

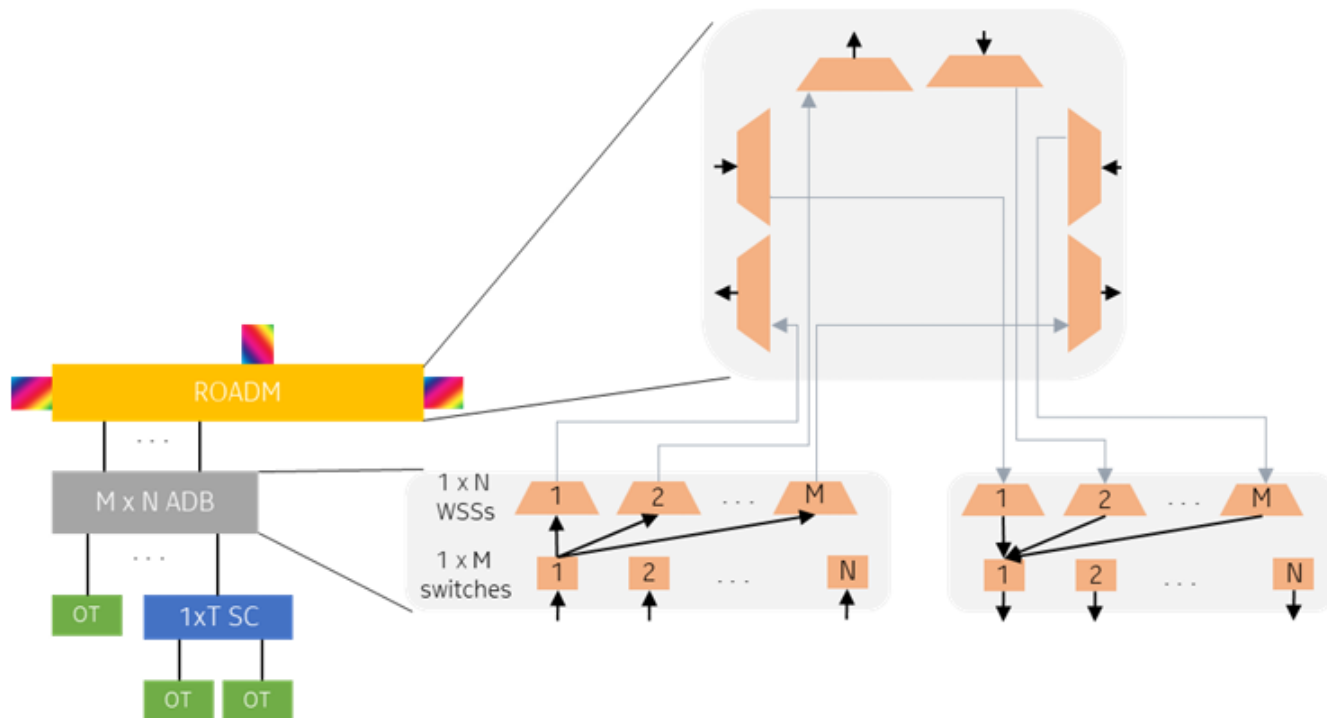
Project #3 (Add/Drop Block Contention Constraints)

PUGGELLI CHIARA, MESSINA GIORGIO, CHIROLI LORENZO

COMMUNICATION NETWORK DESIGN - NOKIA

A.Y. 2025-26

Setup



- N OTs connected to a MxN ADB
- Possibility of connecting to N 1xT SC
- OTs connected to the same SC must:
 - Share a spectrum slice of X GHz
 - Be added/dropped to/from the same ROADMs direction

Goal

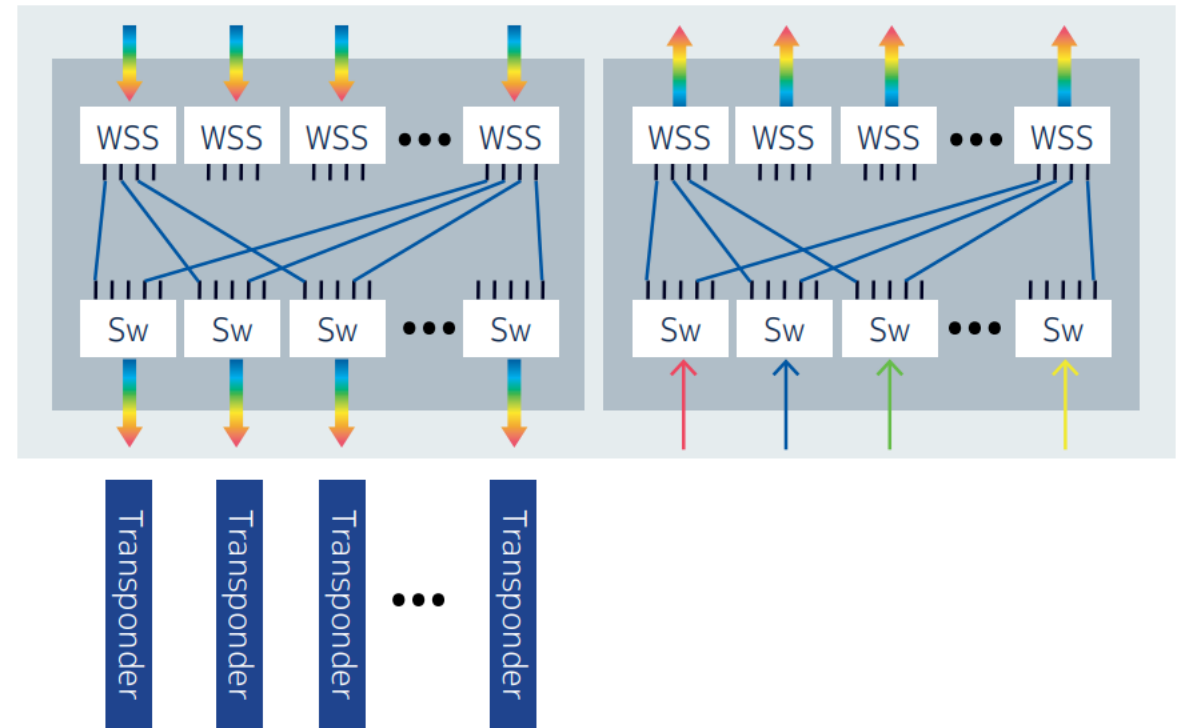
Evaluation of the changes in performance depending on the number of ADB ports equipped with SCs and their bandwidth

Variables:

- ADB ports connected with SCs: 0 - 24 (step 1).
- *Passband SC*: 50 - 300 GHz (step 50 GHz).

Evaluation Parameters:

- *Total Transported Capacity* (Tbps) before reaching blocking threshold.
- Ratio over baseline (configuration without SCs).



Topologies

| | Nodes | Links | Min length L_{avg} | Max Length L_{max} |
|--------------------|----------|----------------|----------------------|----------------------|
| National | 6 - 12 | $1N \div 2.5N$ | 150 km | 400 km |
| Continental | 60 - 120 | $1N \div 2.5N$ | 300 km | 1000 km |

Generation Algorithm

- Randomized spanning tree (to guarantee connectivity)
- Add casual links until reaching the target
- Lengths are normally distributed with a suitable clamping algorithm

$$val \sim N \left(\mu = L_{avg}, \sigma = \frac{L_{avg}}{3} \right)$$

$$L = \max(10 \text{ km}, \min(val, L_{max}))$$

- **ROADM specifications:**
 - *Maximum degree* (M): 8
 - *ADB ports* (N): 24
 - *ADB ports connectable to SCs*: 0 - 24
 - *Fiber Spectrum* (C-band): 96 slot × 50 GHz.
 - For simplicity's sake, spectrum is discretized in slots of 50 GHz each)
- **SC specifications:**
 - *Client SC ports* (T): 2
 - If connected, a SC always occupies all its band!

Why $1N \div 2.5N$?

Analysis of the legacy Italian Backbone (formerly SIP/Telecom Italia) highlights an average nodal degree of 3.1 (range 2–5)

Physical consistency check

$$\sum_{v \in V} \deg(v) = 2|E|$$

Handshake Lemma guarantees that the generated links ($|E|$) strictly respect the physical limitations of ROADMs.

Seminario IEEE Photonics Society, Pavia, 27 Novembre 2009
Reti di Trasporto ottico: criteri di progetto ed esempi realizzativi

Struttura del nuovo Backbone fotonico

Schema preliminare Del nuovo backbone



- ▶ **Diametro di rete: 2400-3100 km (working-protection)**
- ▶ **Massimo numero di hop: 11**
- ▶ **Grado nodale: $2 \div 5$ (media 3.1)**

- ▶ **Tecnologia:**
- ▶ **~40 nodi a commutazione di λ basati su ROADM**
- ▶ **~60 sistemi DWDM ULH con 80 lambda**
- ▶ **Fibre G.655 e G.652**
- ▶ **Canali ottici (OCh) a 10 e 40 Gbit/s**
- ▶ **Pronto per trasmissione a 100 G**

Benchmark

1. Generate 200 random topologies (100 “national” and 100 “continental”).
2. For every possible combination of: number of SC equipped ports($\#SC \mid 0 \leq \#SC \leq 24$) \times SC bandwidth ($B_{SC} \mid B_{SC} \in \{50, 100, 150, 200, 250, 300\}$ GHz):
 - 1'. Generate demands in batches of 50 each (n. b: initial batch=100).
 - 2'. Process demands up to a *Blocking Rate* $\geq 1\%$.
 - i. Order over decreasing bitrate: bigger demands are served earlier.
 - ii. Group for src-dst couple: it maximizes grooming opportunities
 - 3'. Store total accepted capacity
3. Compare results to baseline (0 SC) to get a clearer performance analysis

Benchmark

1. Generate 200 random topologies (100 “national” and 100 “continental”).
2. For every possible combination of: number of SC equipped ports($\#SC \mid 0 \leq \#SC \leq 24$) \times SC bandwidth ($B_{SC} \mid B_{SC} \in \{50, 100, 150, 200, 250, 300\}$ GHz):
 - 1'. Generate demands in batches of 50 each (n. b: initial batch=100).
 - 2'. Process demands up to a *Blocking Rate* $\geq 1\%$.
 - i. Order over decreasing bitrate: bigger demands are served earlier.
 - ii. Group for src-dst couple: it maximizes grooming opportunities
 - 3'. Store total accepted capacity
3. Compare results to baseline (0 SC) to get a clearer performance analysis

Benchmark – Process?

We need 1000Gbps between Lamezia and Rome

1. 1st Problem: Routing. Which one of the multiple available path should we pick?
2. 2nd Problem: Transponder Selection. What OT should we pick from the catalogue?
3. 3rd Problem: Grooming. Should we use an ADB port with an SC attached or not?
4. 4th Problem: Wavelength Assignment. On what wavelength should we tune our lasers?

1. Routing



K-Shortest Paths: for each demand $K=10$ candidate routes are generated (alg. Yen), each with a specific cost:

- **Cost:** path_length

We try to route on the most economic path; if it fails due to limited spectrum, we attempt using the next one.

2. Transponder Selection

Source/Destination: random nodes (uniform).

Bitrate: 100G - 1000G (step 100G, uniform distribution).

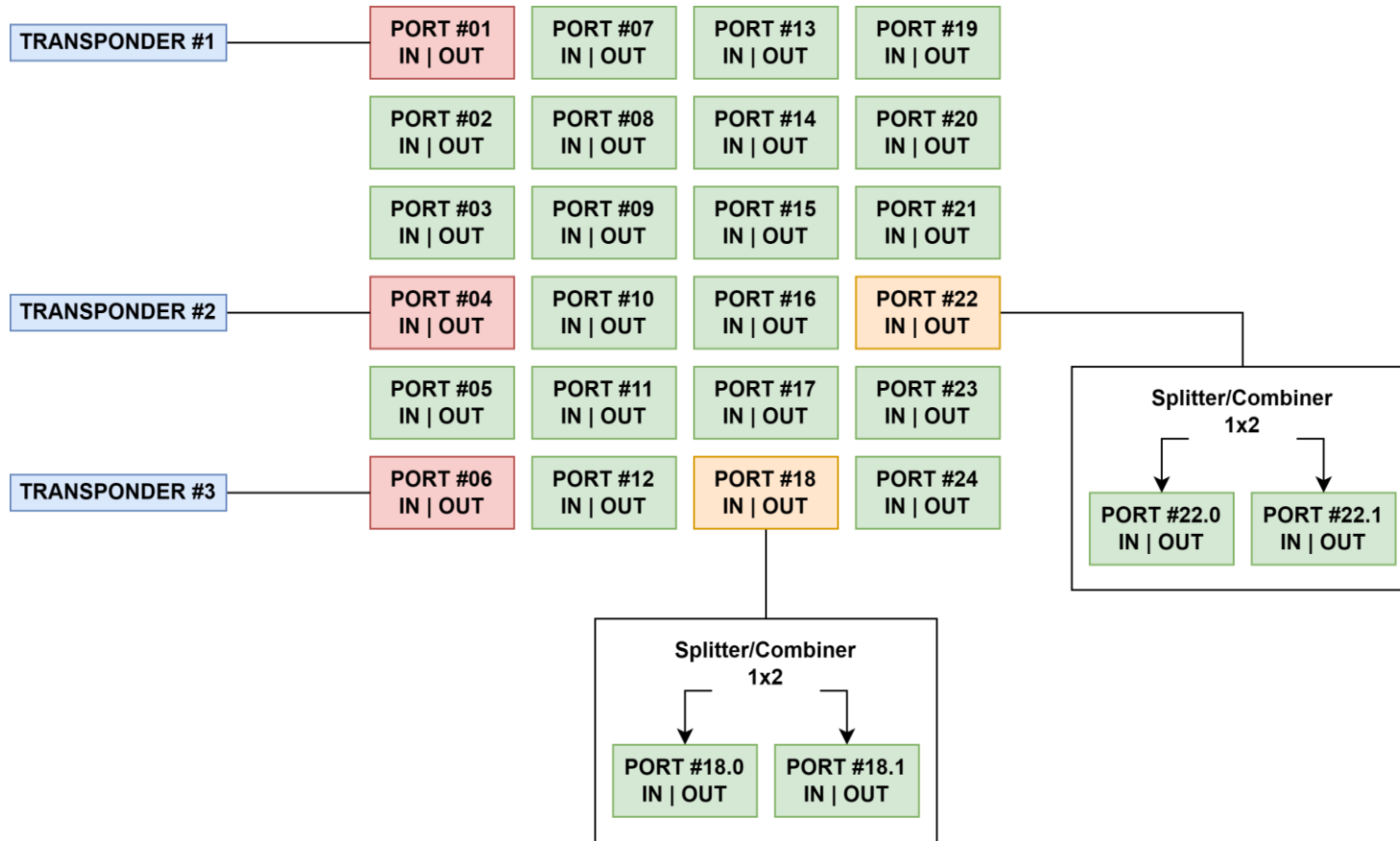
Given a demand, **OTs (Optical Transponder)** are selected based on the lightpath's length.

- Filter OTs with reach \geq route length.
- Order over decreasing spectral efficiency (Gbps/Hz).
- Reach requested capacity with the most efficient OTs.

| Data Rate (Gb/s) | Modulation format | Channel spacing Δf (GHz) | Reach (km) |
|------------------|-------------------|----------------------------------|------------|
| 800 | PCS 64 QAM | 100 | 150 |
| 700 | PCS 64 QAM | 100 | 400 |
| 600 | 16 QAM | 100 | 700 |
| 500 | PCS 16 QAM | 100 | 1300 |
| 400 | PCS 16 QAM | 100 | 2500 |
| 300 | PCS 16 QAM | 100 | 4700 |
| 300 | 64 QAM | 50 | 100 |
| 200 | 16 QAM | 50 | 900 |
| 100 | QPSK | 50 | 3000 |

1000G, 600km: 1x600Gbps (700km reach) + 1x400Gbps (2500 km reach).

3. Grooming



Where should we connect our new OTs?

3. Grooming

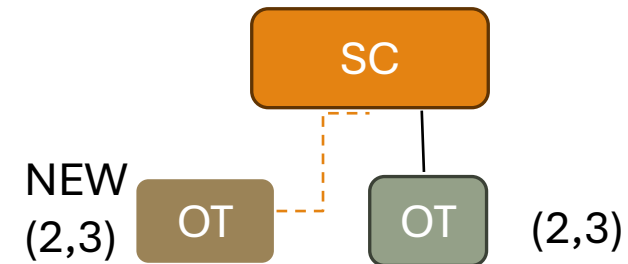
Three Strategies. If one fails, the following one is deployed.

Plan A: Grooming on already paired SCs.

Precondition: a source–destination SC pair already exists with available spectrum and client ports.

1. Search for source ports with a “paired” SC toward the destination.
2. Check residual capacity (both spectrum and customer ports).
- 2a. if more than one SC is available, fill the most occupied SCs first.
4. Connect the OT pair to the customer ports on the identified free SC.

No new allocation on fiber!



Has the demand been split into more than one OT? Are there future demands that can be aggregated?

3. Grooming



Plan B: Activation of a new SC couple.

Precondition: Ports with non "paired" SC exist (both for src and dst)

1. Find src port with free SC(non paired).
2. Find dst port with free SC (non paired).
3. Allocate SC bandwidth in the fiber.
4. Connect OT to the SC couple.
5. Register the pair for future grooming.

All the SC passband has to be allocated even with just one OT!

Failure

Plan C: Connection to a port without SC (Fallback)

Precondition: There are empty ADB ports (without SC).

1. Find empty src and dst ADB ports .
2. Allocate only the requested OT bandwidth.
3. Connect the OT directly to the port.

No aggregation is possible, but less spectral waste

Implementation

The simulation software is implemented in basically pure Python with NetworkX as the sole main dependency.



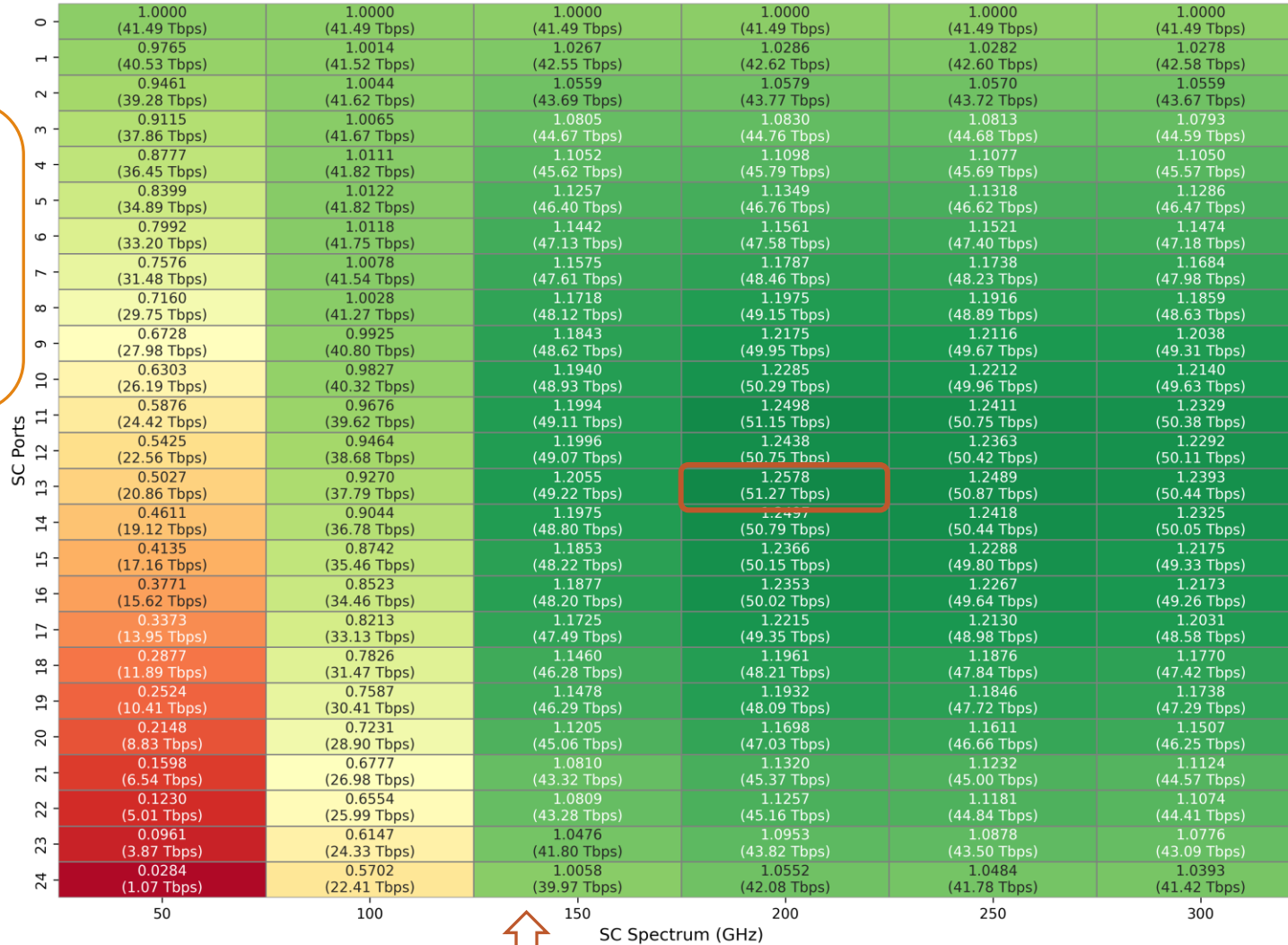
NetworkX
Network Analysis in Python



python™

Results – National Networks

Capacity Ratio - National Network
(Higher is Better)

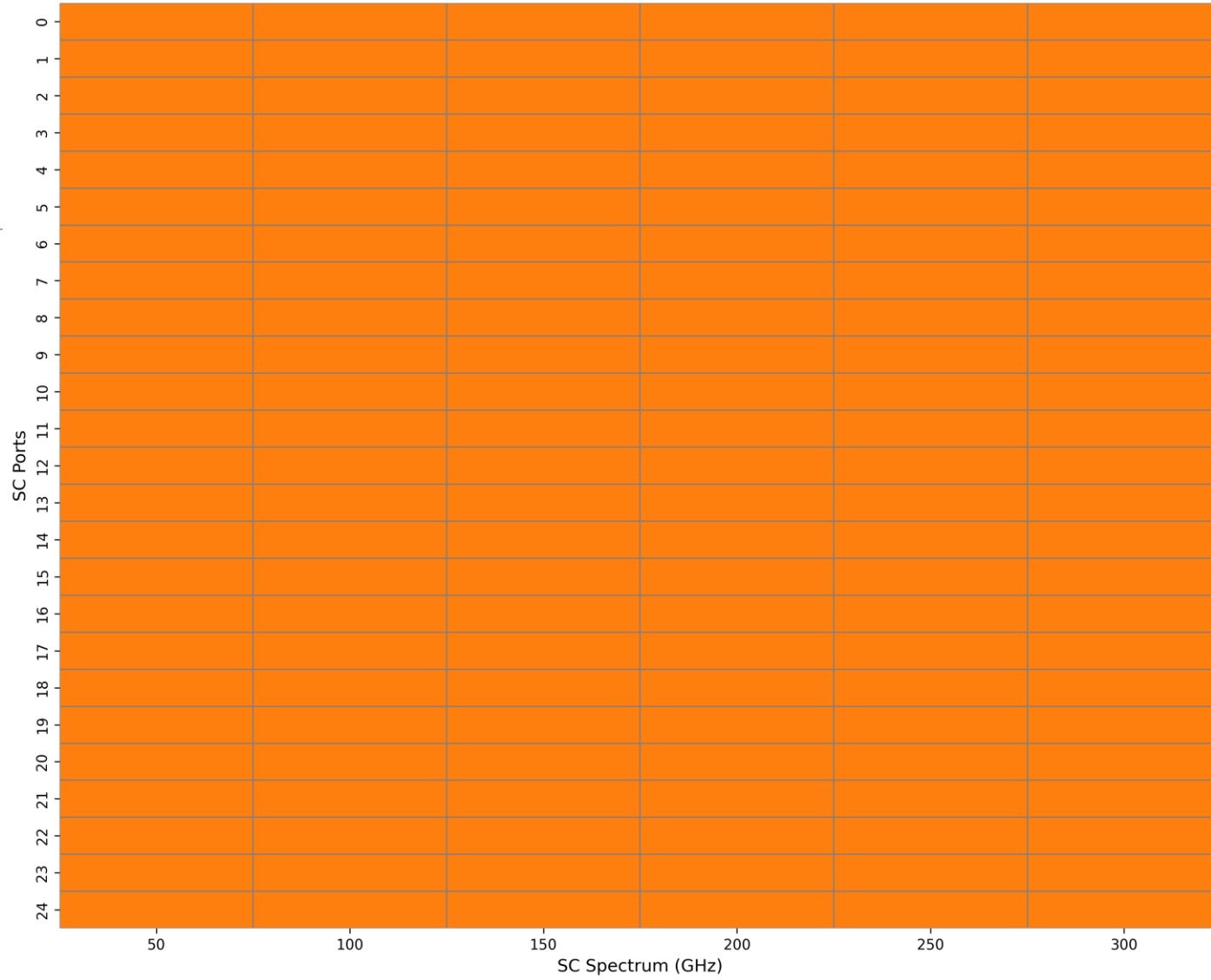


Growing improvements up to 13 ports connected to SCs

Maximum performance = 1.2578 (51.27 Tbps). Achieved with 13 ports and 200 GHz

At least 150 GHz are needed, more than 200 GHz is wasted band

Dominant Failure Type - National Network

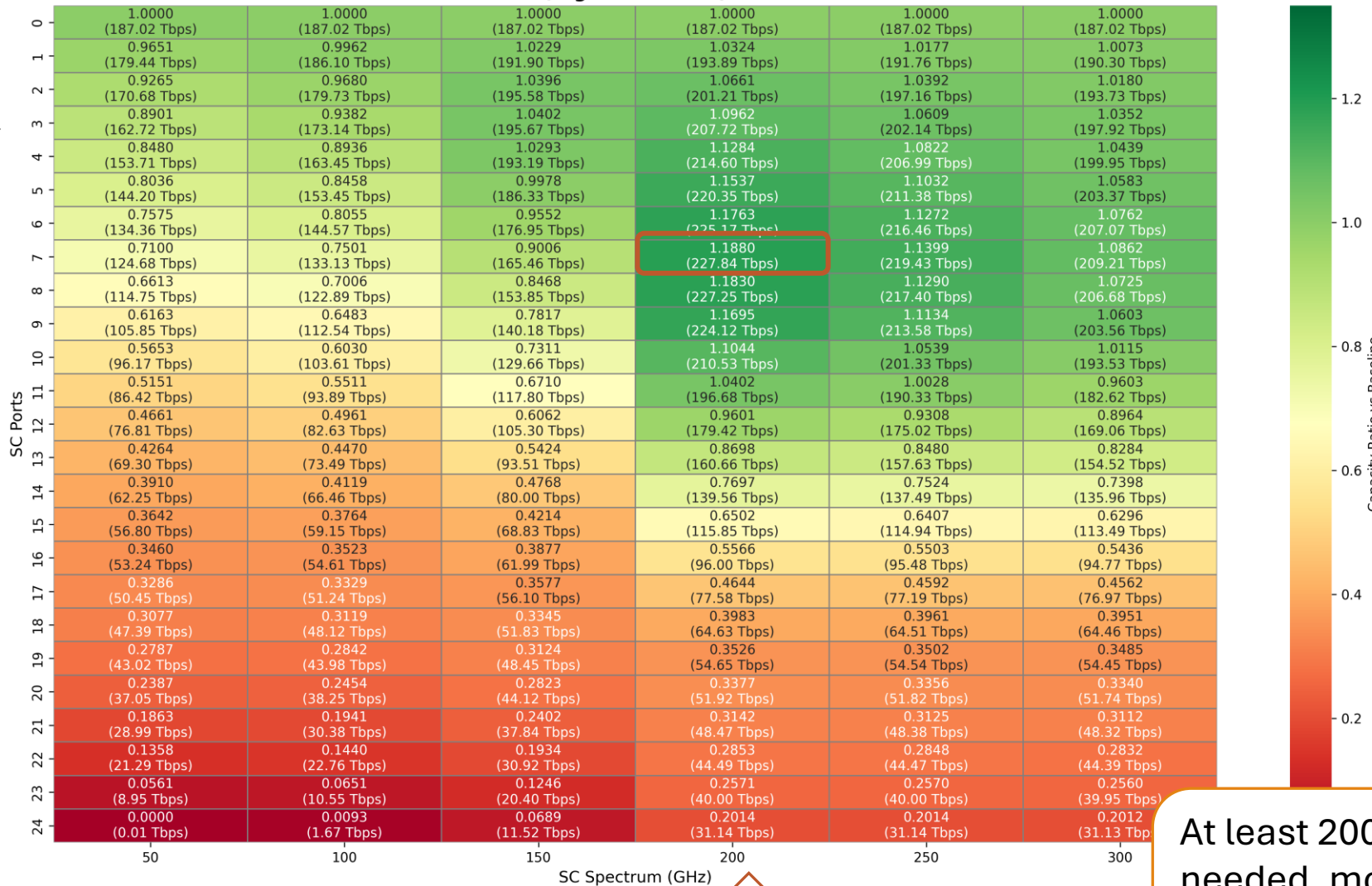


- Failure Type
- No Path/Reach
- SC Ports
- ADB Ports
- Spectrum
- Resource Combo
- Other

**All configurations
are limited by ADB
ports shortage**

Results – Continental Networks

Capacity Ratio - Continental Network
(Higher is Better)

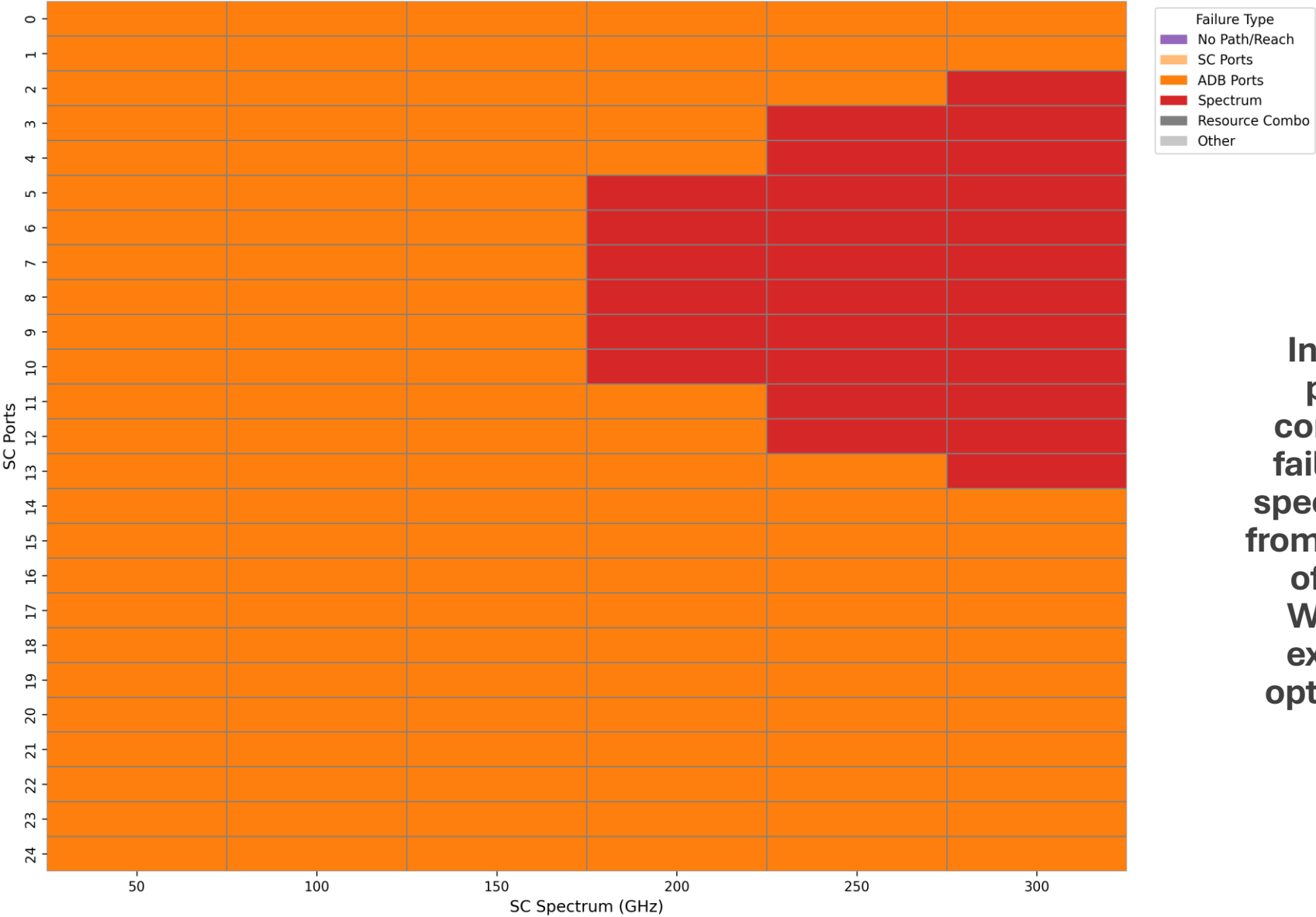


Growing improvements up to 8 ports connected to SCs

Maximum performance = 1.1880 (227.84 Tbps) Achieved with 8 ports and 200 GHz

At least 200 GHz are needed, more than that is wasted band (and is harmful to performance!!)

Dominant Failure Type - Continental Network



In the highest performing configurations, failure is due to spectrum and not from unavailability of ADB ports. We are better exploiting the optical network!

Why do national networks improve more than continental?

| | National | | Continental | | |
|---------------|----------------|-------------|----------------|-------------|--------------------|
| Demand (Gbps) | Spectrum (Ghz) | OT (Number) | Spectrum (Ghz) | OT (Number) | Demand probability |
| 100 | 50 | 1 | 50 | 1 | 0,1 |
| 200 | 50 | 1 | 50 | 1 | 0,1 |
| 300 | 100 | 1 | 100 | 1 | 0,1 |
| 400 | 100 | 1 | 100 | 1 | 0,1 |
| 500 | 100 | 1 | 100 | 1 | 0,1 |
| 600 | 100 | 1 | 100 | 1 | 0,1 |
| 700 | 100 | 1 | 100 | 1 | 0,1 |
| 800 | 100 | 1 | 150 | 2 | 0,1 |
| 900 | 150 | 2 | 150 | 2 | 0,1 |
| 1000 | 150 | 2 | 200 | 2 | 0,1 |

$$E[OT|National] = \sum_{i=1}^{10} P_i * \#OT_i = 1.2 \text{ OT/request}$$

$$E[OT|Continental] = \sum_{j=1}^{10} P_j * \#OT_j = 1.3 \text{ OT/request}$$

Node/Port ratio

- National: nodes count is comparable to ADB ports (~20 nodes vs 24 ports).
- Continental: massive discrepancy (~100 nodes vs 24 ports). The network is port-constrained at the edge.

Continental links are longer (300km vs 150km avg), increasing the probability of multi-OT demands from 20% to 30%.

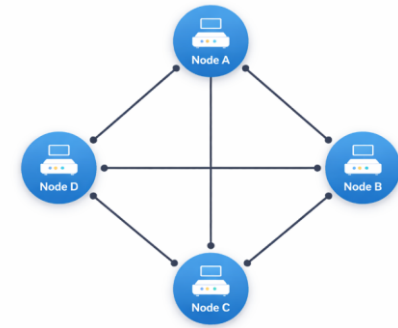
The sudden influx of traffic, combined with inefficient spectrum usage (e.g., allocating entire SC bands for single OTs), quickly clogs the core links.

Adding SCs improves performance in well-connected port-unconstrained topologies, in which the number of nodes is limited.

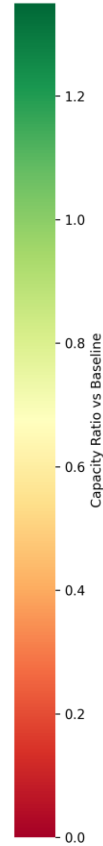
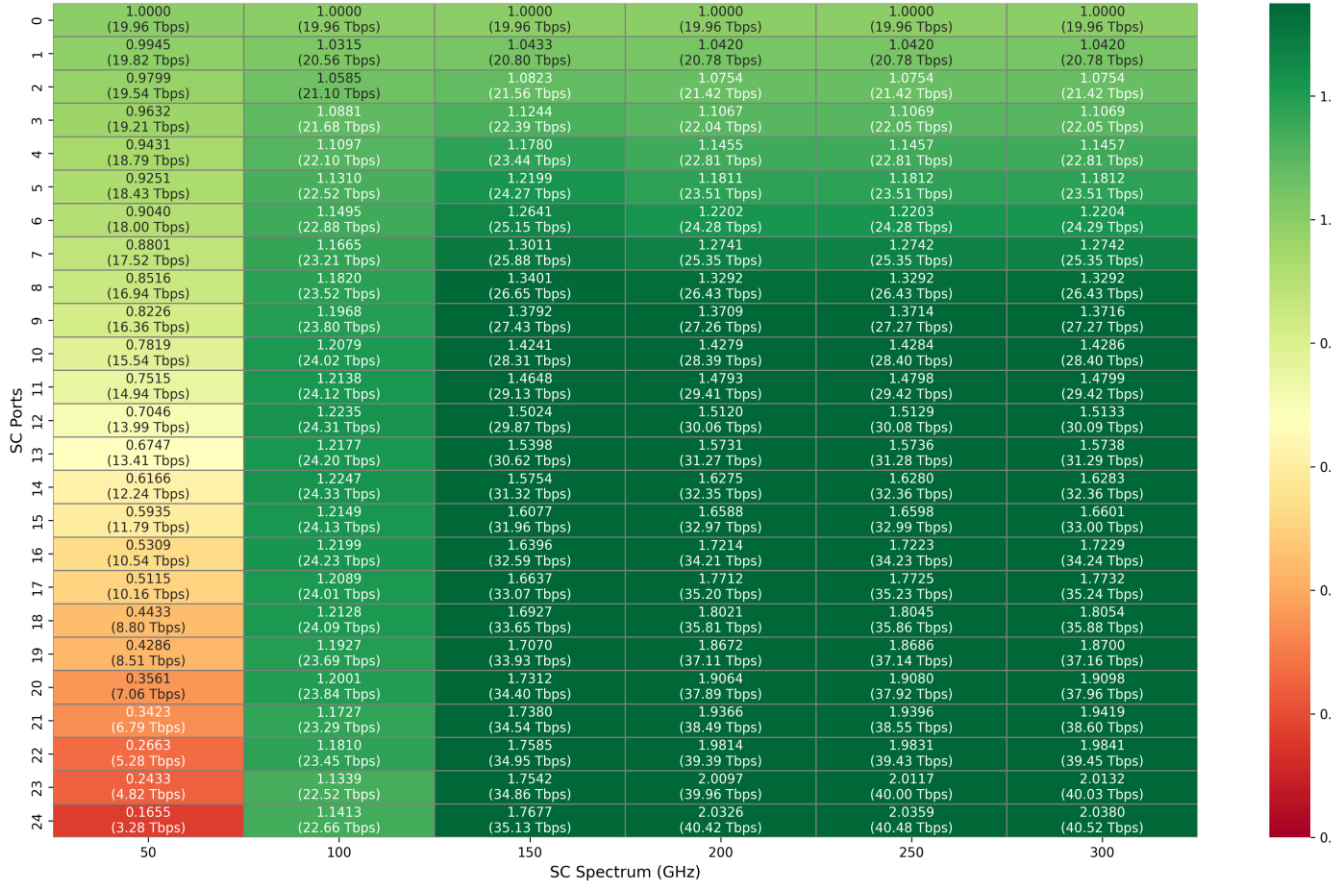
$$E[Spectrum|National] = \sum_{i=1}^{10} P_i * \#Spectrum_i = 100 \text{ GHz/request}$$

$$E[Spectrum|Continental] = \sum_{j=1}^{10} P_j * \#Spectrum_j = 110 \text{ GHz/request}$$

Theoretical limit (algorithm sanity check)



Capacity Ratio - SUPERPOP_CORE Network
(Higher is Better)



Idealized topology: a 4-node fully meshed network designed to eliminate routing bottlenecks and isolate the grooming performance.

The 2x multiplier: since each evaluated SC provides exactly 2 client ports, the absolute maximum theoretical capacity gain is intrinsically capped at 2x.

Validation passed: the heatmap confirms our algorithm efficiently aggregates Ots without premature spectrum failure, peaking at Capacity Ratio of ≈ 2.03 . This convergence to the theoretical limit proves the routing and grooming logic works exactly as intended before scaling to complex deployments.

Conclusions and Future works



With our implementation:
+25% for national networks
+19% for continental networks
What else could be tried out?

- Another degree of freedom: number of ADB ports/nodes degree
Would we get the same results with 16-degree nodes?
- More accurate/case study specific traffic model
- Capacity Gain/Hardware Cost study
in which cases using SCs is monetarily worth it?