How to use Machine Learning for Testing and Implementing Optical Networks

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October 4, 2017
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 ROADM, 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

IP/Optical grooming
Optical margin reduction
Optical network defragmentation

NetUNIX

Data Center 1

Data Center 2

Polarization Sensor
OSNR Sensor
“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 \( E \)."
Dynamic and Flexible Networks

- Data Center 1
- Flex Ethernet client interface
- Disturbance /Impairment
- Bandwidth variable transponders and channels
- Flexgrid ROADM
- Optical Layer
- IP Layer
- Data Center 2
- Data Center 3
WDM Transmission Capacity and Flexible Optical Transponders
Get the Most Capacity out of Your WDM System
NetOS: The Network Brain

Application needs
- capacity
- latency
- security
- reliability

Network state

Network resources
- coordinate
- schedule
- control

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

Implementation: Adaptation to Network Elements

NetGraph abstract network representation maps to network resources

Populate network elements into NetUNIX
Gather statistics
Control network elements

NetGraph Mgr
Resource Mgr
Intent Mgr
Device Mgr
Link Mgr
Host Mgr
Flow Mgr
Device/Link/Host/Flow Providers
Device Drivers

Network-level granularity
Device-level granularity
Device-specific adaptors
Protocols

Resource Mgr
Intent Mgr
Flow Mgr
Flow Mgr
Host Mgr
Link Mgr
Device Mgr

Rest/GRPC
1830PSSs
Telnet
SSH
WiFi
APs
NokiaNE Proxy
SAM
- SOAP
Telnet
/SSH
TCP

Event Box

OF Switches
Optical Transport
WiFi APs
PXC
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OSNR Sensing with an Artificial Neural Network

- Single photodiode eye diagram machine learning analysis:

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

\[
PR_{4,full} = 2 \sin^{-1}\left(0.5 \sqrt{\Delta S_1^2 + \Delta S_2^2 + \Delta S_3^2}\right)SR_{\text{analyzer}}
\]

Full analyzer measurement

\[
PR_{4,2\text{-Arm}} = 2 \sin^{-1}\left(0.5 \left| \frac{P_1 - P_2}{P_1 + P_2} \right| \right)SR_{\text{analyzer}}
\]

“2-Arm” analyzer calculation

\[
PR_{5,2\text{-Arm}} = 2 \sin^{-1}\left(0.5 \left| \frac{V_1 - V_2}{V_1 + V_2} \right| \right)SR_{\text{scope}}
\]

2-Arm scope measurement
Results Summary

58 Fiber Impacts

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

\[ F_{A,2,Arm} = 0.62 \pm 0.22 \]

\[ F_{S,2,Arm} = 0.58 \pm 0.22 \]

Coherent Transponder Polarization Sensing – Path Monitoring

Machine Learning Event Classification

![Diagram](image)

Event classification: $Y = f(X)$

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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!

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[Diagram showing Q factor, Margin, FEC threshold, Predicted performance, Actual performance across baseline and improved planning tools, and "Supervised learning" (TRX feedback) with wavelength on the x-axis.]
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Optical System Margin Reduction
Learning process to reduce uncertainties

Lifecycle

Deployment
Greenfield planning (resource allocation, QoT prediction)
Design margins m

Training
- Input parameters estimation (monitoring, specifications)
- Learning process
SDN data base
Re-training
Design margins m' << m

Prediction
Brownfield planning (resource allocation, QoT prediction)

New demands

Learning Algorithm

Starting values of the input parameters

\[ C = (\text{SNR}_e - \text{SNR}_m)^2 \]

Comparison with the measured SNR

Convergence towards actual values

Yes

C = (SNR\(_e\) - SNR\(_m\))^2 < \varepsilon

No

Modification of the input parameters.

\[ X'_e = X_e - \alpha \frac{\partial C}{\partial X} \]

Gradient descent algorithm

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SDN Testbed at Bell Labs

Executive Briefing Center

- AirFrame POD
- AirFrame Rack
- Photonic Crossconnect (PXC)
- TOR Switches & Servers

Optical switching inside data center
PXC MEMS switch

NetUNIX

Fiber Connectivity

IP Transformation Center (IPTC)

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

Optical Transport
Error-Aware Rerouting

![Diagram showing a network with SDN switches and optical transports, highlighting regular and error-aware intents.]

- Regular intent
- Error-aware intent
Challenges and Discussion Points for Network Operators

• 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

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