Optical Networking Gym

an overview

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Agenda

- Quality-of-transmission-aware resource assignment in optical networks
- What and why “gym”?
- Tool overview
- Use cases
  - Launch power optimization
  - Quality-of-transmission-aware resource assignment algorithms in elastic optical networks
  - Generation of datasets for ML
- Open challenges & opportunities
- Final remarks

Disclaimer

Optical Networking Gym: An Open-Source Toolkit for Resource Assignment Problems in Optical Networks

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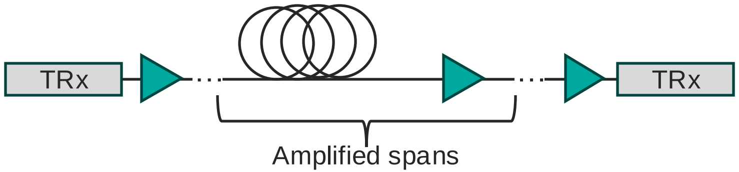
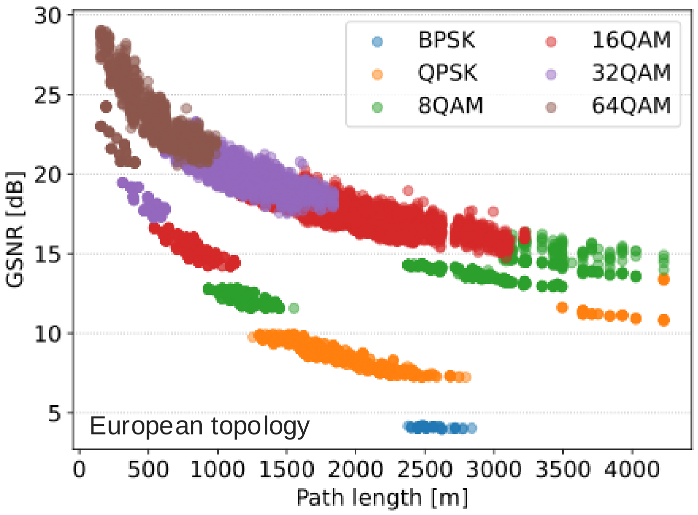
https://research.chalmers.se/en/publication/543769

QoT-Aware Resource Assignment in Elastic Optical Networks

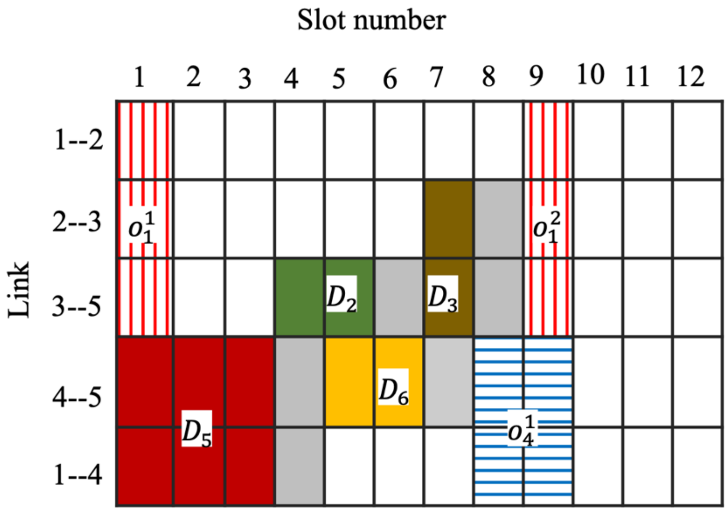
- Elastic optical networks enable the provisioning of lightpaths with variable bandwidth and modulation format
- Modulation format can be defined as a function of
  - Path length/distance
  - Generalized Signal-to-Noise Ratio (GSNR)
- The GSNR can be calculated using several alternatives:
  - Split-step Fourier method (SSFM)
  - Integral-based methods (e.g., Gaussian Noise model - GN)
  - Closed-form analytical models (e.g., Enhanced Gaussian Model – EGN)
  - Machine learning (ML)





Research areas & solutions

- Network planning/dimensioning
  - Design a network based on an estimated capacity
  - Solutions: heuristics, meta-heuristics, and optimization models
- Network operation
  - Lightpath provisioning
  - Network re-optimization
  - Defragmentation *
  - Solutions: heuristics, meta-heuristics, optimization, and reinforcement learning



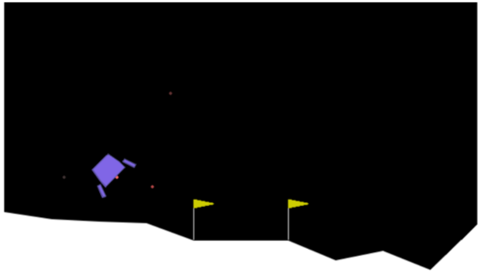
*Etezadi, JOCN, 2023.

What is a “gym”? 1/3

- Open AI Gym ➔ Gymnasium

Gymnasium

An API standard for reinforcement learning with a diverse collection of reference environments

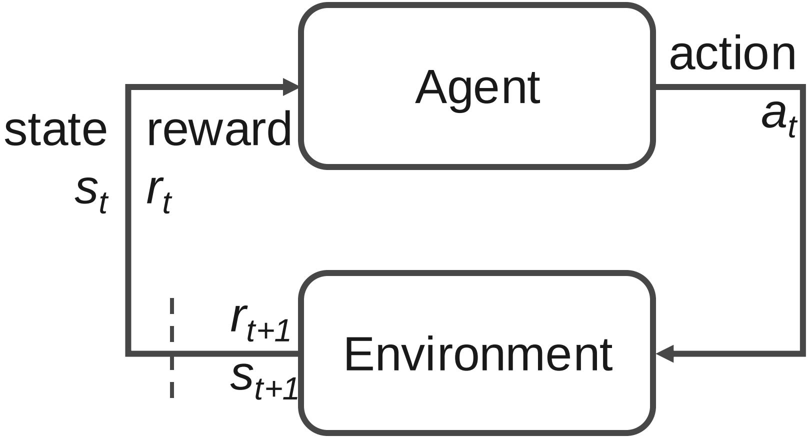


```python
import gymnasium as gym

# Initialise the environment
env = gym.make("LunarLander-v3", render_mode="human")

# Reset the environment to generate the first observation
observation, info = env.reset(seed=42)
for _ in range(1000):
    # this is where you would insert your policy
    action = env.action_space.sample()

    # step (transition) through the environment with the action
    # receiving the next observation, reward and if the episode has terminated or truncated
    observation, reward, terminated, truncated, info = env.step(action)

    # If the episode has ended then we can reset to start a new episode
    if terminated or truncated:
        observation, info = env.reset()

env.close()
```

https://gymnasium.farama.org

Why build a new “gym”? 2/3

- 2018-2020:
  - Interest in reinforcement learning
  - Lack of standard tools and resources
  - Difficulty to build and/or use custom-made code
  - Challenges from needing to build the agent and the environment



The Optical RL-Gym: an open-source toolkit for applying reinforcement learning in optical networks

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C. Natalino, Proc. Of ICTON, 2020.

Why build a new “gym”? 2/2

- 2022-2024:
  - Lack of well-documented, good Python simulators for optical networks
  - Lack of well-documented analytical models for optical networks
  - The gym interface is also suitable for general-purpose simulations

```python
import gymnasium as gym

# Initialise the environment
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env.close()
```

Policy can be anything, not only RL

https://gymnasium.farama.org

Why build a new “gym”? 3/3

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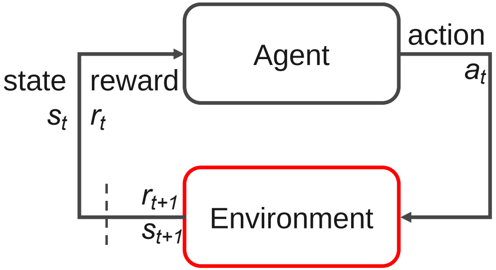
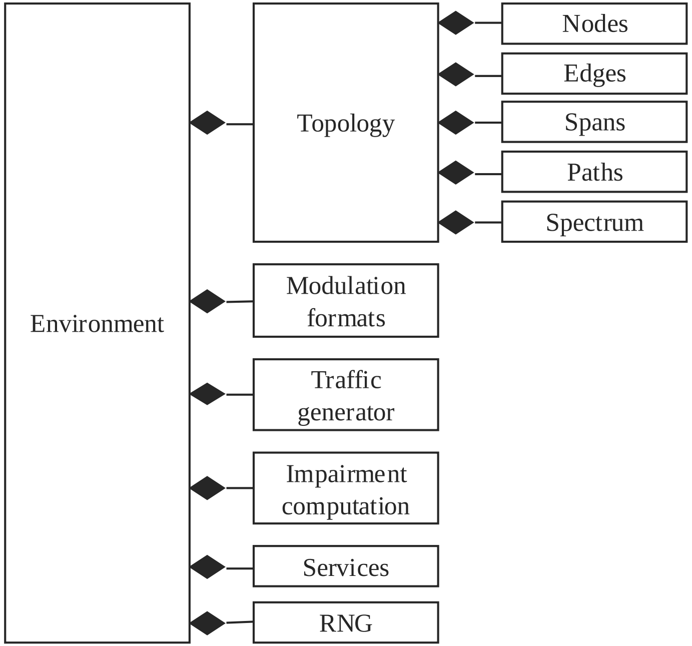
https://opg.optica.org/content/feature/announcement/item/jocn-bon/

Tool overview

High-level architecture

- Environment that encompasses an optical network
  - Elastic optical network in our case today
- Python and Cython
  - Familiarity of Python
  - Speed of Cython





Interface

Listing 1. Interface of an Optical Networking Gym (ONG) environment.

```
from typing import Any, SupportsFloat

import gymnasium as gym

class OpticalEnv(gym.Env[ObsType, ActType]):

    def __init__(self, **kwargs):
        # initialization

    def step(self, action: ActType) -> tuple[ObsType, SupportsFloat, bool, bool, dict[str, Any]]:
        # implementation
        return observation, reward, terminated, truncated, info

    def reset(self,
        *,
        seed: int | None = None,
        options: dict[str, Any] | None = None,
    ) -> tuple[ObsType, dict[str, Any]]:
        # implementation
        return observation, info

    def render(self) -> RenderFrame | list[RenderFrame] | None:
        # implementation

    def close(self) -> None:
        # implementation
```

Illustrative example

Listing 2. Illustrative use of the adopted environment interface.

```
env = OpticalEnv(env_kwargs)
algo = Algorithm(alg_kwargs)
obs, info = env.reset(seed=42)
for episode in range(1000):
    while not (term or trunc):
        action = algo.solution(obs)
        obs, rew, term, trunc, info \
            = env.step(action)
    obs, info = env.reset()
env.close()
```

Enhanced Gaussian Noise model implementation

$$G_{\mathrm{NLI}}^{\mathrm{Rx}}\left(f_{\mathrm{CUT}}\right)=\sum_{n=1}^{N_{\mathrm{span}}}\left(G_{\mathrm{NLI}}^{(n)}\left(f_{\mathrm{CUT}}\right)\prod_{k=n+1}^{N_{\mathrm{span}}}\Gamma^{(k)}(f_{\mathrm{CUT}})\cdot e^{-2\cdot\alpha^{(k)}\left(f_{\mathrm{CUT}}\right)\cdot L_{\mathrm{span}}^{(k)}}\right) \tag{1}$$

$$G_{\mathrm{NLI}}^{(n)}\left(f_{\mathrm{CUT}}\right)=\frac{16}{27}(\gamma^{(n)})^2\,\Gamma^{(n)}(f_{\mathrm{CUT}})\cdot e^{-2\alpha^{(n)}\left(f_{\mathrm{CUT}}\right)\cdot L_{\mathrm{span}}^{(n)}}\cdot\bar{G}_{\mathrm{CUT}}^{(n)}\cdot\left(\rho_{\mathrm{CUT}}^{(n)}\cdot\left[\bar{G}_{\mathrm{CUT}}^{(n)}\right]^2 I_{\mathrm{CUT}}^{(n)}+\sum_{n_{\mathrm{ch}}=1\ ,\ n_{\mathrm{ch}}\neq n_{\mathrm{CUT}}^{(n)}}^{N_{\mathrm{ch}}^{(n)}}2\rho_{n_{\mathrm{ch}}}^{(n)}\cdot\left[\bar{G}_{n_{\mathrm{ch}}}^{(n)}\right]^2 I_{n_{\mathrm{ch}}}^{(n)}\right) \tag{2}$$

$$I_{\mathrm{CUT}}^{(n)}=\frac{1}{2\pi\mid\bar{\beta}_{2,\mathrm{CUT}}^{(n)}\mid\cdot2\alpha^{(n)}(f_{\mathrm{CUT}})}\cdot\mathrm{asinh}\left(\frac{\pi^2}{2}\left|\frac{\bar{\beta}_{2,\mathrm{CUT}}^{(n)}}{2\alpha^{(n)}(f_{\mathrm{CUT}})}\right|R_{\mathrm{CUT}}^2\right) \tag{3}$$

$$I_{n_{\mathrm{ch}}}^{(n)}=\frac{\mathrm{asinh}\left(\pi^2\left|\frac{\bar{\beta}_{2,n_{\mathrm{ch}}}^{(n)}}{2\alpha^{(n)}\left(f_{n_{\mathrm{ch}}}^{(n)}\right)}\right|\left[f_{n_{\mathrm{ch}}}^{(n)}-f_{\mathrm{CUT}}+\frac{R_{n_{\mathrm{ch}}}^{(n)}}{2}\right]R_{\mathrm{CUT}}\right)-\mathrm{asinh}\left(\pi^2\left|\frac{\bar{\beta}_{2,n_{\mathrm{ch}}}^{(n)}}{2\alpha^{(n)}\left(f_{n_{\mathrm{ch}}}^{(n)}\right)}\right|\left[f_{n_{\mathrm{ch}}}^{(n)}-f_{\mathrm{CUT}}-\frac{R_{n_{\mathrm{ch}}}^{(n)}}{2}\right]R_{\mathrm{CUT}}\right)}{4\pi\left|\bar{\beta}_{2,n_{\mathrm{ch}}}^{(n)}\right|\cdot2\alpha^{(n)}\left(f_{n_{\mathrm{ch}}}^{(n)}\right)} \tag{4}$$

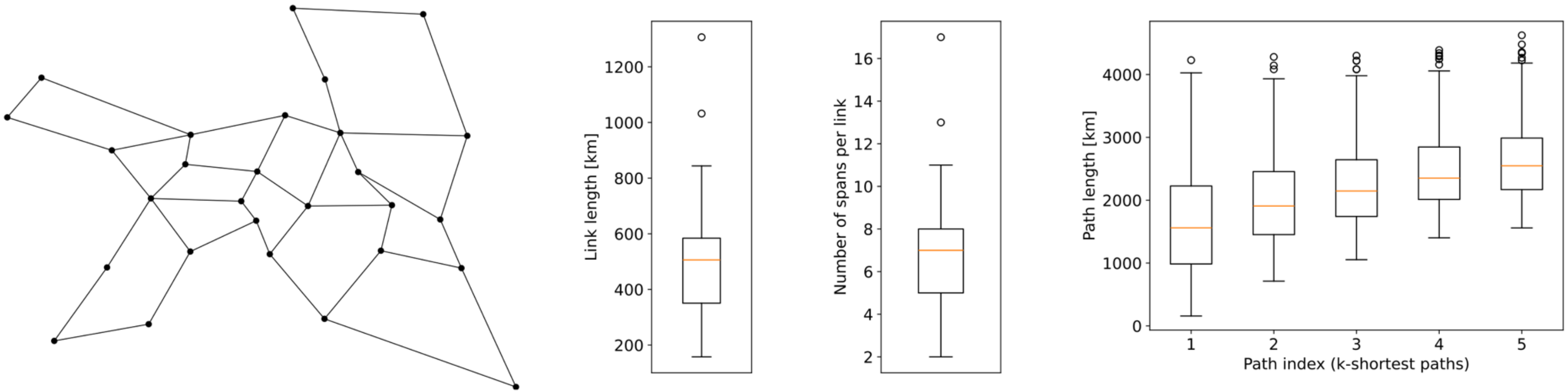
$$\bar{\beta}_{2,\mathrm{CUT}}^{(n)}=\beta_2^{(n)}+\pi\beta_3^{(n)}\left[2f_{\mathrm{CUT}}-2f_c^{(n)}\right]\quad,\quad\bar{\beta}_{2,n_{\mathrm{ch}}}^{(n)}=\beta_2^{(n)}+\pi\beta_3^{(n)}\left[f_{n_{\mathrm{ch}}}^{(n)}+f_{\mathrm{CUT}}-2f_c^{(n)}\right] \tag{5}$$

Ranjbar Zefreh, JLT, 2020.

Use cases

Scenario

Use cases

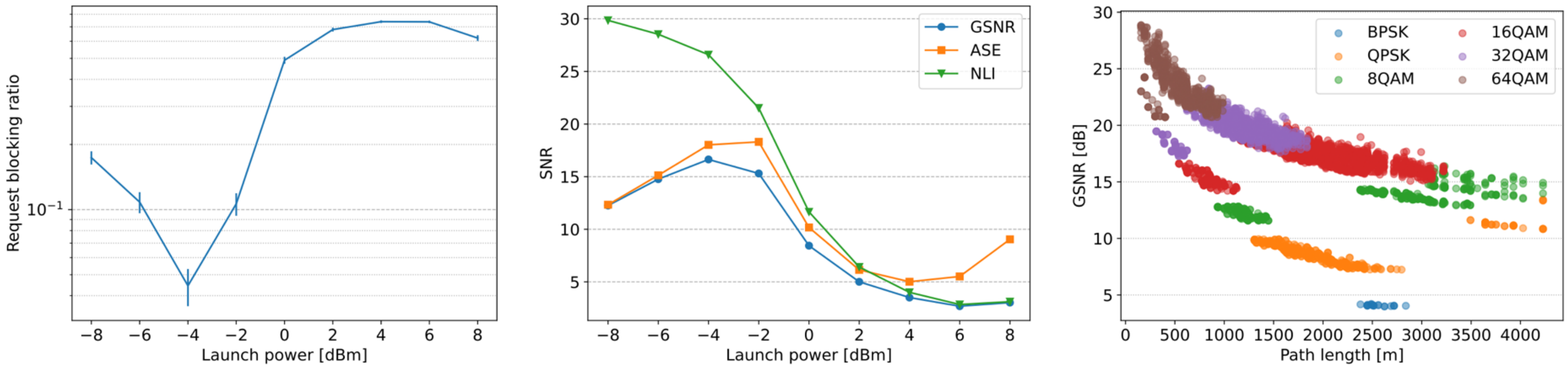


(a) Topology **(b)** Link length **(c)** Spans per link **(d)** Path length per shortest path

Fig. 2. The European network topology with link and path length distributions.

Launch power optimization

Use cases

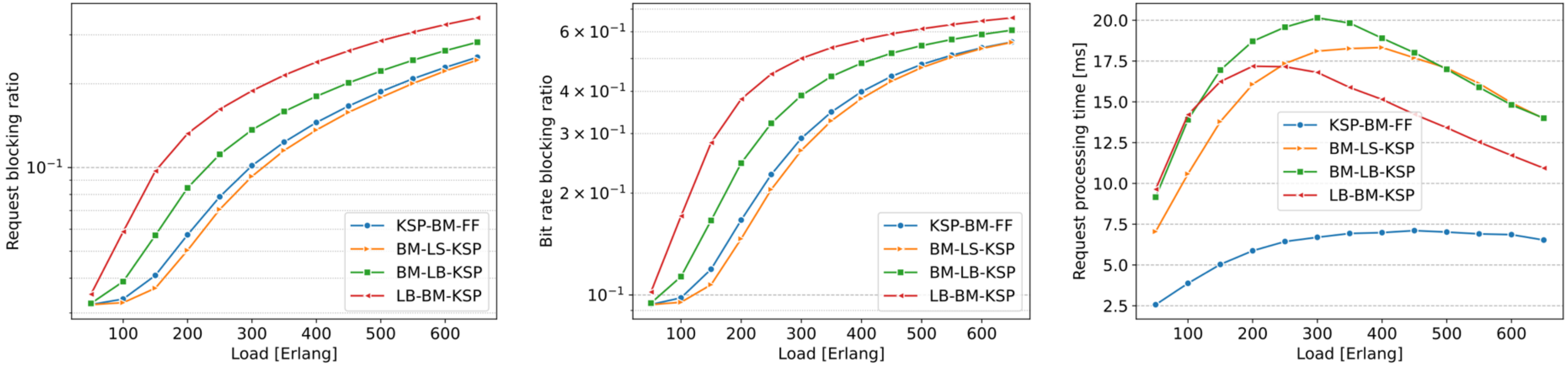


(a) Request blocking ratio **(b)** Generalized signal-to-noise ratio (GSNR) **(c)** GSNR vs. path length for launch power of -4 dBm

Fig. 3. Impact of the launch power on the overall request blocking rate for the European topology considering a load of 210 Erlang.

Benchmarking QoT-Aware Dynamic RMSA Algorithms

Use cases

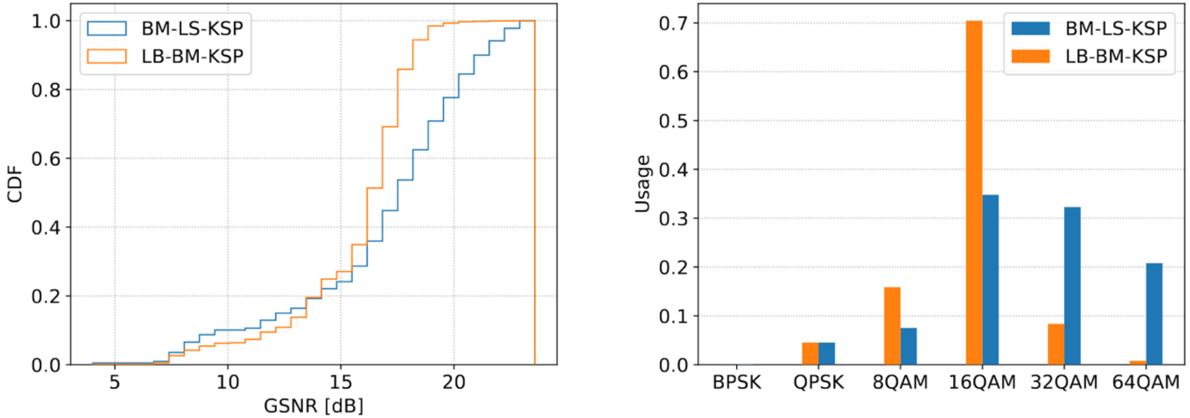


(a) Request blocking rate (b) Bit rate blocking ratio (c) Average step time

Fig. 4. Analysis of the RMSA heuristics over the offered load for the European topology with -8 dBm as the launch power.

Generation of datasets for AI/ML

Use cases



(a) Cummulative distribution function (CDF) of the GSNR

(b) Modulation format usage

Fig. 5. Statistical analysis of the dataset generated by the ONG for the European topology with 210 Erlang load and -8 dBm as the launch power.

Open challenges & opportunities 1/2

1. How to manage the margin in an optical network?
   - A single margin for all lightpaths? Custom link penalties?
2. How to adapt the model to an evolving/aging/time-varying optical network?

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Lifelong QoT prediction: an adaptation to real-world optical networks

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RESEARCH ARTICLE

Integrating Knowledge Distillation and Transfer Learning for Enhanced QoT-Estimation in Optical Networks

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Domain adversarial adaptation framework for few-shot QoT estimation in optical networks

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Open challenges & opportunities 2/2

- Dynamic operation of elastic optical networks
  - Per-span power optimization
  - Consideration of more detailed physical layer aspects such as amplifier tilt
  - Spectrum defragmentation algorithms
  - Use of specific-purpose analytical models
  - Use of more precise analytical models
- Dynamic operation of multi-band optical networks
- Dynamic operation of multi-core optical networks

Reflection

How and what can I open-source as a result of my PhD?

Relevant references

- Pointurier, Yvan. "Design of low-margin optical networks." Journal of Optical Communications and Networking 9.1 (2017): A9-A17.
- C. Natalino and P. Monti, "The Optical RL-Gym: An open-source toolkit for applying reinforcement learning in optical networks," *2020 22nd International Conference on Transparent Optical Networks (ICTON)*, Bari, Italy, 2020, pp. 1-5, doi: 10.1109/ICTON51198.2020.9203239.
- M. Ranjbar Zefreh, F. Forghieri, S. Piciaccia and P. Poggiolini, "Accurate Closed-Form Real-Time EGN Model Formula Leveraging Machine-Learning Over 8500 Thoroughly Randomized Full C-Band Systems," in *Journal of Lightwave Technology*, vol. 38, no. 18, pp. 4987-4999, 15 Sept.15, 2020, doi: 10.1109/JLT.2020.2997395.
- E. Etezadi *et al*., "Deep reinforcement learning for proactive spectrum defragmentation in elastic optical networks," in *Journal of Optical Communications and Networking*, vol. 15, no. 10, pp. E86-E96, October 2023, doi: 10.1364/JOCN.489577.
- Natalino, Carlos, et al. "Combining ML Regression and Classification for Reliable QoT-Aware Lightpath Provisioning in Elastic Optical Networks." Proc. Of SBRT, Oct. 2024, Belém, Pará, Brasil.
- C. Natalino et al., "Optical Networking Gym: an open-source toolkit for resource assignment problems in optical networks," in Journal of Optical Communications and Networking, vol. 16, no. 12, pp. G40-G51, December 2024, doi: 10.1364/JOCN.532850.
- F. Arpanaei *et al*., "Synergizing Hyper-accelerated Power Optimization and Wavelength-Dependent QoT-Aware Cross-Layer Design in Next-Generation Multi-Band EONs," in *IEEE Journal on Selected Areas in Communications*, doi: 10.1109/JSAC.2025.3543528.
- https://gymnasium.farama.org
- https://github.com/openai/gym
- https://github.com/carlosnatalino/optical-networking-gym

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