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Centre for Future Networks

A digital twin optical network for scalable control plane development and evaluation

Marco Ruffini, Dan Kilper et al.
CONNECT research centre, Trinity College Dublin

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Networks of the Future

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The people behind today's presentation

OpenIreland | COSMOS

NGIAtlantic: experimentation

Mininet Optical

NGIAtlantic: experimentation

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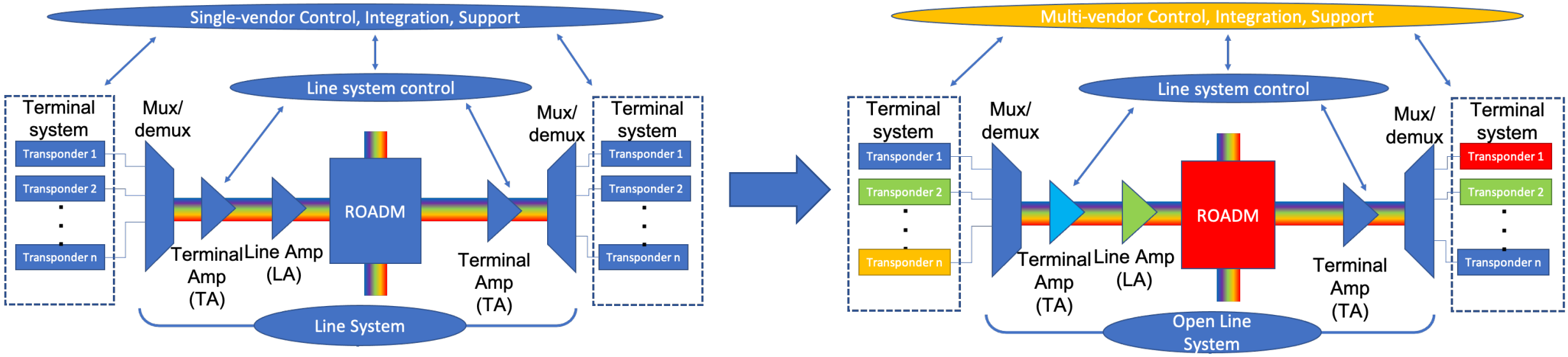
Optical layer disaggregation

- Disaggregation enables mix and matching of the different components of an optical transmission network

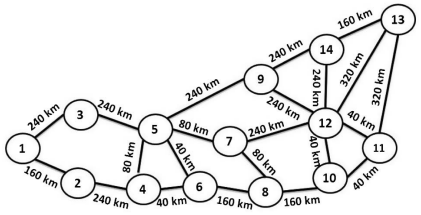


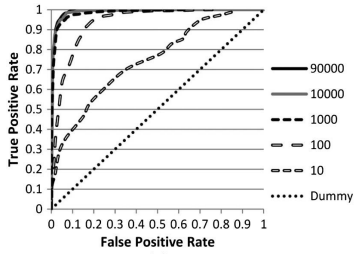
- It also opens up the control plane for development of algorithms for network provisioning, monitoring, etc.

Developing, testing and live operation of AI-based algorithms

QoT prediction using random forest ML algorithm

Dependency on training set size

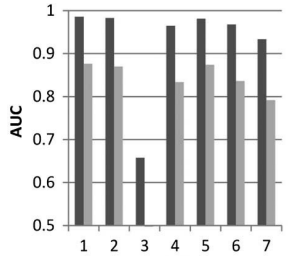




Relevance of different features

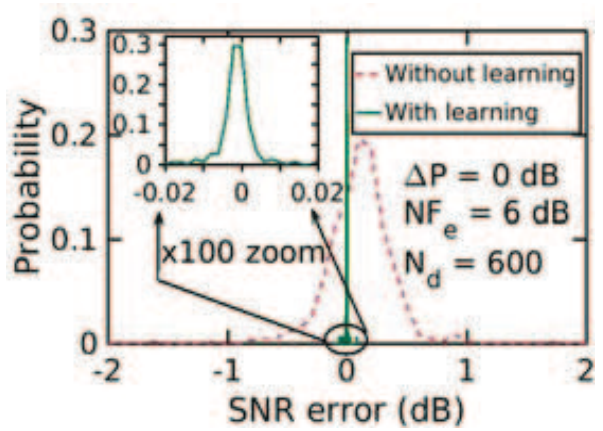
CONSIDERED FEATURE SUBSETS

	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	✓						



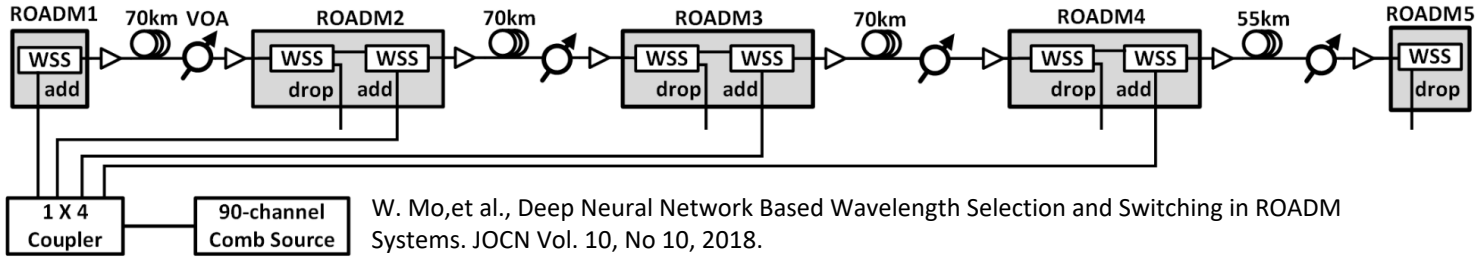
Source: C. Rottondi, et al. Machine-learning method for quality of transmission prediction of unestablished lightpaths. JOCN Vol. 10, No. 2, Feb. 2018

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

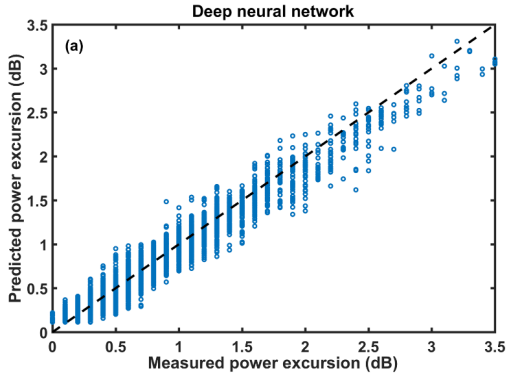


Source: E. Seve, J. Pesic, C. Delezoide, and Y. Pointurier. Learning process for reducing uncertainties on network parameters and design margins. OFC 2017.

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

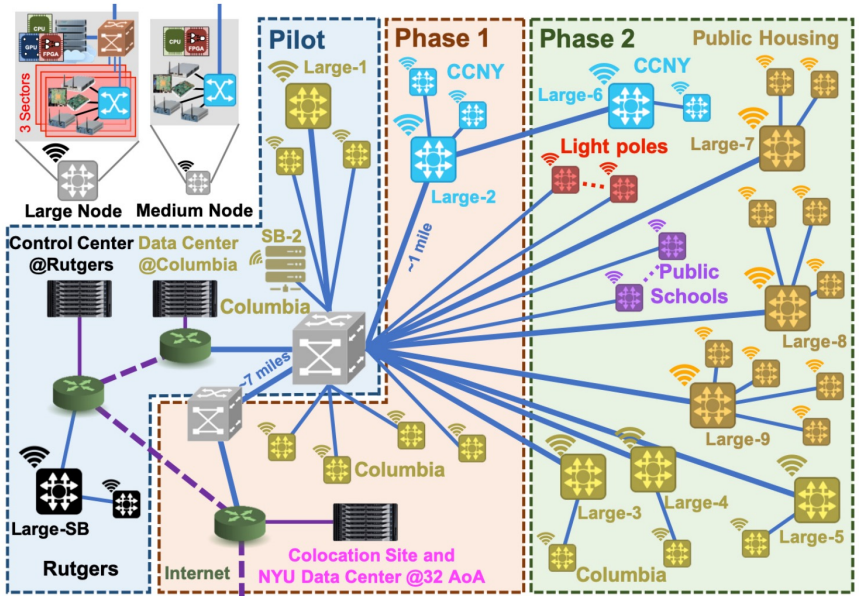


W. Mo,et al., Deep Neural Network Based Wavelength Selection and Switching in ROADM Systems. JOCN Vol. 10, No 10, 2018.

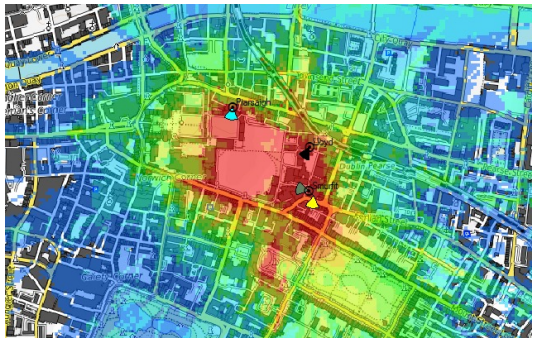


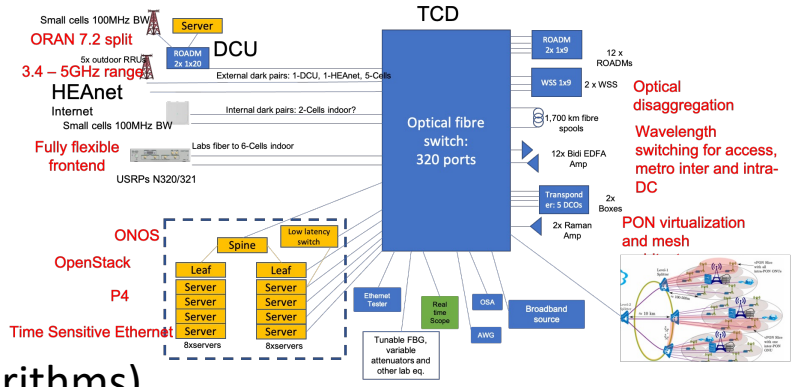
Control plane design, experimentation or simulation?

COSMOS

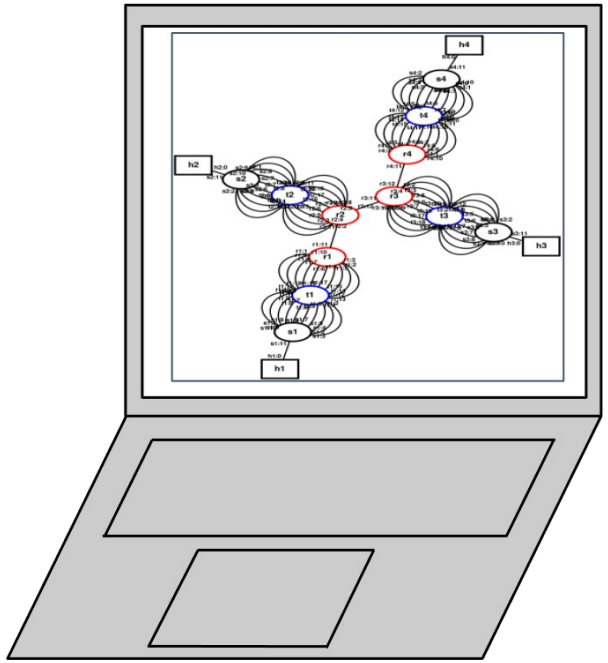


OpenIreland





Mininet-Optical



Network infrastructure experimentation for:

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

Network emulation for:

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

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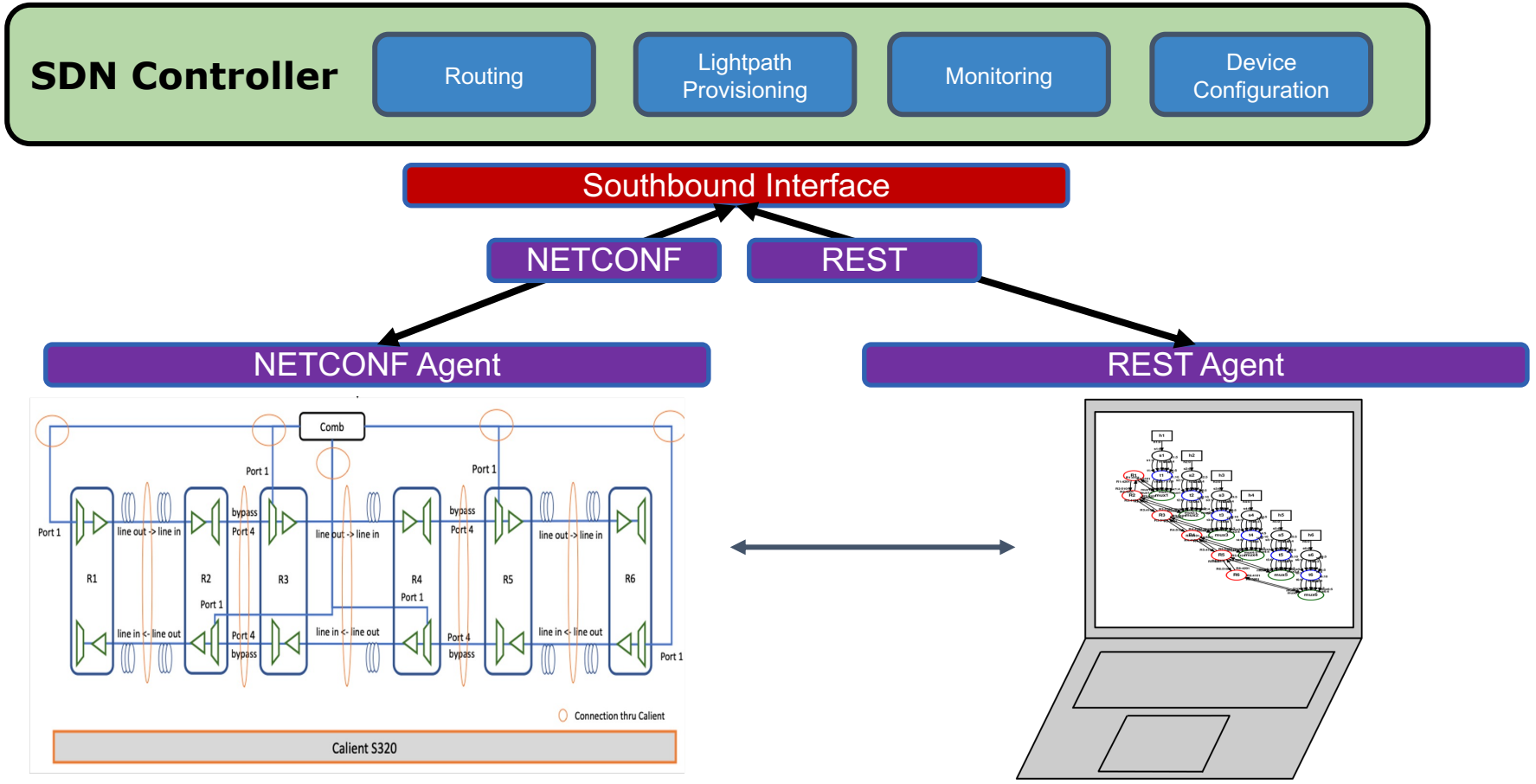
Building a digital twin for Open Access testbeds



Hardware network on testbed

Virtual network in Mininet-Optical

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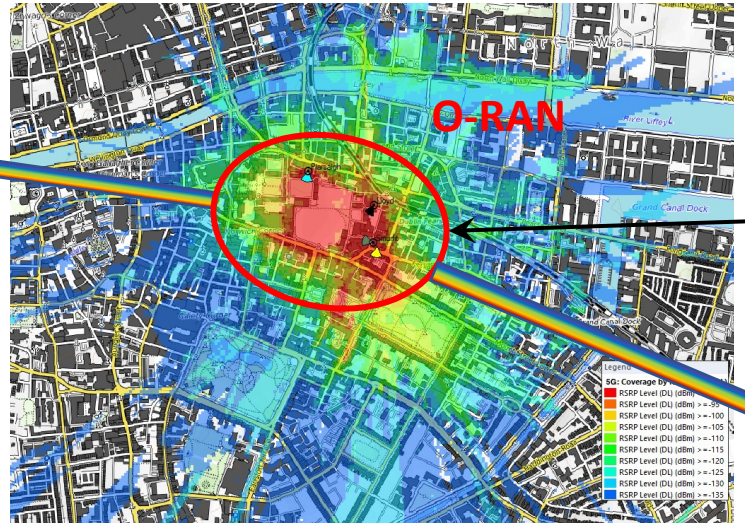
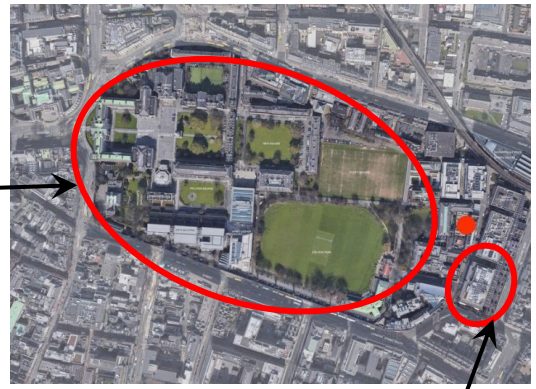
Experimentation through open testbed: OpenIreland

www.openireland.eu

Radio and Optical Communications Laboratory



Based in Trinity College campus



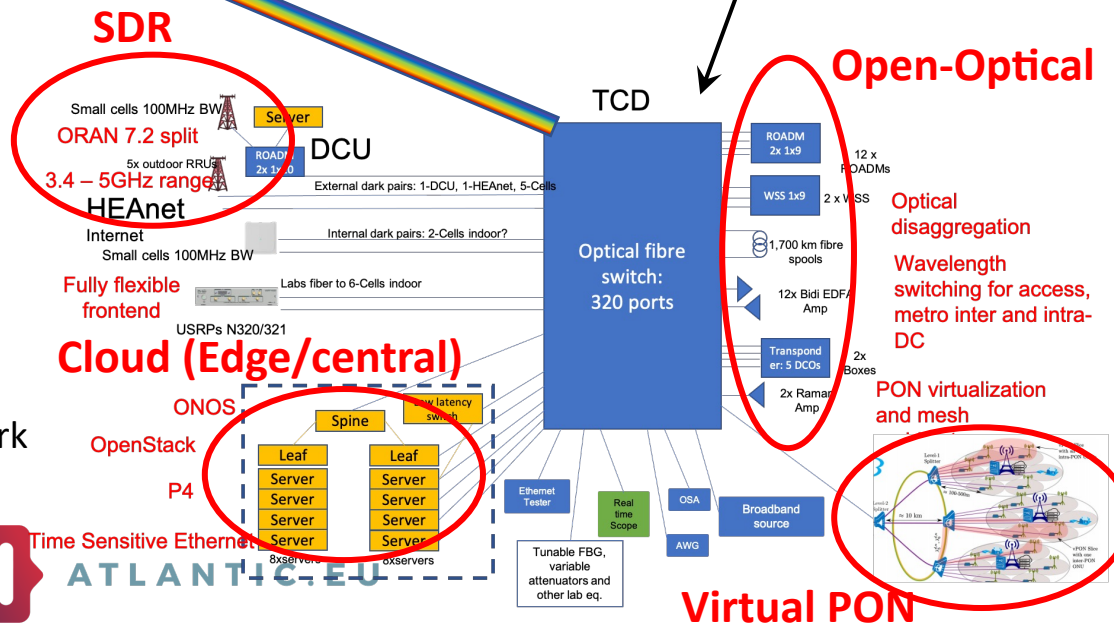
CONNECT research centre building

Reconfigurable and Lego-like topology reconfiguration with following blocks:

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

Run an experiment:

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



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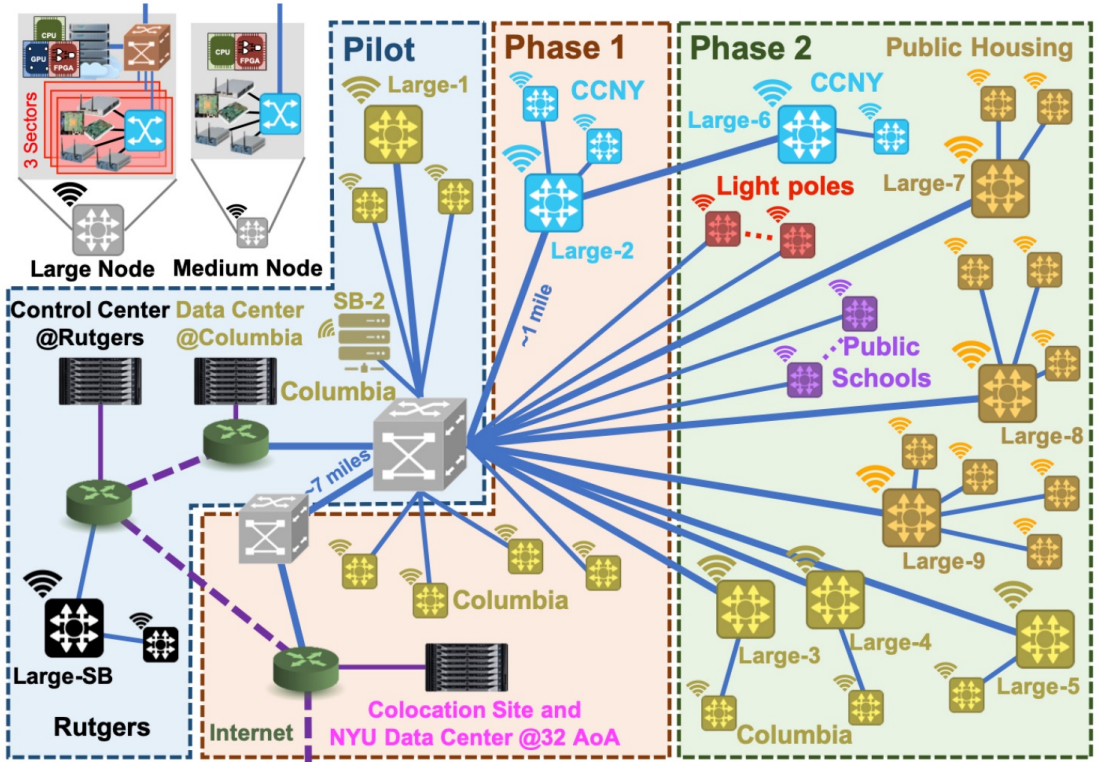
Experimentation through open testbed

US-based COSMOS



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

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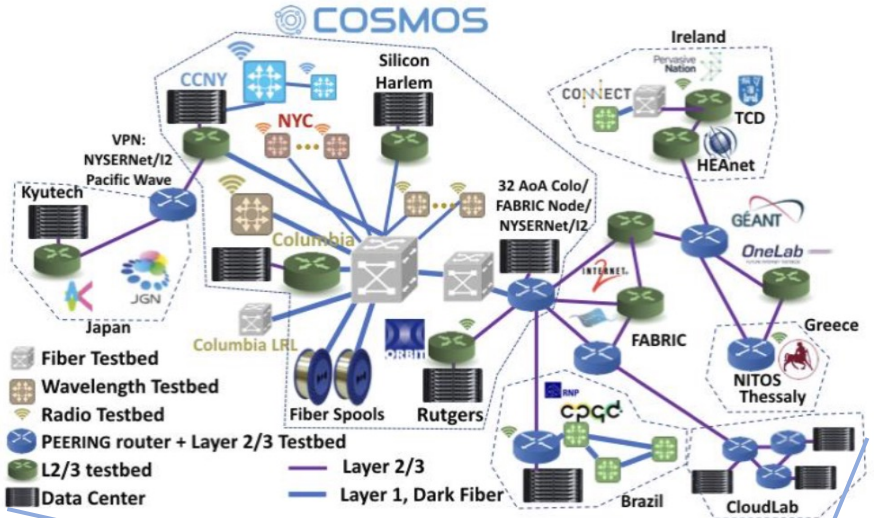
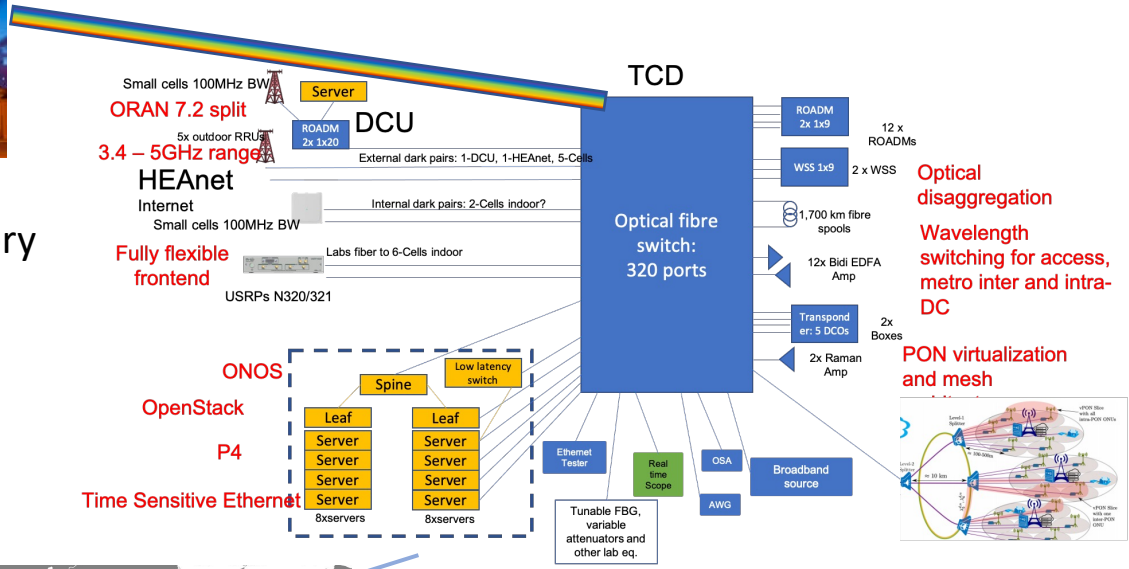
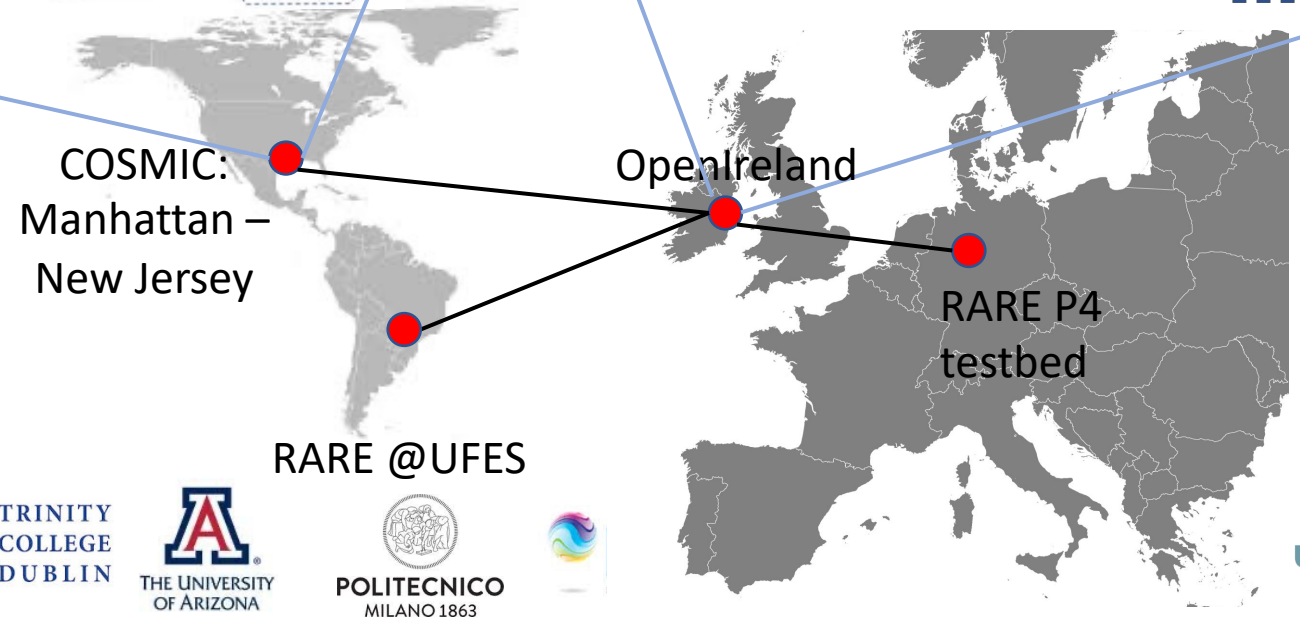
Experimentation through open testbed: global interconnectivity



Radio and Optical Communications Laboratory





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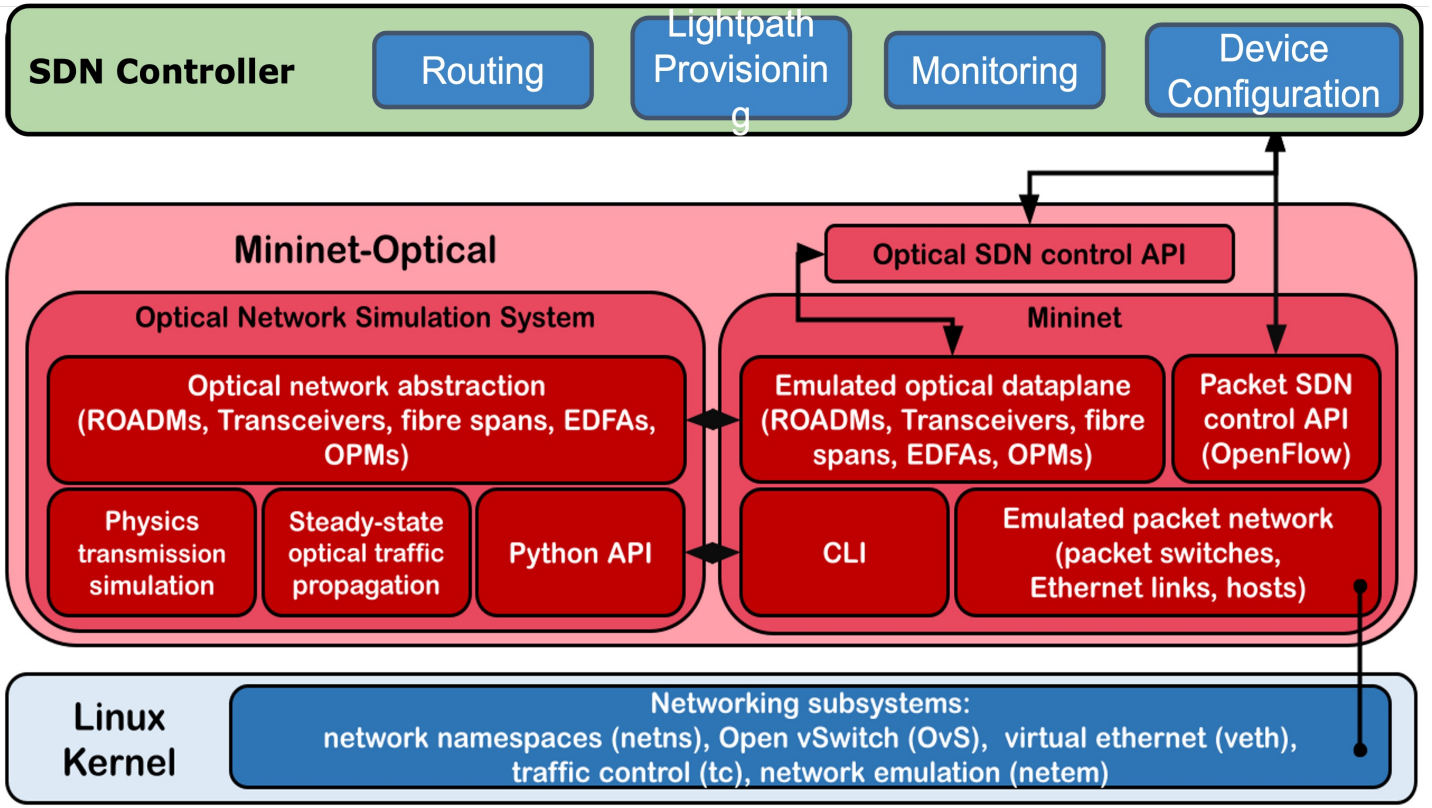
Experimentation through open source software: Mininet-Optical



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

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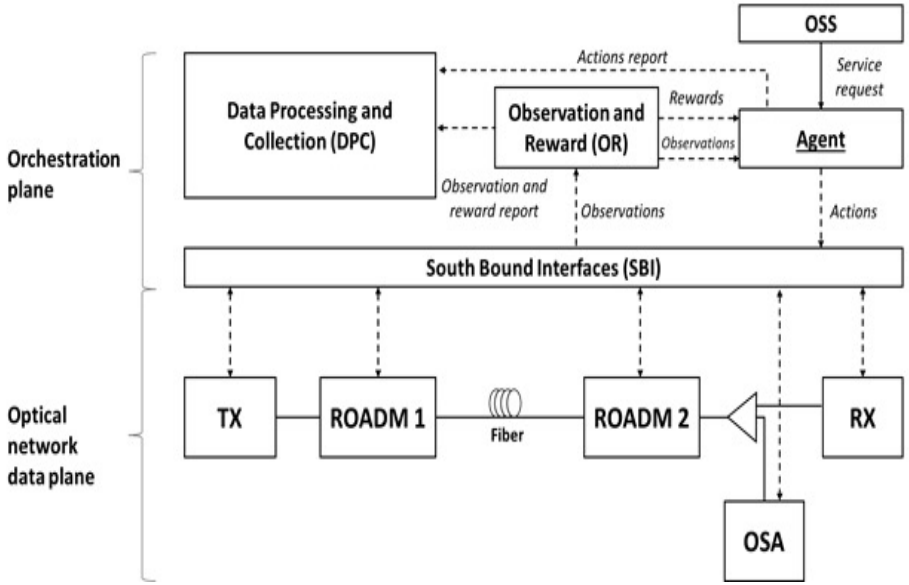
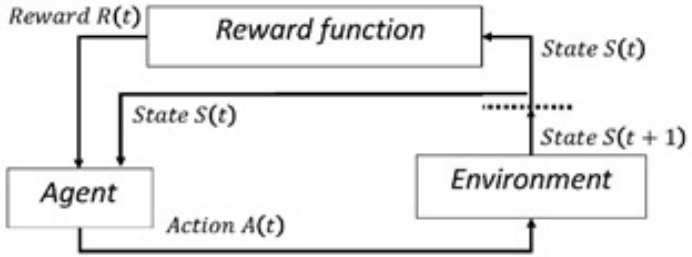
Use case: Building a QoT estimation algorithm

Control plane algorithm development and test based on simulation:

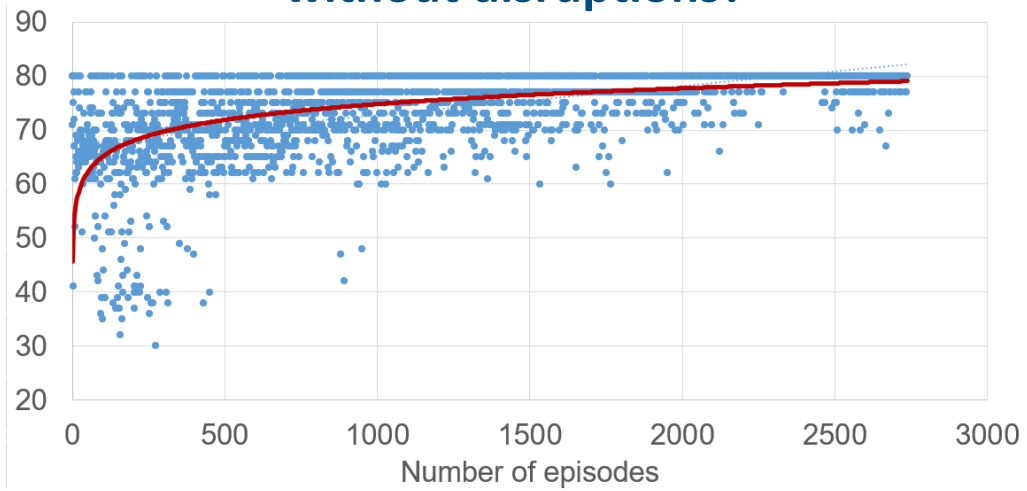
- Online learning through agent that loads the optical spectrum with optical channel and measures OSRN variation
- Through multiple iterations the agent improves strategy for channel selection





Work carried out by Politecnico di Milano optical group

How many channels are allocated without disruptions?



Use of simulated data plane

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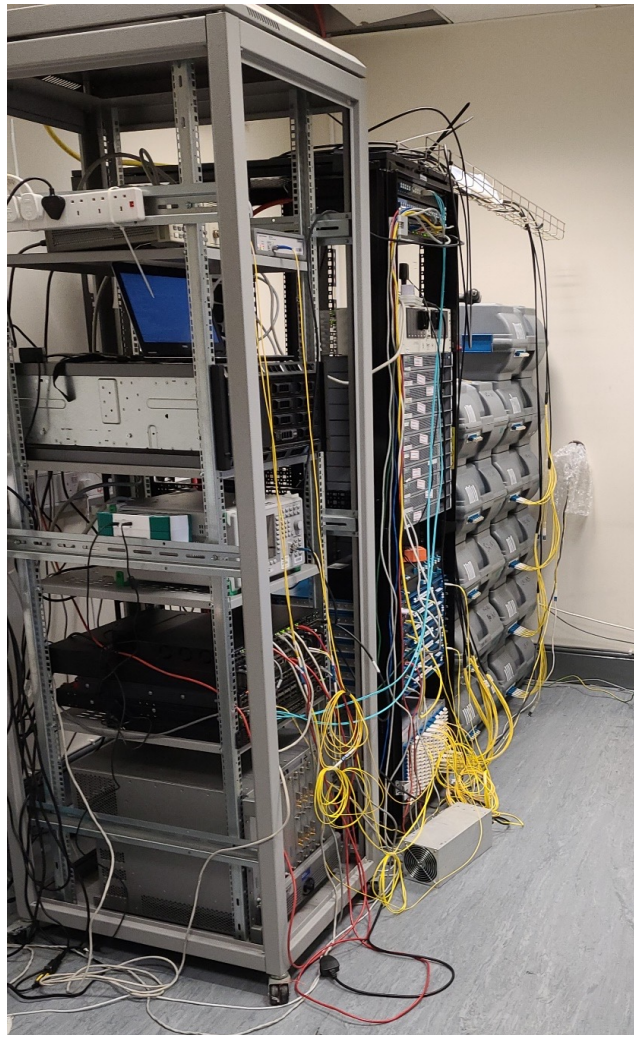
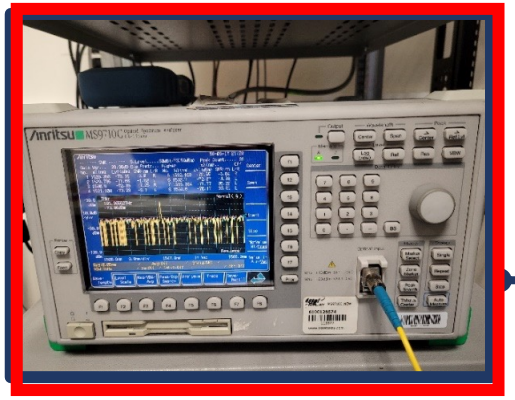
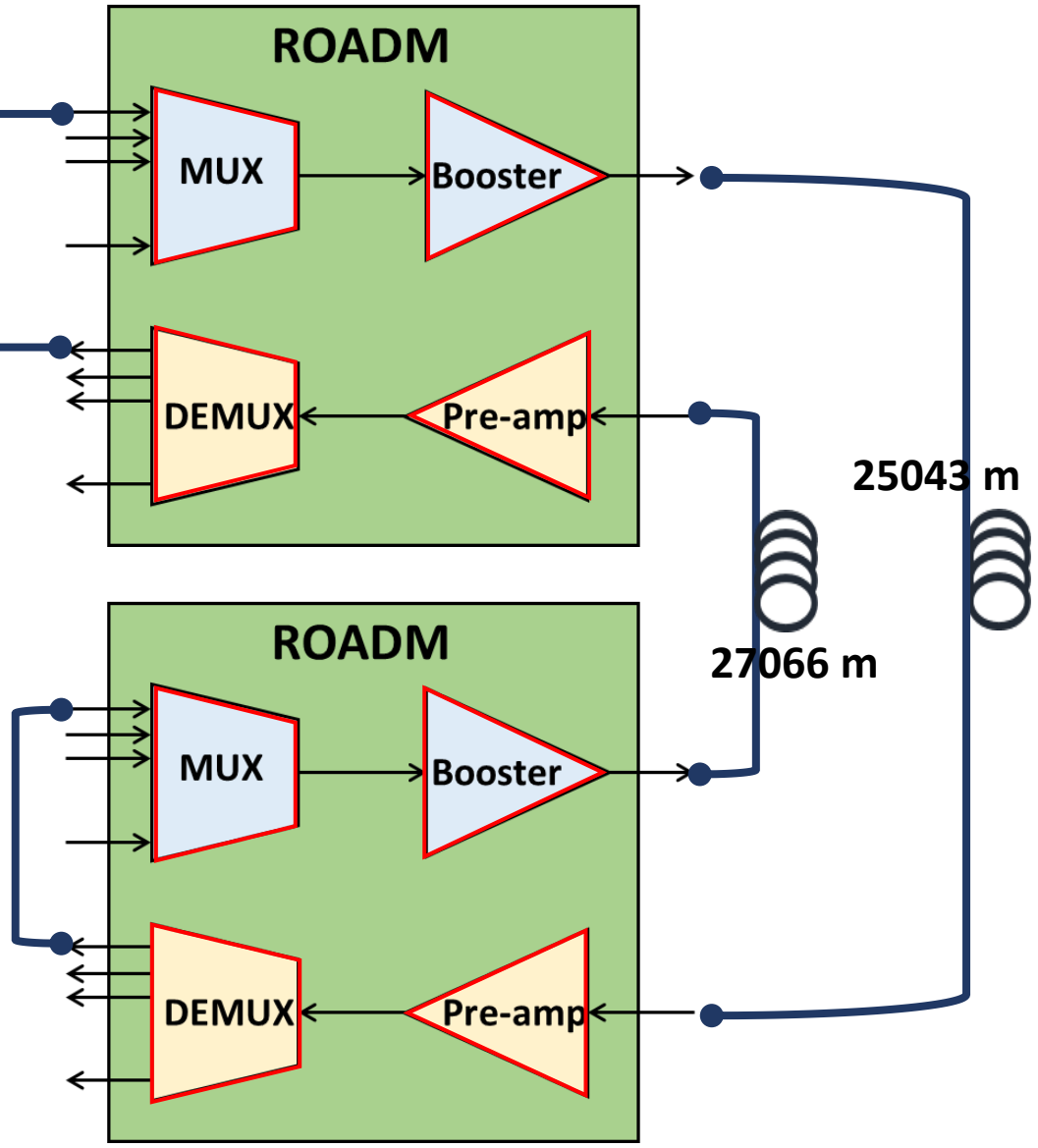
Moving into OpenIreland testbed



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

OSA





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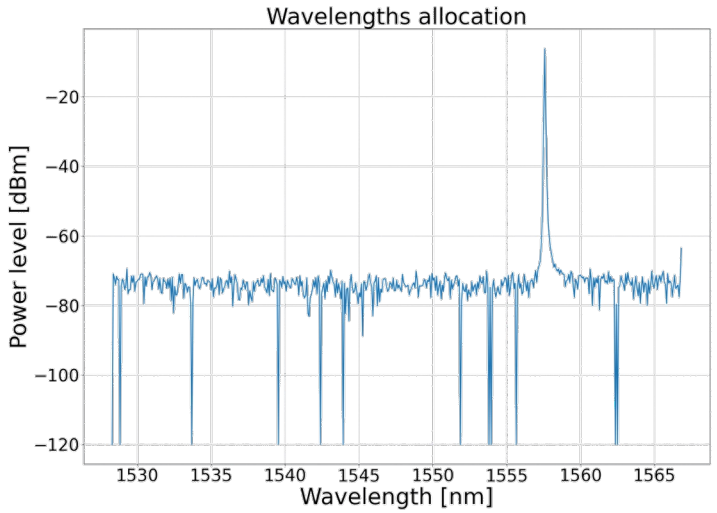
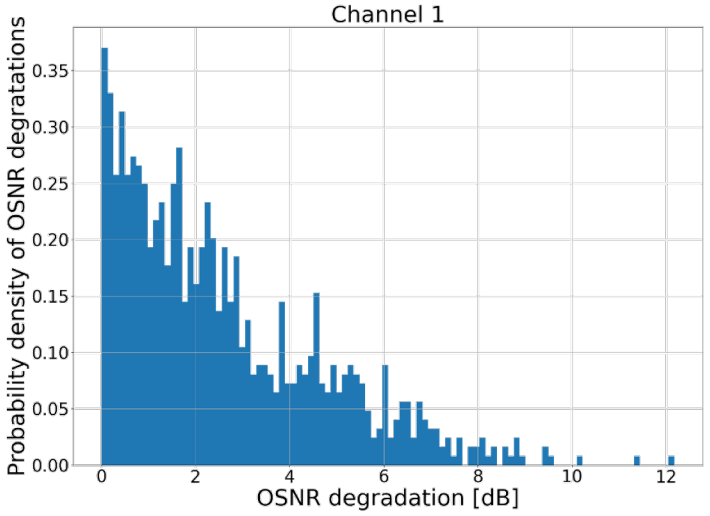
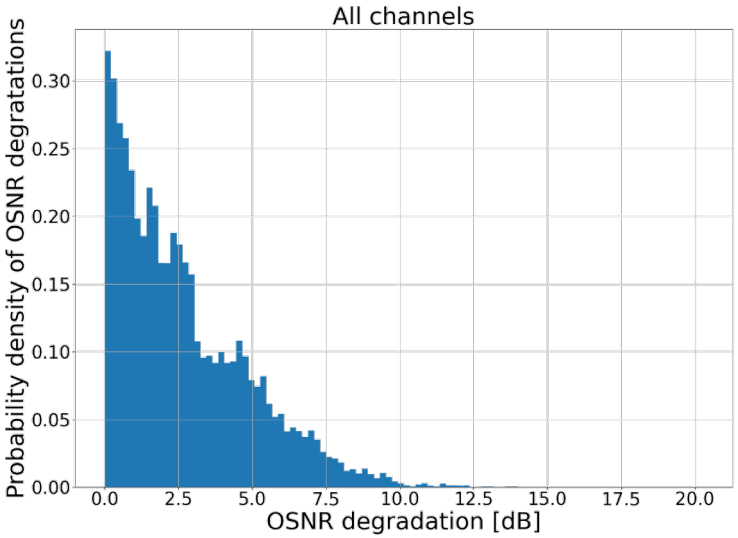
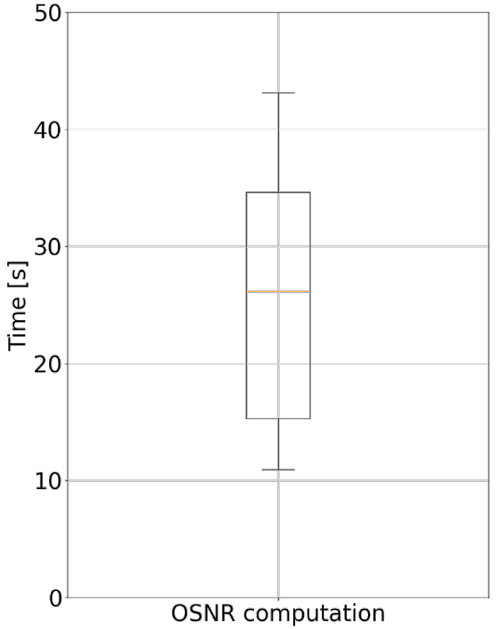
Some initial results







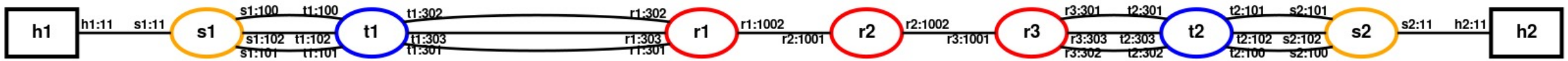


Iteration: fill the whole spectrum with a random selection of 80 channels

1 iteration = 40 mins

50 iterations

… and onto the digital twin: mininet-optical



L2 switch Transceivers ROADMs

Testbed control plane vs Digital twin control plane

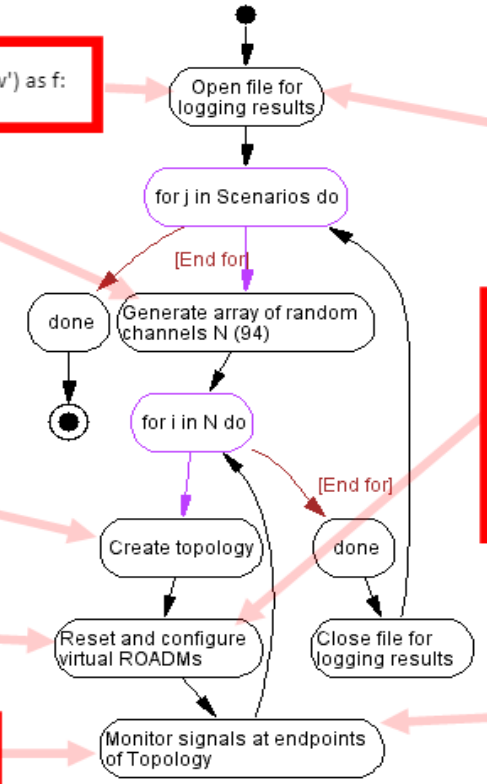
```
with open('data_collection/sample_channels_4.txt', 'w') as f:
    f.write("%s\n" % channels)
```

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

Physical Topology
Configured already

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

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




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

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

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

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

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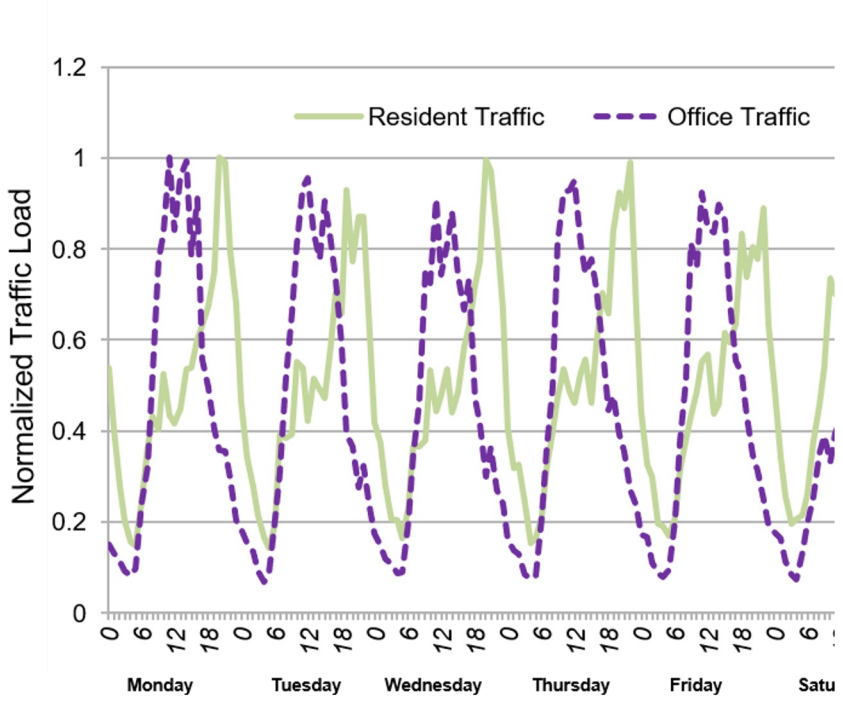
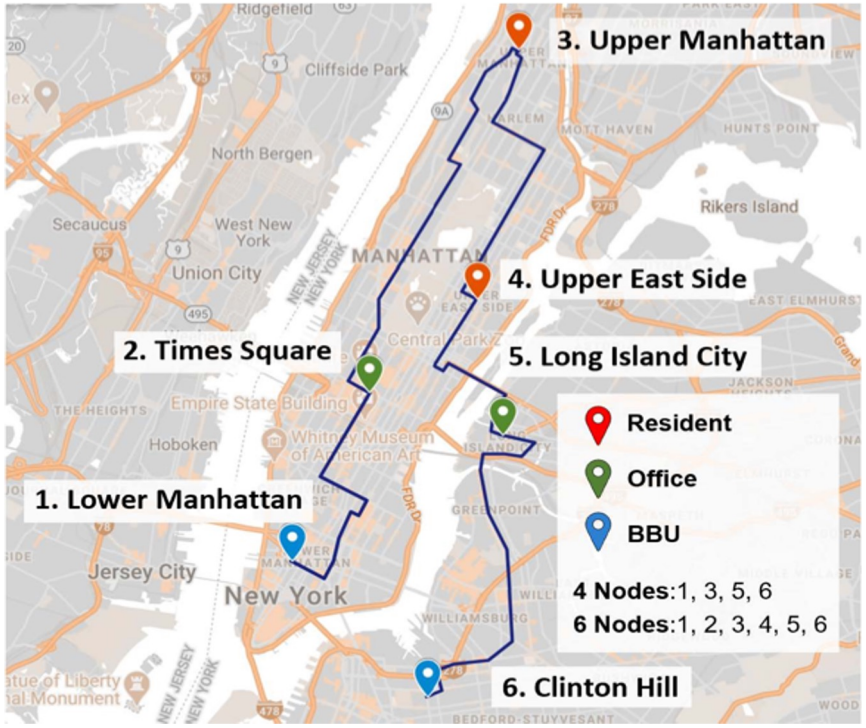
Use case 2: Metro Front-haul Provisioning



Diurnal traffic variation of Residential vs. Office traffic

This changes the traffic pattern over the transport network

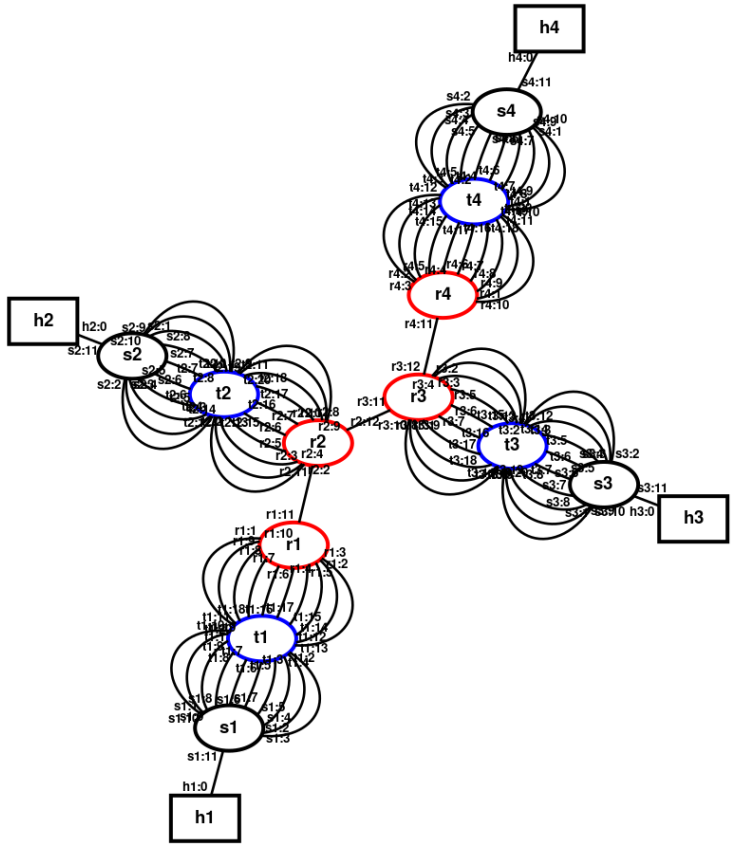
The controller associates RUs to BBU locations, depending on demand and available network and computing resources



The controller also monitors OSNR. If this goes below given thresholds, it reduces modulation from 16-QAM (200 Gb/s) to QPSK (100 Gb/s) or BPSK (50 Gb/s). Rerouting and re-provisioning is also possible.

B. Lantz, J. Yu, A. Bhardwaj, A. Diaz-Montiel, A. Quraishy, S. Santaniello, T. Chen, R. Fujieda, A. Mukhopadhyay, G. Zussman, M. Ruffini and D. Kilper. SDN-controlled Dynamic Front-haul Provisioning, Emulated on Hardware and Virtual COSMOS Optical x-Haul Testbeds. OSA Optical Fiber Communications Conference (OFC), June 2021

Metro Front-haul Provisioning – Mininet-Optical



Four ROADMs:

(r1,r4): 1-degree

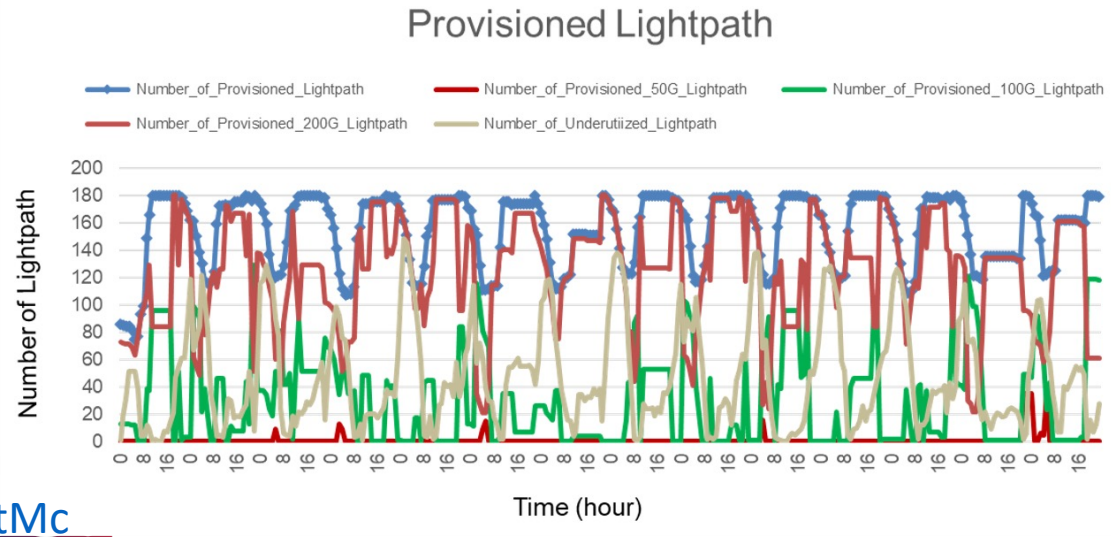
(r2,r3): 2-degree

Links are fiber pairs (i.e. both directions)

Endpoints: Data Centers (h1, h4); RU aggregation (h2, h3)

90 transceivers/channels per endpoint

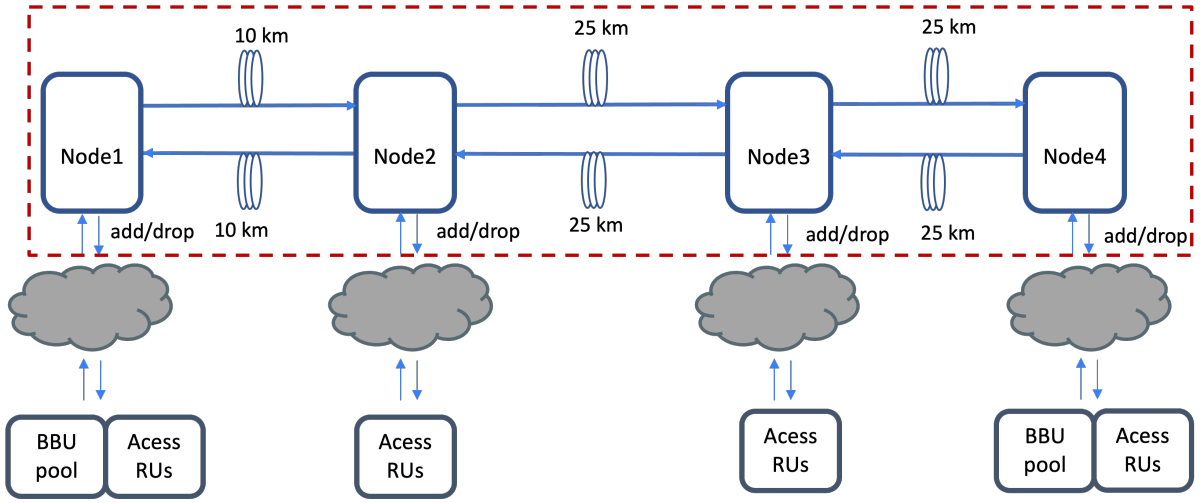
End-to-end model with Optical (ROADM rN, Terminal tN) as well as packet (Host hN, Router sN) elements



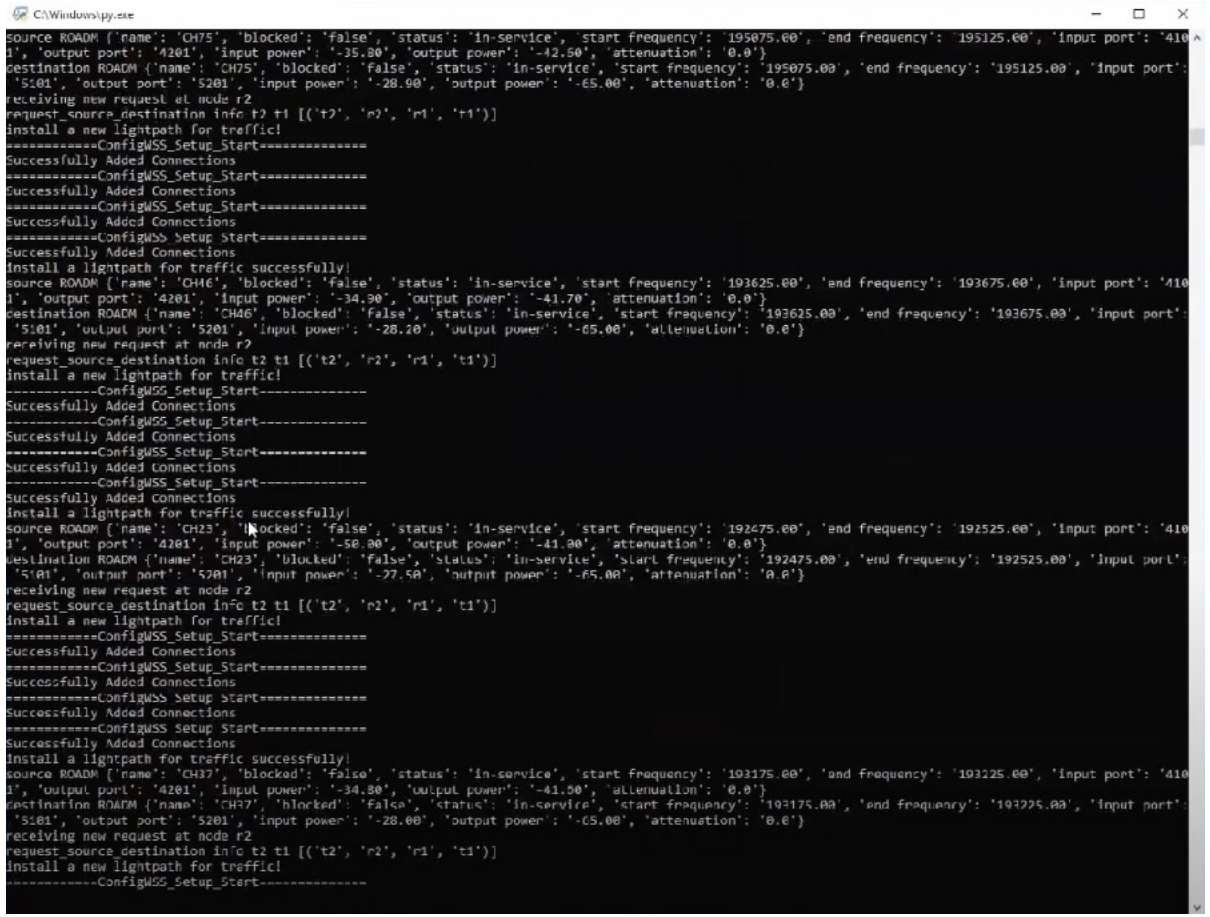
- The emulation shows an example of how the lightpaths are reprovisioned over time.

Watch the video at: https://www.youtube.com/watch?v=Bi2E-sGytMc

Use case 1: Metro Front-haul Provisioning – COSMOS



Control plane



Run same controller used for Mininet-Optical for setting up and tearing down of lightpaths:

- Configuration across multiple ROADMs
- Configuration of transceiver
- Measurement of power levels

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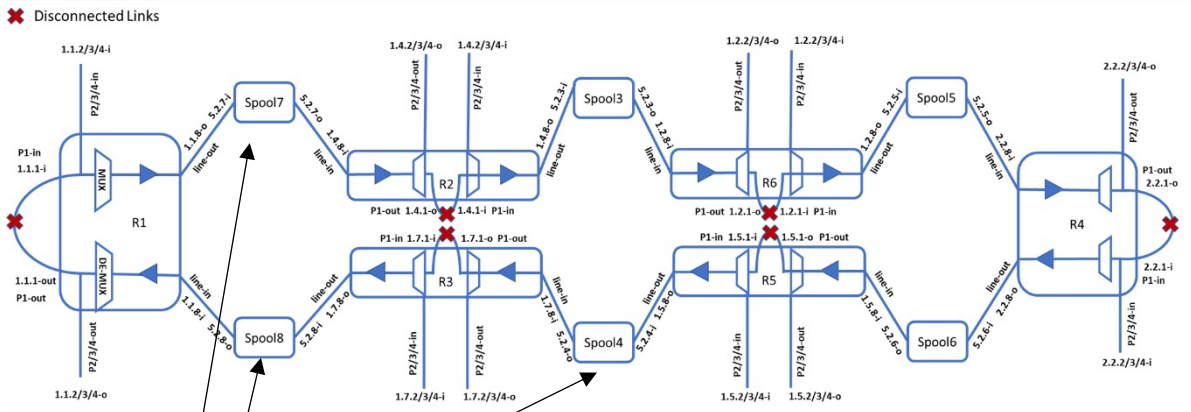
Use case 1: Metro Front-haul Provisioning – OpenIreland



Modified propagation distances

Control plane

```
fslyne@ol02: ~/optical-network-emulator/ofcdemo
============ConfigWSS_Setup_Start==============
Successfully Added Connections
install a lightpath for traffic successfully!
source ROADM {'name': 'CH28', 'blocked': 'false', 'status': 'in-service', 'start frequency': '192725.00', '
end frequency': '192775.00', 'input port': '4101', 'output port': '4201', 'input power': '-50.00', 'output
power': '-40.70', 'attenuation': '0.0'}
destination ROADM {'name': 'CH28', 'blocked': 'false', 'status': 'in-service', 'start frequency': '192725.0
0', 'end frequency': '192775.00', 'input port': '5101', 'output port': '5201', 'input power': '-17.20', 'ou
tput power': '-20.91', 'attenuation': '0.0'}
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
receiving new request at node r2
request_source_destination info t2 t1 [('t2', 'r2', 'r1', 't1')]
install a new lightpath for traffic!
============ConfigWSS_Setup_Start==============
Successfully Added Connections
============ConfigWSS_Setup_Start==============
Successfully Added Connections
============ConfigWSS_Setup_Start==============
Successfully Added Connections
============ConfigWSS_Setup_Start==============
Successfully Added Connections
install a lightpath for traffic successfully!
source ROADM {'name': 'CH33', 'blocked': 'false', 'status': 'in-service', 'start frequency': '192975.00', '
end frequency': '193025.00', 'input port': '4101', 'output port': '4201', 'input power': '-50.00', 'output
power': '-40.70', 'attenuation': '0.0'}
destination ROADM {'name': 'CH33', 'blocked': 'false', 'status': 'in-service', 'start frequency': '192975.0
0', 'end frequency': '193025.00', 'input port': '5101', 'output port': '5201', 'input power': '-17.10', 'ou
tput power': '-20.81', 'attenuation': '0.0'}
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
downgrading lightpath capacity from 200G to 100G
receiving new request at node r2
request_source_destination info t2 t1 [('t2', 'r2', 'r1', 't1')]
install a new lightpath for traffic!
============ConfigWSS_Setup_Start==============
Successfully Added Connections
============ConfigWSS_Setup_Start==============
Successfully Added Connections
============ConfigWSS_Setup_Start==============
```

Run same controller used for Mininet-Optical and COSMOS for OpenIreland:

- Configuration across multiple ROADMs
- Configuration of transceiver
- Measurement of power levels, BER

```
stroia@ol02:~/testbed-setup$ sudo python3 actions.py test
Output power:  1.200000e-01
Input power:  4.100000
Current output power:  4.600000e-01
Operation status:  ready
DSP operation status:  ready
Modulation format:  dp-16-qam
Laser frequency:  193900000000000
Post-fec BER:  3.412794e-02
Pre-fec BER:  2.448365e-02
SD-fec BER:  2.447128e-02,2.449601e-02
HD-fec BER:  8.164130e-04,2.049768e-02
```

```
stroia@ol02:~/testbed-setup$ sudo python3 test.py
1) get powers; 2) get OSA; -> 2
marker:  193.93398,-17.57DBM
```

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Conclusions

- Open access testbeds are key for widespread (i.e., all active research community) and accurate development of control plane mechanisms, machine learning algorithms, etc.
  - This is an important contribution to the community: provide access to testbed facilities so researchers can explore activates that are otherwise limited to limited number of industry and academic institutions.

- Simulation (at control and data plane) can become fully synergetic with testbed implementation, implementing the digital twin concept.
  - Typical goal: Investigate outcome of optical layer operation before deploying
  - But also:
    - Mix of simulation and real testbed learning
    - Accurate emulation of control plane behavior (in addition to physical layer)
    - Test efficacy of novel devices (i.e., gOSNR monitors, etc.)
    - …

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Thank you for your attention

Marco Ruffini (marco.Ruffini@tcd.ie)

CONNECT research centre, Trinity College Dublin

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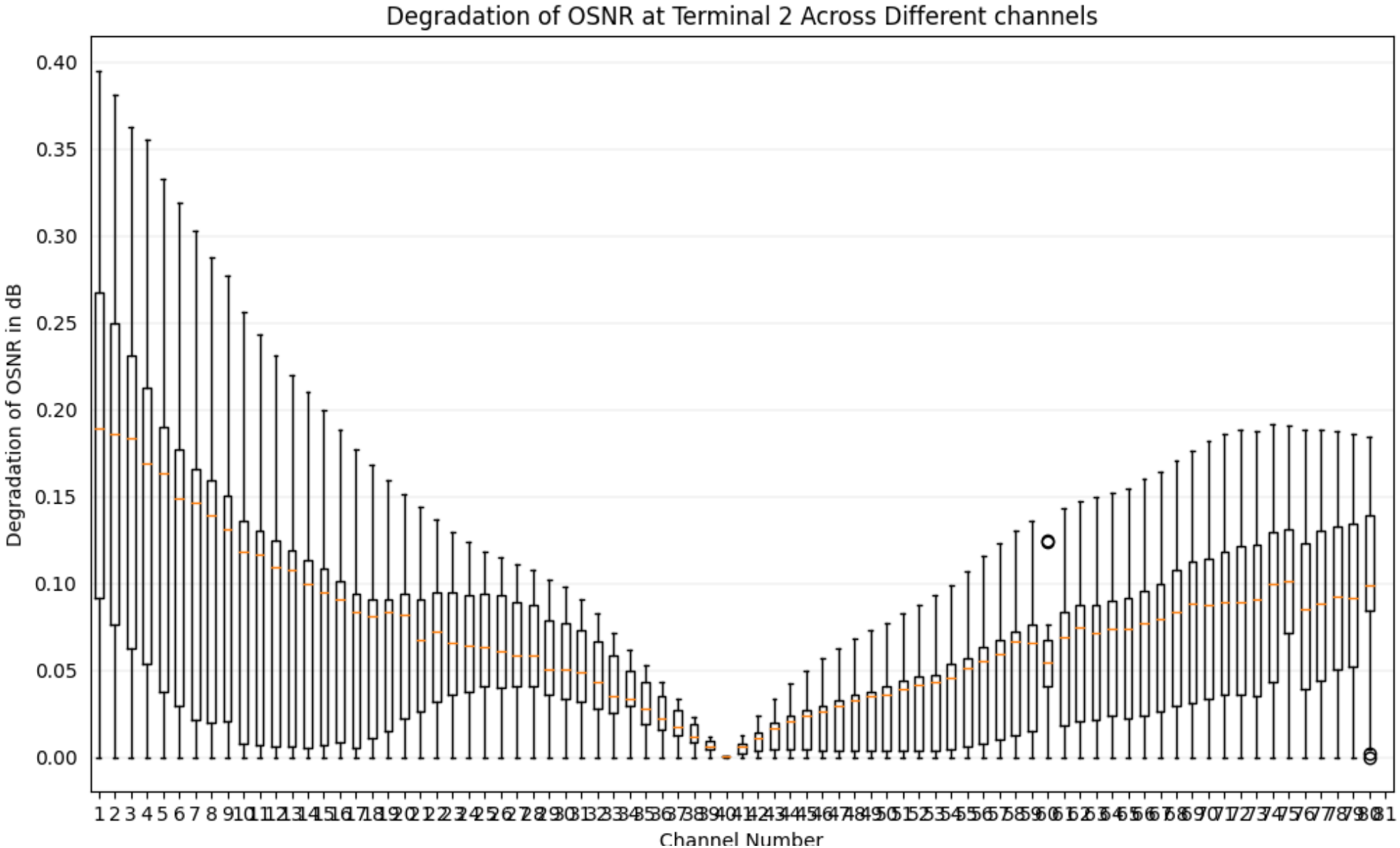
Degradation of OSNR at Terminal 2 Across Different channels
Degradation of OSNR in dB
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Channel Number