A World Leading SFI Research Centre

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

CONNECT
Centre for Future Networks

SDN control of optical networks: from network automation to quantum communications

NetSoft 2022, PVE-SDN workshop

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

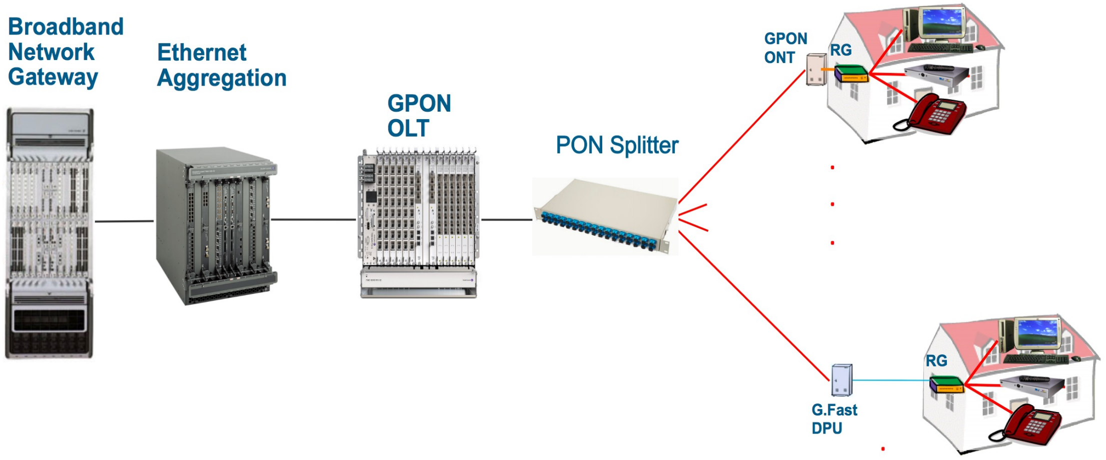
Trinity College Dublin
The University of Dublin
Ireland's European Structural and Investment Funds Programmes 2014-2020
Co-funded by the Irish Government and the European Union
European Union
European Regional Development Fund
Science Foundation Ireland
For what's next
IPIC
BRINGING PHOTONICS TO LIFE

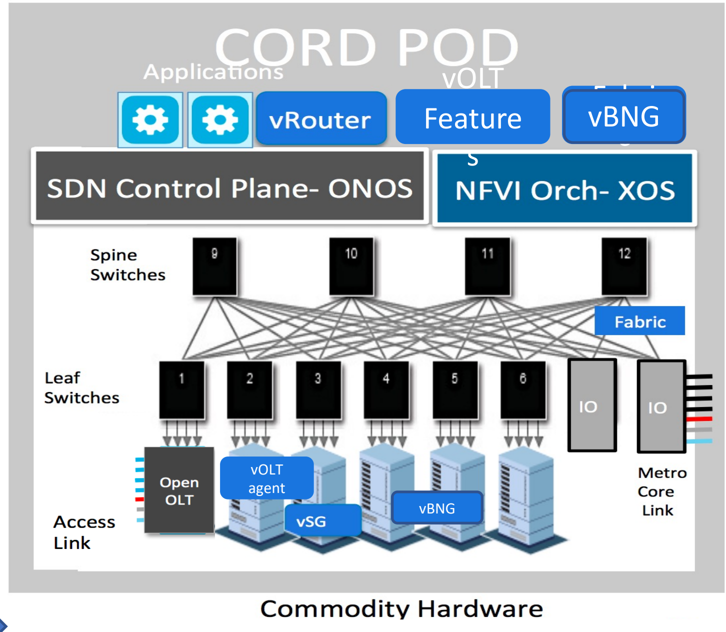
Summary of the talk

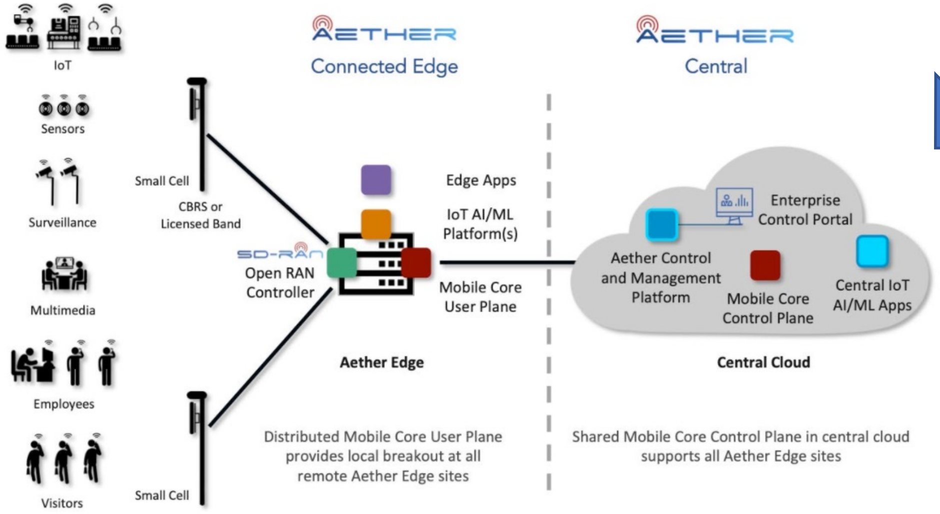
- Open & Diusagregated Networking trends: CORD, OpenRAN, Open optical
- Optical disaggregation
  - Pros, challenges and the GSNR margin issue
  - Use of Machine learning
- Digital twin
  - Early work: consortia, architectures and control plane
  - Our approach
    - Mininet-optical
    - City testbed (Open Ireland & COSMOS)
- Next generation: quantum

The Network Virtualisation and Open Networking Trend I

- Open networking in central office:





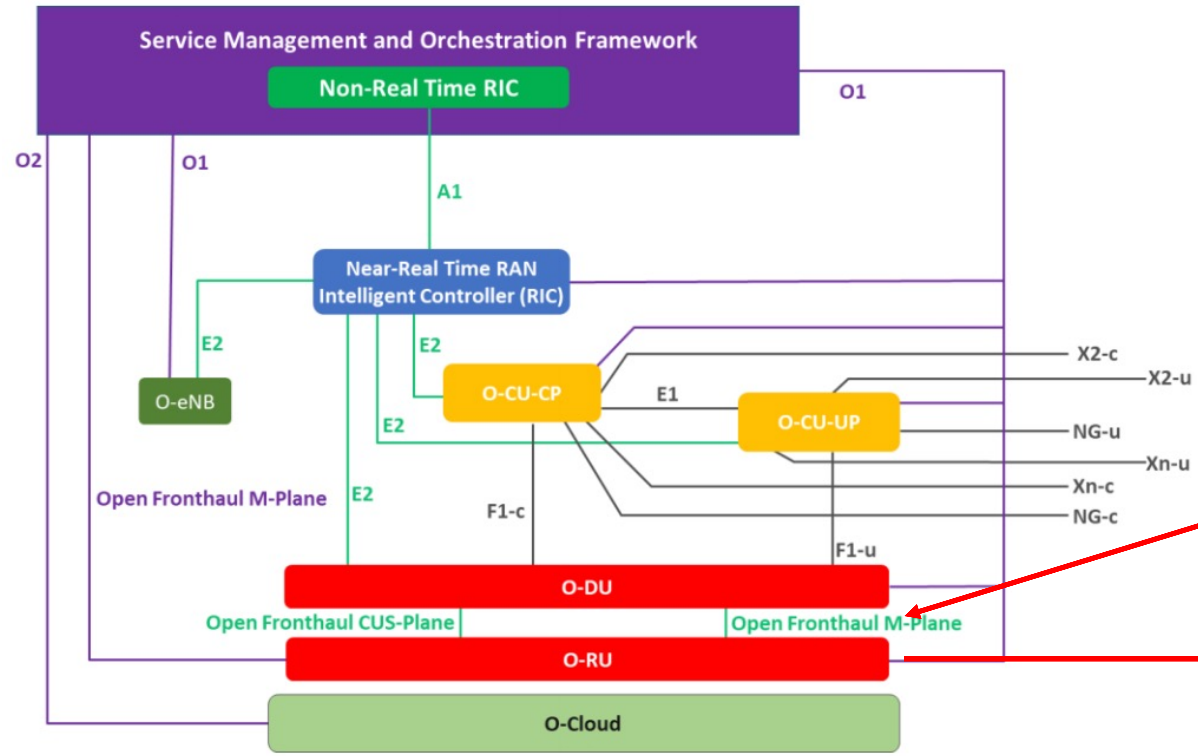


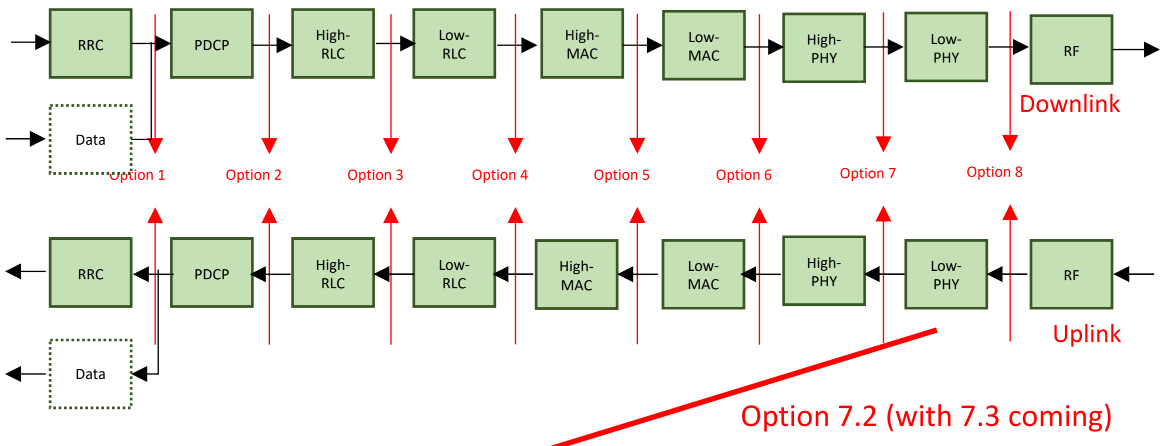
<u>This has now evolved into the SDN-Enabled Broadband (SEBA)</u>
<u>And more recently into a converged MEC/Cloud - AETHER</u>

The Network Virtualisation and Open Networking Trend II

- Open networking in mobile base stations

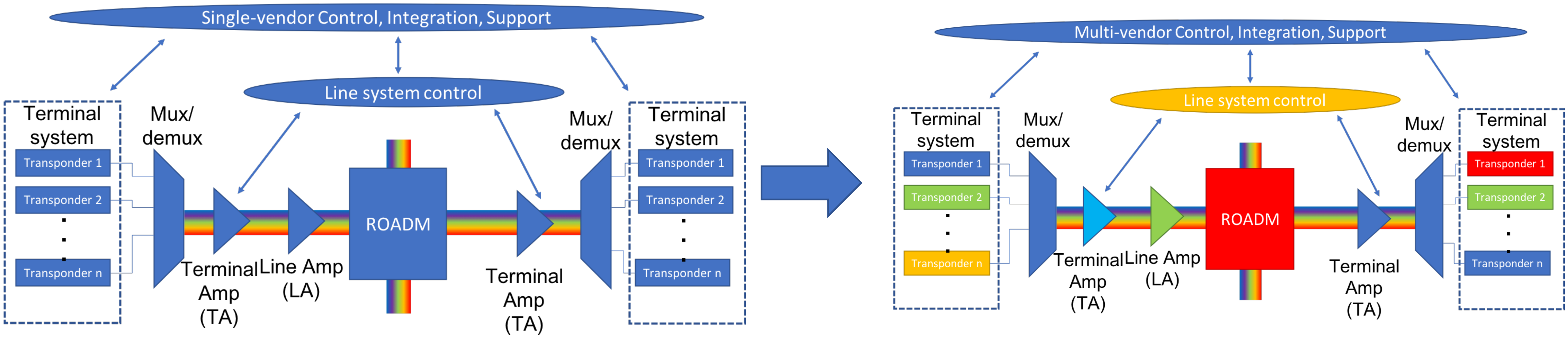
OpenRAN





Opening the optical layer

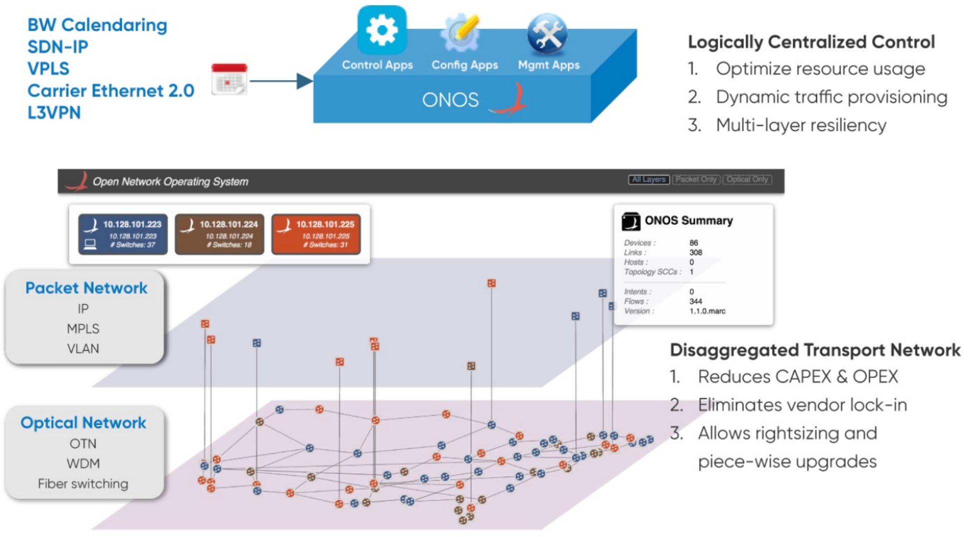
- This is a difficult one!
- Optical transmission is analogue, meaning that different devices have different behavior (unlike digital)
- Nonetheless now there are SDN-controlled ”whitebox” devices, like ROADMs, amplifiers and transponders..



Pros vs challenges

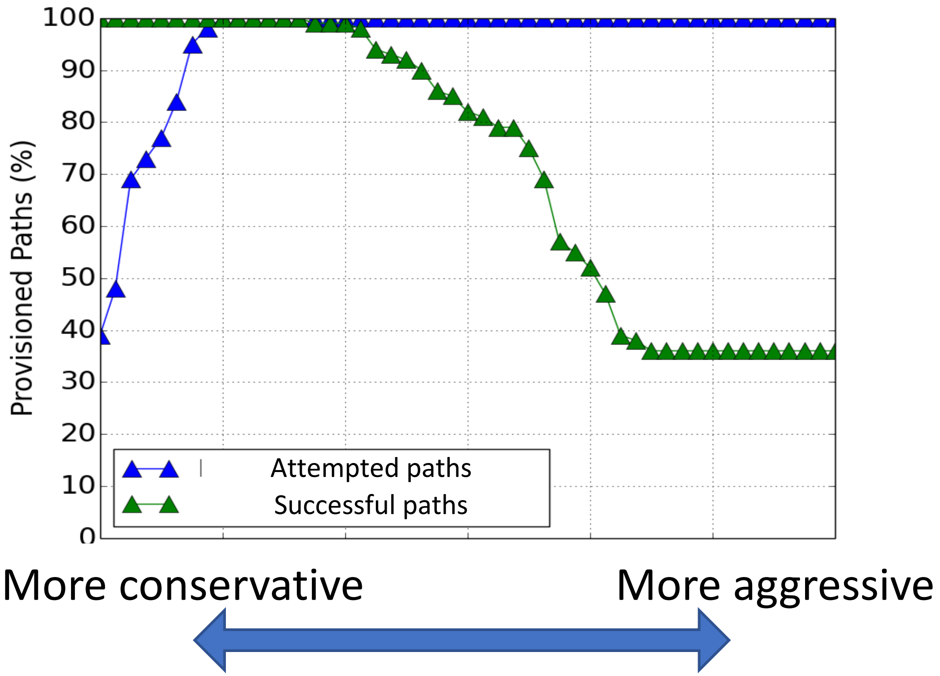
Pros:

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



Challenges:

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

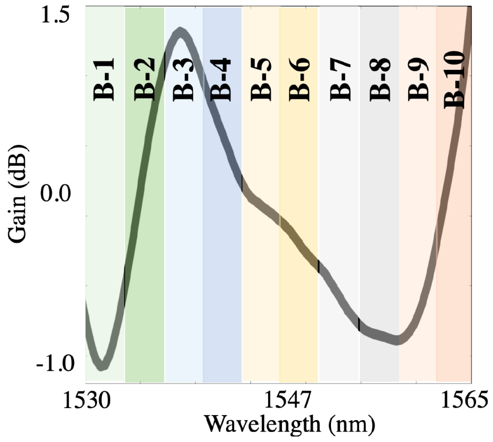


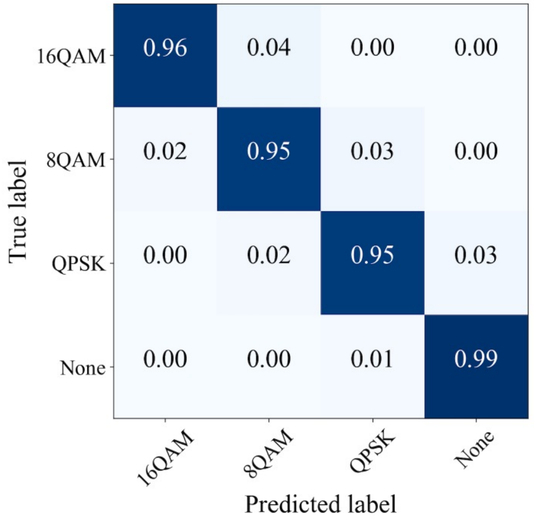
X axis: how conservative are the margins

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…

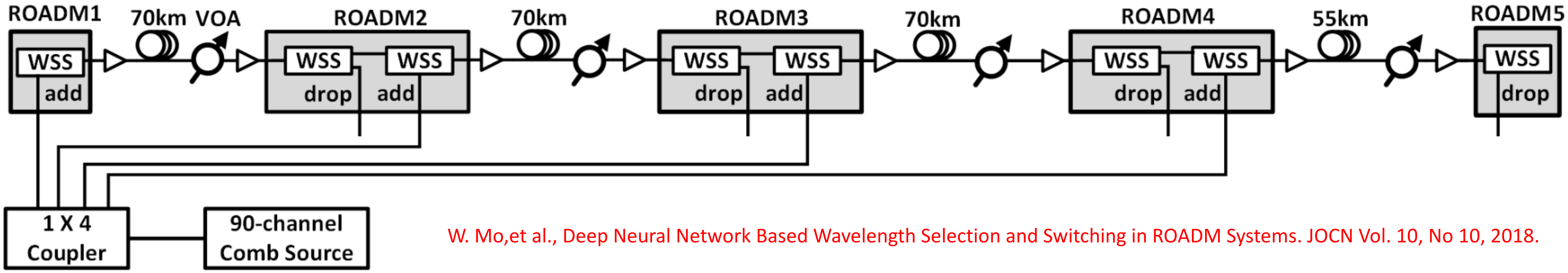
  ➔ Adding a wavelength channel can increase/decrease the power and OSNR of all other channel
- Quality of Transmission estimation is an important research area, and ML techniques have been used to provide such estimation
- Build multi-class SVM classifier to decide what modulation is possible (e.g., related 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.



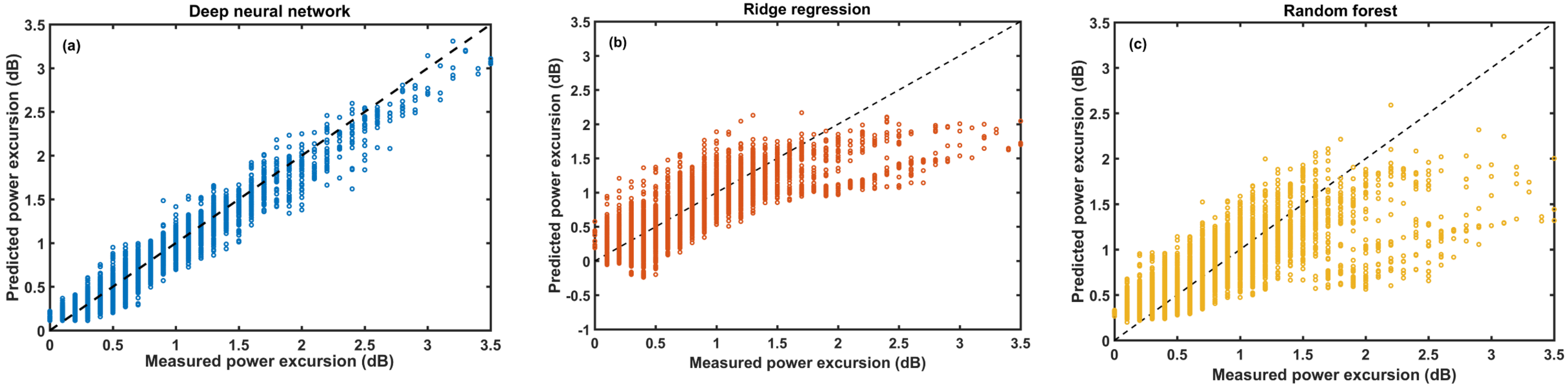


- F. Musumeci, C. Rottondi, A. Nag, I. Macaluso, D. Zibar, M. Ruffini and M. Tornatore. An Overview on Application of Machine Learning Techniques in Optical Networks. IEEE Surveys and Tutorials, Vol. 21 , No: 2, second quarter 2019
- S. Zhu, C. Gutterman, A. Diaz Montiel, J. Yu, M. Rufini, G. Zussman 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

Deep Learning Shown Effective for Predicting Optical Signal Powers



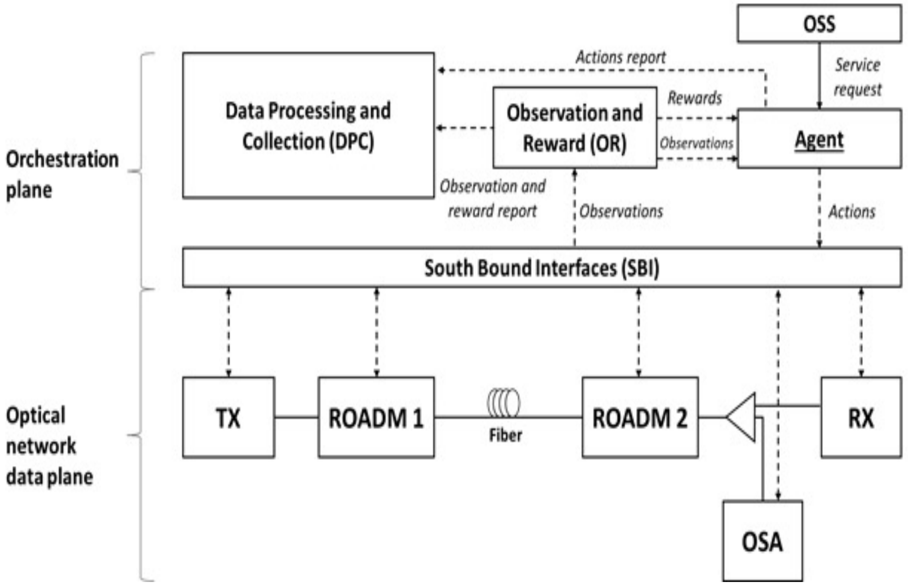
W. Mo,et al., Deep Neural Network Based Wavelength Selection and Switching in ROADM Systems. JOCN Vol. 10, No 10, 2018.



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

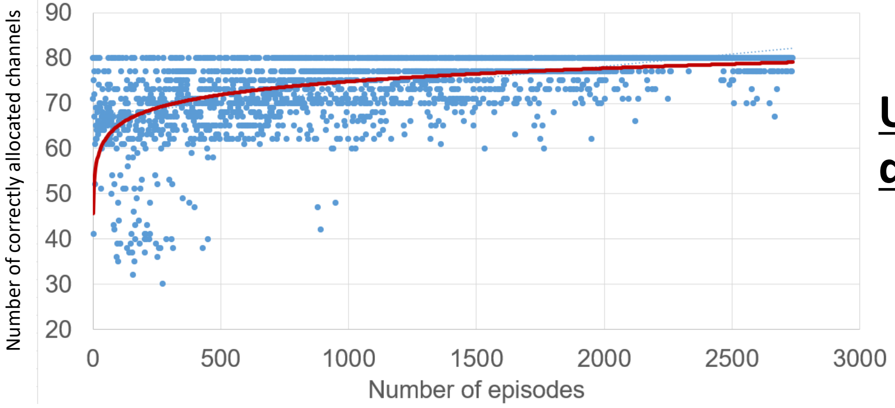
Sample use case: Building a QoT estimation algorithm

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

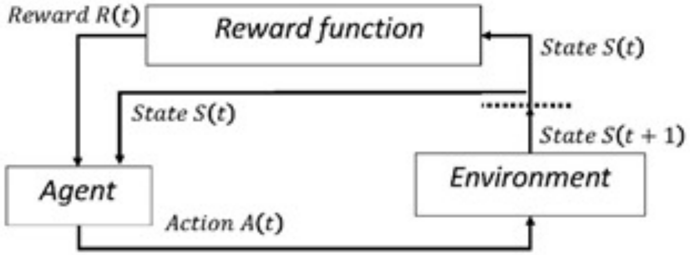


Work carried out with Politecnico di Milano optical group

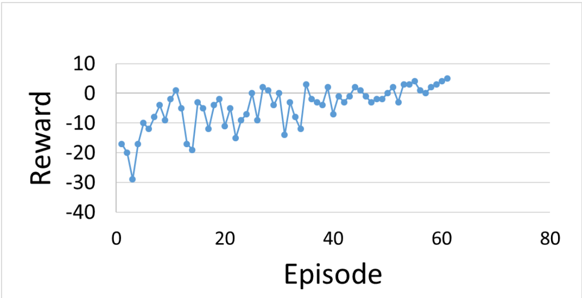
How many channels are allocated without disruptions?



Use of simulated data plane



ONIS OPERATION TIMINGS		
	OSA-based OSNR computation	ROADM-based OSNR computation
Algorithm initialization	3.15 s	
Single step channel opening + OSNR + reward	1.31 s	
Episode (full spectrum filled)	2400 s (40 mins)	182.2 s (3 mins)
OSNR computation	25.84 s	1.18 s



Has machine learning solved the problem?

- All of this helps, but it still a highly manual process of appropriate measurements, data collection, model building, model validation…

… and then a black box neural network could still provide unexpected outliers

Machine Learning is part of the solution, but still far from "Zero Touch" fully automated system

➔ Concept of digital twin

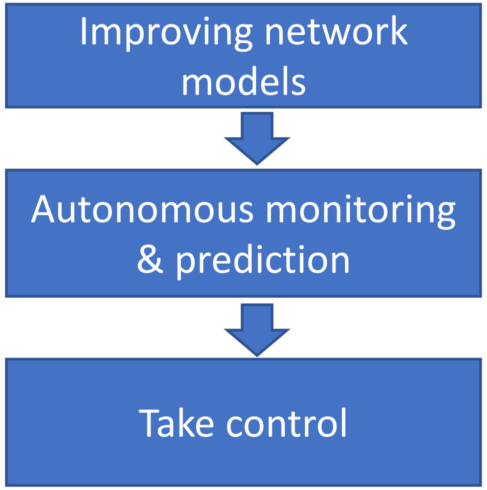
digital twin® CONSORTIUM

- Academia & Research
- Aerospace & Defense
- Agriculture, Food & Beverage
- Architecture, Engineering, Construction & Operations
- FinTech
- Healthcare & Life Sciences
- Manufacturing
- Mobility & Transportation
- Natural Resources
- Security & Trustworthiness
- Technology, Terminology & Taxonomy (3T)

www.digitaltwinconsortium.org

Next steps towards digital twinning

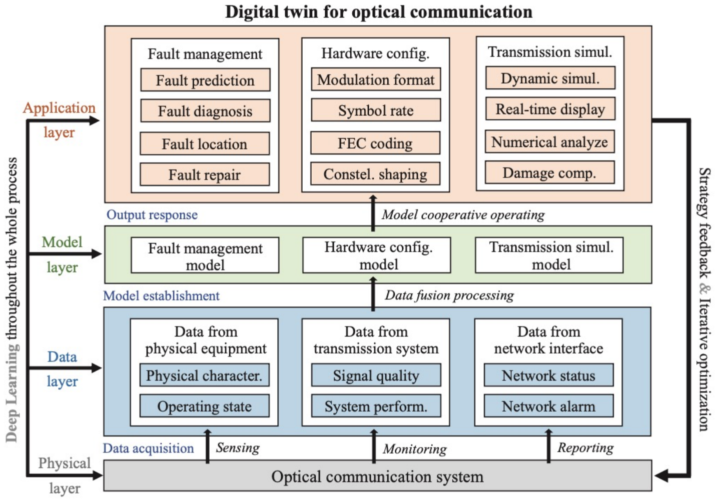
- What is a digital twin is a good topic of discussion:
- Emulation of specific aspects of its twin network (i.e., doesn't need to replicate all layers)
- Live interaction between emulated and real network:
  - Use real input/output data from network to improve models across an increasing number of states/scenarios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



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

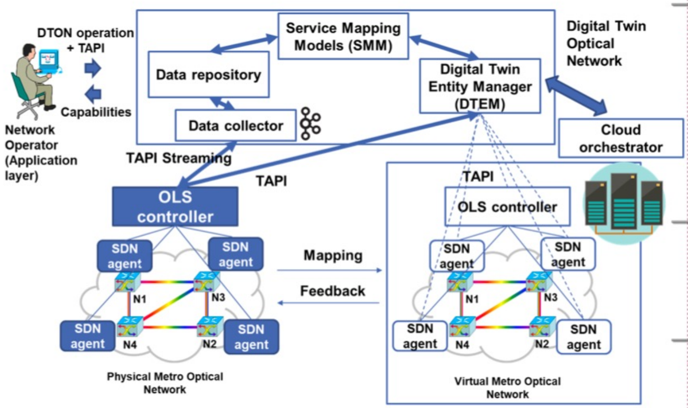
Early work

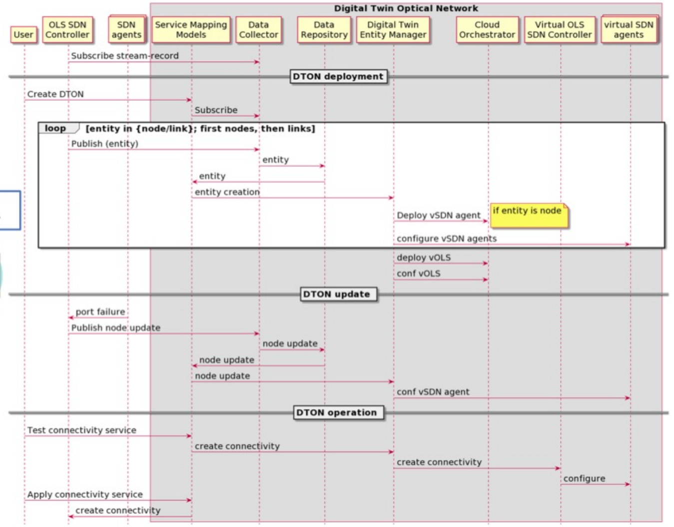
- Real digital twin contribution are very early stage
  - Some conceptual architectures



D. Wang *et al.*, "The Role of Digital Twin in Optical Communication: Fault Management, Hardware Configuration, and Transmission Simulation," in *IEEE Communications Magazine*, vol. 59, no. 1, pp. 133-139, January 2021, doi: 10.1109/MCOM.001.2000727.

  - Some early control plane work

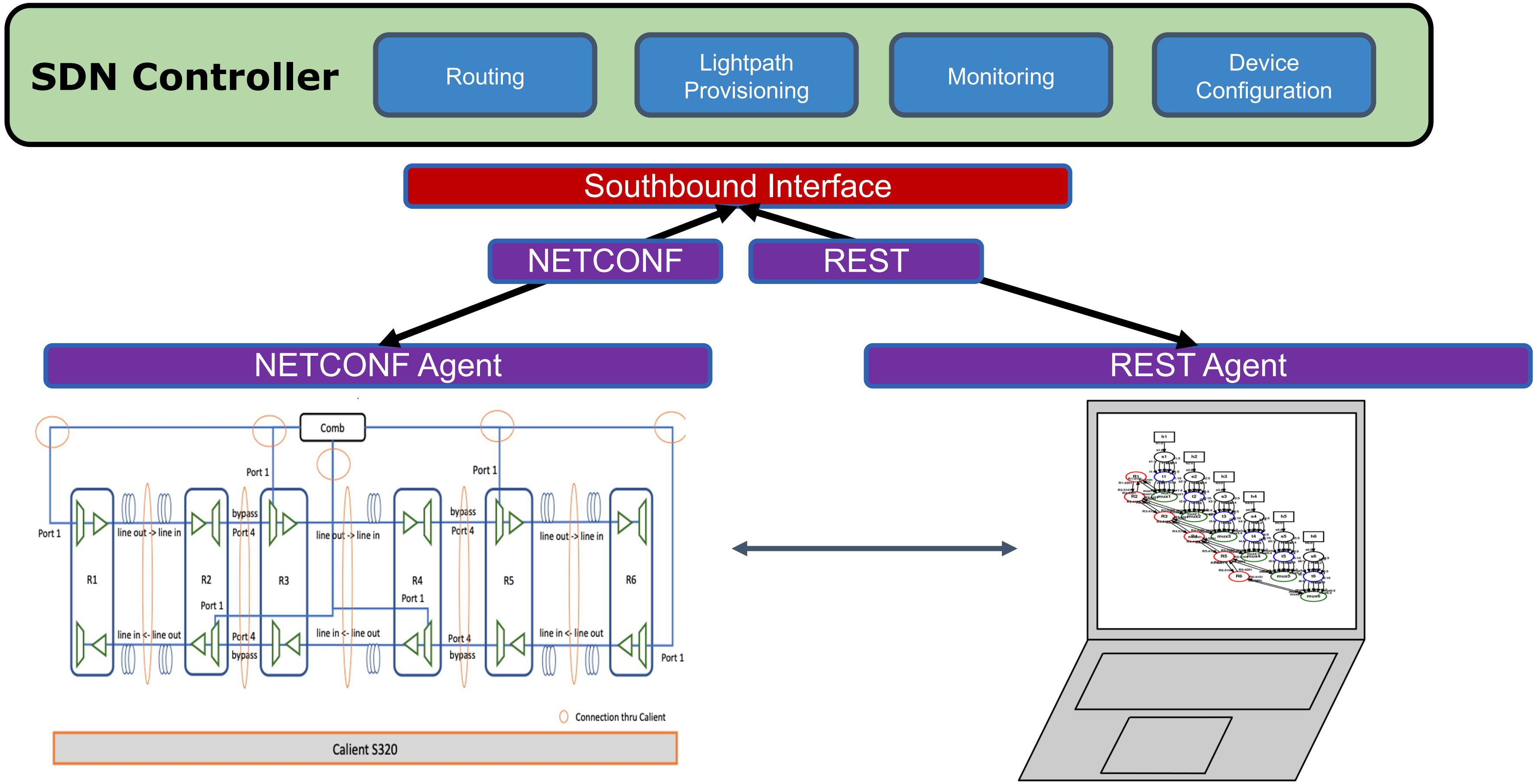




R. Vilalta *et al.*, "Architecture to Deploy and Operate a Digital Twin Optical Network," *2022 Optical Fiber Communications Conference and Exhibition (OFC)*, 2022, pp. 1-3.

- A reference physical network is essential
  - Aim is zero margin, not even for component ageing… the twin ages with the network

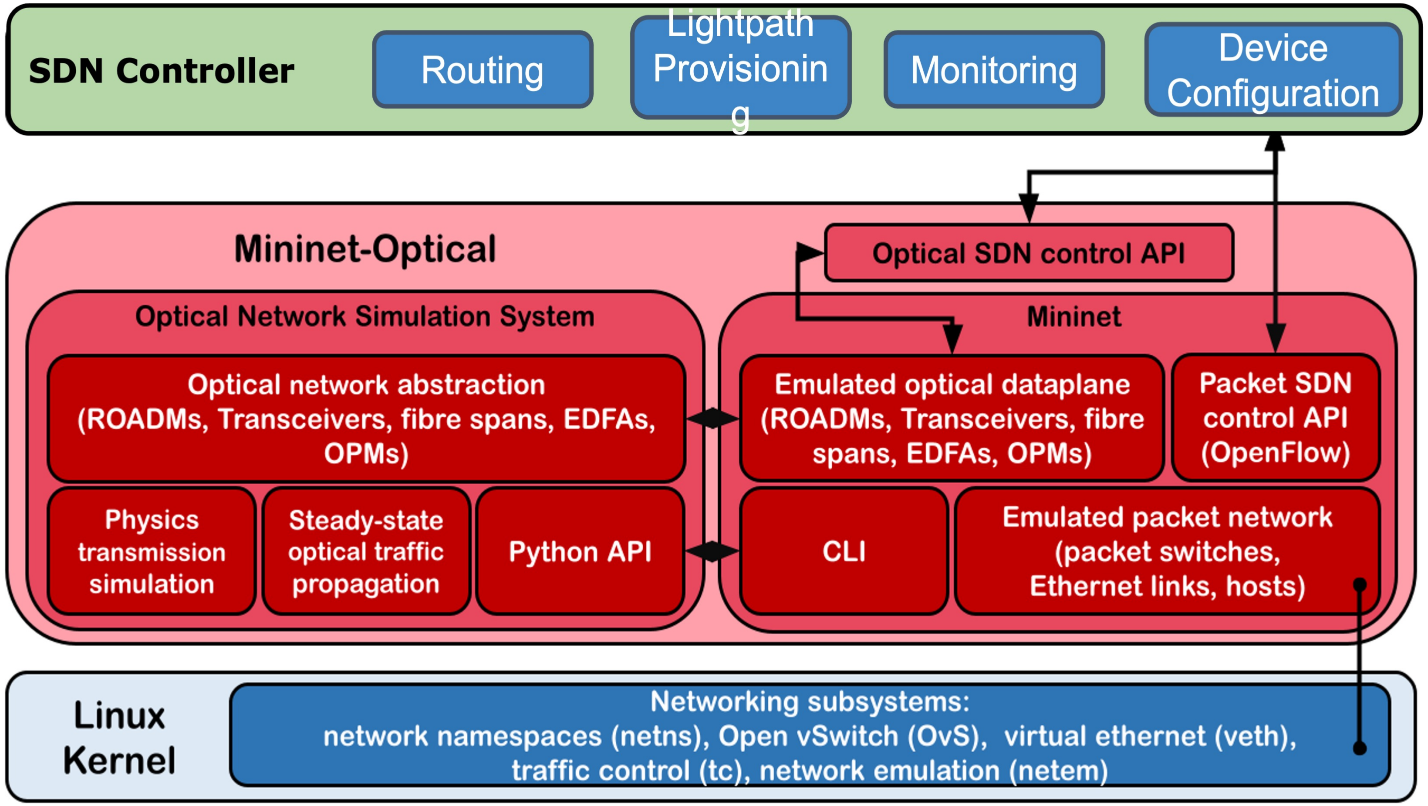
Our approach to the digital twin



Hardware network on testbed

Virtual network in Mininet-Optical

The emulation side: Mininet-Optical



Node types:

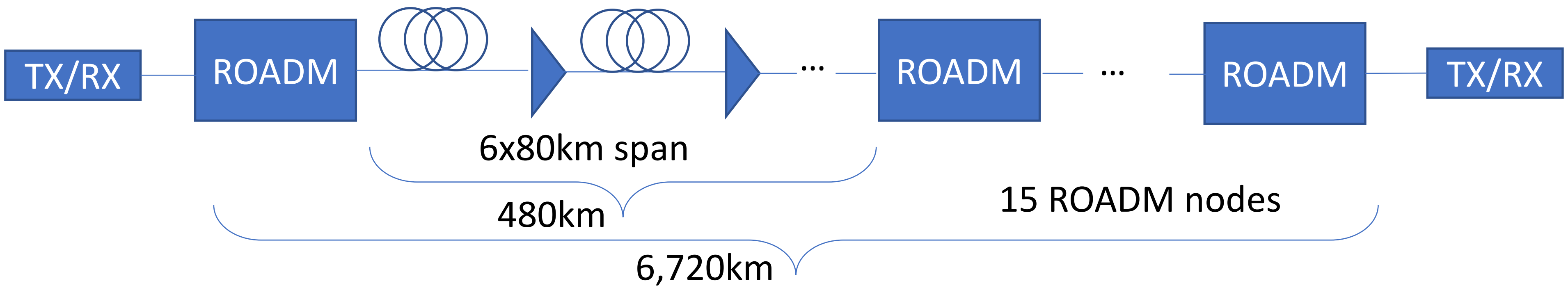
- Transponders: modulation, baud rate, power, wavelength, BER from gOSNR
- ROADMs: insertion loss, variable attenuation, wavelength routing, booster/preamp
- EDFA: linear gain, wavelength dependent gain, ASE, automatic gain control mode
- Fibre length: attenuation, dispersion, SRS, nonlinear impairments 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

Now open source: https://mininet-optical.org

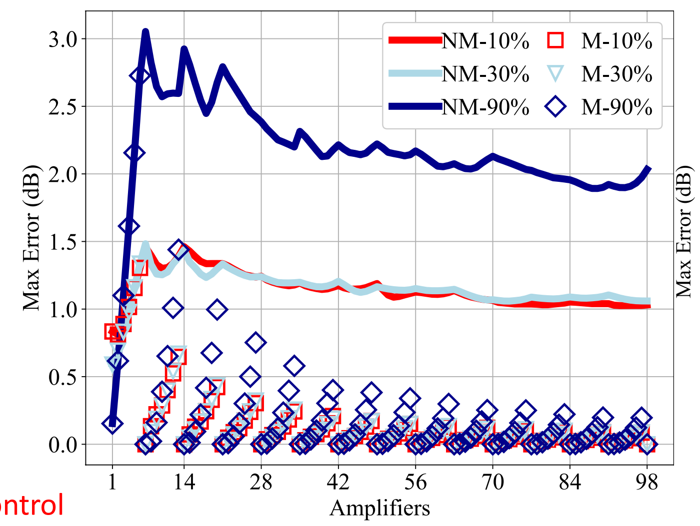
Example of operation: Use OPM to improve controller’s QoT estimation



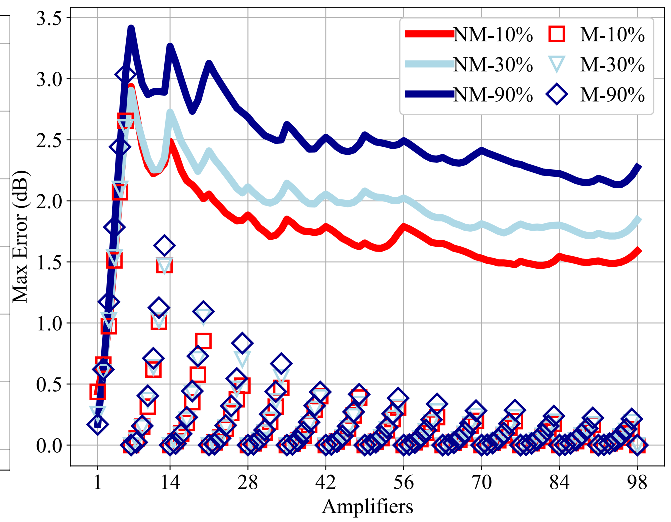
- Loading channels on a 90-wavelength transmission system.
- The <u>unknown EDFA wavelength dependent gain</u> causes errors on the QoT estimation algorithm.
- The controller can use OPM to correct the estimation error

- 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>

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.

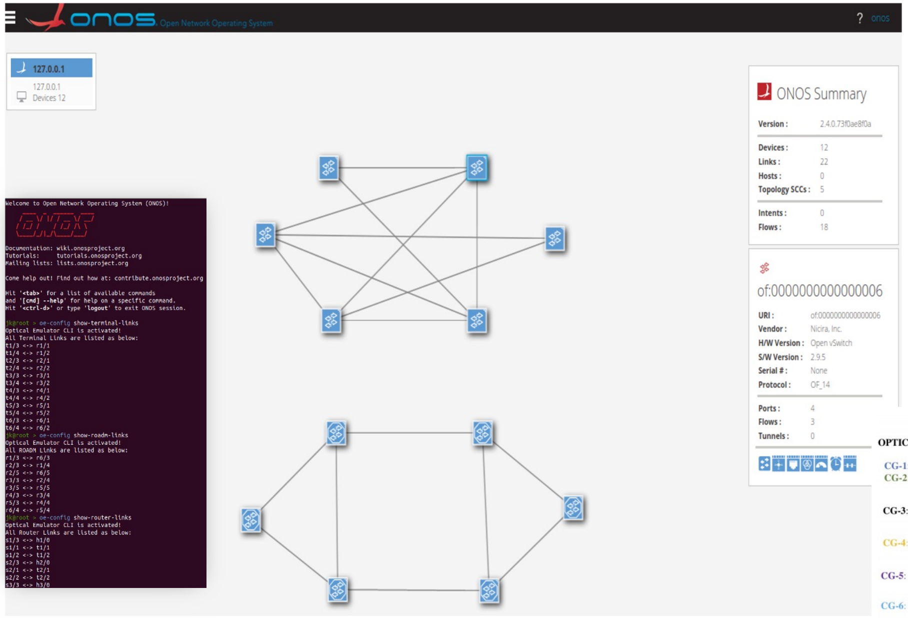


Sequential channel loading



Random channel loading

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

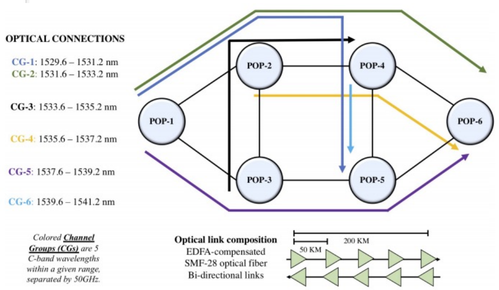
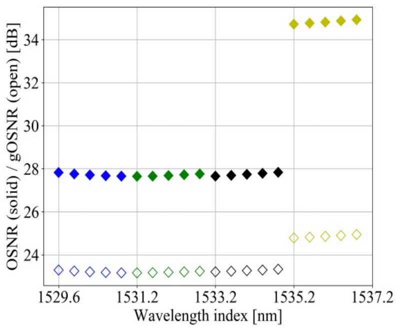


Fig. 3: Controller monitors OSNR (solid) and gOSNR (open) of all channels entering POP-4 (via POP-2) during the initial transmission



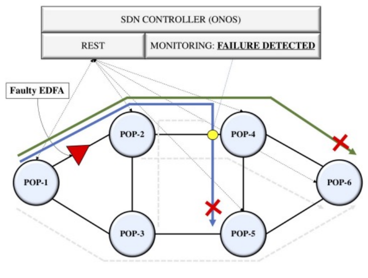
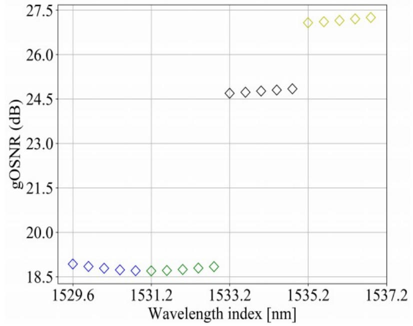


Fig. 4: Faulty EDFA degrades CG-1 and CG-2; controller observes low monitored gOSNR for signals entering POP-4 (via POP-2)



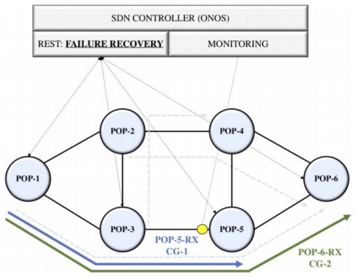
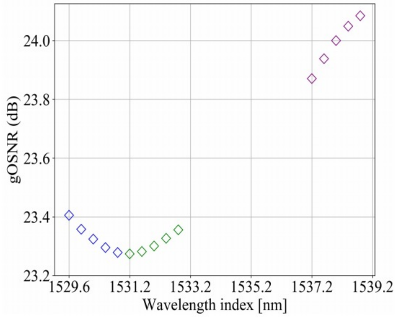


Fig. 5: Controller re-routes CG-1 and CG-2, resulting in high monitored gOSNR for signals entering POP-5 (via POP-3)



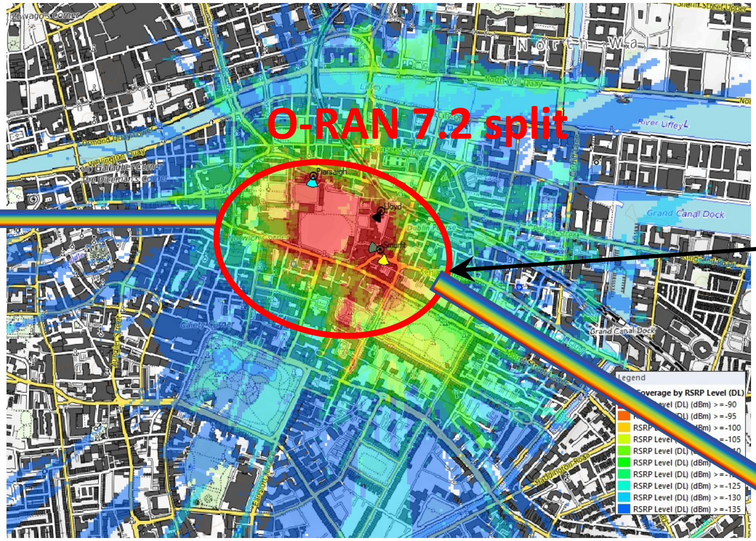
Bob Lantz, Alan A. Díaz-Montiel, Jiakai Yu, Christian Rios, Marco Ruffini, Dan Kilper. Demonstration of Software-Defined Packet-Optical Network Emulation with Mininet-Optical and ONOS. OFC 2020.

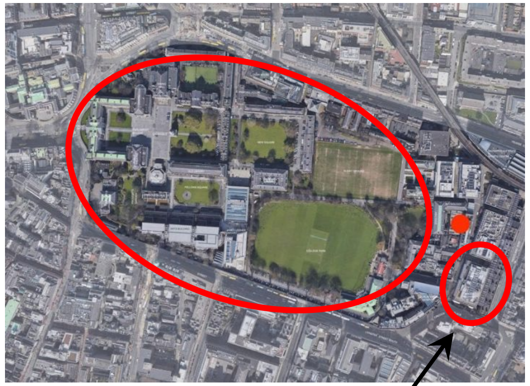
Open Ireland: Ireland's Open Networking Testbed

www.openireland.eu

Based in Trinity College campus

Optical transmission, analog RoF, mmWave-THz





O-RAN

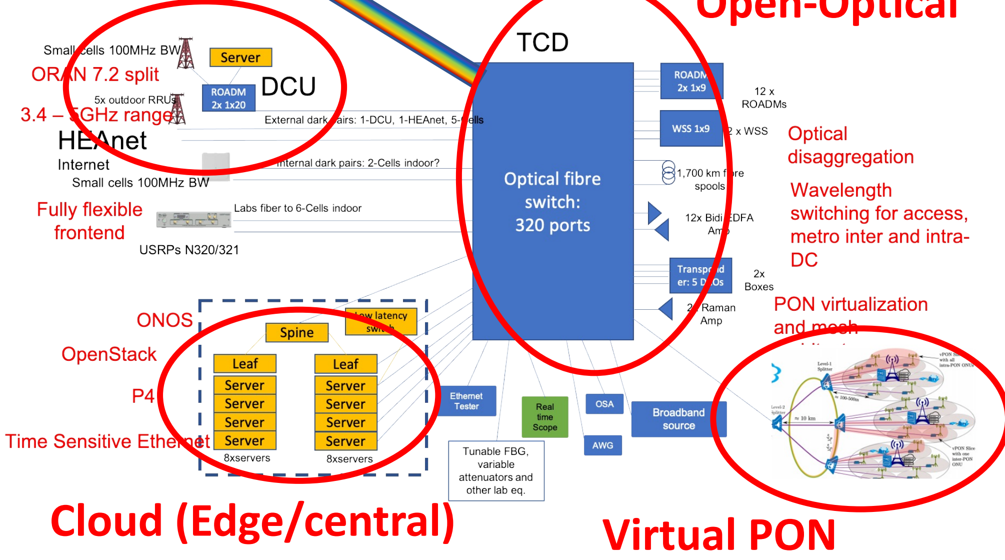
CONNECT research centre building

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

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

SDR

Open-Optical

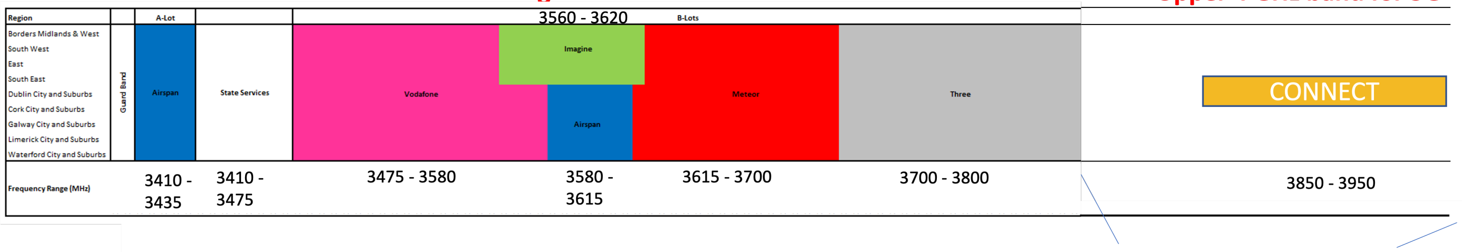


Cloud (Edge/central)

Virtual PON

Existing 3.6 GHz for 5G

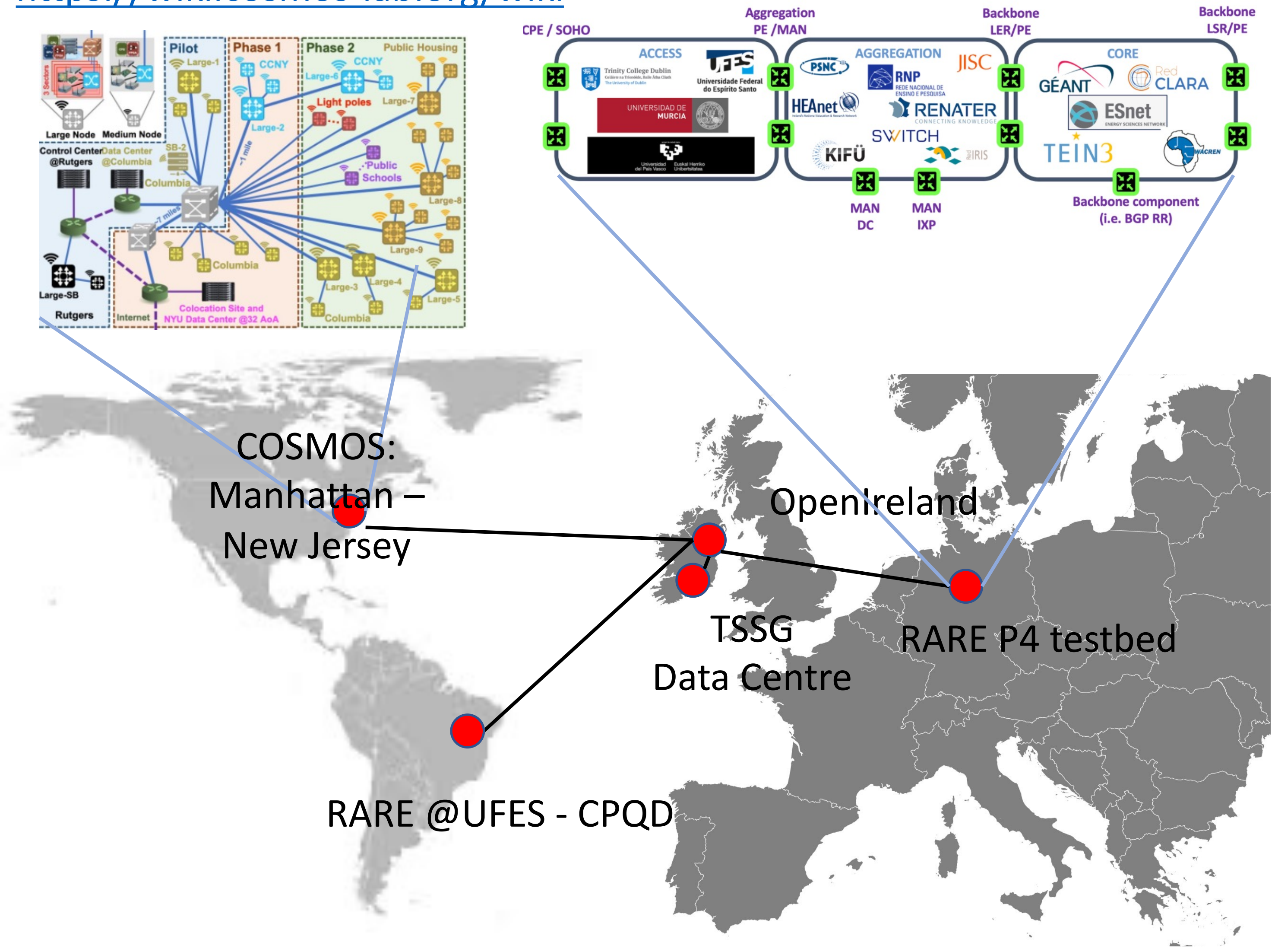
Upper 4 GHz band for 5G



Upper N77 band: 3.8 – 4.2 GHZ

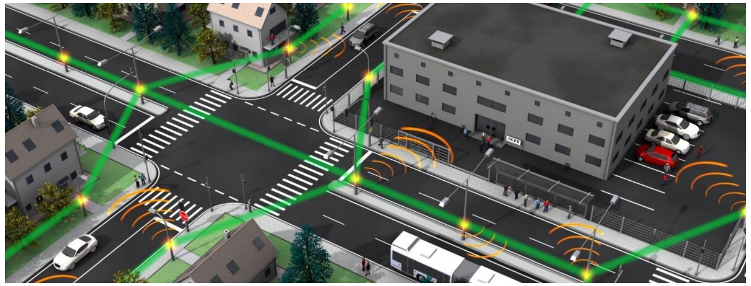
Worldwide reach… and further plans

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

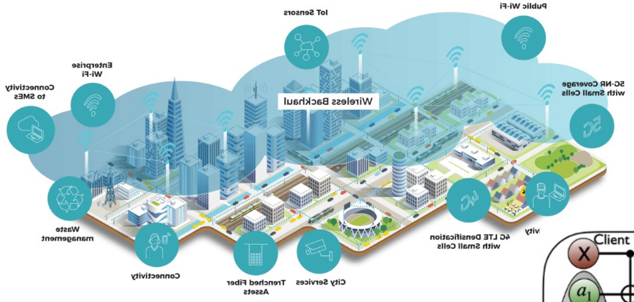


Foundation testbed in CONNECT2
Starting point for further exploration:

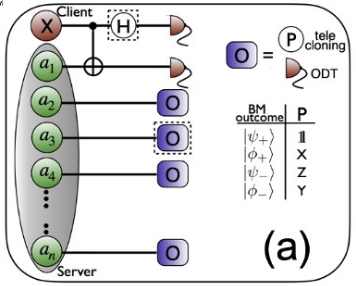
⇒ ***mmWave and THz experimentation***



⇒ ***Connected City Infrastructure***

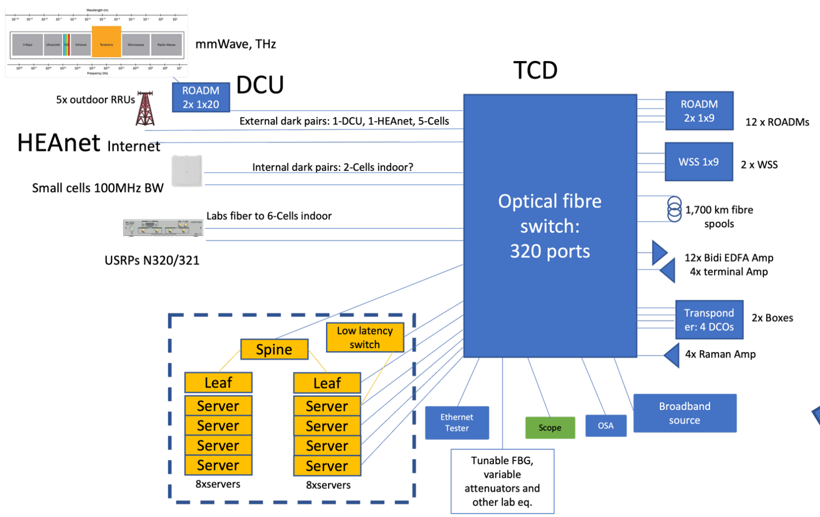


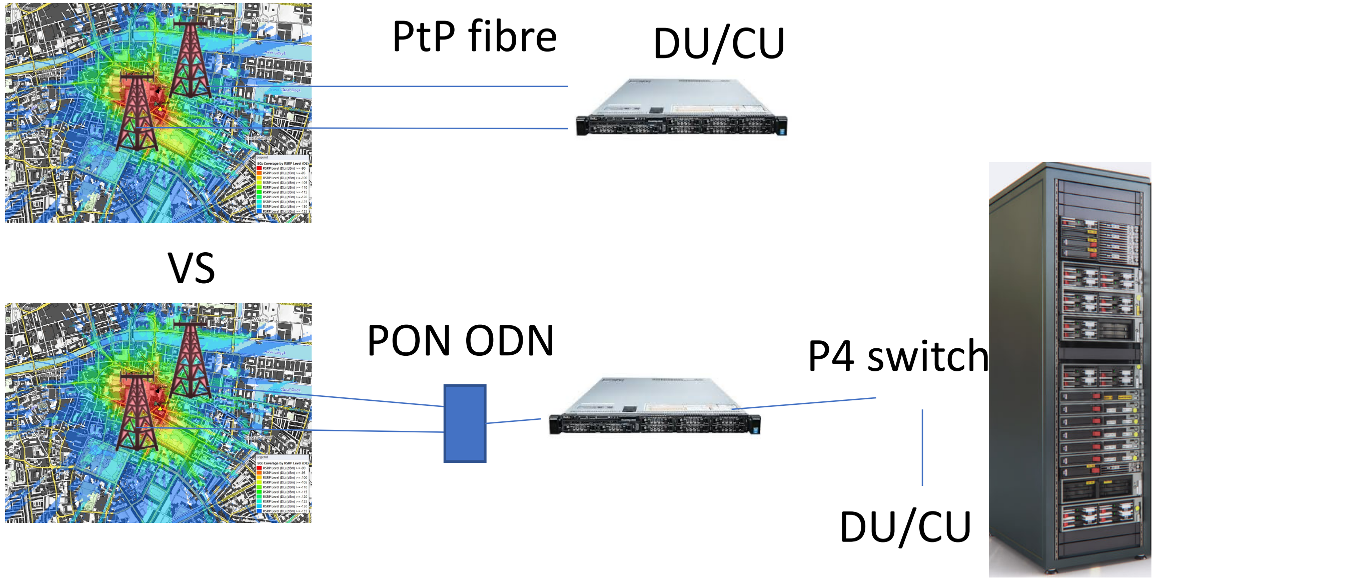
⇒ ***Quantum Internet***



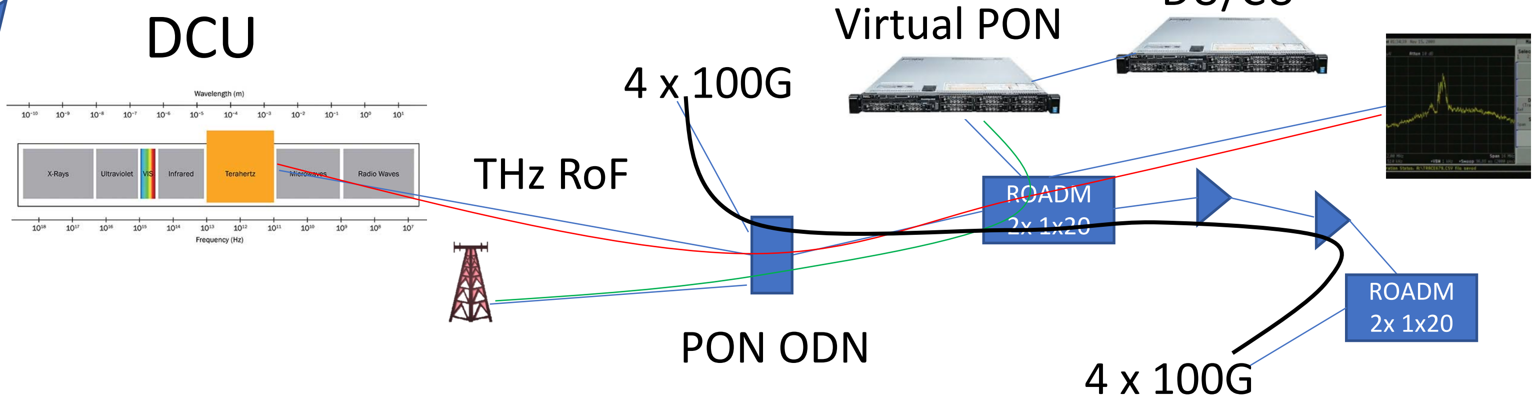
The power of topological reconfiguration

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

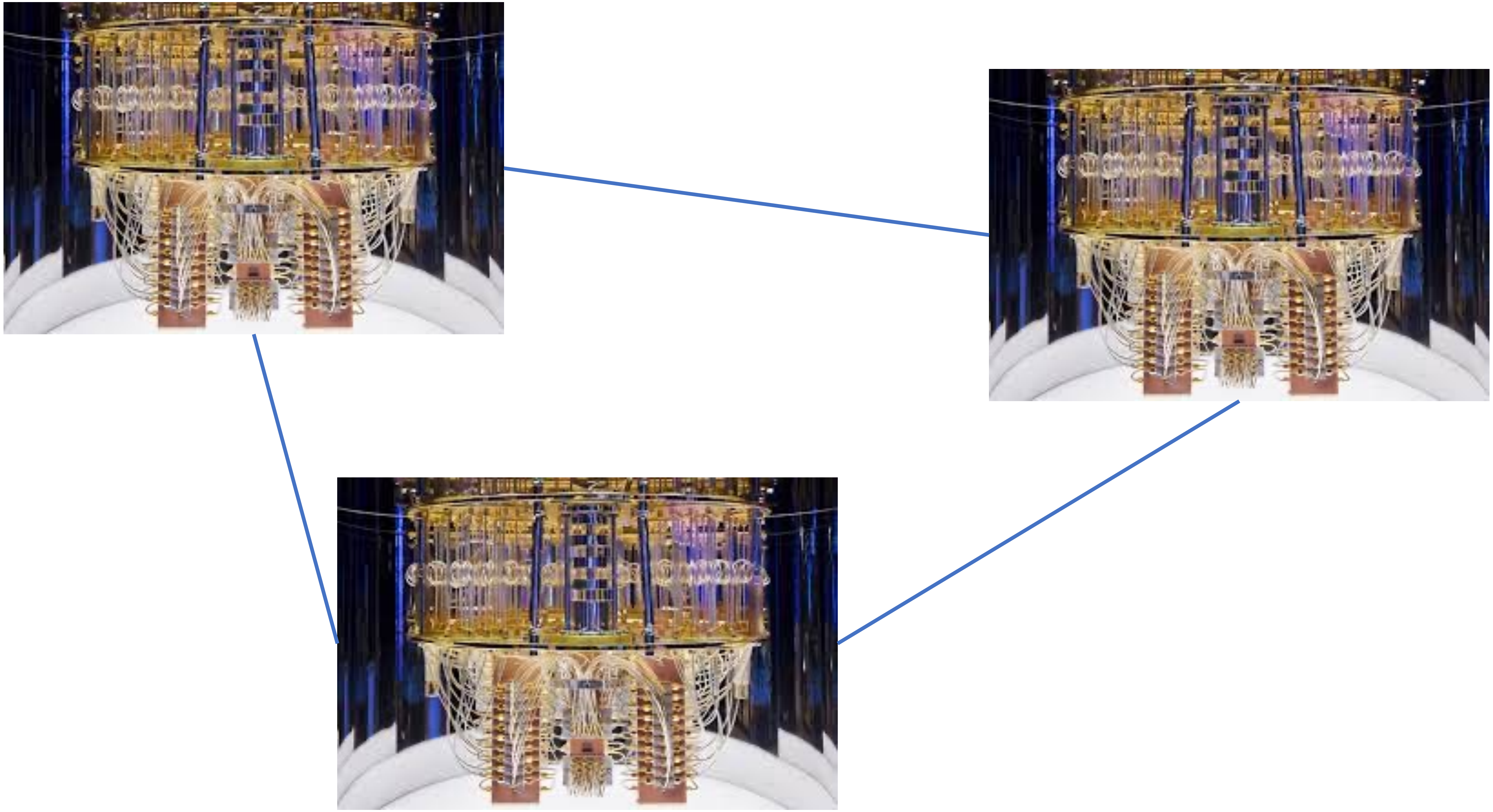




- Use case 2: Examine coexistence of different transmission formats analogue, digital RoF for support of 6G dense mmWave, THz



What’s next?



Really?

- Arguments against:
  - Very early stage of computing – expensive cryogenic devices
  - Not many around to build a network
  - No quantum memory
  - Transmission of quantum states very delicate…

	MSc (grad)	POST DOC (2 years)	1-2 years (industry)	2-3 years (industry)	3-4 years (industry)	5+ years +
Quantum Algorithm Scientist	$90k +	$115k - $145k	$130k - $150k	$155k - $180k	$190k - $225k	$250k +
Quantum Hardware Engineer	$80k +	$95k - $125k	$115k - $130k	$125k - $160k	$160k - $180k	$200k +
Quantum Software Engineer	$90k +	$115k - $145k	$130k - $150k	$155k - $180k	$190k - $225k	$250k +
Optomechanical Engineer	$85k +	$110k - $125k	$125k - $140k	$145k - $155k	$160k - $180k	$200k +
Superconducting Circuit Designer	$90k +	$110k - $125k	$125k - $140k	$145k - $155k	$160k - $180k	$200k +
Business Development	$75k +	$90k - $110k	$105k - $115k	$120k - $135k	$140k - $155k	$175k +

For more information or to discusss career opportunities contact Connor@quantum-futures.com

- But:
  - Recent prog
  - Hardware is … ntum algorithms and for netw … dware is there)

Hybrid quantum/classical SDN controller

- Quantum computing will require the ability to distribute quantum information across multiple locations:
  - <u>Scaling quantum computing</u>: increase the power of quantum computing through distributed quantum computing
  - <u>Ubiquitous access to quantum resources</u>: end user access to quantum state information from centralized quantum computing nodes
  - <u>Secure communication</u>: 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)

- New US-Ireland project with scope 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.

Mininet quantum

- We are working in joint US-Ireland projects on quantum communications
- Centre-to-centre (CQN – CONNECT) project looking at multiple aspects of quantum communication (both hardware and software)

  - Plan is to 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

Take away message

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

The big question is if will we be able to orchestrate AI algorithm to build a reliable digital twin framework?

➔ … and going ahead, a digital twin that builds itself?

The second big question is how long before we need a quantum network…

… and an SDN controller?

➔ SDN controller already being used for QKD…

CONNECT Centre for Future Networks

IPIC BRINGING PHOTONICS TO LIFE

Thank you

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

NetSoft 2022, PVE-SDN workshop

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

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