How to use Machine Learning for Testing and Implementing Optical Networks

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Outline

1. Introduction
   - Machine learning applications and algorithms
   - Network operating system
   - Network abstractions
2. Sensors
   - OSNR
   - Fiber polarization sensing
3. Algorithms
   - QoT estimation optimization for margin reduction
4. Actions
   - Error-aware rerouting - SLA to set error tolerance
5. Challenges

Introduction

- Ubiquitous cloud services will drive bandwidth and dynamism
  - Computing resources instantiated in minutes
  - Comparable flexibility presently not possible in IP/Optical networks
- Today: Largely quasi-statically re-configurable components
  - Flexgrid ROADMs, flexible bitrate transponders, tunable lasers, FlexEthernet, …
- Dynamic networking requires sophisticated Network Operating System (OS)
  - Manage and allocate resources for optimal network capacity, security and reliability
  - Need to be able to physically *sense* and *control* the optical network
  - Advanced machine learning *algorithms* *on top of the Network OS*
  - Dynamic Networking = Sensors + Abstraction + Algorithms + Actuators
- Communications industry efforts:
  - Optical Internetworking Forum (OIF): SDN for transport networks
  - Open Daylight controller (ODL)
  - Open Network OS (ONOS): Open-source NetOS from ON.Lab, Linux Foundation

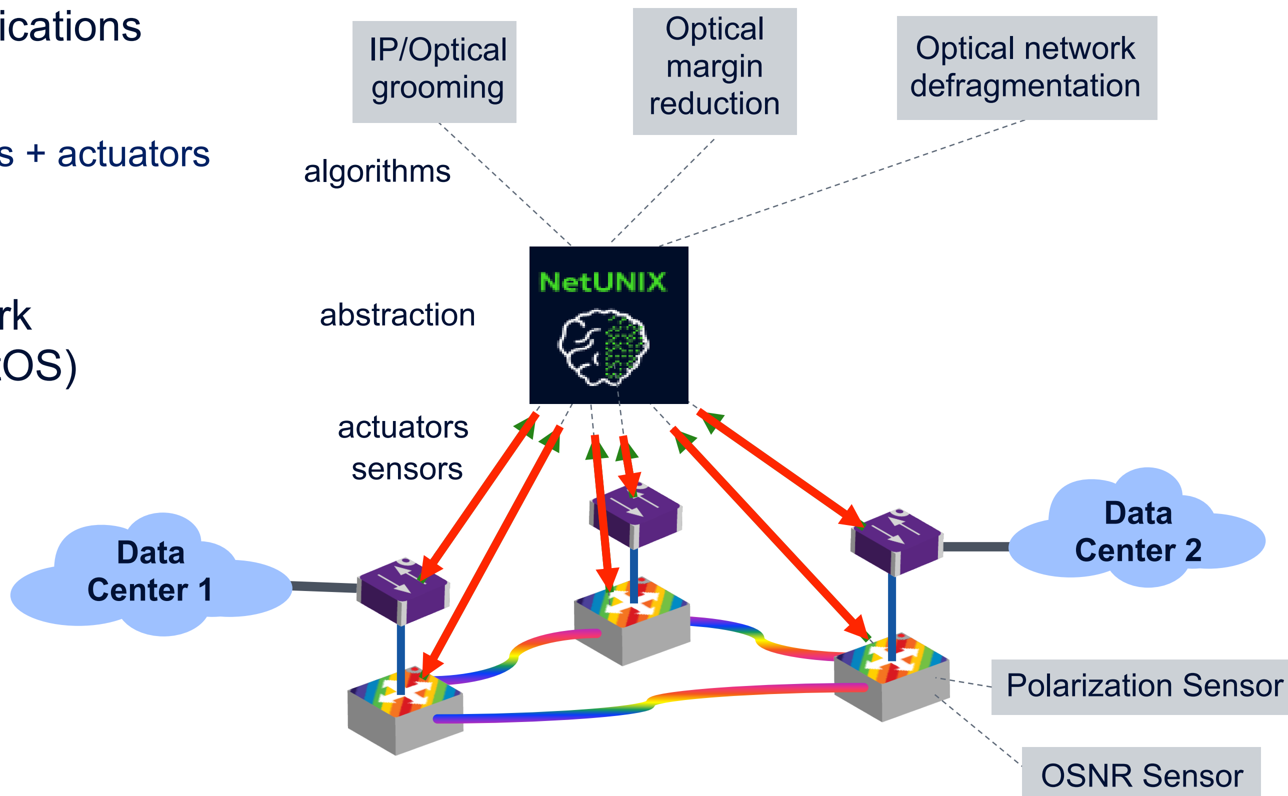
Foundations of Machine Learning Applications

Machine learning applications

sensors + abstraction + algorithms + actuators

Programmable network operating system (netOS)

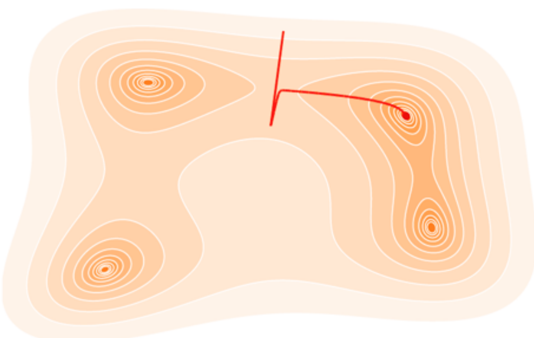
Flexible, tunable network



Algorithms

Machine Learning

Numerical Optimization



http://www.benfrederickson.com/numerical-optimization/

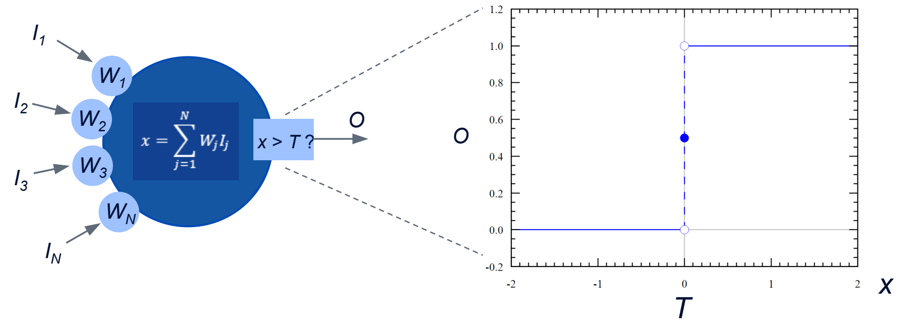
T. Mitchell, *Machine Learning*, McGraw Hill (1997)

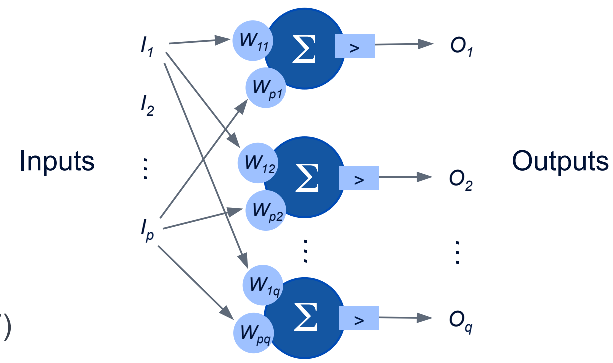
"A computer program is said to learn

- from experience *E*
- with respect to some class of tasks *T*
- and performance measure *P*

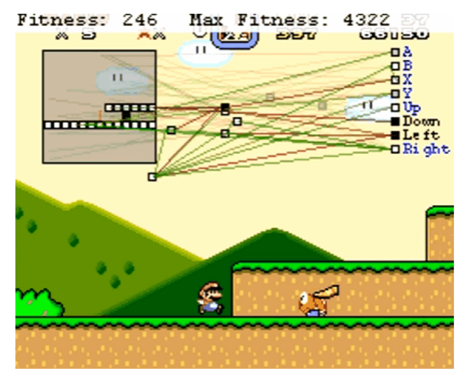
if its performance at tasks in *T*, as measured by *P*, improves with experience *E*."

Artificial Neural Networks



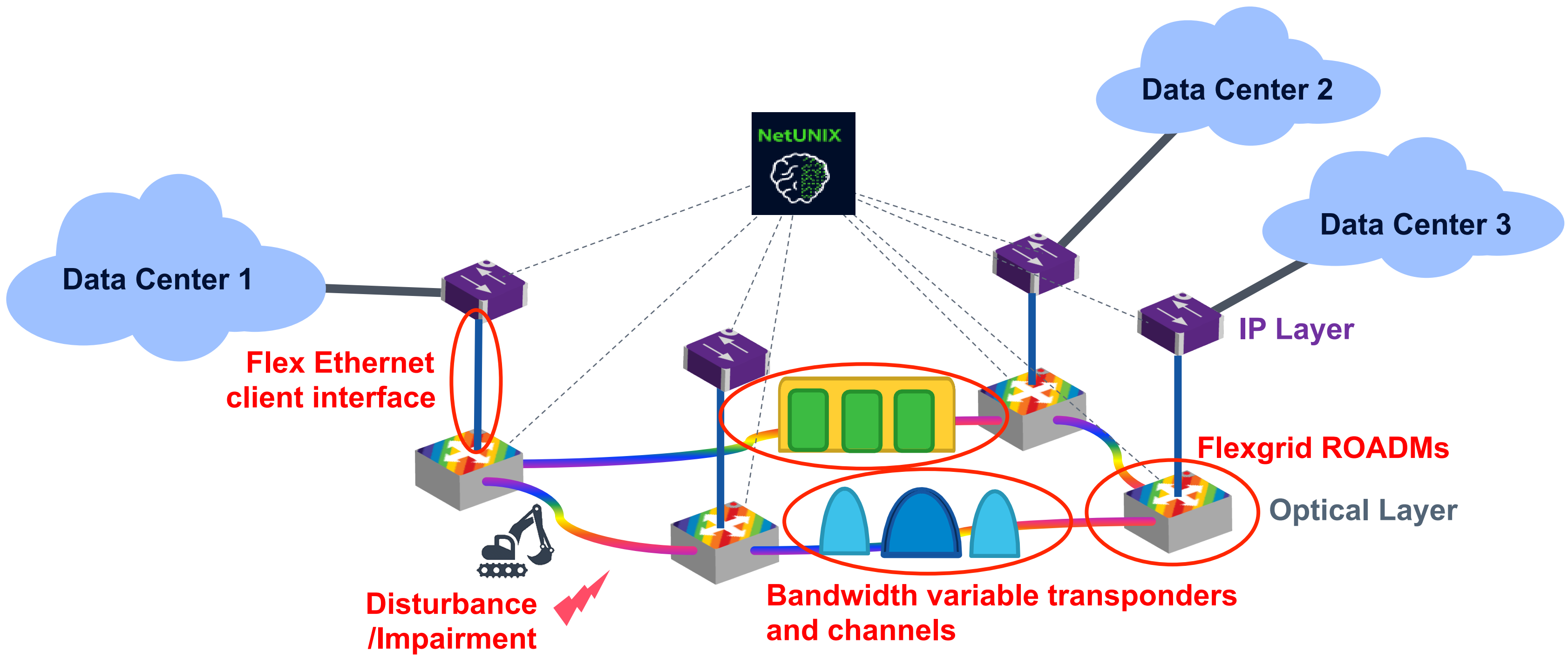


MarI/O: Artificial Neural Network



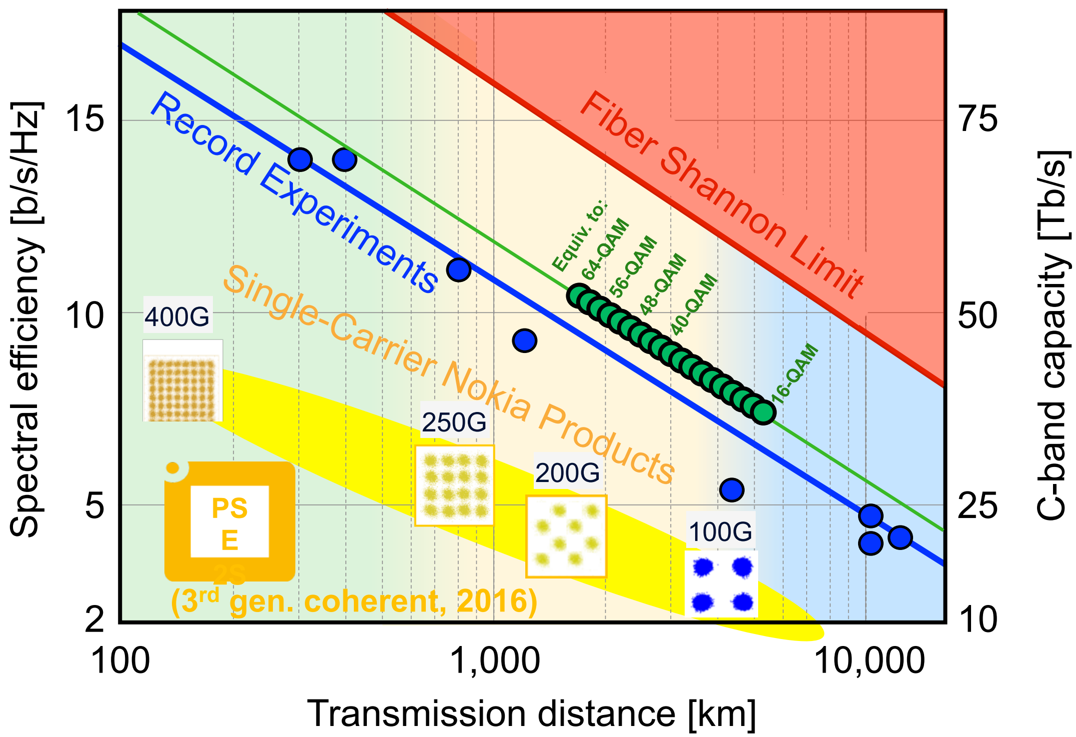
https://www.youtube.com/watch?v=qv6UVOQ0F44

Dynamic and Flexible Networks



WDM Transmission Capacity and Flexible Optical Transponders

Get the Most Capacity out of Your WDM System



Bell Labs 1 Tb/s Field Trial

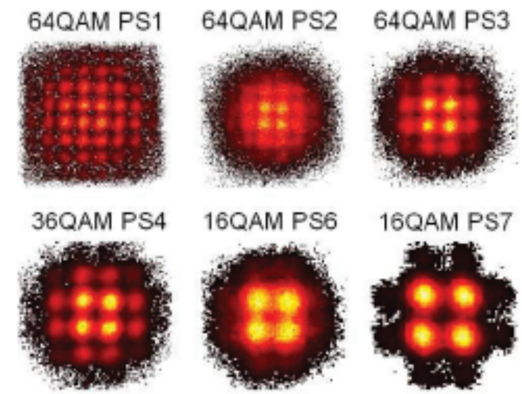
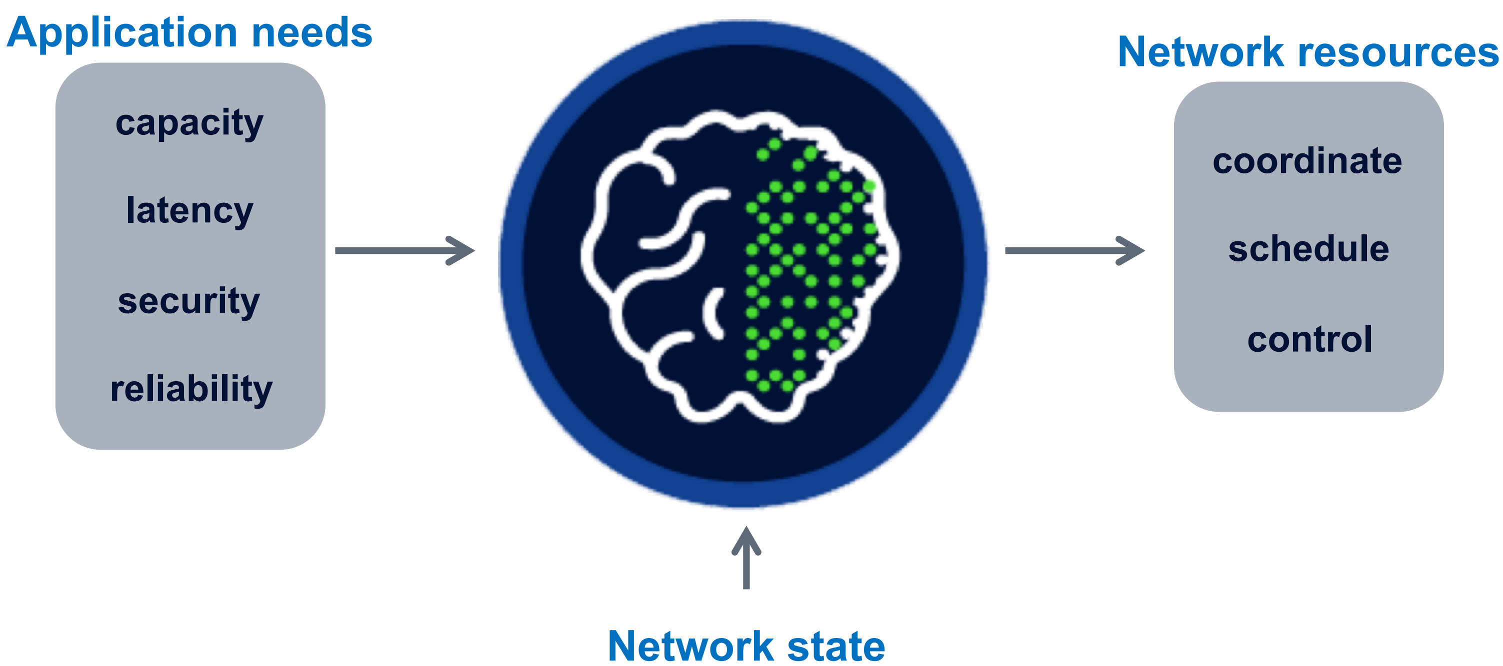


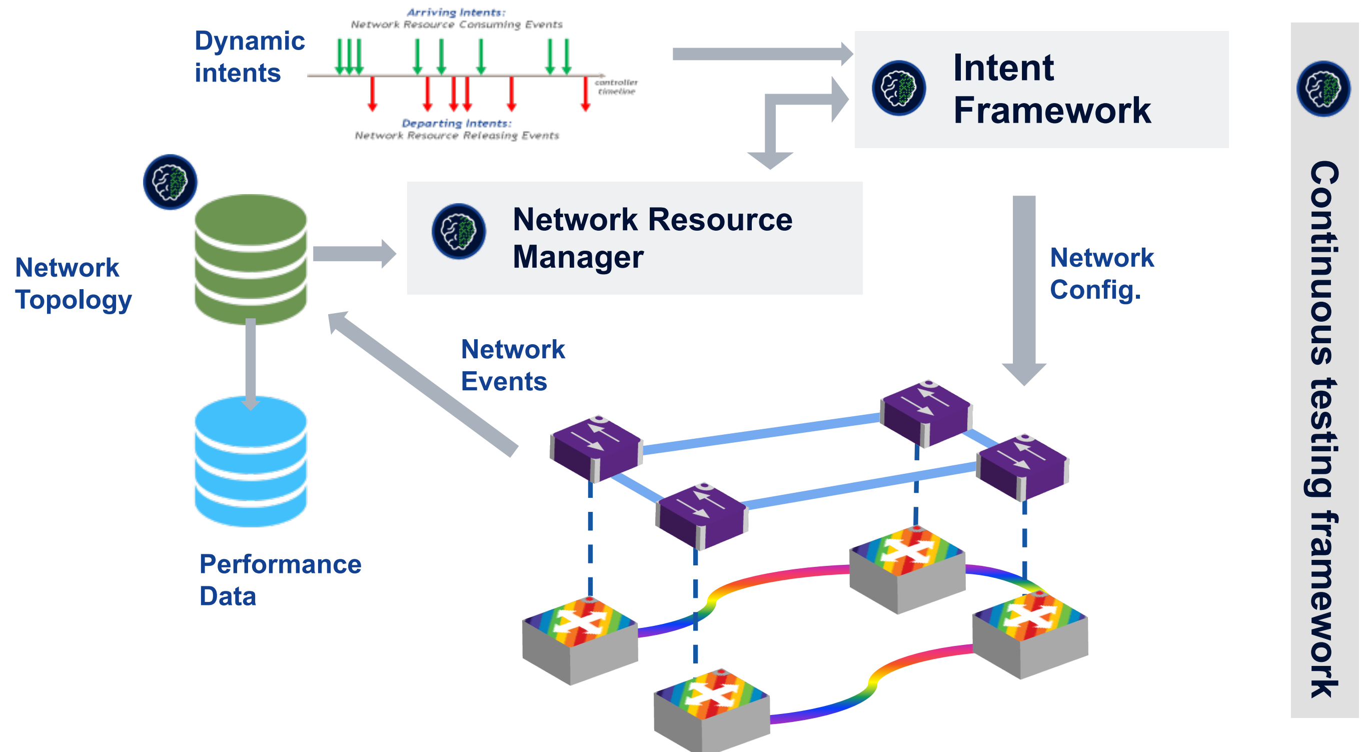
Fig. 2: Examples of the six different PS-MQAM constellations.

NetOS: The Network Brain



The network brain is a cognitive global network control plane

NetUNIX NetOS Functions



Prototype NetUNIX system designed and demonstrated

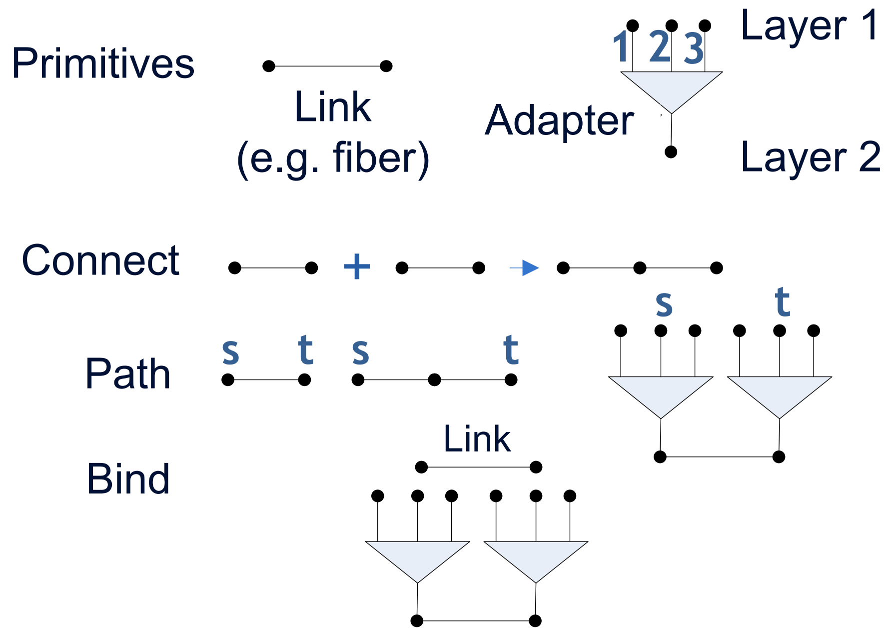
Data Models, Network Abstraction

- Advanced algorithms on an vendor-independent, abstract network representation
  - What information is needed? How many data points are needed?
  - Joint IP/Optical network grooming and optimization - IP/Optical network topology is needed
  - Optical margin reduction - optical network OSNR data is needed

  - The Internet Engineering Task Force (IETF)
    - YANG data modeling language to model configuration of network elements
  - OpenROADM (AT&T, Ciena, Fujitsu, Nokia, SK Telecom…)
    - Defines interoperability specifications for ROADMs, transponders, pluggable optics
    - Includes YANG data models for devices, network, services
  - OpenConfig (Google, AT&T, Microsoft, BT, Facebook…)
    - YANG data models for optical transport: terminal optics, wavelength router, optical amplifier
  - OpenFlow 1.4 (Open Networking Foundation)
    - Common southbound interface definition for multi-vendor network element control
  - NetGraph - mathematically-rigorous, expresses multilayer network complexity
    - Does not replace other efforts, adds explicit layering and mathematical rigor to network model

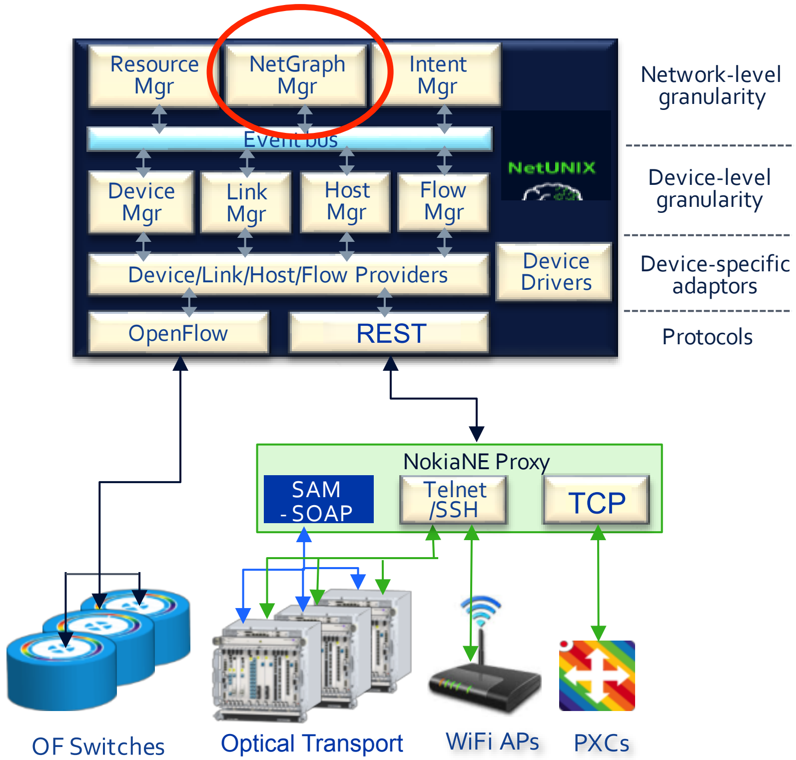
NetGraph Primitives

Underlying Mathematical Model



S. Fortune, “Equivalence and generalization in a layered network model”, *J. Comput. Syst. Sci.*, vol. 81, no, 8, pp. 1698–1714, 2015.

Implementation: Adaptation to Network Elements



NetGraph abstract network representation maps to network resources

Populate network elements into NetUNIX

Gather statistics

Control network elements

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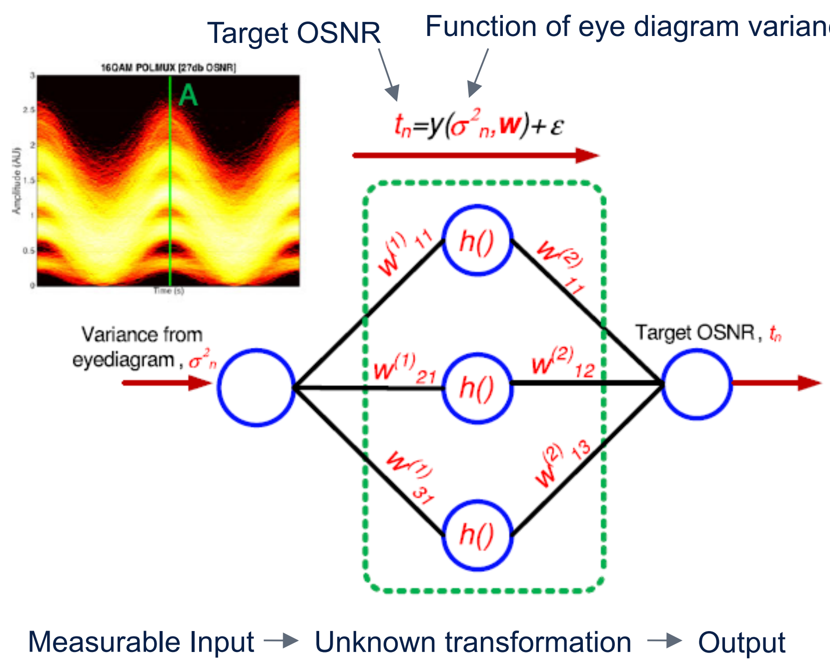
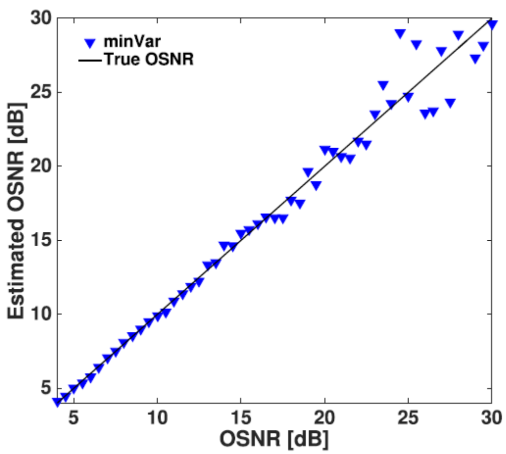
OSNR Sensing with an Artificial Neural Network

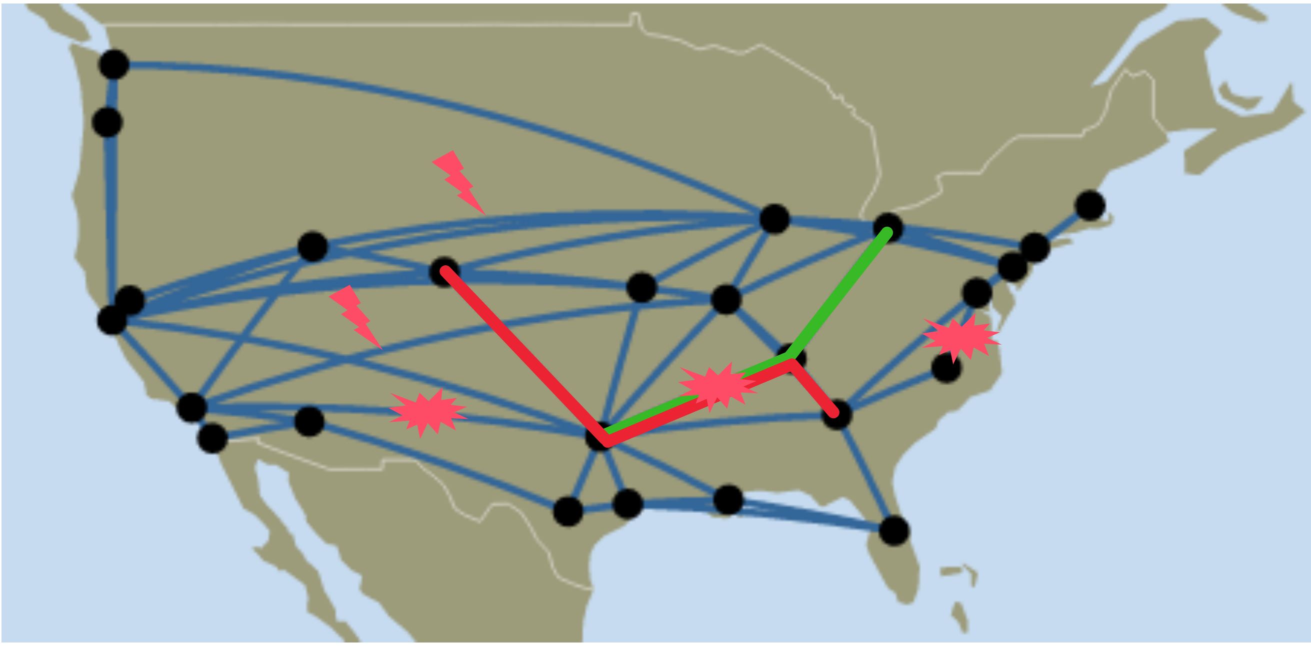
- Single photodiode eye diagram machine learning analysis:
  - J. Thrane, J. Wass, M. Piels, J. C. M. Diniz, R. Jones, and D. Zibar, “Machine learning techniques for optical performance monitoring from directly detected PDM-QAM signals,” Journal of Lightwave Technol., vol. 35, no. 4, 2017.





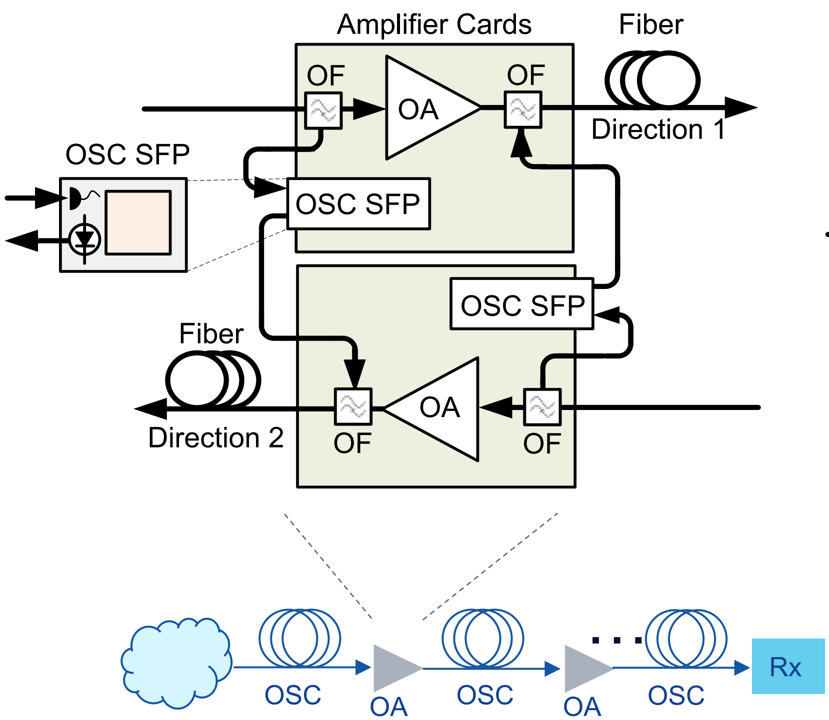
Artificial neural network used to estimate OSNR from eye diagram

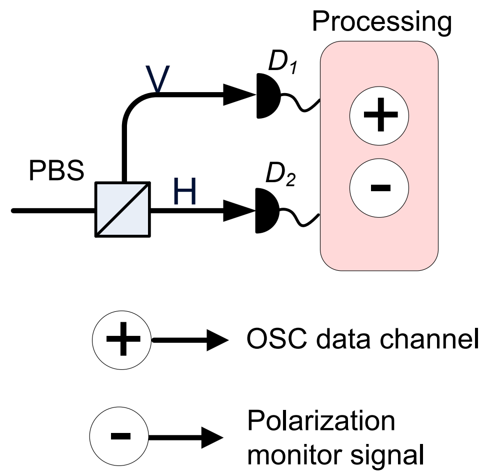
Fiber as a Sensor

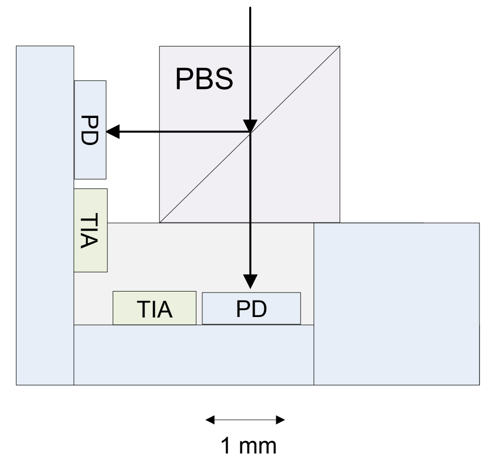


Optical fiber network becomes a massively-distributed motion detector

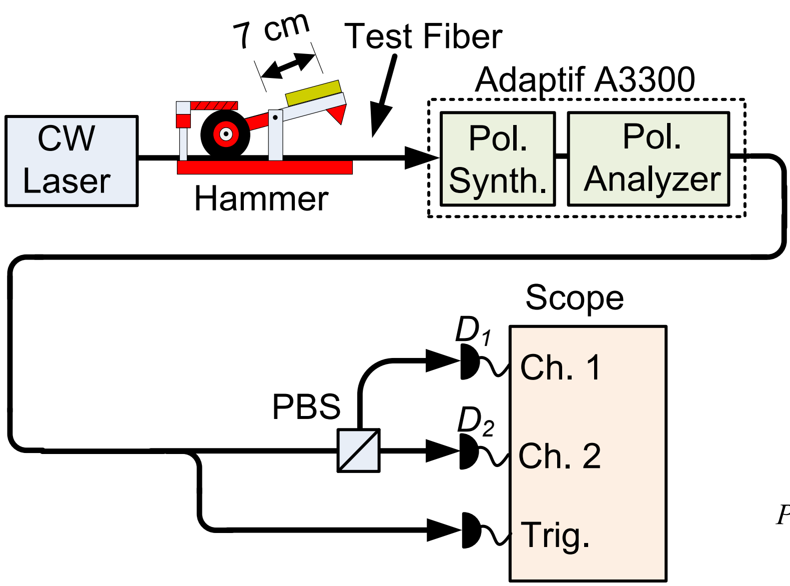
OSC for Polarization Sensing – Span Monitoring

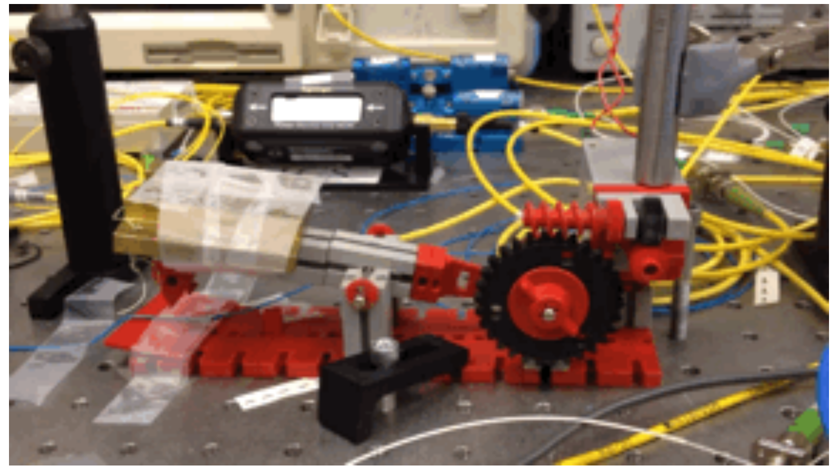






Experiment





3 Results for Comparison

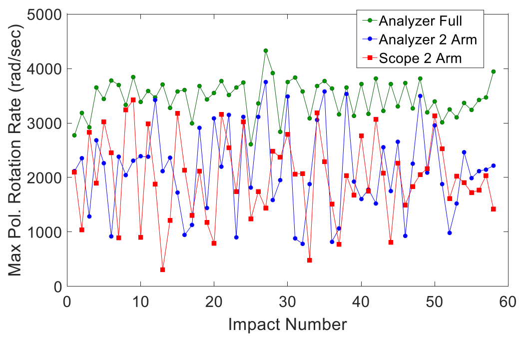
$$PR_{A,full} = 2\sin^{-1}\left(0.5\sqrt{\Delta S_1^2 + \Delta S_2^2 + \Delta S_3^2}\right)SR_{analyzer}$$ Full analyzer measurement

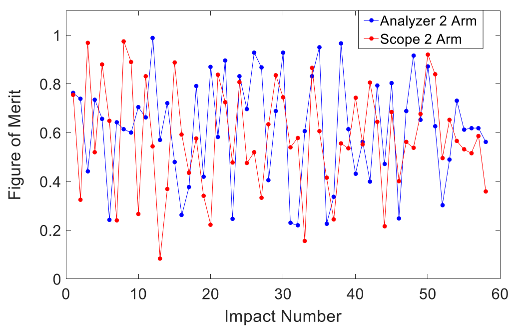
$$PR_{A,2Arm} = 2\sin^{-1}\left(0.5\left|\Delta\frac{(P_1 - P_2)}{(P_1 + P_2)}\right|\right)SR_{analyzer}$$ "2-Arm" analyzer calculation

$$PR_{S,2Arm} = 2\sin^{-1}\left(0.5\left|\Delta\frac{(V_1 - V_2)}{(V_1 + V_2)}\right|\right)SR_{scope}$$ 2-Arm scope measurement

Results Summary

58 Fiber Impacts



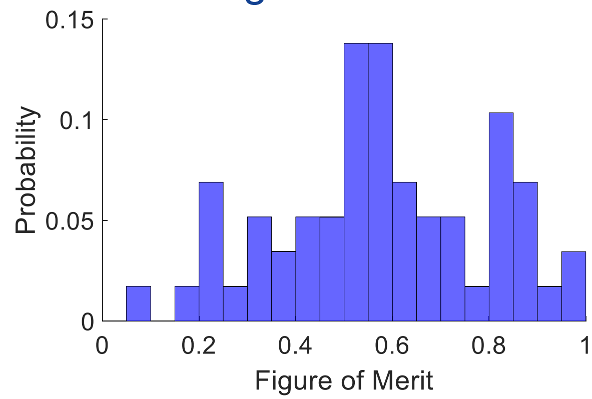


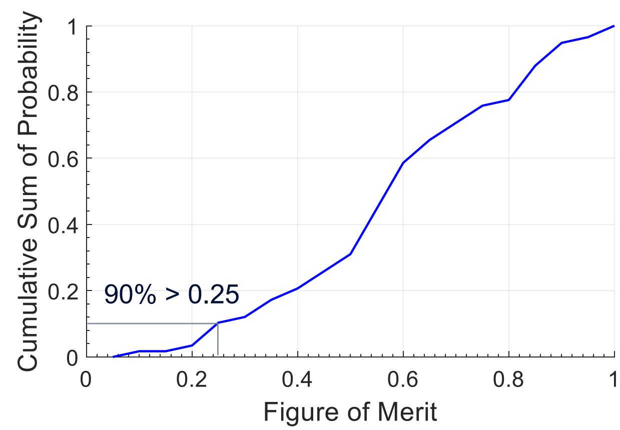
$$F = \frac{\max(PR_{2Arm})}{\max(PR_{A,full})}$$

$$\overline{F_{A,2Arm}} = 0.62 \pm 0.22$$

$$\overline{F_{S,2Arm}} = 0.58 \pm 0.22$$

Figure of Merit

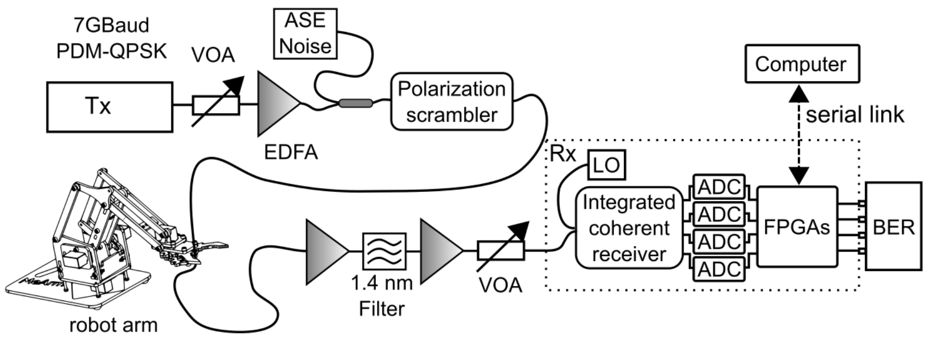


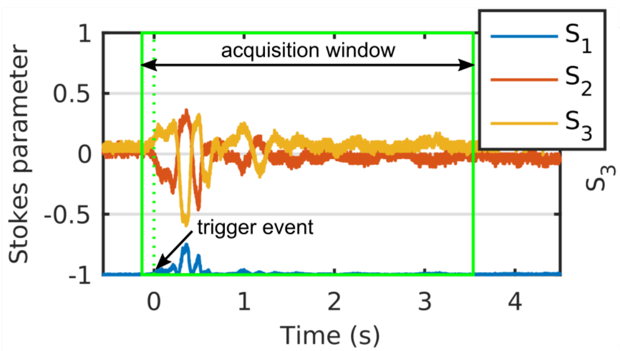


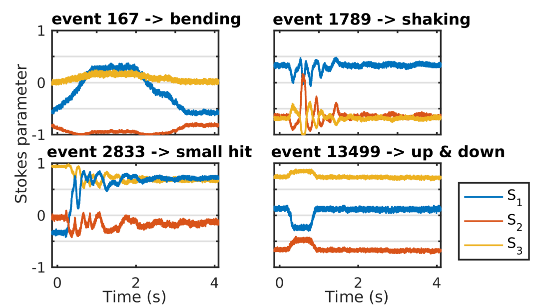
J. E. Simsarian and P. J. Winzer, “Shake Before Break: Per-Span Fiber Sensing with In-Line Polarization Monitoring,” in *Proc. OFC 2017*, paper M2E.6, 2017.

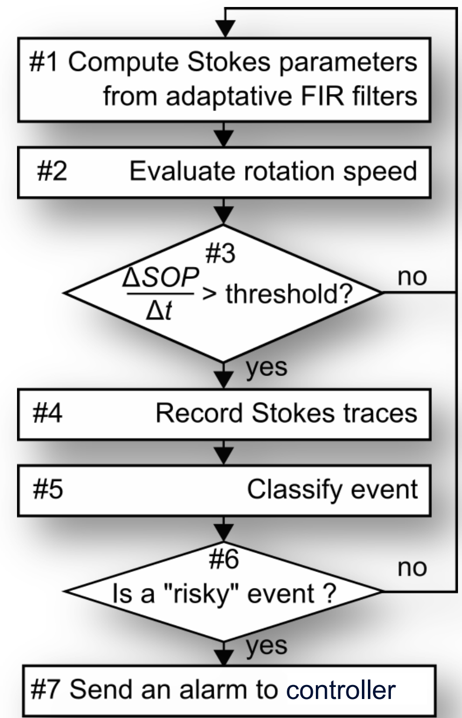
Coherent Transponder Polarization Sensing – Path Monitoring

Machine Learning Event Classification









Event classification: $Y = f(X)$

F. Boitier, V. Lemaire, J. Pesic, L. Chavarría, P. Layec, S. Bigo, E. Dutisseuil, “Proactive fiber damage detection in real-time coherent receiver,” ECOC 2017.

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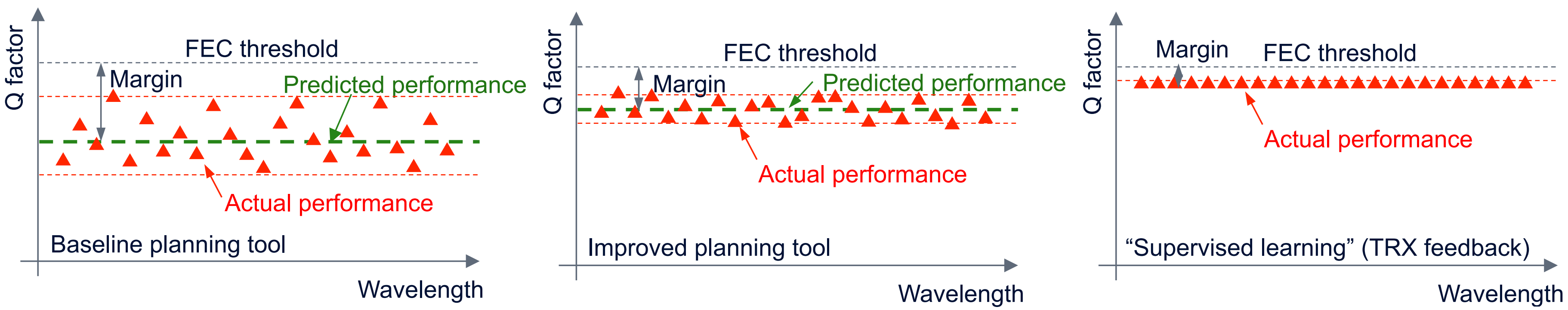
Why and When do We Need to “Learn from Experience”

(As opposed to “knowing what we are doing”)

- Good models of the underlying physics are generally best
  - *Subsystem:* Chromatic dispersion compensation in a coherent DSP
  - *System:* Predicting physical-layer performance through adequate models
  - *Network:* Rule-based (x-layer) routing and wavelength assignment

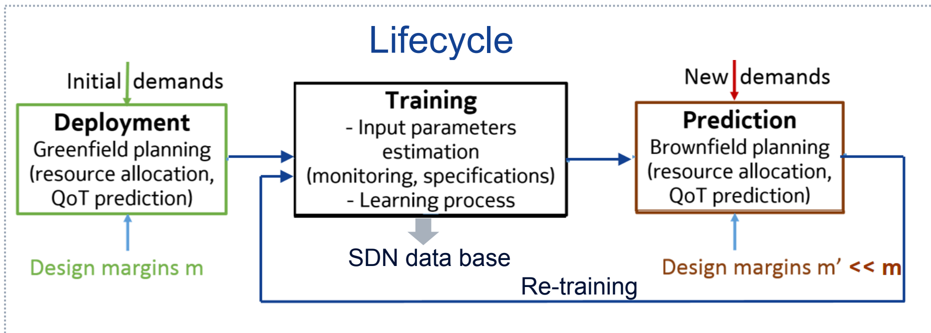
- But: How good / comprehensive is the respective model ?
- Hybrid approach: physical model + parameter tuning with machine learning

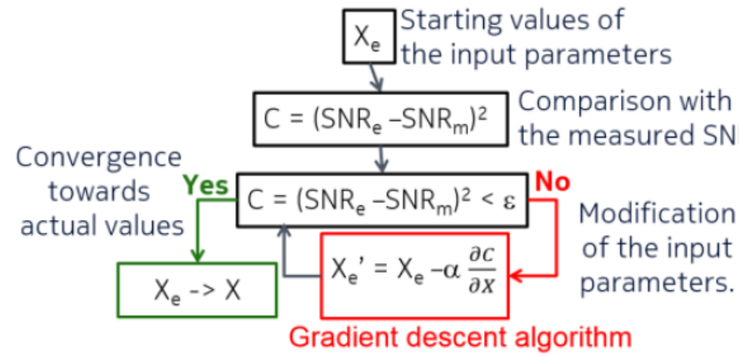
  - A dB in system planning accuracy is as valuable as a dB in coding gain!

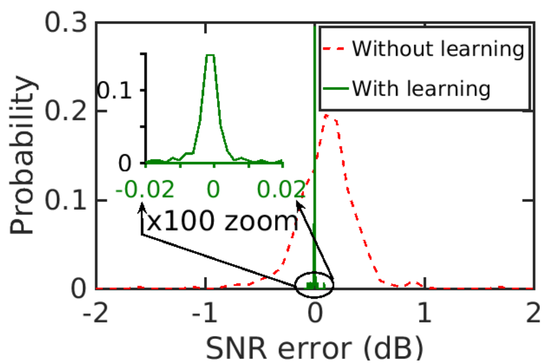


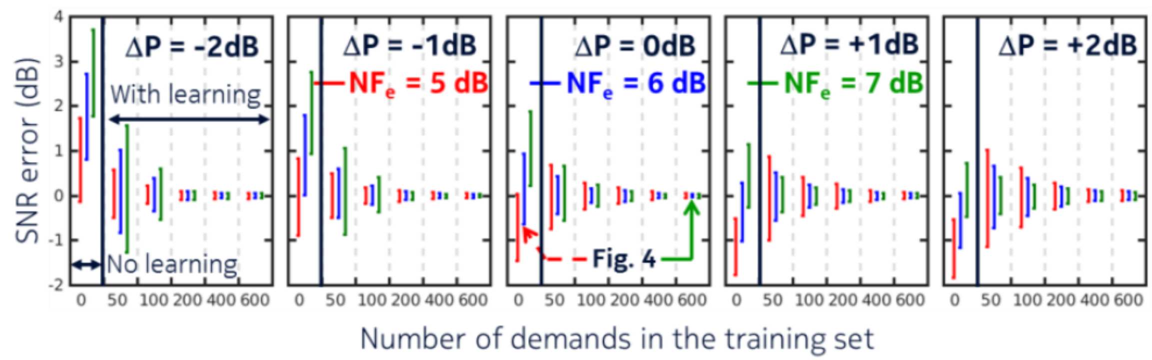
Optical System Margin Reduction

Learning process to reduce uncertainties









E. Seve, J. Pesic, C. Delezoide and Y. Pointurier, “Learning process for reducing uncertainties on network parameters and design margins,” in Proc. OFC 2017, paper W4F.6.

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SDN Testbed at Bell Labs

Executive Briefing Center

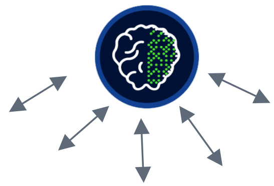
AirFrame POD

AirFrame Rack

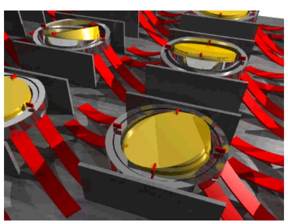
Photonic Crossconnect (PXC)

TOR Switches & Servers

NetUNIX



Fiber Connectivity



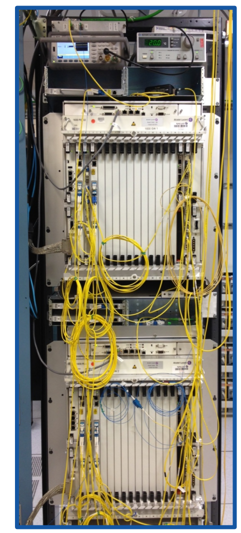
Optical switching inside data center

PXC MEMS switch

IP Transformation Center (IPTC)

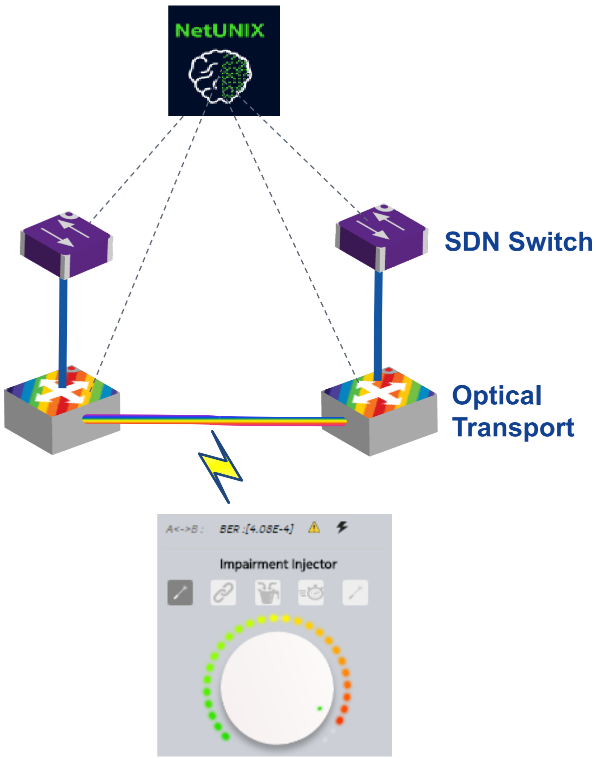
Service Routers

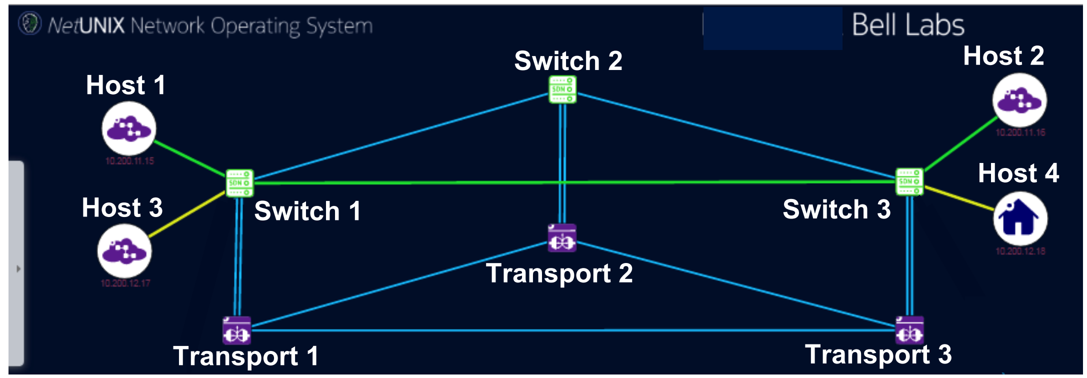
Optical Transport

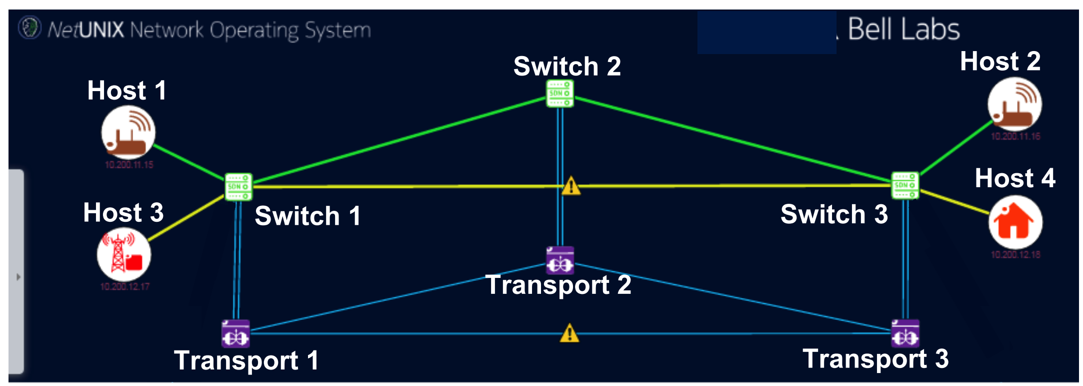


- Error-aware networking
- Optical Transport
- Service Routers
- SDN Switches

Error-Aware Rerouting



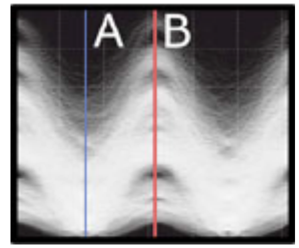




Regular intent
Error-aware intent

Challenges and Discussion Points for Network Operators

Classification of Modulation format



Predicted \ Pre-set	QPSK	8QAM	16QAM	64QAM
QPSK	0.96	0.00	0.00	0.00
8QAM	0.02	1.00	0.00	0.00
16QAM	0.02	0.00	0.87	0.08
64QAM	0.00	0.00	0.13	0.92

- Stability and reliability
  - Event classification probability
- How much data is “enough” as a basis for machine learning?
  - What data is needed at which layer of the network? (abstraction)
  - Machine learning algorithms local to network element for sensor data
- Reliability and operational implications
  - Human operator confirmation of network operations
  - Business structures - IP and optical businesses
  - What are operational barriers to more efficient and dynamic network operation?
  - Outages and accountability – applications on top of NetOS

*J. Thrane, J. Wass, M. Piels, J. C. M. Diniz, R. Jones, and D. Zibar, “Machine learning techniques for optical performance monitoring from directly detected PDM-QAM signals,” Journal of Lightwave Technol., vol. 35, no. 4, 2017.

Conclusions

- Cloud services as drivers of bandwidth and network dynamism
- Dynamic networks = Sensors + Abstraction + Algorithms + Actuators
- Machine learning algorithms to identify network events, reduce optical system margins, and optimize the network
  - Built on programmable NetOS and flexible network infrastructure
  - Different machine learning methods ranging from “black box” artificial neural networks, to event classification, to hybrid methods using a physical model of the system and machine learning
- NetUNIX prototype NetOS
  - Improve sensing of the physical layer to detect impairment or possible disruption
  - Abstract representations of the network layers with NetGraph
- Applications
  - Impairment aware IP/optical re-routing
  - Optical channel monitoring