Amplifier Control using Machine Learning in Optical Networks

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Outline

- Towards Flexible Optical Networks
- Power Excursion Issue in Optical Networks
- Amplifier Control using Machine Learning in Optical Networks
  - Power Excursion Prediction
  - Power Excursion Pre-compensation using Reinforcement Learning
  - BER and OSNR aware Modulation and Wavelength Assignment under Reinforcement Learning Control
- Conclusion

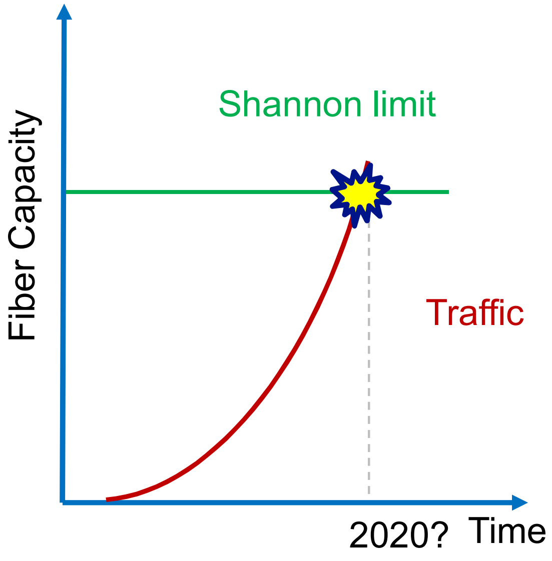
Towards Flexible Optical Networks

Main Challenges in Optical Networks

- ❑ Power consumption increase

- ❑ Exponential Increase of the Traffic
  - 3D, HD, VoD, Streaming, Cloud, etc.
  - IoT, 5G, etc.

- ❑ Efficient use of the fiber capacity and the resources of the networks
  - WDM and SDM techniques
  - Complex modulation formats
  - Spectrum Management
  - Network dimensioning



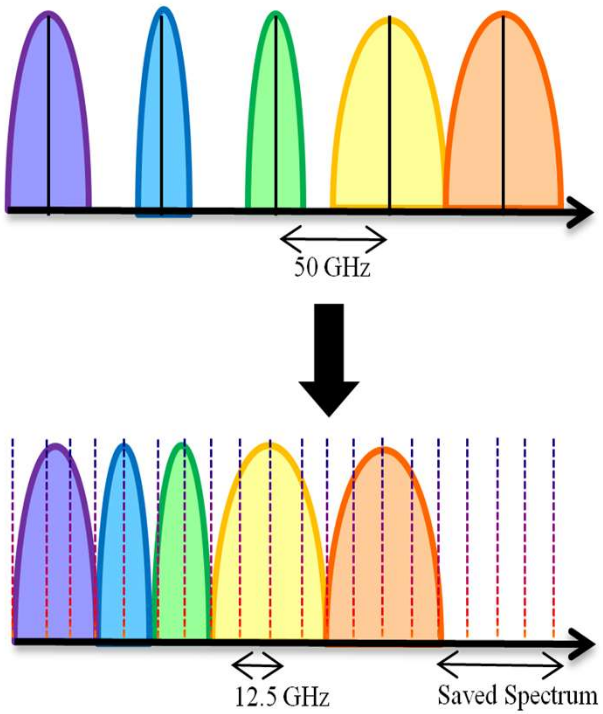
Flexible Optical Networks

Flexi-Rate

- Adapt the channel to demand requirements
  - Symbol rate, modulation format
  - Reach, spectrum, energy

Flex-Grid

- Frequency slots of 12.5 GHz
- Lower granularity
  - 25% = saved spectrum
  - Compatible with freq. channel spacing > 50 GHz



Optical Network Flexibility and Dynamics Impact on Devices

- For any given connection at a specific bitrate
  - Reconfigurable Optical Add/Drop multiplexers (ROADMs) with Wavelength Selective Switch [1]
  - Band Variable Transponders [2]: Modulation format selection is performed accounting for:
    - Minimum occupied spectrum
    - Optical reach (which depends on the path, on the modulation format…)
  - EDFA with varying channel load at its input
    - Mean input optical power change [3]
    - Fragmentation issue [4]
    - Optical Power Excursion Issue

1. D. Marom et al., Survey of Photonic Switching Architectures and Technologies in Support of Spatially and Spectrally Flexible Optical Networking, JOCN vol 9 N°1, 2017
2. M. Jinno et al., Multiflow Optical Transponder for Efficient Multilayer Optical Networking, IEEE Comm. Magazine 2012
3. D. Amar et al., "Optical power aware network dimensioning and link design in flexgrid optical networks," Photonics in Switching 2015
4. D. Amar et al., "Traffic forecast impact on spectrum fragmentation in gridless optical networks," ECOC 2014.

Power Excursion Issue in Optical Networks

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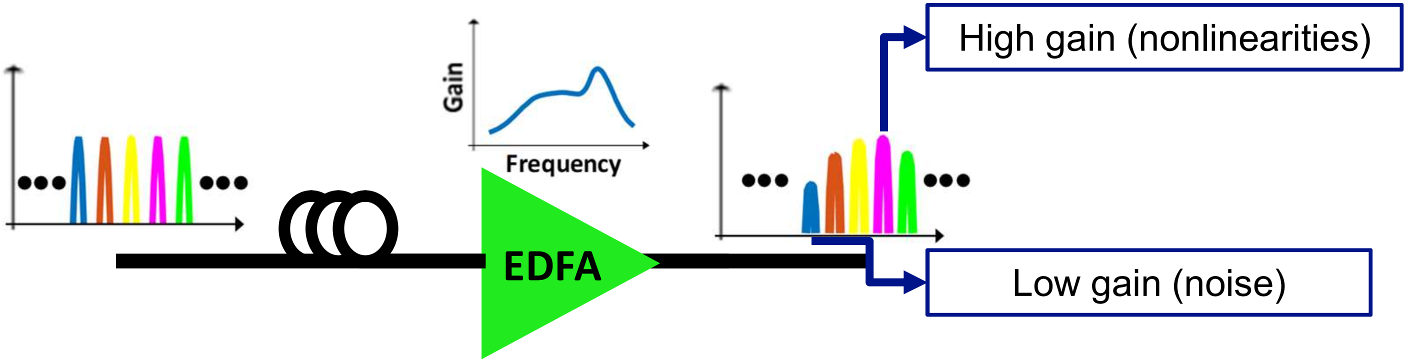
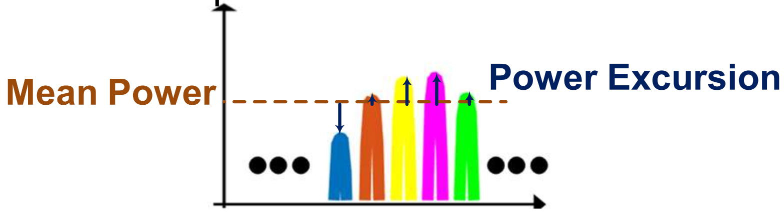
Power Excursion Issue

- **Gain and Noise Figure spectrum of EDFAs are wavelength dependent**

→ Impact in optical networks, with WDM channels undergoing different power excursions

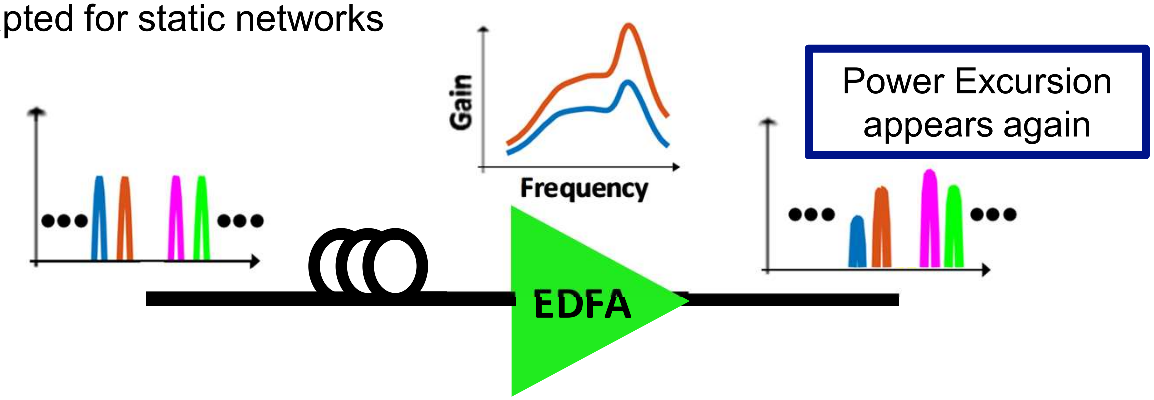


- **Power excursion:** Difference between the mean channel power and the actual channel power



Power Excursion Control in Optical Networks

- Output power level of EDFAs can be controlled via **Automatic Gain Control (AGC)** which maintains constant the global mean gain
- **Gain flattening techniques to overcome** disparity among channel powers during add/drop process
  - Well-adapted for static networks



To Summarize

- Dynamic gain equalization filters allow operation of EDFAs with constant ACG but does not solve optical power excursion problem

  → Mean global optical gain at each EDFA is maintained constant whatever the number of established wavelengths but the gain of each individual channel is wavelength dependent.

- The wavelength dependence of EDFA channel gain can increase the optical power excursion even stronger with Flex-Grid technology where connections occupy different optical bandwidths depending on their symbol rates.

  → Optical Power Excursion varies from one connection to another one.

- To solve power excursion problem, analytical methods have been implemented based on the prior knowledge of one specific network. What happens in dynamically changing networks?

  → Machine Learning techniques seem well-adapted to deal with the flexibility and the dynamicity of the future optical networks [5]

5. Huang Y S et al. A machine learning approach for dynamic optical channel add/drop strategies that minimize EDFA power excursions, Proceedings of ECOC, 2016.

Amplifier Control using Machine Learning in Optical Networks

Power Excursion Prediction

Machine Learning in Optical Networks

Network layer domain

- Traffic prediction
- Virtual topology design
- Failure management
- Path computation

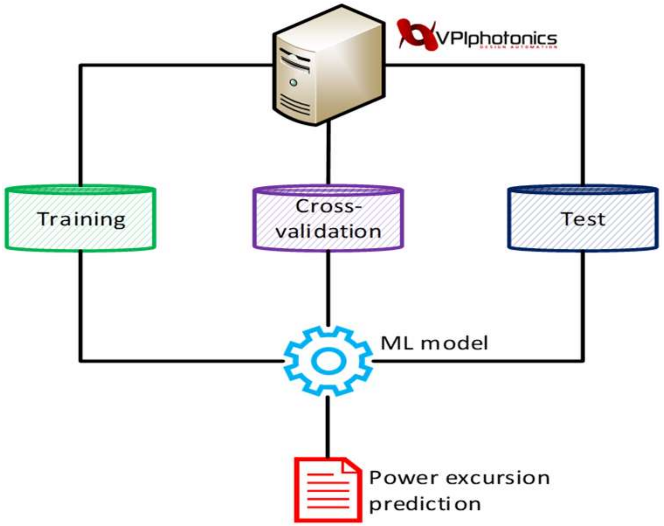
Physical layer domain

- Quality of Transmission (QoT) estimation
- Modulation format recognition
- Nonlinearity mitigation
- Optical performance monitoring
- Optical amplifier control

[6] Musumeci F.et al.. An overview on application of machine learning techniques in optical networks. *IEEE Communications Surveys & Tutorials*.

Power Excursion Prediction based on Neural Networks

Power Excursion prediction: output optical power post-compensation or input optical power pre-distortion

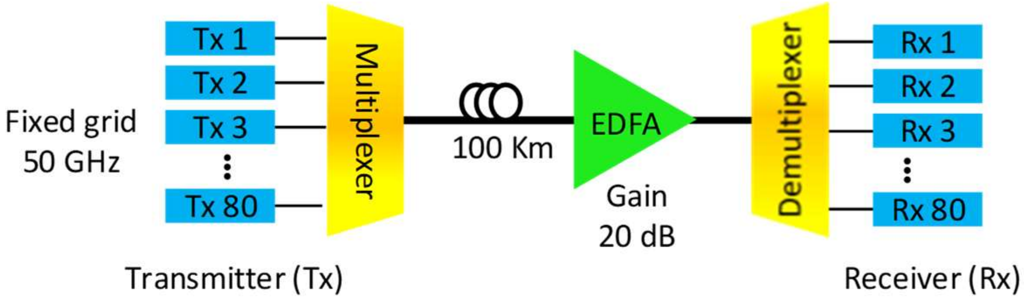


- **Overview:**
  - Training, cross-validation and test dataset using VPI Photonics, an advanced software for simulation of optical communication systems
  - Training and cross-validation of the Machine learning module
  - Test of the prediction of the optical power excursion with part of the dataset not used for the training and the cross-validation

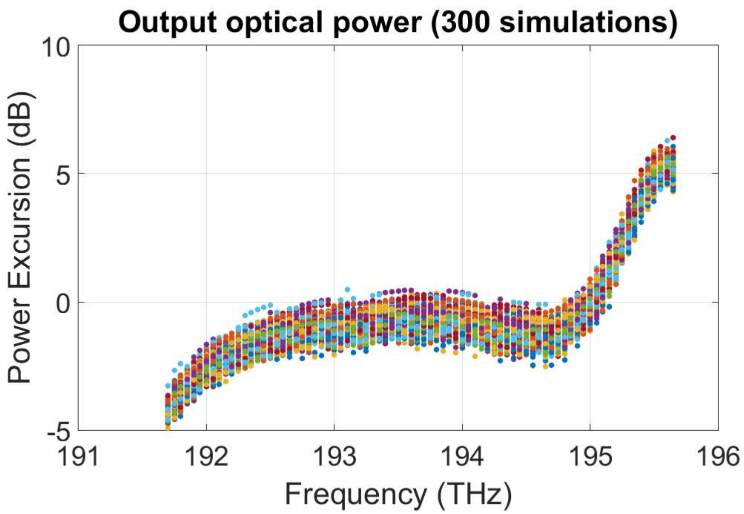
7. M.Freire et al., Predicting Optical Power Excursions in Erbium Doped Fiber Amplifiers using Neural Networks, Proceedings ACP2018

Dataset Generation

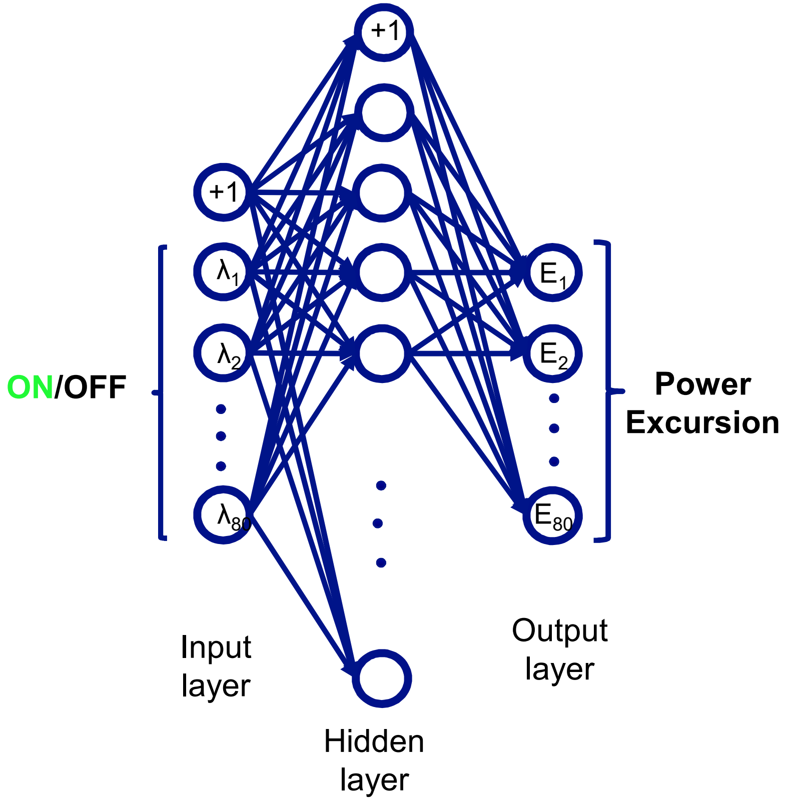
WDM System



- Dataset (300 simulations)
  - Channel load from 40% to 87.5%
  - Data stored in every simulation
    - Input feature vector for each channel (active or not)
    - Output vector representing the power excursion for each channel

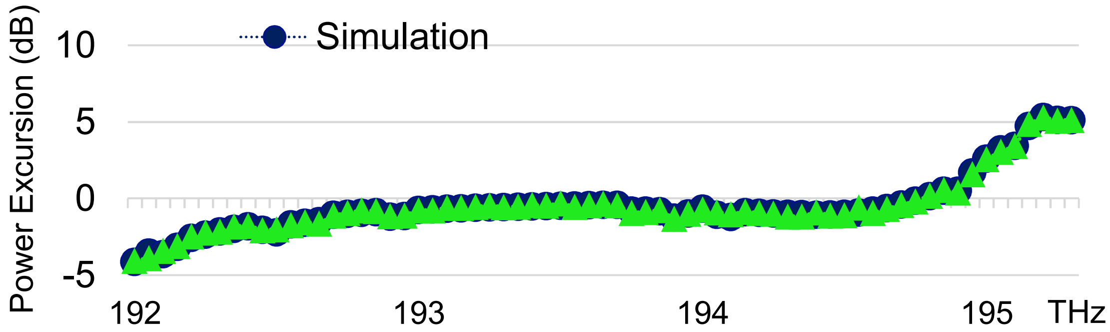


Machine Learning Module

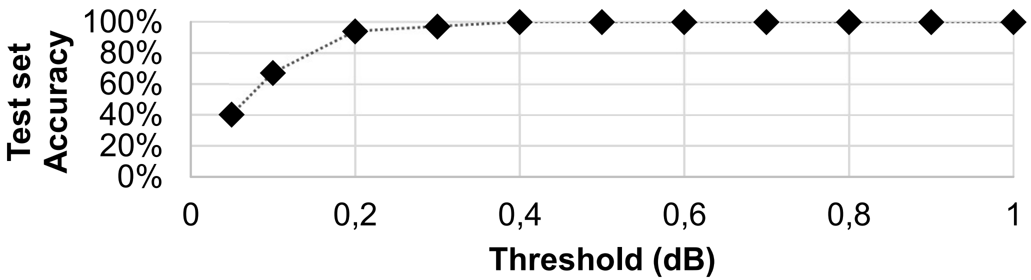


- Machine learning model based on Neural Networks, developed in Keras, to predict power excursion
- Structure: Neural Network (160 neurons in the hidden layer)
  - Hidden layer: ReLU (Rectified Linear Unit) activation
  - Output layer: linear activation
- Optimization: Stochastic Gradient Descent, batch size 10 % of the training dataset

Test: Simulated vs Predicted Power Excursion using Machine Learning Model



- Test set accuracy vs minimum acceptable difference between the simulated values and the predicted values
- 90% accuracy for 0.2 dB threshold



Optical Amplifier Control using Machine Learning

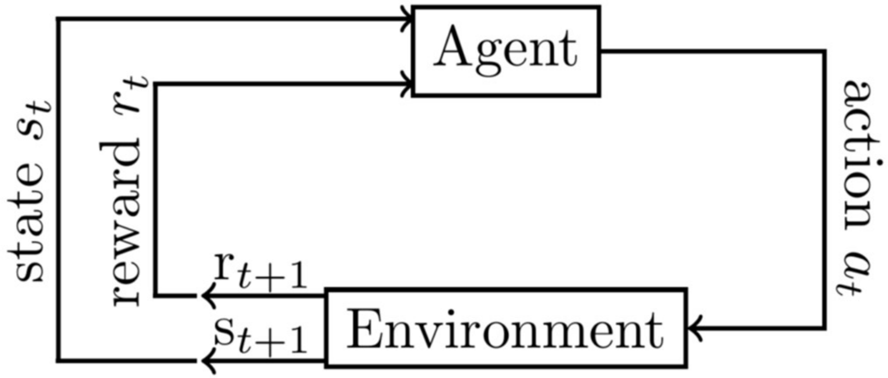
Power Excursion Pre-compensation using Reinforcement Learning

Power Excursion Pre-compensation and Reinforcement Learning Approach

- Objectives of the power excursion pre-compensation: Dynamic adjustment of launch optical power per each channel in a WDM system in order to reduce the cumulative mean power excursion.

- Strengths of the reinforcement learning approach: Reinforcement Learning techniques are very powerful, solving complex problems. Using direct learning or **combined with learning model**, this approach contributes to the autonomous network operation.

Power Excursion Pre-compensation using Reinforcement Learning



- Agent = Predistortion module
- Environment = fix-grid WDM system
- State = Power excursion per channel at the output of the WDM system
- Action = Input power per channel increase (decrease) by 0.1 dB depending on the reward

8. M. Freire et al., Dynamic Power Predistortion Implementation with Reinforcement Learning for Excursion-Free Amplified Optical Systems, ONDM2020

Environment's Model

- Environment based on simulations done with VPItransmissionMakerTM for a cascade of 10 spans with amplifiers experimentally characterized

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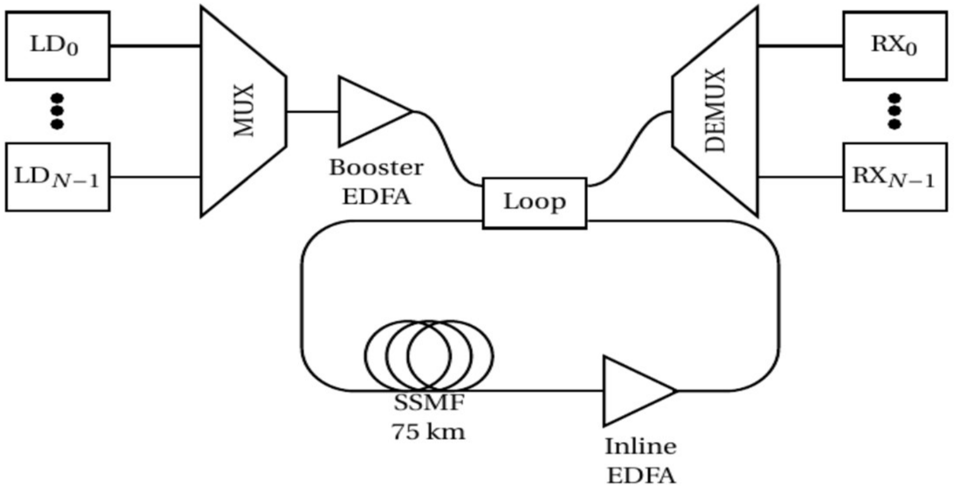
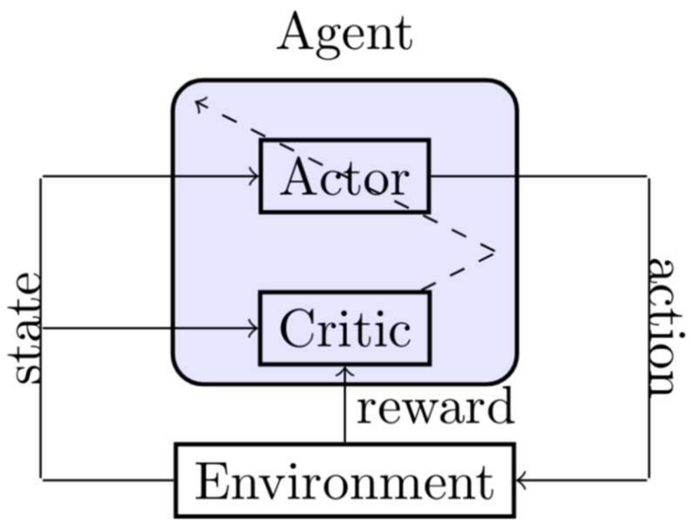


- **Learning model** based on Neural Networks predicting power excursion per channel
- Environment's model together with reward function to complete the environment

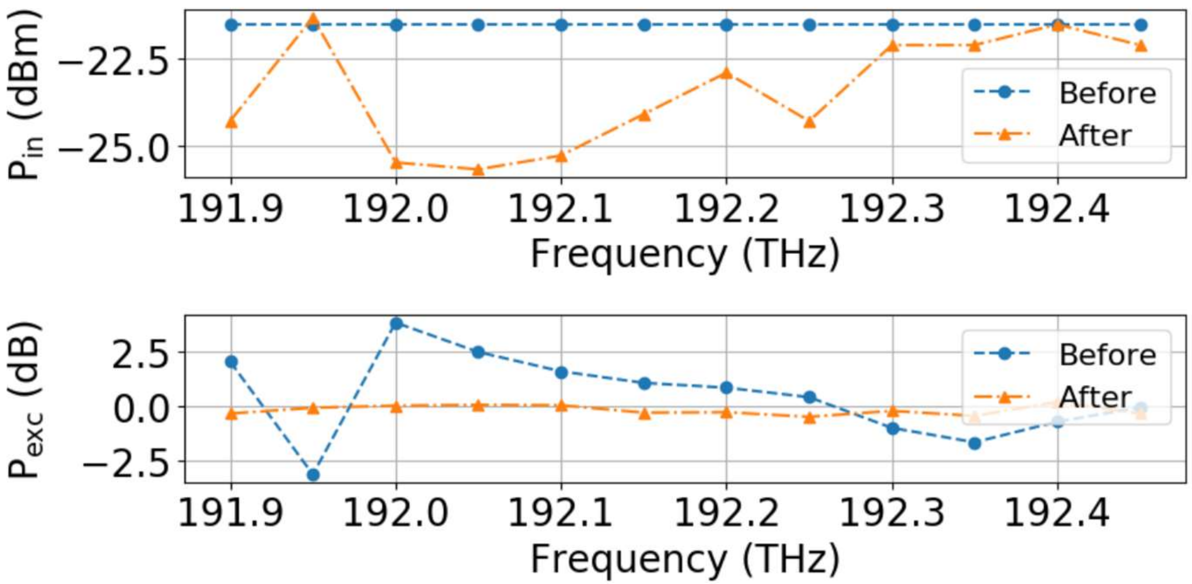
Actor-Critic in Agent

- Actor-Critic method
  - Actor decides which action has to be taken depending on the current state
  - Critic evaluates the actions of the actor based on the rewards.



Results with 12-channel 50 GHz grid WDM system

- After training the Reinforcement Learning algorithm, for a 12-channel scenario with 50 GH spacing, we observe that the launch power predistortion module is able to reduce the power excursion.



BER and OSNR aware Modulation and Wavelength Assignment under Reinforcement Learning Control

QoT Estimation based on Neural Networks

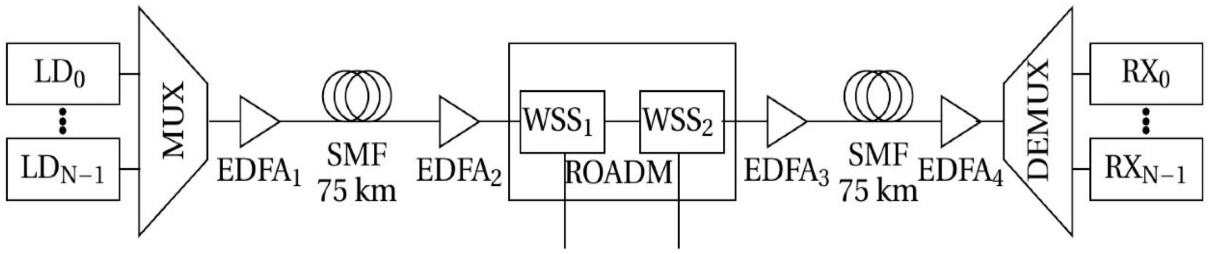


Fig. 1: Simulation setup.

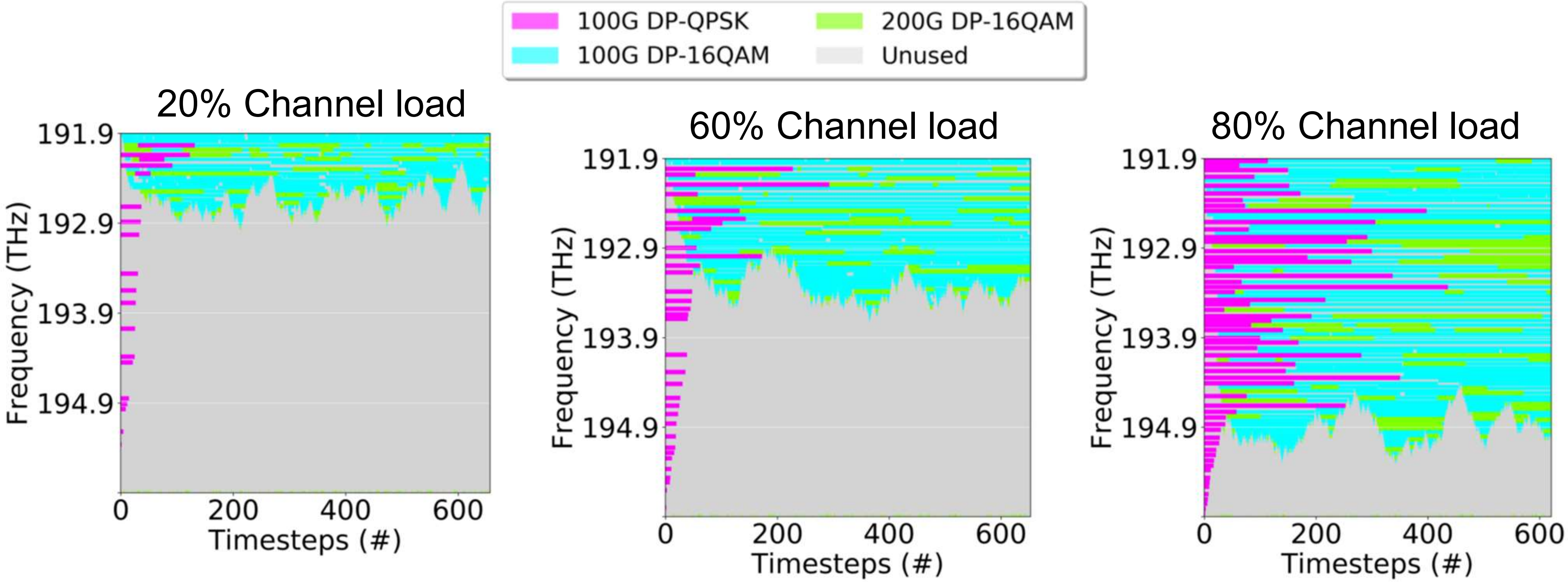
Mixed Line Rate WDM System (100G-DPQPSK, 100G-DP16QAM and 200G-DP16QAM)

QoT estimation model:
- Power excursion as input vector
- OSNR and BER estimations are derived

Implementation of an impairment aware wavelength and modulation format assignment using RL

- Integration of QoT estimation model into an environment used for training a RL algorithm to implement impairment aware wavelength and modulation assignment in a mixed line rate WDM system

Results



Most of traffic demands are in lower frequency slots due to amplifier characteristics. 100G and 200G demands are assigned to DP-16QAM, occupying less frequency slots, saving spectrum resources

Conclusion

- Flexible use of resources permits to envisage dynamics networks.

→ Power excursion becomes a time varying impairment.

- Machine learning is a very efficient way to predict and to pre-compensate this power excursion

- Impairment aware modulation and wavelength assignment in optical networks is achieved under RL control

In main conclusion, as machine learning is able to solve complex problems efficiently, it should play an important role to design power optimization strategy in complex flexible heterogeneous optical networks.

Thank you for your attention !

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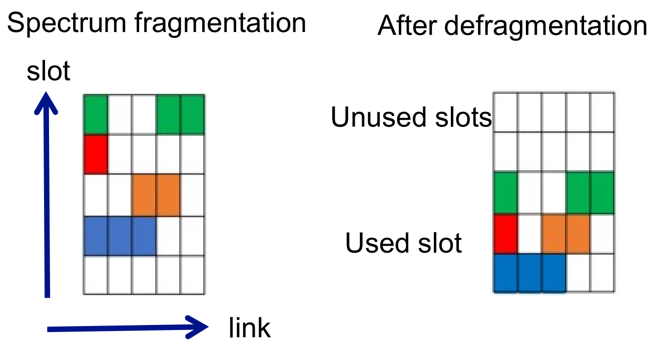
Fragmentation and Defragmentation in Flexible Optical Networks [9]

- Fragmentation of the spectrum due partitioning in frequency slots
- Free fall polynomial time algorithm defragmentation moves connections or demands in order to reduce the used fiber capacity
- This process may be used with Push-Pull technique that requires free intermediate slots before moving connections



Example of 5-slot and 5-link before and after free-fall defragmentation

9. D. Amar et al., Power Excursion Reduction in Flex-Grid Optical Networks with Symbol Rate Adaptation, ACP 2017

Power Excursion Mitigation for Flex-grid Defragmentation

- Objectives
  - Move connections in order to decrease the used fiber capacity
  - Connection symbol rate optimization to reduce power excursion before and after defragmentation process

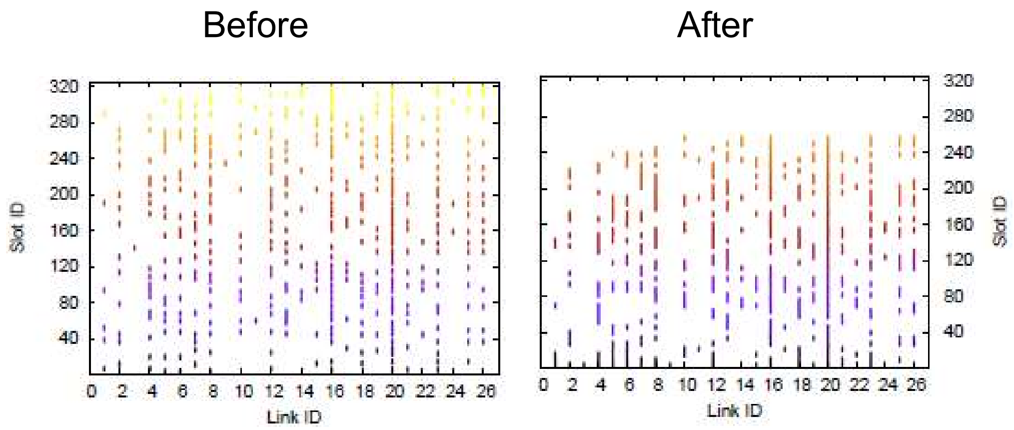
1- Symbol rate adaptation before spectrum defragmentation

→ Impact of connection dynamicity on power excursion during following defragmentation process?

3- Symbol rate adaptation after spectrum defragmentation

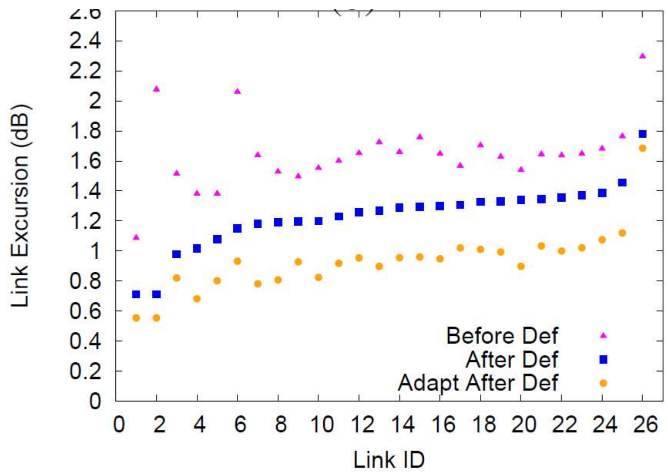
→Symbol rate reconfiguration could be even performed during spectrum defragmentation as most defragmentation processes are not hitless (connection is lost)

Free Fall Defragmentation Algorithm Results



- Use case: 30% average load
  - 20% of contiguous spectrum is freed after free fall algorithm to respect slot continuity constraints

Link Excursion Results [9]



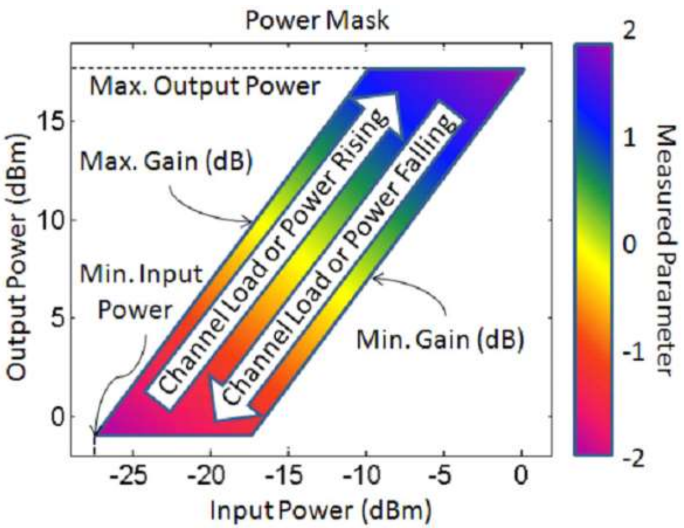
Excursion in the whole network

- 1- Defragmentation reduces power excursion (After Def)
- 2- Symbol rate adaptation reduces power excursion as well even for large loads (internal defragmentation) (Adapt after Def)
- During defragmentation process, 70% of connections are retuned, and almost all of them changed the central frequency

Machine Learning in Optical Networks

Physical layer domain

- Optical amplifier control

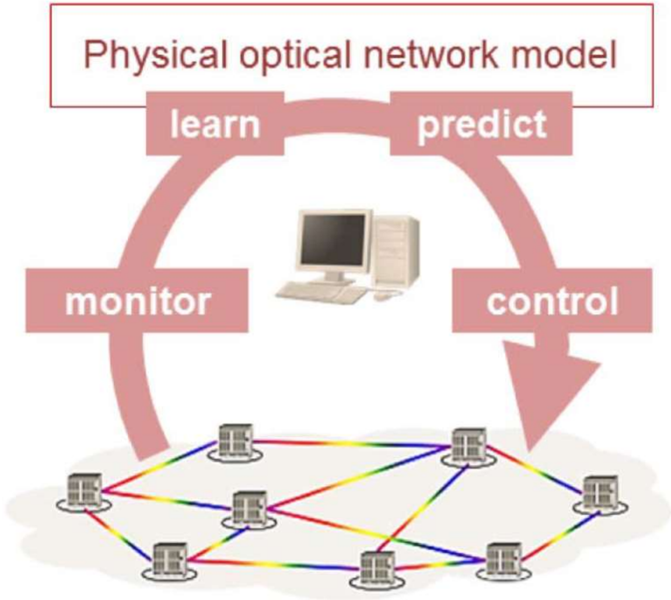


- Input: EDFA input and output power
- Output: EDFA operating point
- Algorithm: Neural Network, Ridge Regression

- **Parameter estimation**
- **Spectrum allocation suggestion**

11. Bastos-Filho et al.. Mapping EDFA Noise Figure and Gain Flatness Over the Power Mask Using Neural Networks. Journal of Microwaves and Optoelectronics. 12, 2013.

Physical Optical Network Model



13. Bouda et al., Accurate Prediction of Quality of Transmission Based on a Dynamically Configurable Optical Impairment Model, JOCN vol10, n°1, 2018