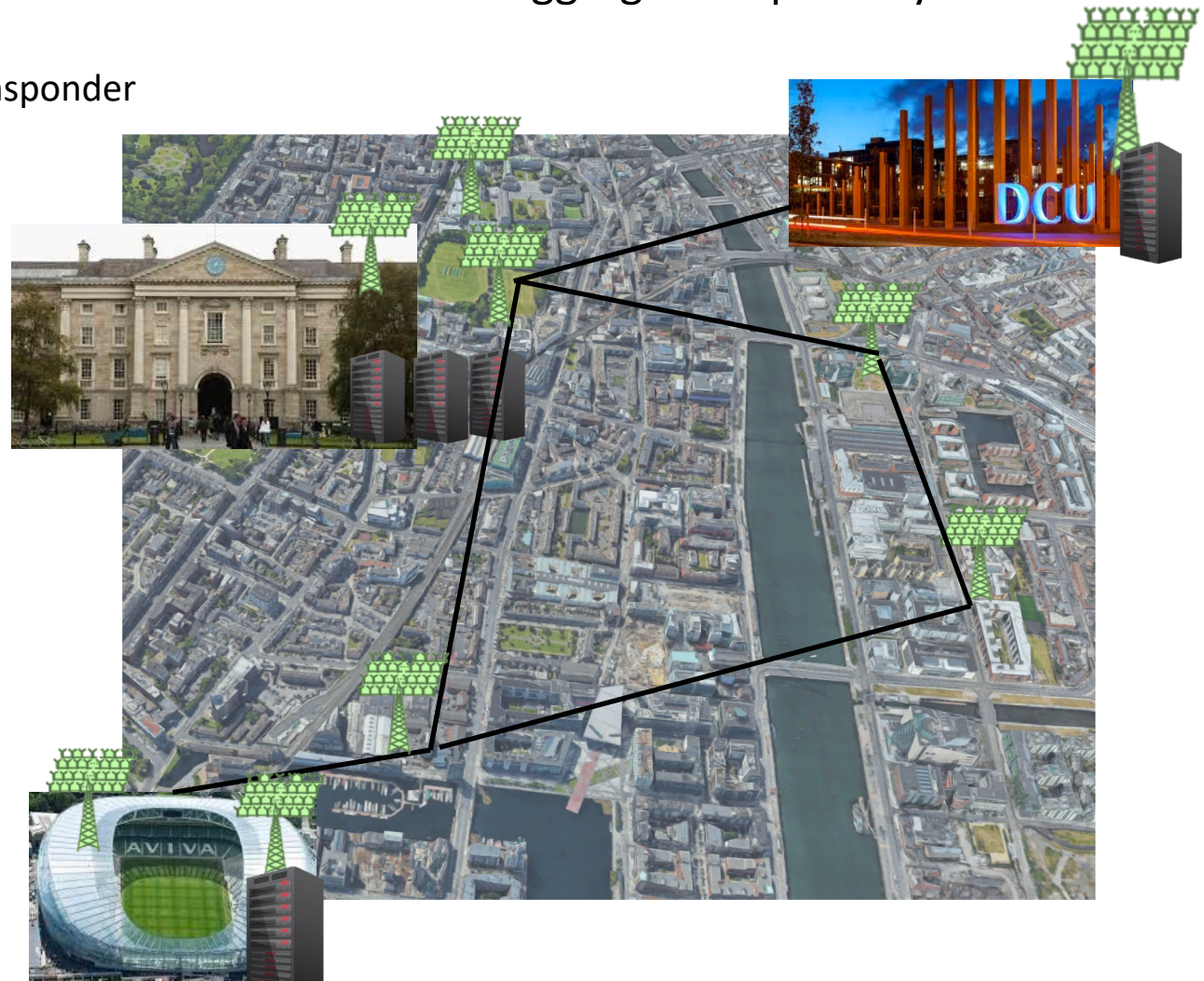
- Testbed for research on end-to-end: wireless-optical-cloud based on **open interfaces** and **open source**
  - **Investigate** end-to-end operation of OpenRAN, Cloud Central Office and Disaggregated optical systems.
    - ORAN 5G Indoor and Outdoor
    - Optical metro: 2,000 km fibre, SDN ROADMs, ESFAs, Transponder
    - Access network (PON) virtualization and edge cloud

Network Orchestration	
AI-driven automation ✓	Customisation ✓
Wireless/optical/cloud Convergence ✓	Open source/interface ✓

In support for new services	
Extended Reality ✓	Connected vehicles ✓
Cloud Robotics ✓	eHealth ✓

New Technology
OpenRAN and radio frequency ✓
Disaggregated Optical networking, transmission and switching ✓
Edge cloud ✓

Infrastructure sharing
Many Services ✓
Many operators ✓
Smart contracts ✓



The physical infrastructure

TCD

Small cells 100MHz BW

ORAN 7.2 split

Server

ROADM 2x 1x20

DCU

5x outdoor RRUs

3.4 – 5GHz range

External dark pairs: 1-DCU, 1-HEAnet, 5-Cells

HEAnet Internet

Internal dark pairs: 2-Cells indoor?

Small cells 100MHz BW

Fully flexible frontend

Labs fiber to 6-Cells indoor

USRPs N320/321

Optical fibre switch: 320 ports

ROADM 2x 1x9

12 x ROADMs

WSS 1x9

2 x WSS

1,700 km fibre spools

12x Bidi EDFA Amp

Transponder: 5 DCOs

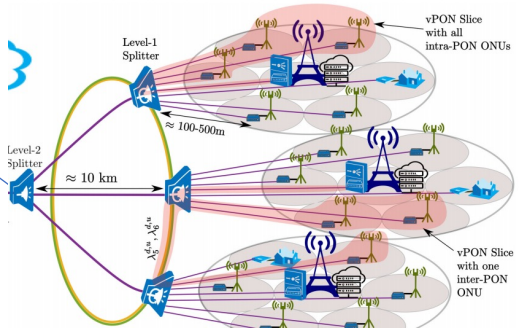
2x Boxes

2x Raman Amp

Optical disaggregation

Wavelength switching for access, metro inter and intra-DC

PON virtualization and mesh architectures



ONOS

OpenStack

P4

Time Sensitive Ethernet

Spine

Low latency switch

Leaf

Server

Server

Server

Server

8xservers

Leaf

Server

Server

Server

Server

8xservers

Ethernet Tester

Real time Scope

OSA

AWG

Broadband source

Tunable FBG, variable attenuators and other lab eq.

A World Leading SFI Research Centre

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

CONNECT
Centre for Future Networks

Thank you

Marco.Ruffini@tcd.ie www.marcoruffini.com

Prof. Marco Ruffini
Dept. Computer Science and Statistics, Trinity College Dublin
CONNECT and IPIC research centres

Trinity College Dublin
The University of Dublin

Ireland's European Structural and Investment Funds Programmes 2014-2020
Co-funded by the Irish Government and the European Union

European Union
European Regional Development Fund

Science Foundation Ireland sfi For what's next

IPIC BRINGING PHOTONICS TO LIFE