A World Leading SFI Research Centre

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

CONNECT
Centre for Future Networks

The Open Ireland research infrastructure: from open networking to digital twins

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CONNECT and IPIC research centres

Trinity College Dublin
The University of Dublin
Ireland's European Structural and Investment Funds Programmes 2014-2020
Co-funded by the Irish Government and the European Union
European Union
European Regional Development Fund
Science Foundation Ireland
For what's next
IPIC
BRINGING PHOTONICS TO LIFE

The Research group





SDN control of quantum networks

OpenRAN Intelligent control

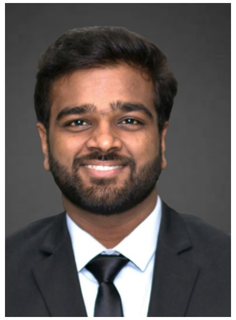
Open Networking testbed

Heterogeneous access-metro networks




Free space
optics backhaul

Mininet-Optical
Optical network digital twin



PON
virtualization

Mesh PON access

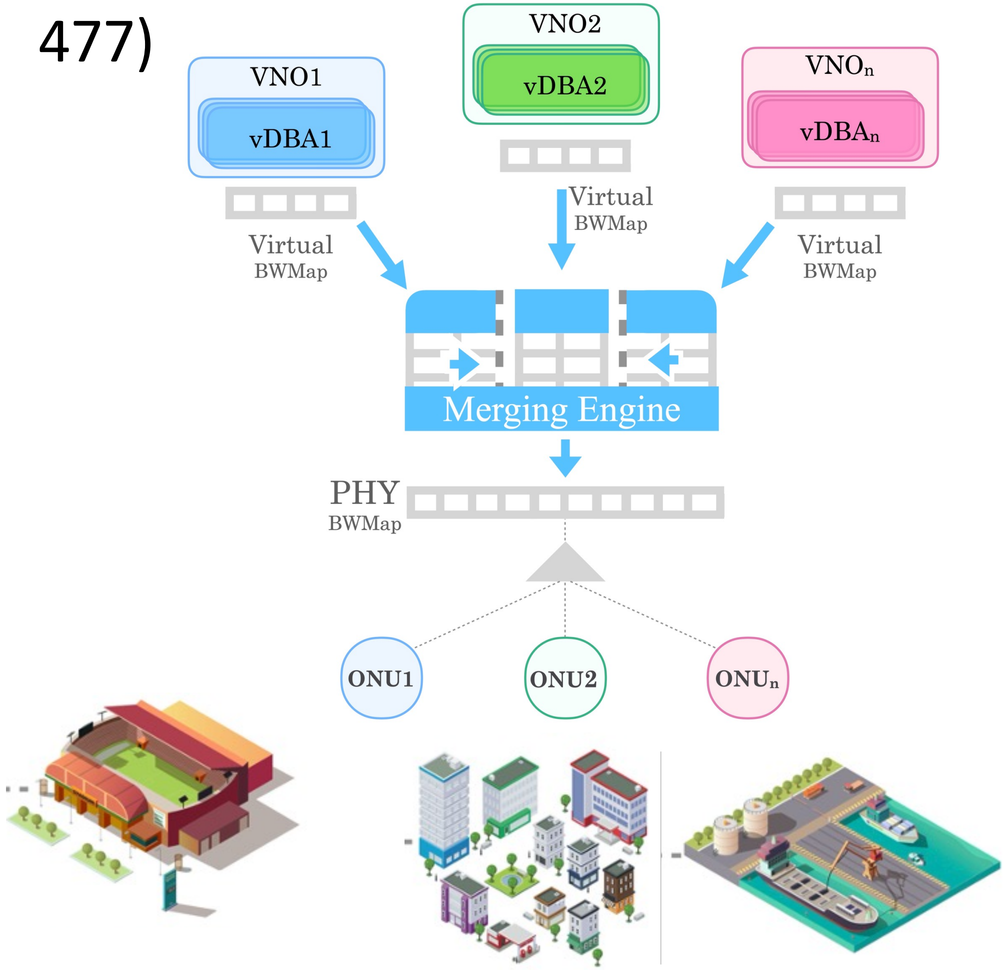
Edge-cloud
optimisation

Multi-RAT
optimisation

Expertise and track record

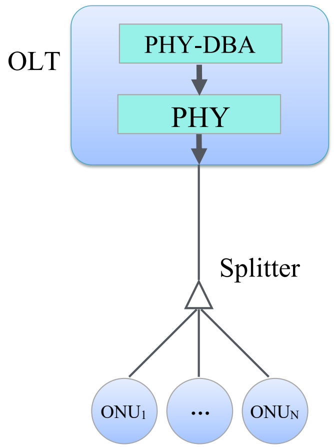
<u>Our research work moves from theory to lab experimentation and prototyping</u>

- Invented, patented and prototyped PON scheduling virtualization, brought to standard at BroadBand Forum (TR-402, TR-370i2, WT-477)

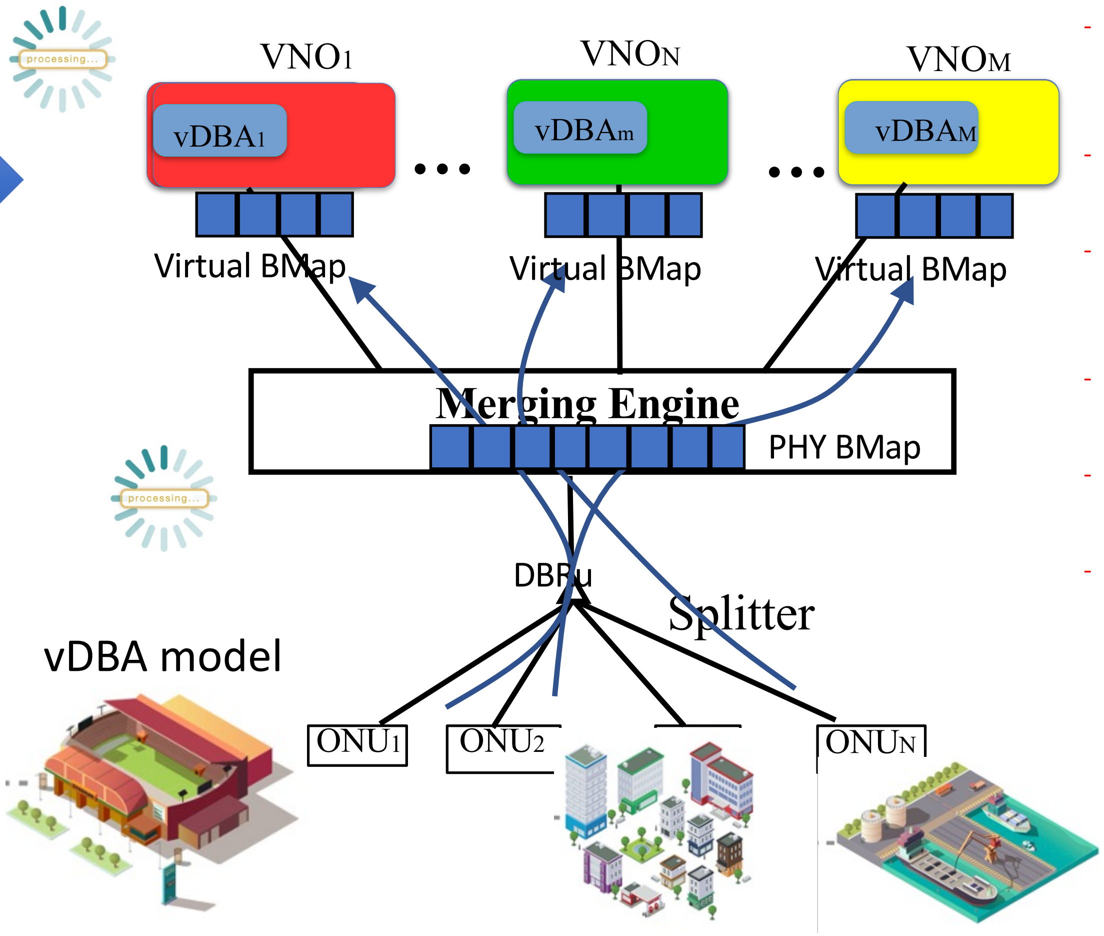


- SDN and network virtualisation:
  - <u>convergence</u> of optical and wireless access systems (coordinated scheduling)
  - <u>optical disaggregated</u> systems (machine learning for quality of transmission estimation) – **<u>mininet optical emulator</u>**
  - <u>low-latency</u> access
  - network <u>multi-tenancy</u> and <u>multi-service</u> operation
  - OpenRAN and RAN Intelligent Controller

Full disaggregation of the OLT with virtual DBA



Current physical DBA model



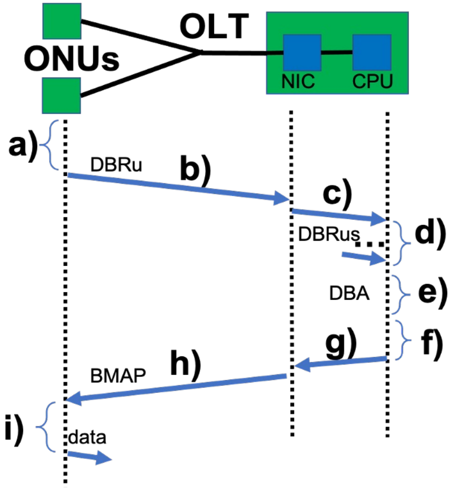
vDBA model

- P. Alvarez, N. Marchetti, and Marco Ruffini. Evaluating Dynamic Bandwidth Allocation of Virtualized Passive Optical Networks Over Mobile Traffic Traces. IEEE/OSA Journal of Optical Communications and Networking, vol. 8, No. 3, March 2016
- F. Slyne, M. Ruffini. Joint Dynamic Bandwidth and Queue Management for Upstream SLA-Oriented QoS in Multi-Tenant, Multi-Service PONs. IEEE ONDM, May 2020
- A. Ahmad, F. Slyne, S. Zeb, A. Wahab, R. Azhar Khan and M. Ruffini. Capacity sharing approaches in multi-tenant, multi-service PONs for low-latency fronthaul applications based on cooperative-DBA. OSA Optical Fiber Communications Conference (OFC), March 2020
- N. Afraz, F. Slyne and M. Ruffini. Full PON Virtulisation Supporting Multi-Tenancy Beyond 5G. Proc. of OSA Advanced Photonics Congress (APC), July 2019
- A. Elrasad and Marco Ruffini, Frame Level Sharing for DBA Virtualization in Multi-Tenant PONs. Proc. Of Optical Networks Design and Modeling (ONDM), May 2017
- A. Elrasad, N. Afraz, and Marco Ruffini, Virtual Dynamic Bandwidth Allocation Enabling True PON Multi-Tenancy. Proc. of Optical Fibre Communications conference (OFC), paper M3I.3, March 2017

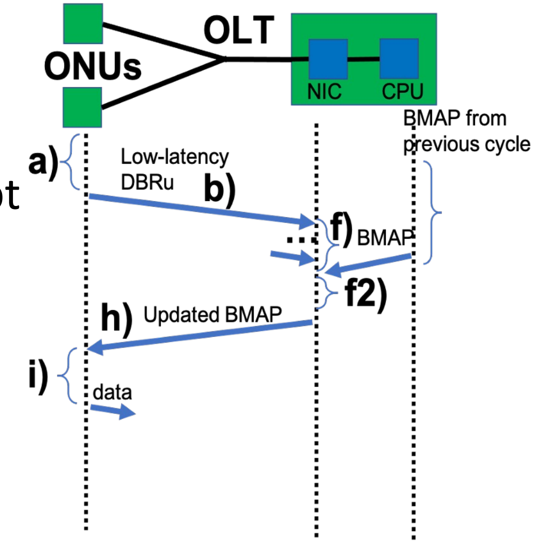
- Work on DBA virtualization to enable fine-grained control to different tenants.
- Also other use cases: e.g., for service differentiation, for mobile front haul (more on this later)
- Also included in BBF TR-402 "PON Abstraction Interface for Time-critical Applications" and recently in TR-370i2 "Fixed Access Network Sharing (FANS) and WT-477 in progress (implementation work flow)

Low latency for unpredictable traffic

Standard DBA process

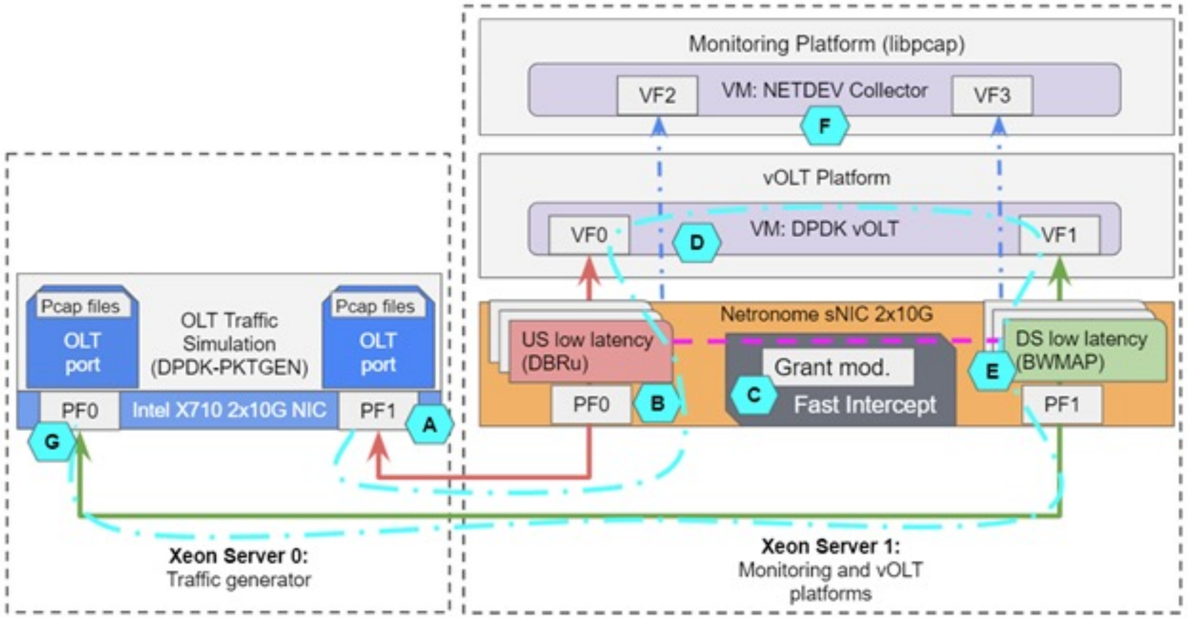


Fast intercept process

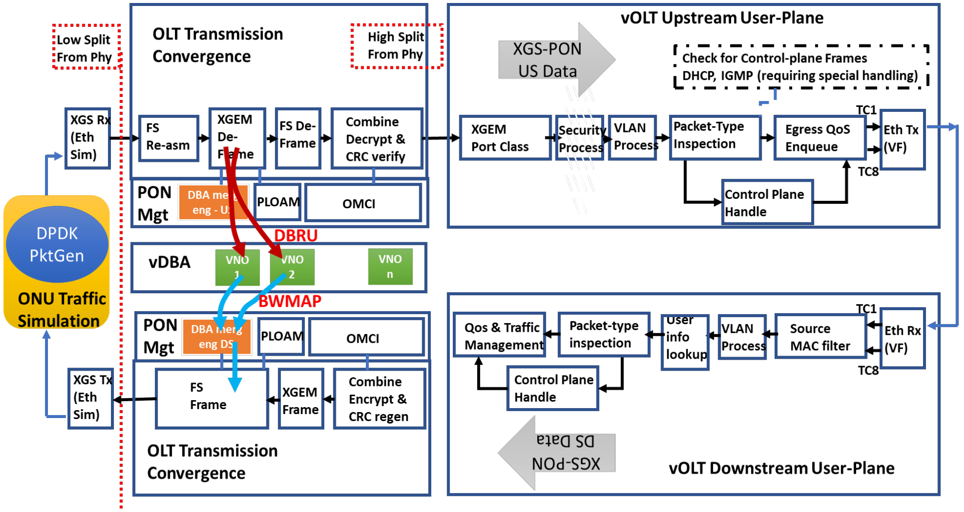


a. ONU waits for the opportunity for the DBRu
b. DBRu propagates through the fibre.
c. Information from phy to virtual process.
d. DBA process waits a time window to receive DBRus.
e. OLT runs the DBA algorithm.
f. BWMAP added to the next downstream frame.
g. BWMAP travels from virtual process to phy.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

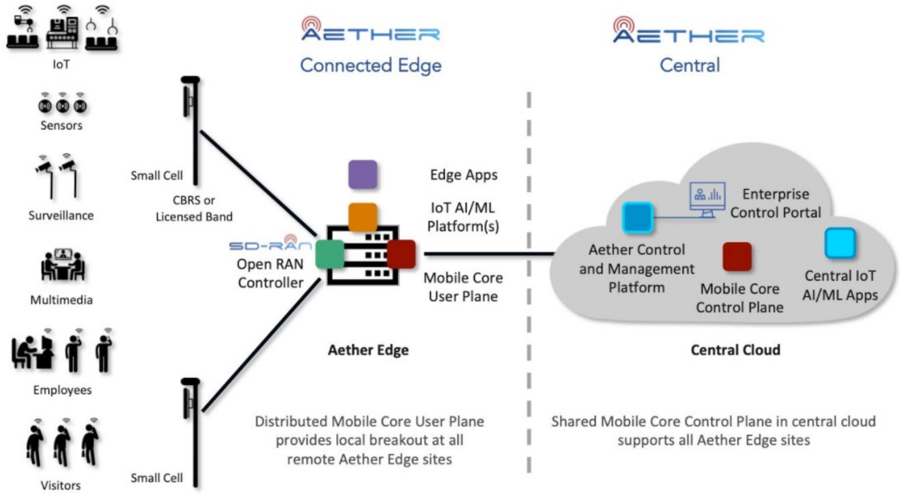
- ➢ Standard DBA best latency =~ **418.5µs** (virtual implementation)
- ➢ Fast intercept avg latency =~ **237 µs** (~ 43% faster)

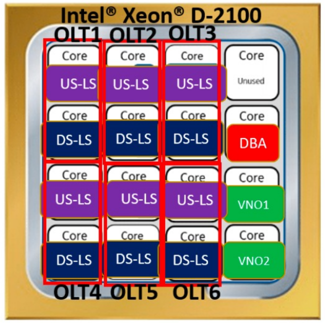


PON virtualization and Mesh PON architectures for low-latency MEC support

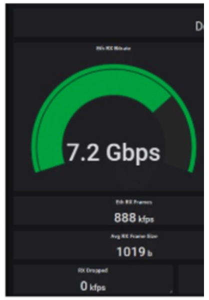


Extend PON physical and virtual layer

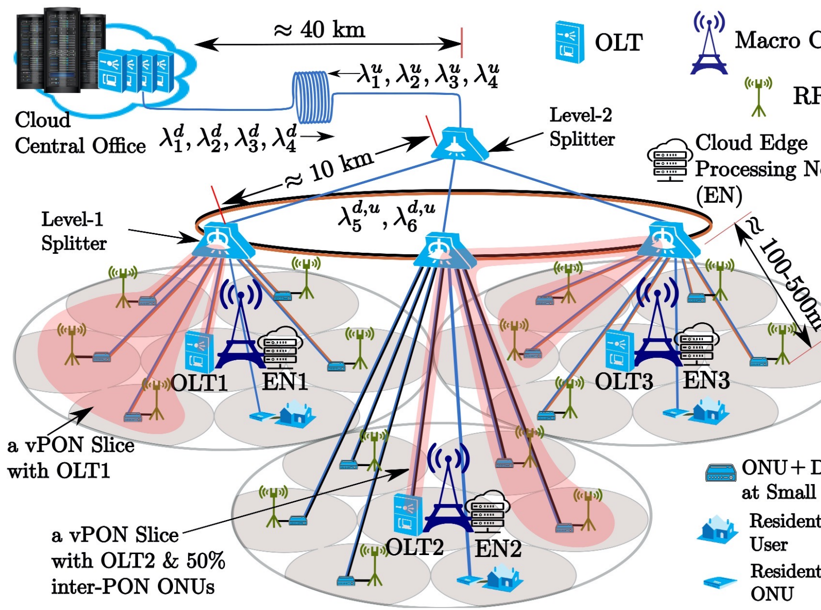




Upstream Downstream



Support high-capacity, low latency communications in a mesh access topology



Overall > 35 publications, including:

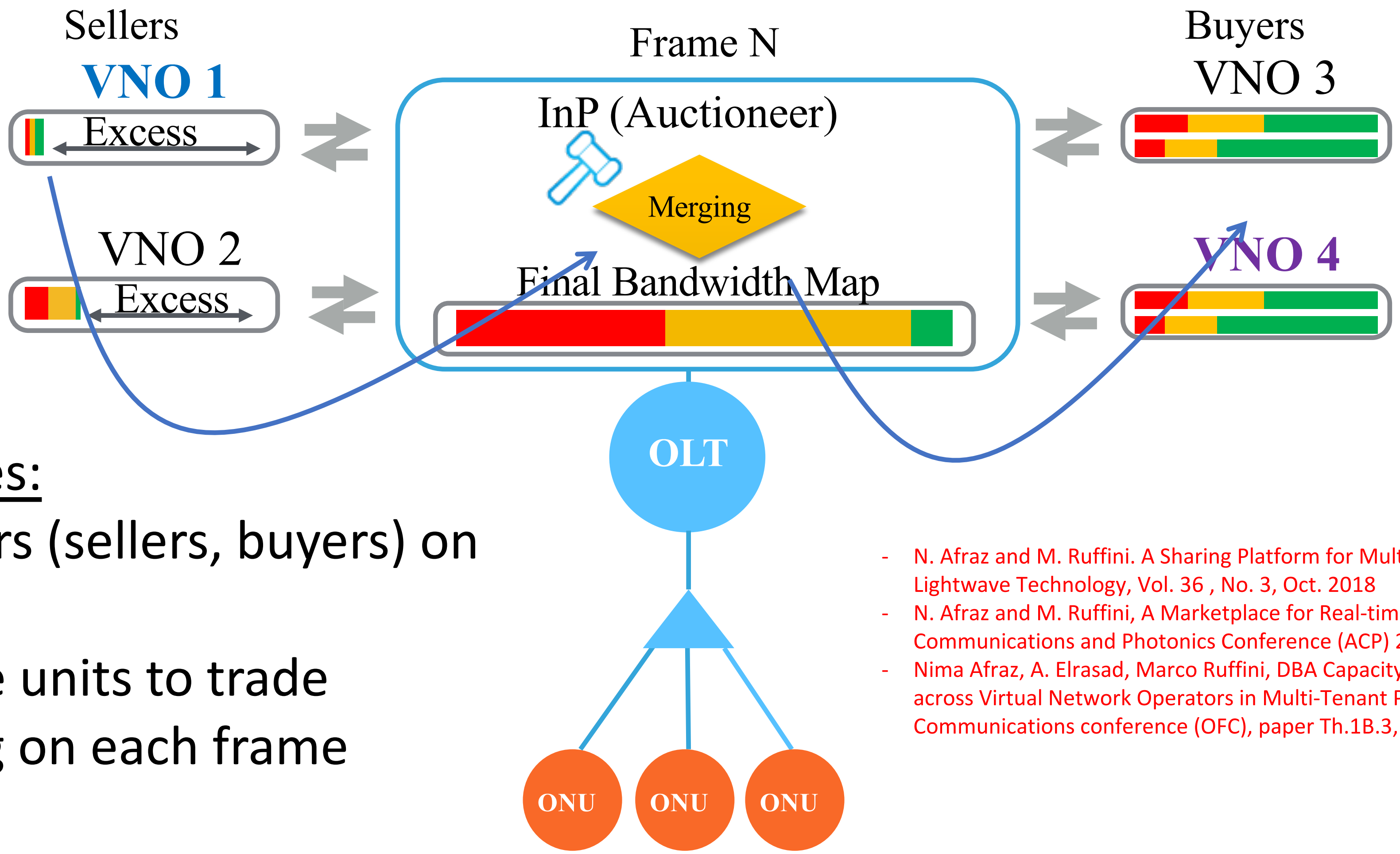
- Journal of optical Communications and Networking (JOCN)
- Journal of Lightwave Technology (JLT)
- IEEE Communications Magazine
- IEEE Communications Survey and Tutorials
- Optical Fibre Conference (OFC)
- European Conference on optical Communications (ECOC)
- Globecom
- Optical Network Design and Modeling (ONDM)

The incentive issue

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
- Multiple frame units to trade
- 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
- N. Afraz and M. Ruffini, A Marketplace for Real-time Virtual PON Sharing. Asia Communications and Photonics Conference (ACP) 2018. **<u>Best student paper award</u>**
- 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

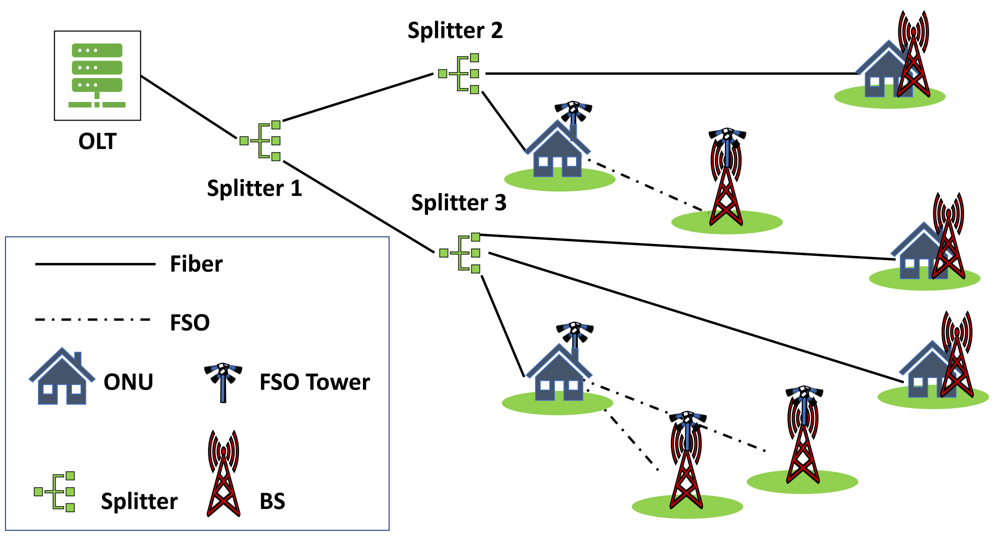
Disruptive Technology Innovation Fund (DTIF) on Free space optics

Objectives:

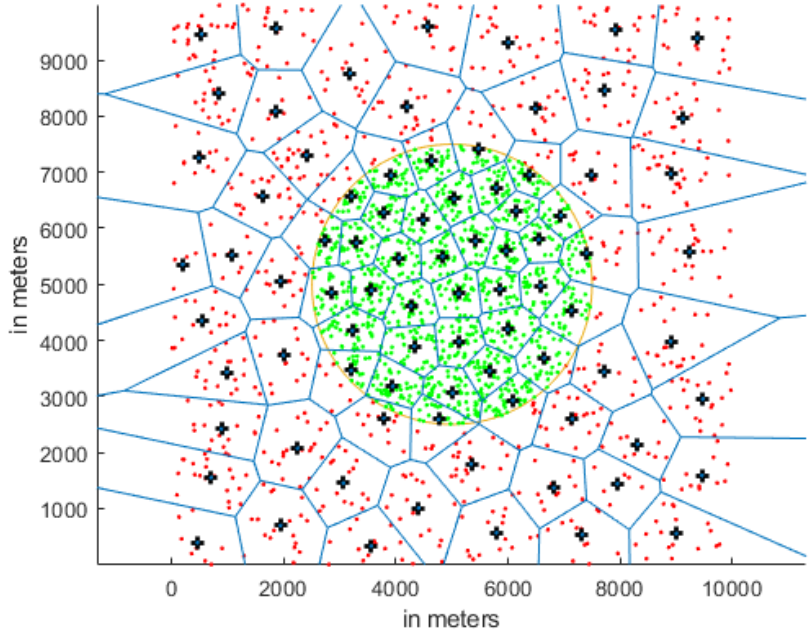
- Identify the optimum number of splitter / FSO tower locations
- Identify the connection technology to be used to connect the BS to the splitter/ FSO tower.

Assumptions:

- Base stations are already placed (randomly) in a geographical area.

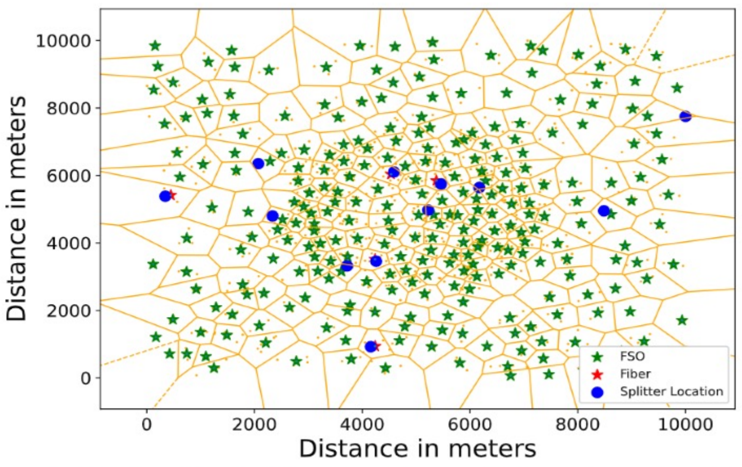


Hybrid Fiber/FSO Network

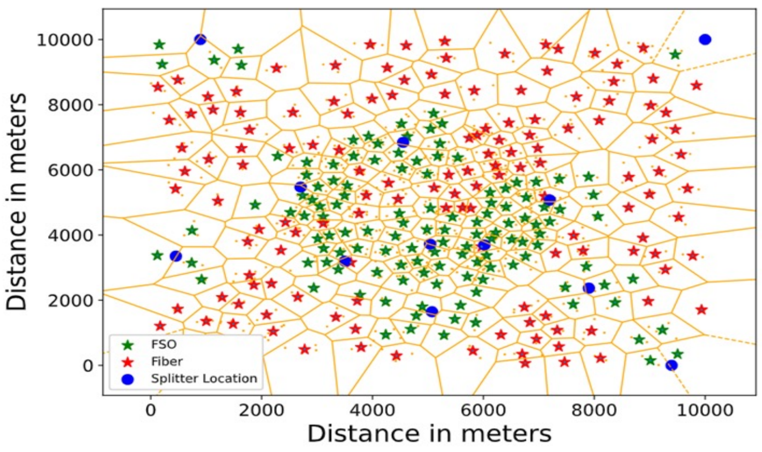


User and Base Station distribution

Tradeoff is cost vs reliability



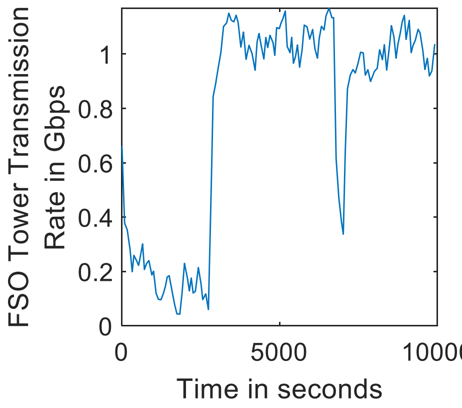
Reliability Threshold = 0.0; Fiber = 0.01%, FSO = 99.99%



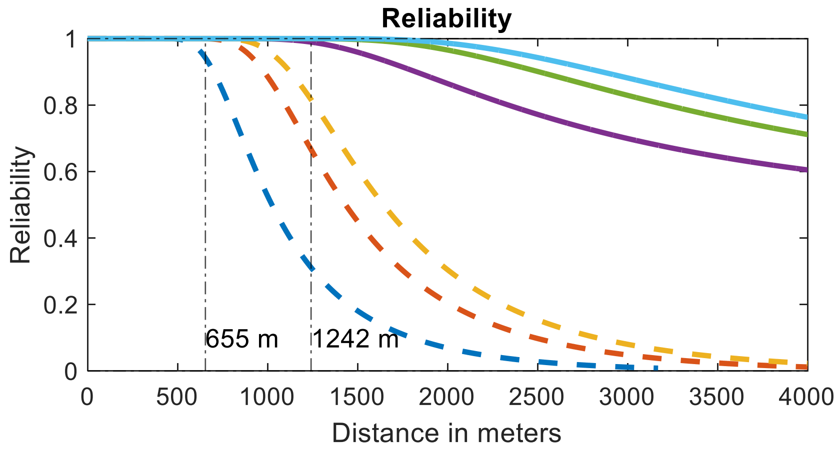
Reliability Threshold = 0.9; Fiber = 52%, FSO = 48%

Currently investigating scenario with tracking and routing (informed by technology – Mbryonics SME)

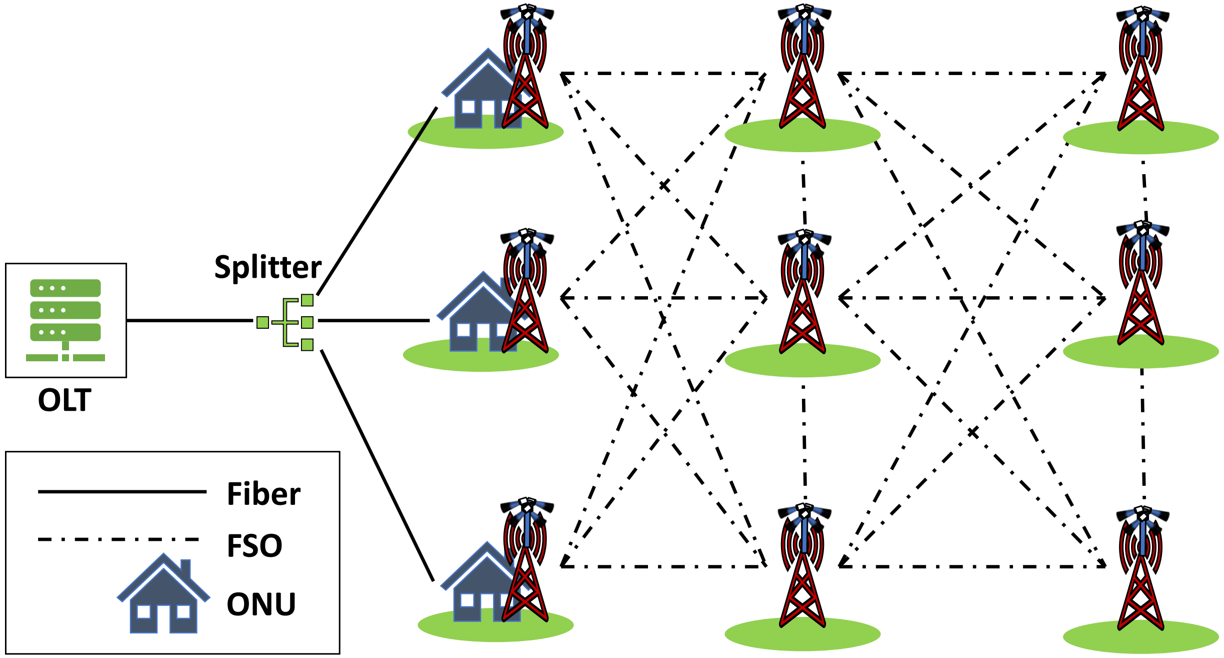
- The towers have steerable transceivers.
- There is temporal traffic variation.
- The weather changes between clear and light fog.
- Number of transceivers per FSO tower is limited.



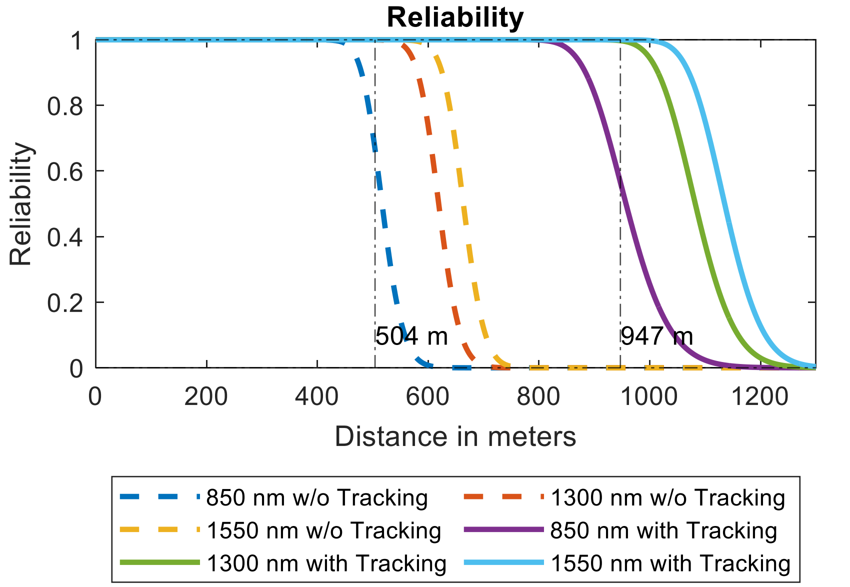
Temporal Traffic Variation



Reliability during Clear Weather



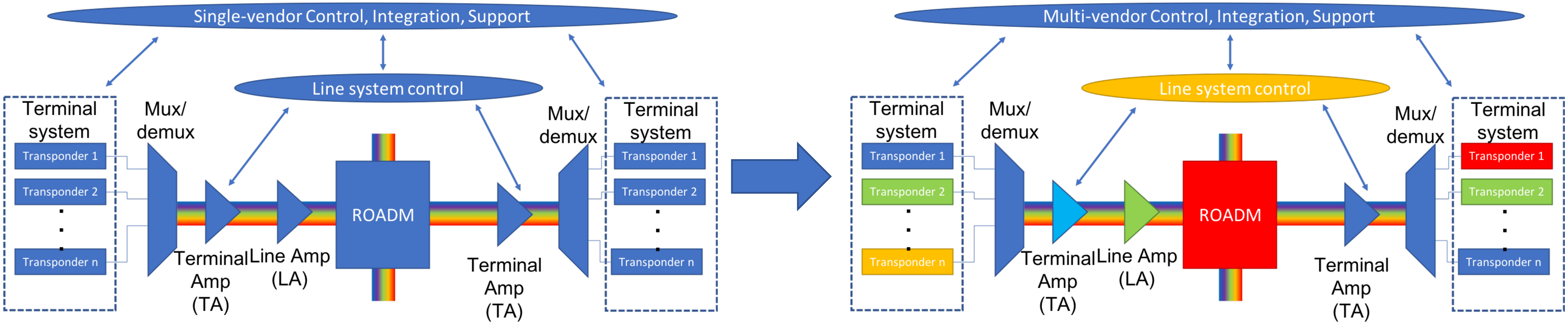
Dynamic Mesh Network with FSO Towers



Reliability during Light Fog

Optical layer disaggregation and application of machine learning

- 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 …

Disaggregated optical control plane and Mininet-Optical

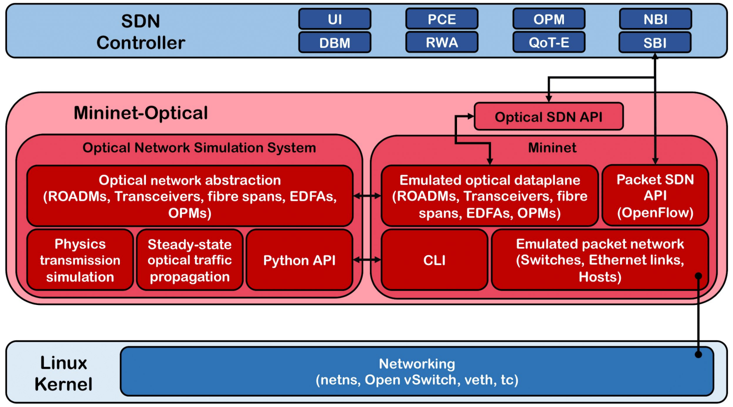
Holistic view of **<u>integrating edge, central office and large DC computing</u>** requires highly dynamic optical transport.

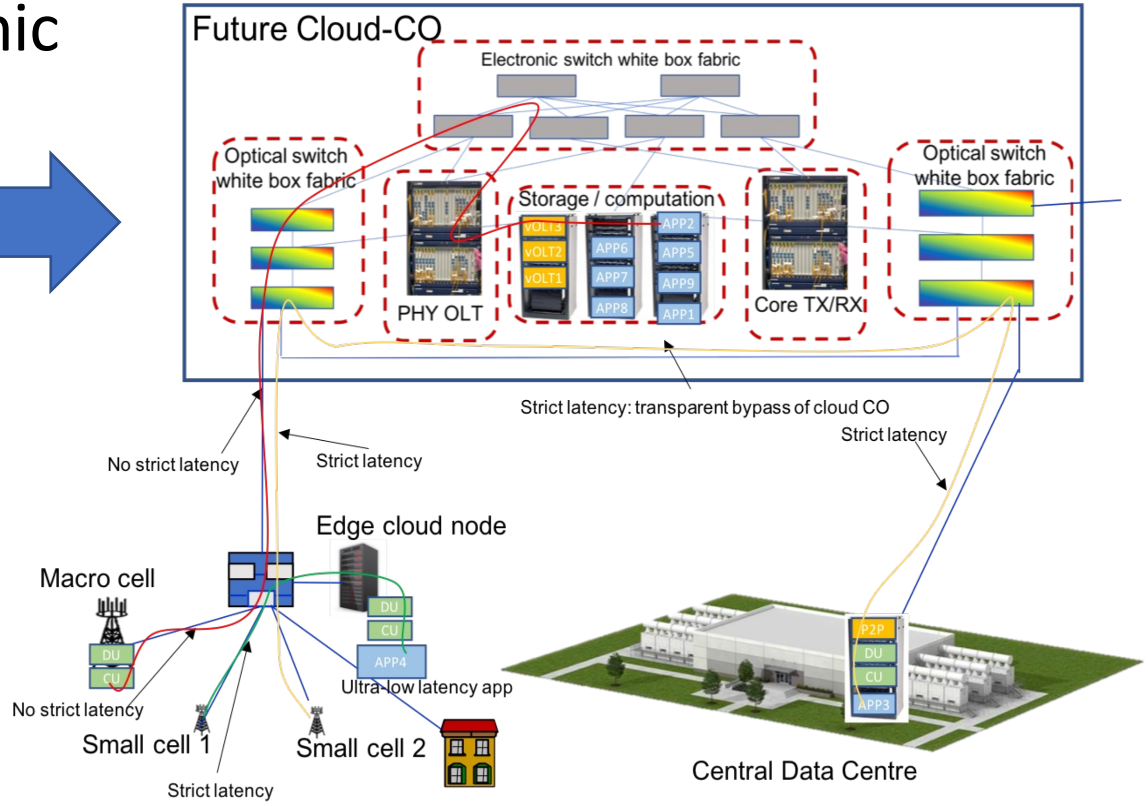
<u>Here it's all about Control!</u>

We developed Mininet for the optical layer **<u>(Mininet-Optical)</u>**

Trinity College Dublin
The University of Dublin
The University of Arizona

➔ Test your optical control plane (routing algorithms, ML-based) in large scale emulated networks

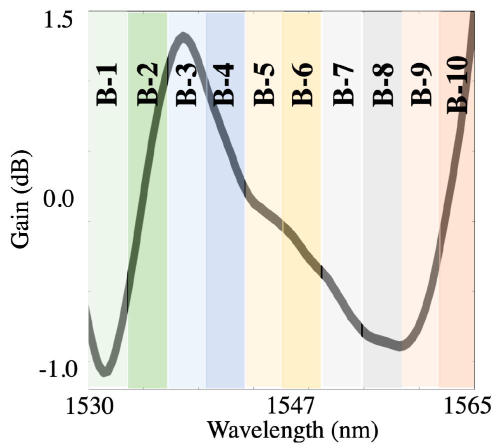


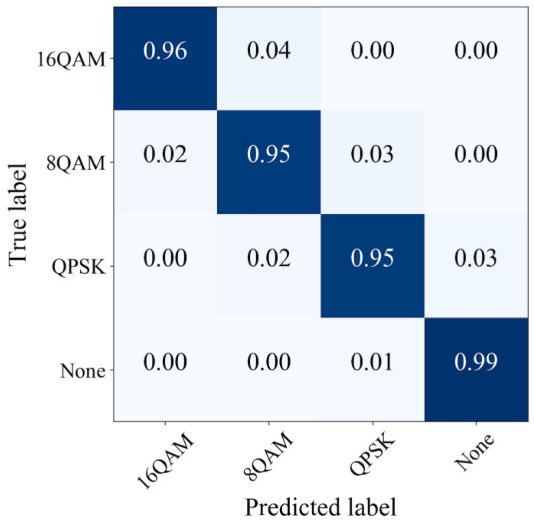


Concept published at OFC, ICC, ONDM, ACP, PTL.

Use of Machine learning for quality of transmission estimation in optical transport networks

- Dynamic wavelength allocation suffers from impairments in optical amplifiers:
  - Amplifier gain is not perfectly flat across wavelengths and this function is not known and depends on amplifier, working point…
  - ➔ Adding a wavelength channel can increase/decrease the power and OSNR of all other channel
- 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.

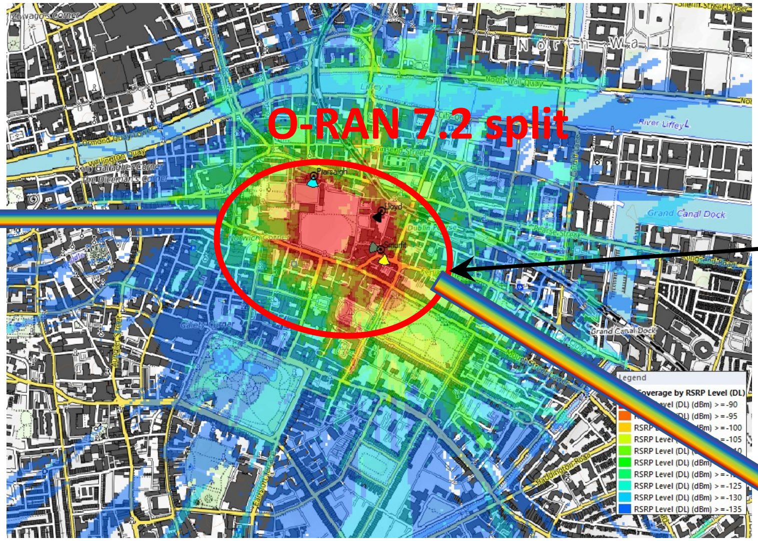




- F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini and M. Tornatore. An Overview on Application of Machine Learning Techniques in Optical Networks. IEEE Surveys and Tutorials, Vol. 21 , No: 2, second quarter 2019
- S. Zhu, C. Gutterman, A. Diaz Montiel, J. Yu, M. Rufini, G. Zussman and D. Kilper. Hybrid Machine Learning EDFA Model. OSA Optical Fiber Communications Conference (OFC), March 2020
- A. A. Dıaz-Montiel and M. Ruffini. A Performance Analysis of Supervised Learning Classifiers for QoT Estimation in ROADM-based Networks. Proc. of Optical Network Design and Modeling conference (ONDM), May 2019
- 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

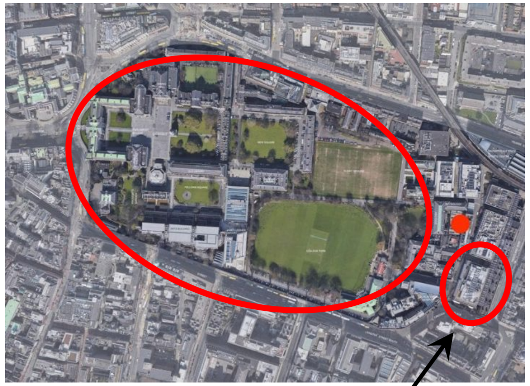
Open Ireland: Ireland's Open Networking Testbed

Optical transmission, analog RoF, mmWave-THz



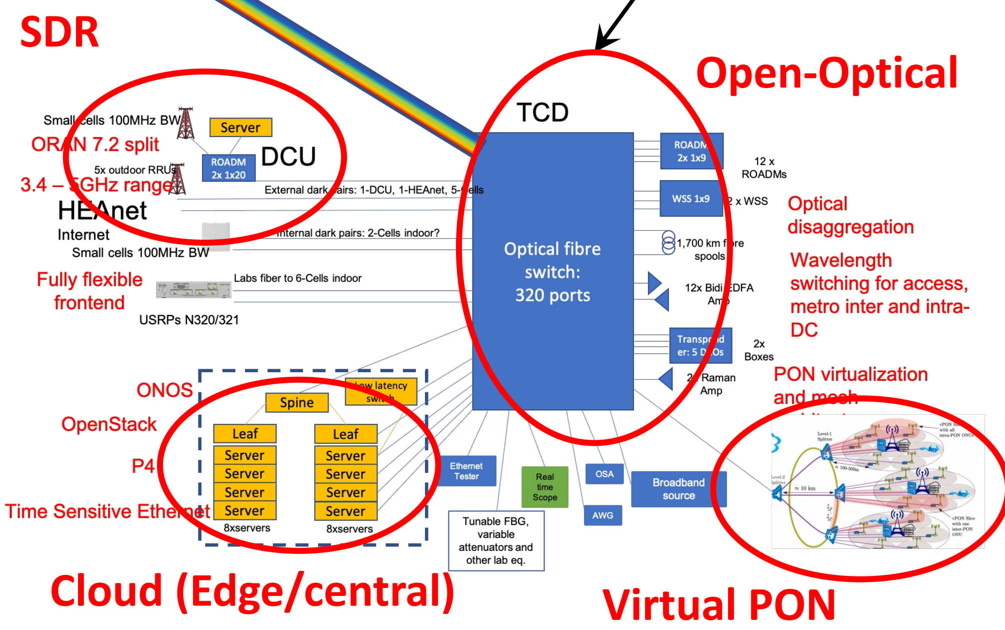
www.openireland.eu

Based in Trinity College campus



CONNECT research centre building

O-RAN



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

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

ComReg 100MHz spectrum license

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

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

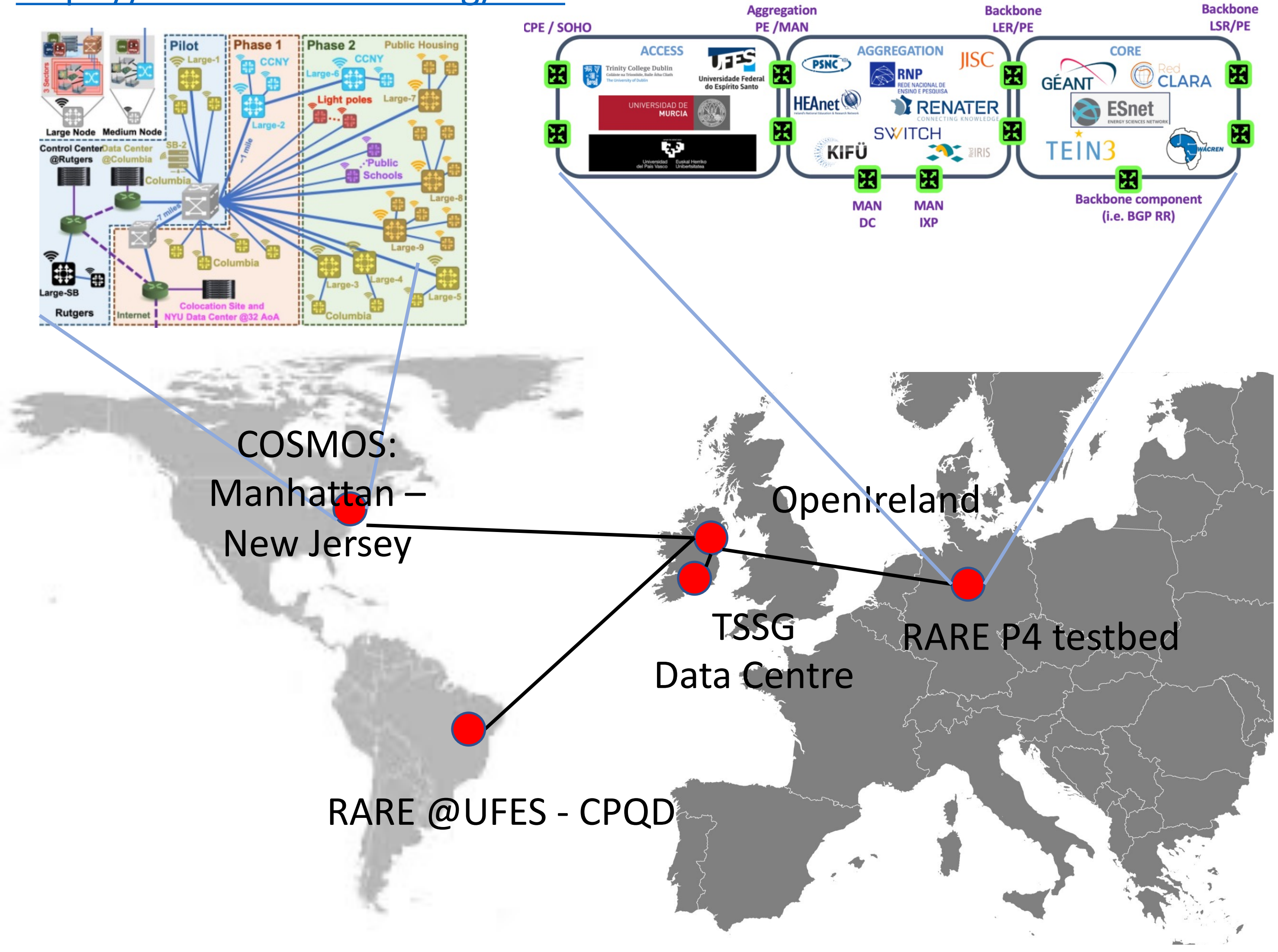
Upper N77 band: 3.8 – 4.2 GHZ

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

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

Worldwide reach… and further plans

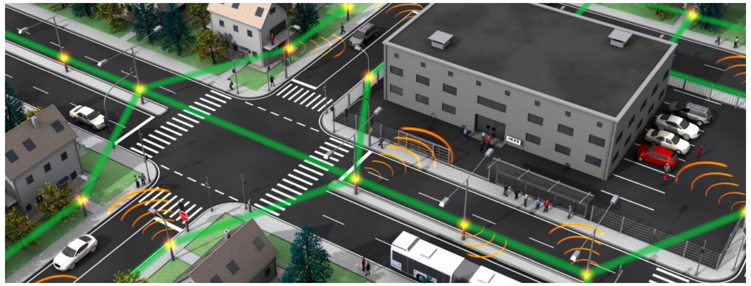
https://wiki.cosmos-lab.org/wiki



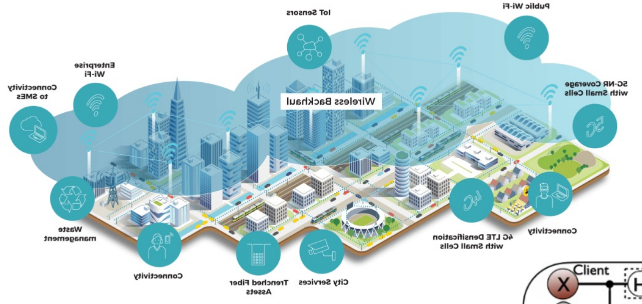
Foundation testbed in CONNECT2

Starting point for further exploration:

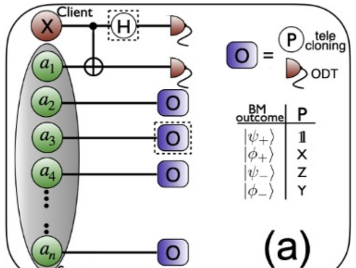
⇒ ***mmWave and THz experimentation***



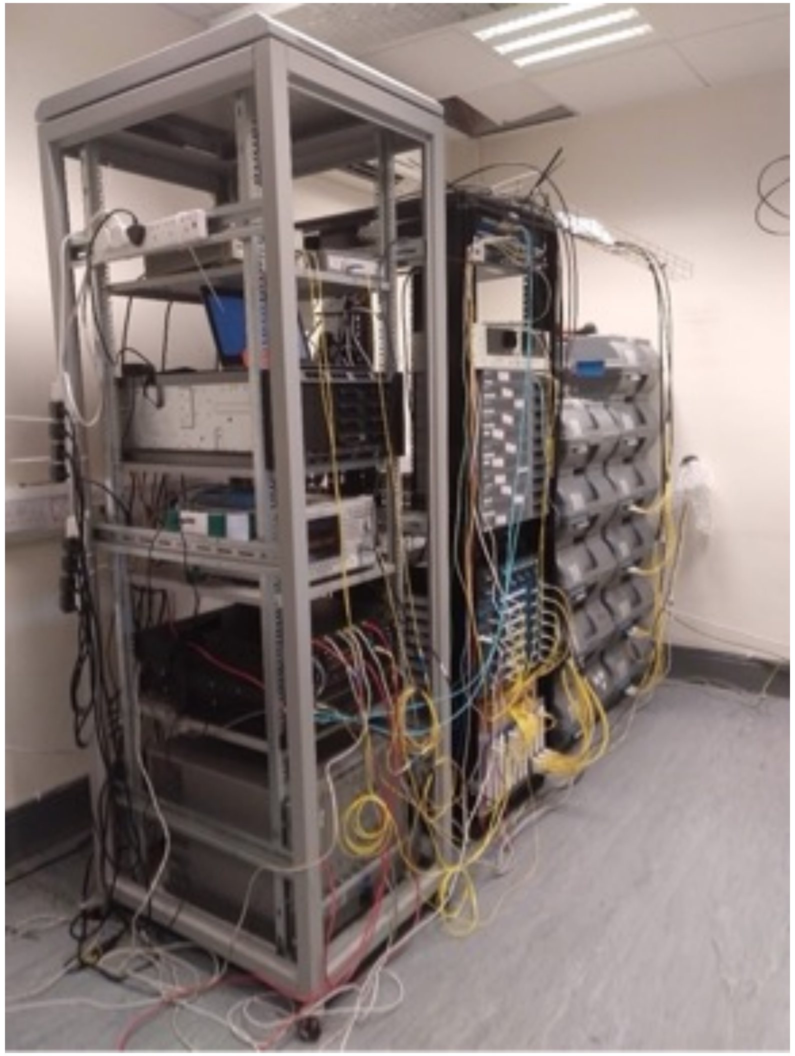
⇒ ***Connected City Infrastructure***

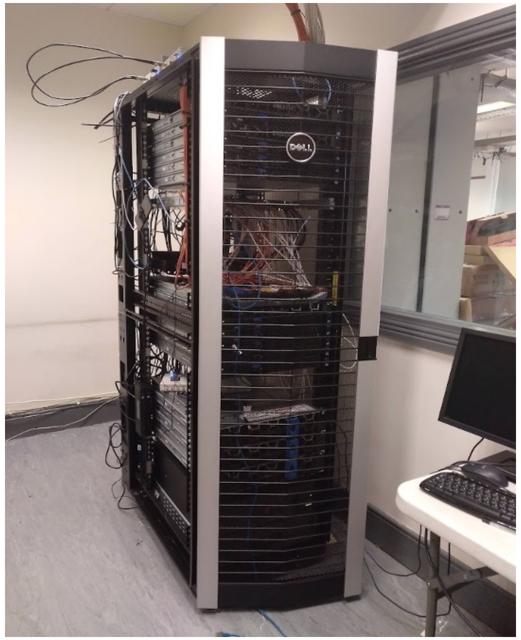


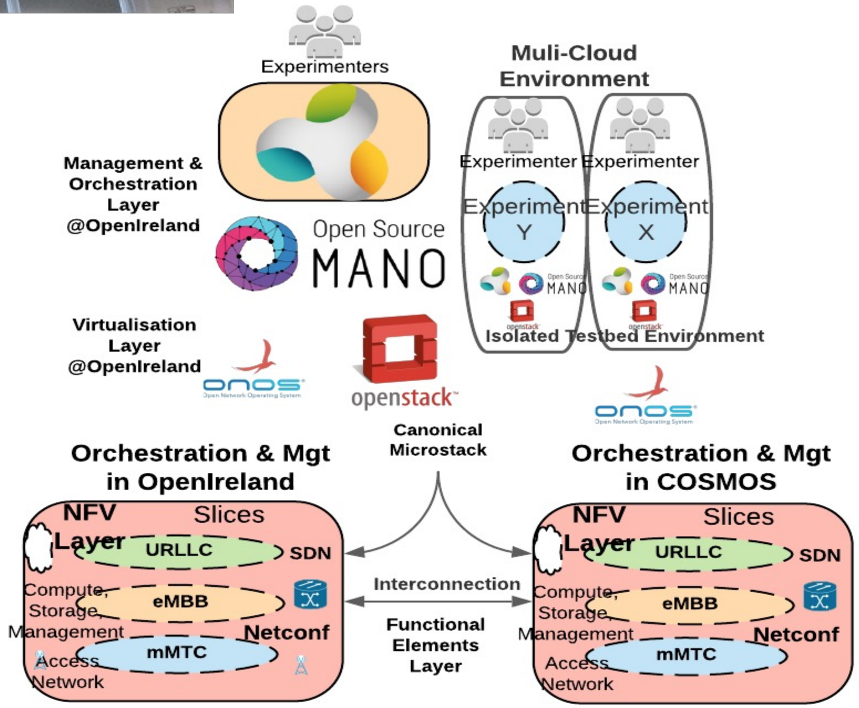
⇒ ***Quantum Internet***



The TCD lab: optical, wireless and computing

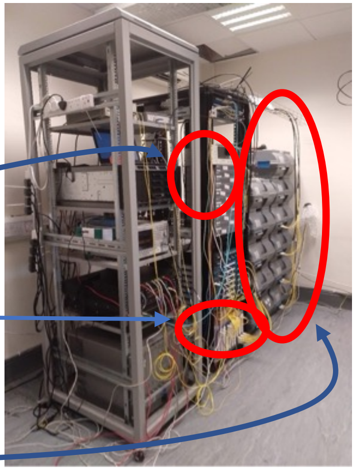




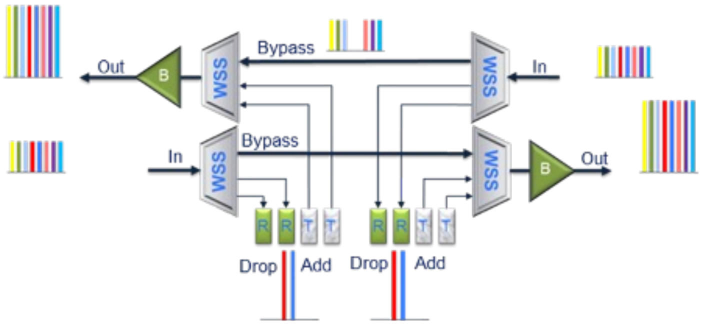


Optical devices

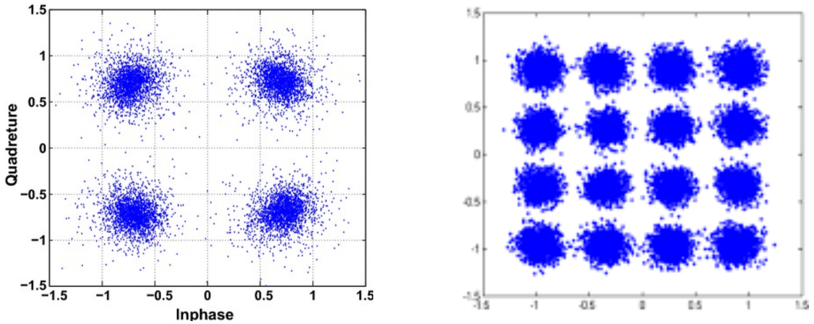
- Large count fibre switch: allows creating any physical fibre topology and interconnect
  - Connect any fibre to any other fibre, measure power
- 1,700 km fibre, power splitters, etc.
- 11 x Inline optical amplifiers



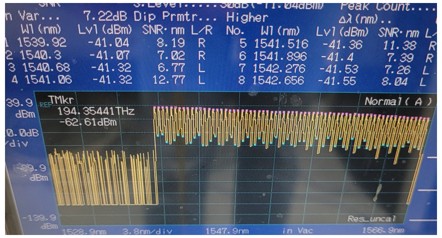
- 11 x ROADMs (lumentum graybox): allow switching of optical wavelength channels across
  - Actions: add/drop channel (set filters), set amplification params, variable attenuation, measure power at wavelengths and ports



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



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

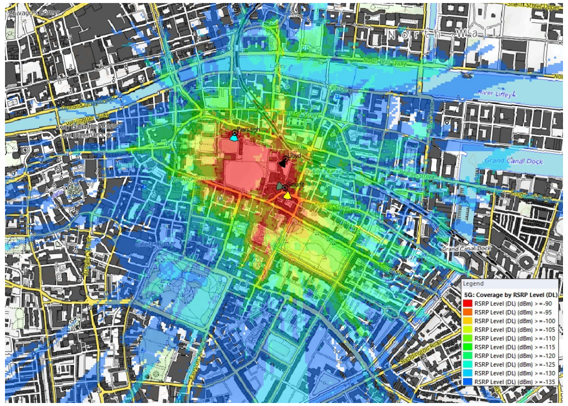


Wireless devices

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

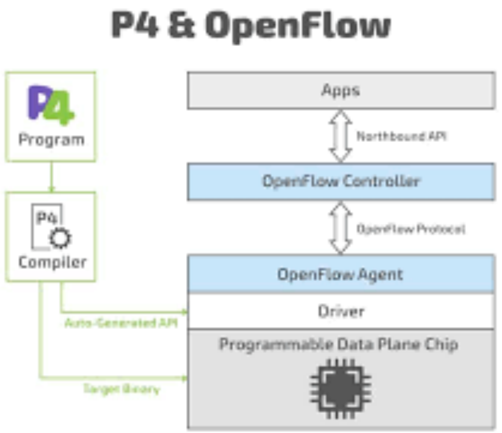
- Commercial O-RAN based on 7.2 split
  - 6 x Indoor/Outdoor units – 100MHz, 4x4 MIMO,

  37 dBm per port* (4GHz band restricted to 30 dBm total EIRP)
  - Accelleran (DU) – CU and RIC, but waiting for open source OpenRAN



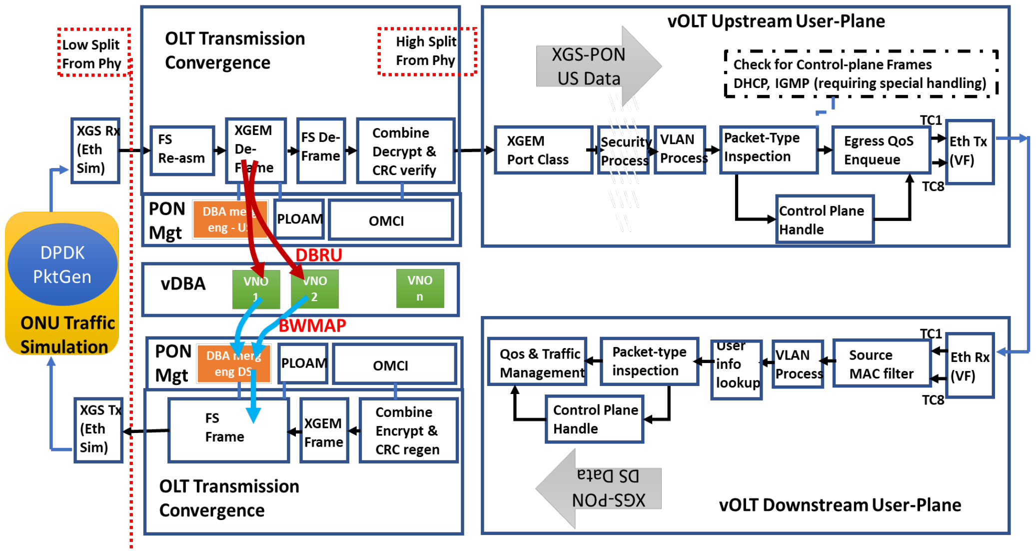
L2 and above infrastructure

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



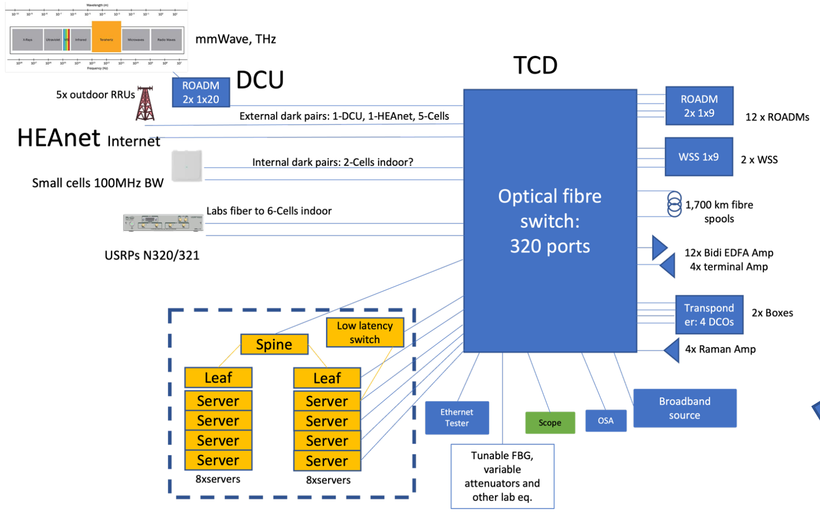
- Switches:
  - P4-enabled SDN switch (programmable data plane)
  - SDN enabled Low latency L2 switch
  - Management switches

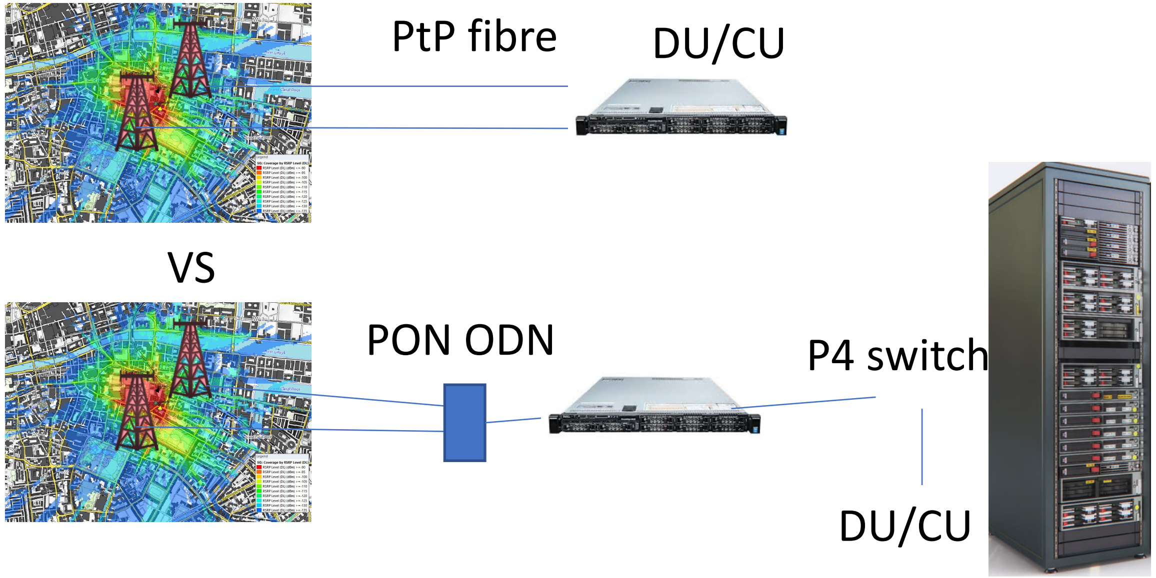
- Virtual PON:
  - Full virtualized Passive Optical Network
  - Standard compliant XGS (10G symmetric) PON
  - Additional TCD IP of virtual DBA (scheduler virtualization)



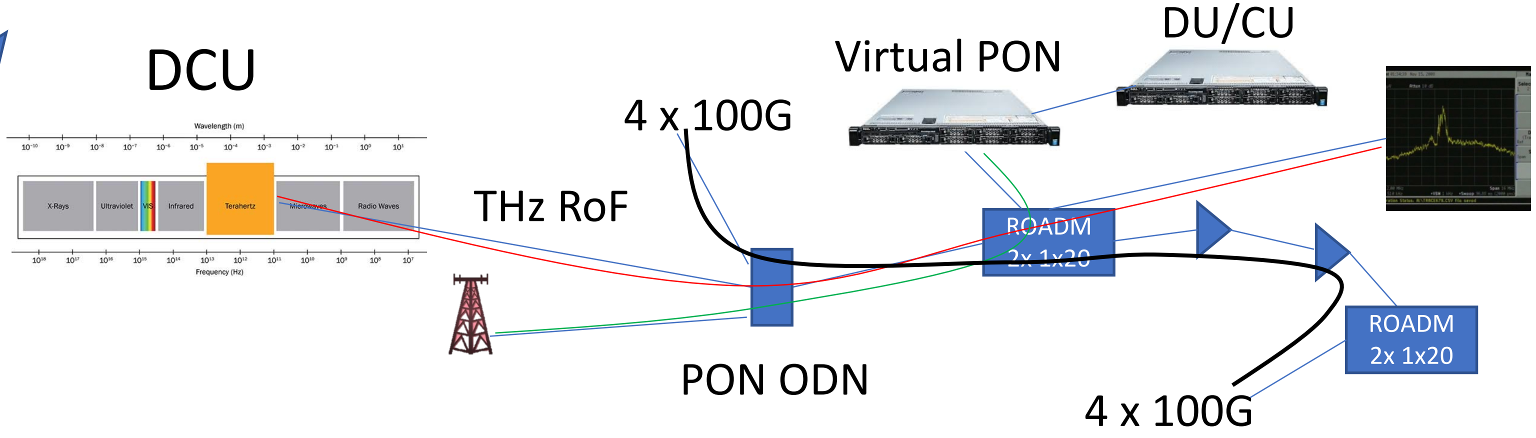
The power of topological reconfiguration

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



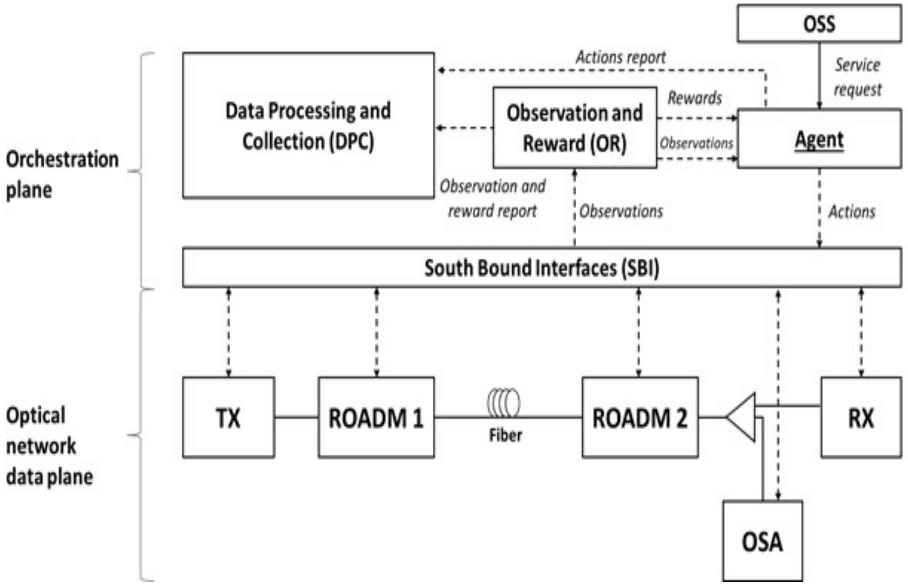


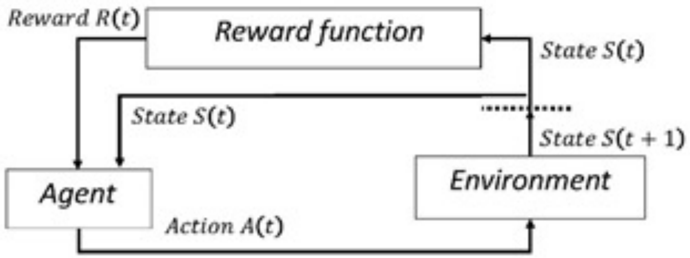
- Use case 2: Examine coexistence of different transmission formats analogue, digital RoF for support of 6G dense mmWave, THz



Sample use case: Building a QoT estimation algorithm

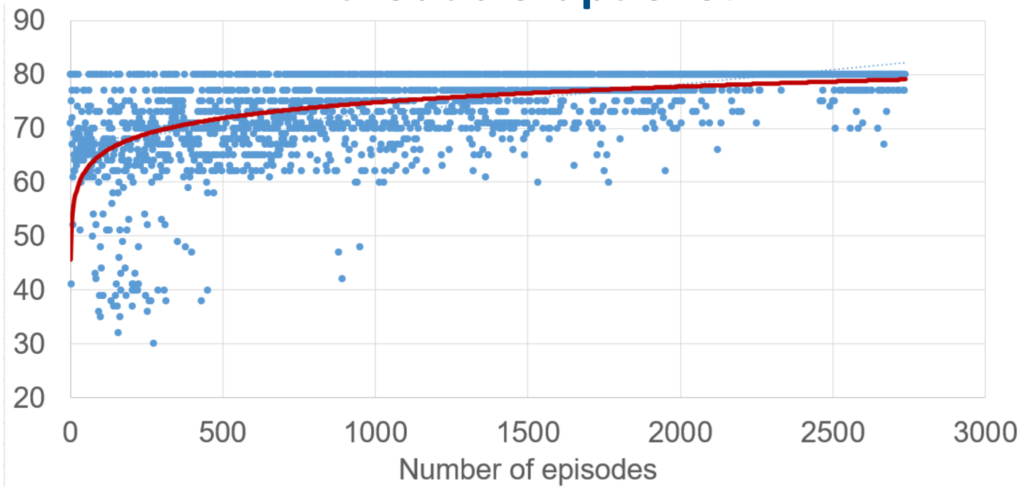
Control plane algorithm development and test based on simulation:
- Online learning through agent that loads the optical spectrum with optical channel and measures OSRN variation
- Through multiple iterations the agent improves strategy for channel selection





Work carried out by Politecnico di Milano optical group

How many channels are allocated without disruptions?

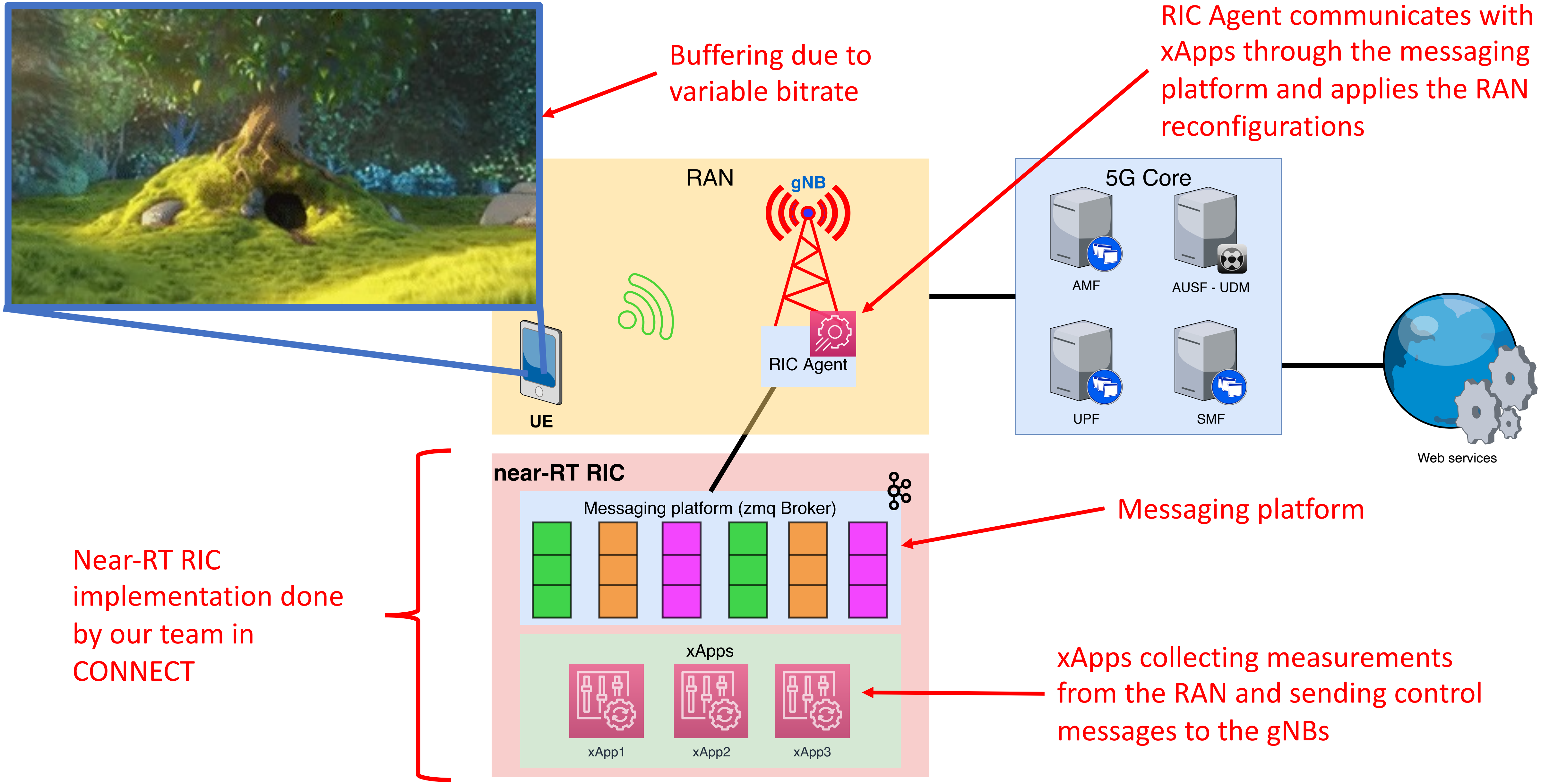


Use of simulated data plane

ORAN and RAN Intelligent Controller: video streaming use case

Buffering due to variable bitrate

RIC Agent communicates with the xApps through the messaging platform and applies the RAN reconfigurations

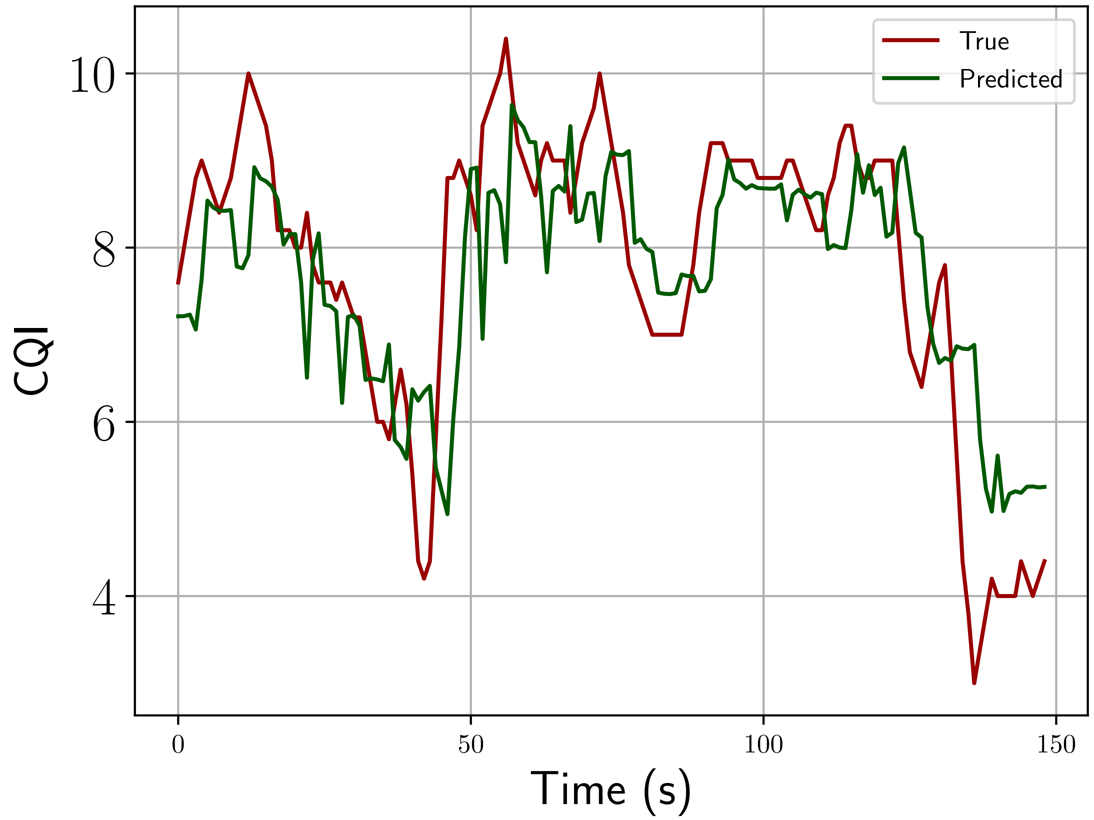


Messaging platform

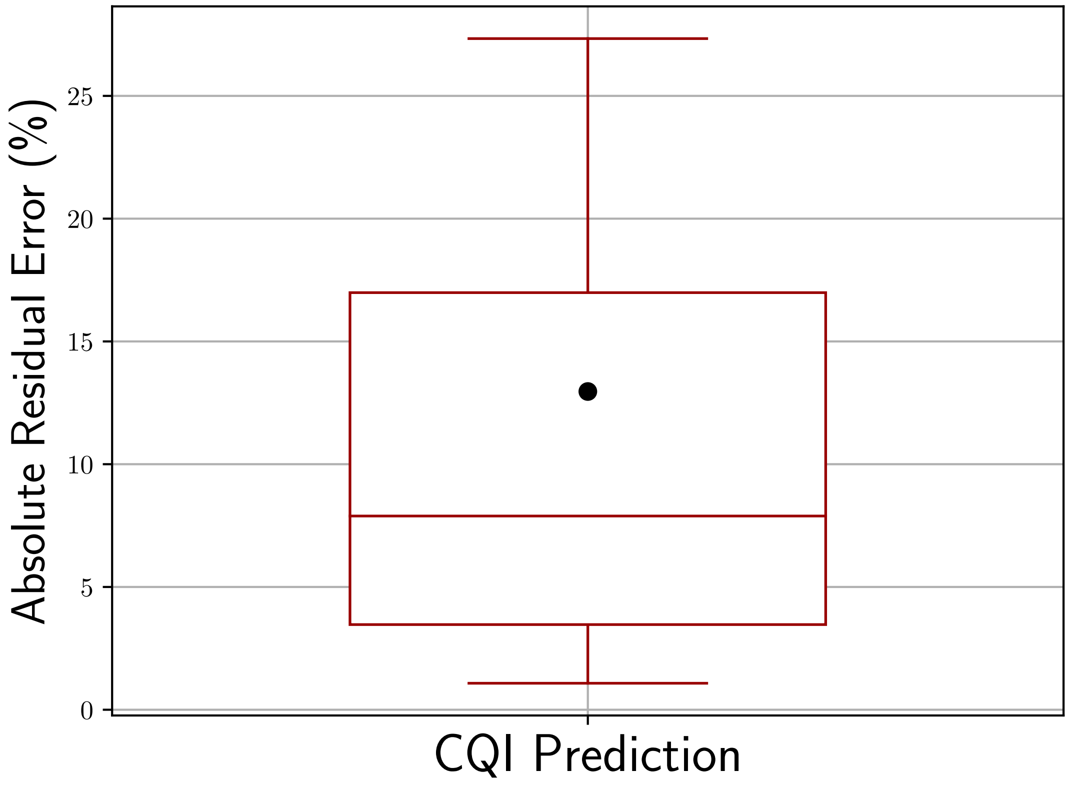
Near-RT RIC implementation done by our team in CONNECT

xApps collecting measurements from the RAN and sending control messages to the gNBs

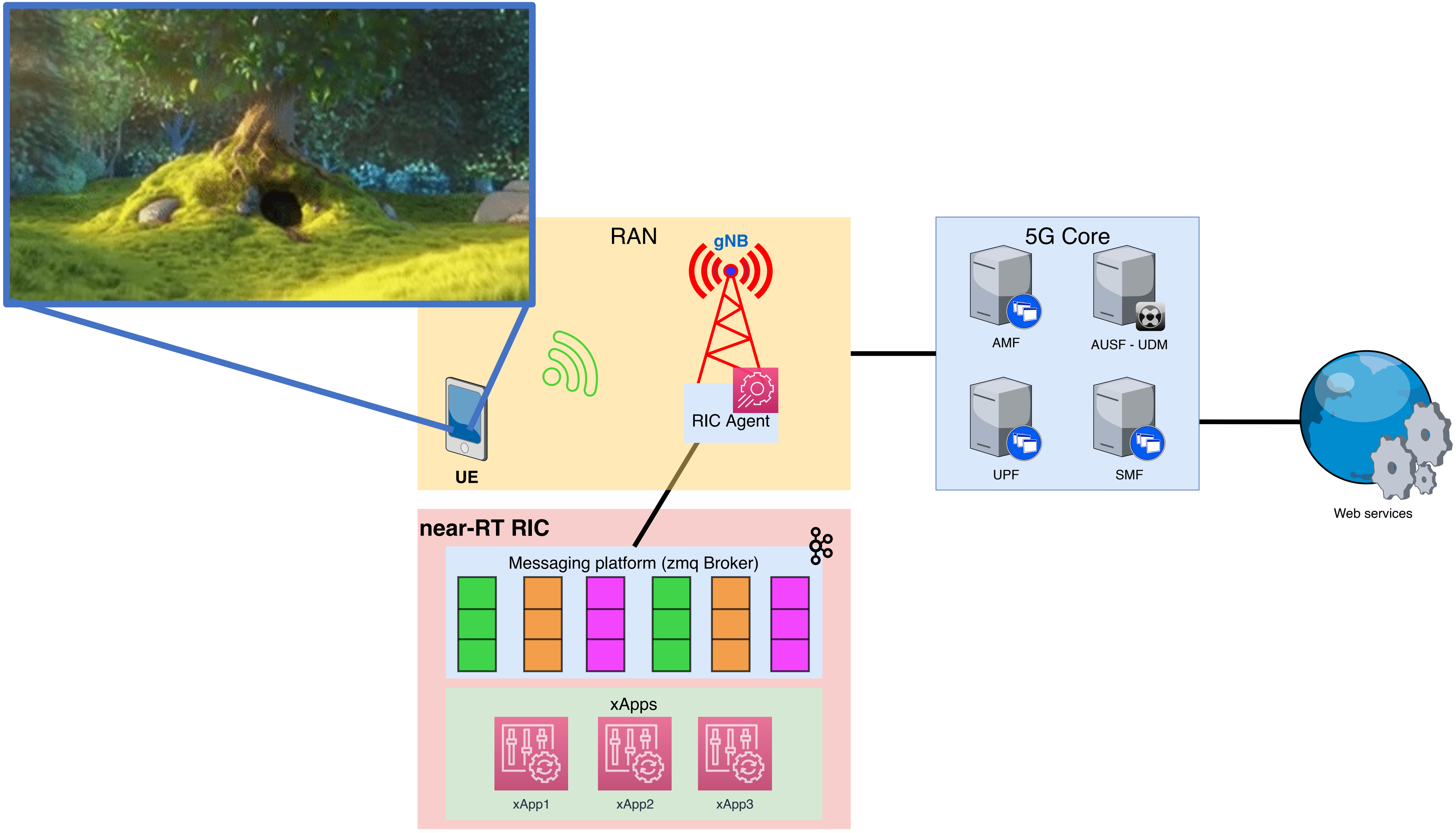
Preliminary results



Difference between the true CQI values measured in the network and the values predicted by the xApp (LSTM model).

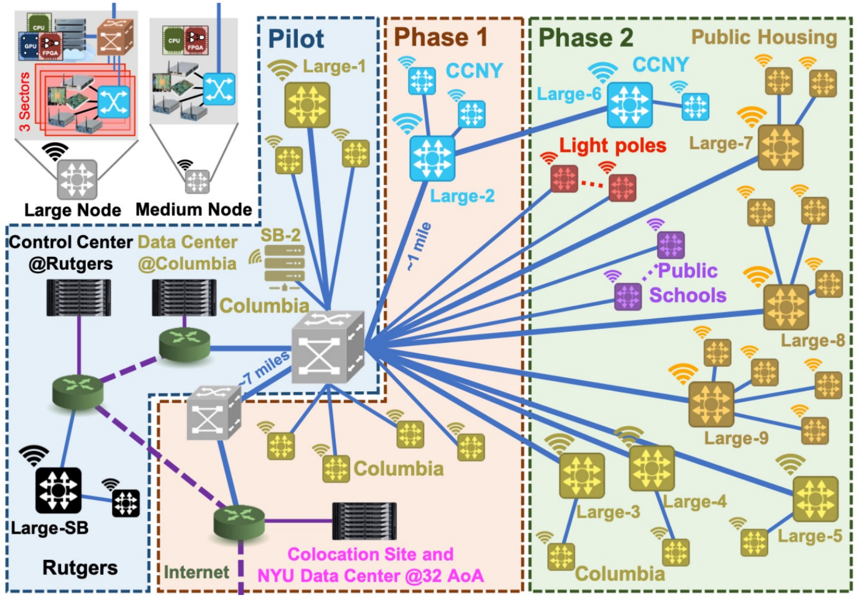


In 50% of the cases the error is below 8%, in 90% of the cases the error is below 26%.

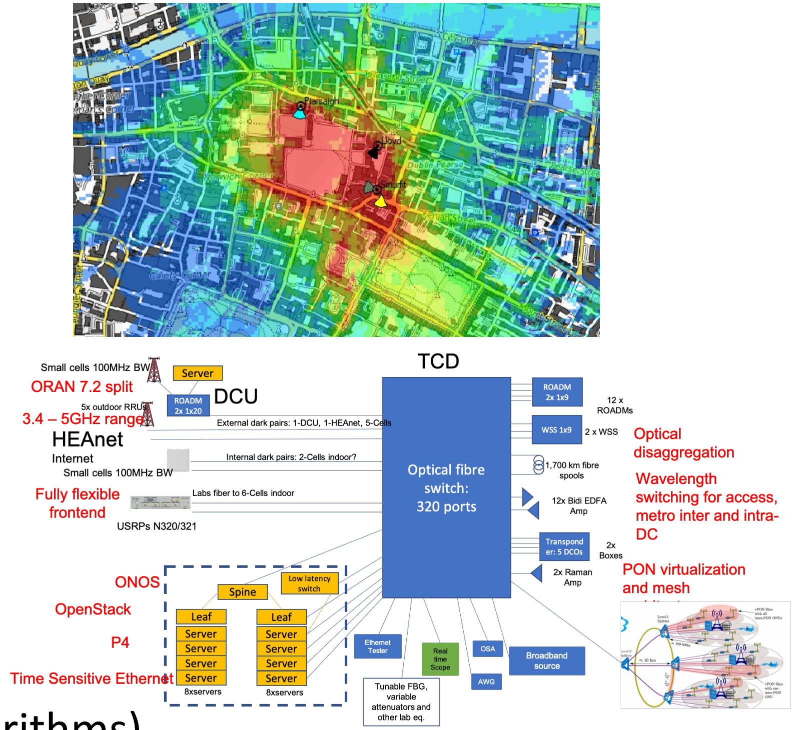

RAN
gNB
RIC Agent
UE
5G Core
AMF
AUSF - UDM
UPF
SMF
Web services
near-RT RIC
Messaging platform (zmq Broker)
xApps
xApp1
xApp2
xApp3

Digital twin for optical communication

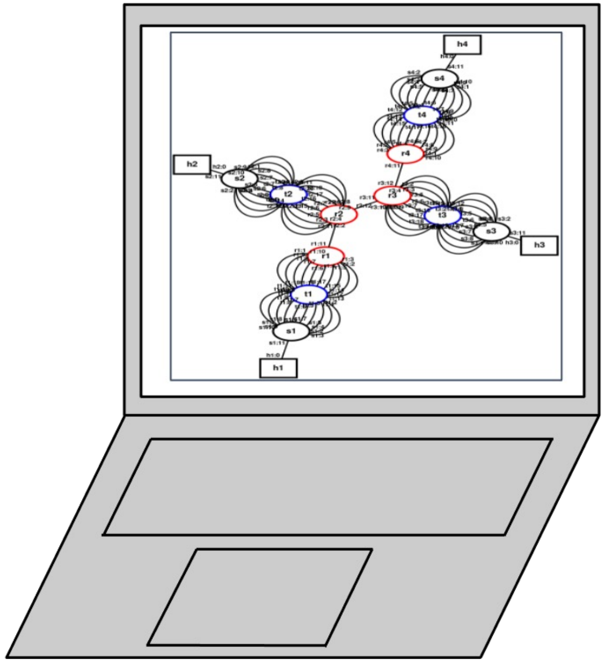
COSMOS



OpenIreland



Mininet-Optical



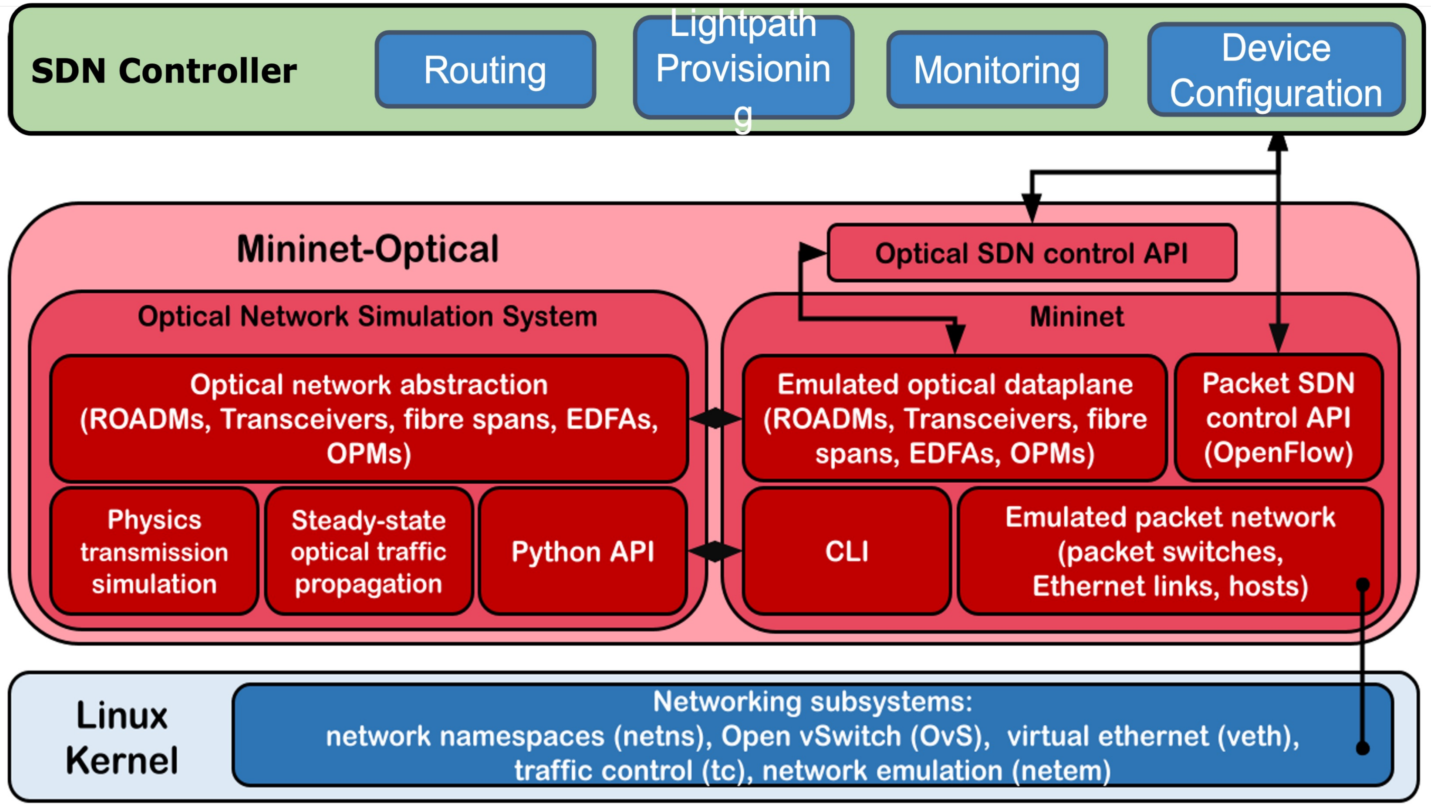
<u>Network infrastructure experimentation for</u>:

- Data collection (especially training of ML algorithms)
- Compatibility test with hardware interfaces
- Understand constraints (features, timing) from hardware devices
- Ultimate test on operability

<u>Network emulation for</u>:

- Fast and ubiquitous experiment setup and testing
- Testing and debugging of conceptual ideas
- Scalability to thousands of nodes
- Accessible to all

Experimentation through open source software: Mininet-Optical



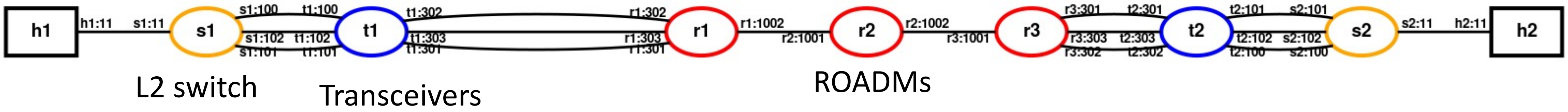
Node types:

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

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


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

Example of QoT use case



Testbed control plane vs Digital twin control plane

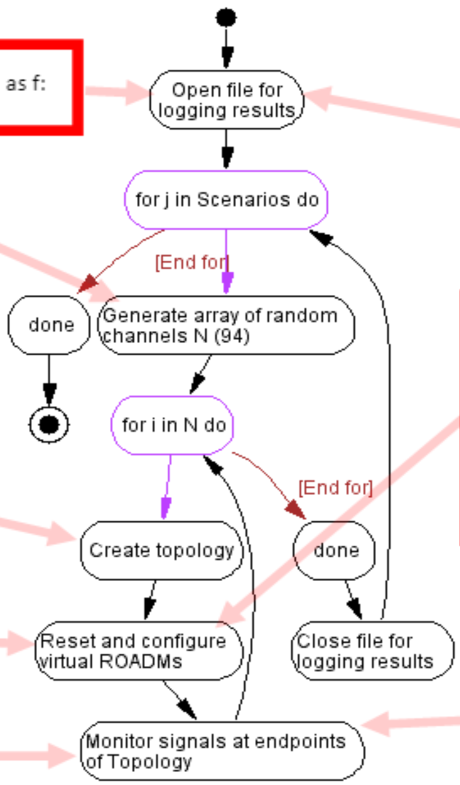
```
with open('data_collection/sample_channels_4.txt', 'w') as f:
    f.write("%s\n" % channels)
```

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

Physical Topology
Configured already

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

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




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

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

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

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

Hybrid quantum/classical SDN controller

- Quantum computing will require the ability to distribute quantum information across multiple locations:
  - Scaling quantum computing: increase the power of quantum computing through distributed quantum computing
  - Ubiquitous access to quantum resources: end user access to quantum state information from centralized quantum computing nodes
  - Secure communication: operate Quantum Key Distribution seamlessly across any access node (fixed and mobile)

- Optical fibre can provide ubiquitous access, particularly through coexistence between quantum and classical channels
  - Issue is that extremely weak quantum signals are very easily impaired by much stronger classical communications signals (order of 100 dB difference in power)

- Project scope is to realize an emulation platform to enable study of quantum network control planes and facilitate coexistence between classical and quantum signals
  - Analyze signals and predict interference; provide suitable routing; cross-optimization of quantum and classical signal generation, detection and routing.

US-Ireland Project: Investigators

- Emulation of quantum & classical communication systems: Dan Kilper

- Classical and quantum control architectures: Marco Ruffini

- Simulating and emulating hybrid non-Markovian quantum systems in quantum networks (modeling quantum noise): Prineha Narang

QUEEN'S UNIVERSITY BELFAST

- Physical Layer Emulation of Quantum Applications: Mauro Paternostro

THE UNIVERSITY OF ARIZONA

- Emulation of quantum covert communications: Boulat Bash
- Emulation of photonic components: Bob Norwood

Mininet quantum

- We recently built an optical layer emulator to extend the Mininet tool to support control plane of optical layer transmission and switching
  - Extend the physical layer model of Mininet-Optical to include quantum transmission models and control architectures
  - Include quantum devices models (photon generators, photon transmission, quantum memories, other components for quantum optics)
  - Design and develop interfaces for the quantum devices