Exascale Virtualized and Programmable Distributed Cyber Resource Control

Software Defined Elastic Optical Network for Petabit Data Movements on Demand

S. J. Ben Yoo, Lei Liu
University of California, Davis
sbyoo@ucdavis.edu
http://sierra.ece.ucdavis.edu

Gregory Lauer, Stephen Dabideen
Raytheon BBN Technologies
glauer@bbn.com
Driving Needs for Intelligent Optical Network Infrastructure

- Big Data (Data-intensive science)
- Extreme-Scale Computing
- Network complexities and Scalability

Software Defined Elastic Optical Networking with Exascale Virtualized and Programmable Distributed Cyber Resource Control

- Dynamic Assignment of Large Bandwidth On-Demand
- Service Automation
- Application Aware & Impairment Aware Adaptive Networking
- High-Availability and Optimized Operation
- Programmability
- Virtualized Resource Control
- Interoperability and Vendor Neutrality
- End-to-End Principle with Intra-domain and Inter-domain Optimization
Software Defined Networking =>
Cognitive/Knowledge Plane Optical Networking

Separation of Control Plane and Data Plane
Separation of Forwarding functions and Routing functions
Virtualization of Lower Layer Functions

McKeown et al
Hierarchical Intelligent Control & Management
(from 1997 Optical Label Switching SJBYoo)

- **Brain: Interelement Control (out-of-band DCC)**
  - Slow but elaborate
  - Overall abstracted view of network
  - Performance monitoring based on labels or abstracted attributes
  - Anomaly detection (global)
  - Listens and instructs to the Reflex

- **Reflex: Distributed Control (in-band DWDM, Label based)**
  - Rapid and reflex-like
  - Local view of network (details)
  - Packet forwarding using labels
  - Anomaly detection (local)
  - Reports and listens to the Brain
Transitioning from **DWDM Networking** to **Elastic Optical (Flex Grid) Networking**

- Limited achievable spectral efficiency due to spectral guard bands
- Single channel bandwidths limited by frequency grid spacing
- Sub-wavelength and super-wavelength channels difficult
- Stranded bandwidth problem

- Spectral efficiency no longer limited by network architecture
- Arbitrary channel bandwidth capable
- Arbitrary modulation format capable
- Capable of sub-wavelength and super-wavelength channels
The more information bits the modulation format contains, the more SNR and energy it requires.

From: Essiambre, Alcatel-Lucent “Capacity Limit of Fiber-Optic Communications,” OFC 2009, also JLT 2010
Elastic Optical Networking

PCE

Data Centers

Business Access

PCE

Residential Access

Elastic Optical Networking

Metropolitan Access

Flex band Add/Drop

Long-haul

Flex Bandwidth Add/Drop

Metropolitan Access

Flex band Add/Drop

Residential Access

Flex bandwidth Add/Drop

Flexible Spectrum Assignment
Elastic Optical Networking

- efficient use of spectrum (~30% savings)
- flexible capacity per flow
- adaptive modulation format on each flow
- accommodate sub-channel capacity
- accommodate super-channel capacity
- terabit bandwidth on-demand
Key Approaches to Elastic Optical Networking

- Routing Spectrum Modulation Format Assignment (RSMA) with Defragmentation in Temporal, Spectral, and Spatial Domains
- QoS-Aware & Impairment-Aware Networking
- Automatic & Adaptive Operation of Networks
- Use Supervisory Channel & Optical Performance Monitoring for EON with Observe-Analyze-Act
- Interoperability and backward-compatibility for Seamless Upgrades
- SDN with Virtualized Resource Control
- Support of Big Data transfer upon demand with efficient resource management.
- Multi-domain SDN with brokers
- SDN-EON Testbed Studies
Challenges in EON:
Fragmentation increases blocking probability

› Non-contiguous spectrum slots in fiber links (spectral domain fragmentation). Caused by:
  › Non-optimized routing and spectrum assignment algorithms make random or biased use of the spectral resources.
  › Dynamic establishment and tear-down of the end-to-end connections.

› Misaligned unused spectrum slots in the neighboring links (spatial domain fragmentation between links, non-continuous). Caused by:
  › Neighboring links are used by different light path connections.
  › The lack of wavelength conversion capability raises the wavelength continuity constraints.
Challenges in EON: Fragmentation increases blocking probability

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Caused by:
- Neighboring links are used by different light path connections.
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Misaligned unused spectrum slots in the neighboring links (spatial domain fragmentation between links, non-continuous). Caused by:
- Non-optimized routing and spectrum assignment algorithms make random or biased use of the spectral resources.
- Dynamic establishment and tear-down of the end-to-end connections.

Challenges in EON:
Fragmentation increases blocking probability.
Fragmentation-Aware and Misalignment Aware RSMA: Simulation Results (Spatio-Spectral Domains)

- SP: Shortest path routing
- P-SP: Shortest path routing in prejudged $k$ shortest path
- P-CF: Combined Factors routing in prejudged $k$ shortest path

45.5% decrease

Bandwidth Blocking Probability

Traffic Load (Erlangs)
Advanced Reservations of RSMA

- Resources allocated in the future when an Advanced Reservation is accepted
- Leads to temporal and spatial fragmentation

Advanced Reservations of RSMA

- New Advanced Request may be blocked due to how resources were allocated to earlier Advanced Reservations.
Advanced Reservations of RSMA

- Reallocating resources to already accepted reservations can decrease blocking probability

Diagram:
- Slots on a path:
  - 13
  - 12
  - 11
  - 10
  - 9
  - 8
  - 7
  - 6
  - 5
  - 4
  - 3
  - 2
  - 1

- Instantiated slots:
  - Slots 10, 11, 12, and 13

- Accepted slots:
  - Slots 8, 9

- Accepted (moved) slot:
  - Slot 7

- New Advanced Request:
  - Slot 6
Temporal-Domain Fragmentation Aware RSMA

![Graph showing Blocking Probability vs Load (Erlangs) for NSF Topology with and without reallocation, indicating a 66% improvement.]
SDN/OpenFlow Controller Design and Implementation

Flow request

Request Manager

Thread 1
Thread 2
Thread N
Thread Pool

Main Thread
Asynchronous I/O

PCE
TED

Data plane Configuration

Extended OpenFlow Protocol

IP Network
(IP Network (Client Layer))

Elastic Optical
Network
(Core)

Datacenter
(Datacenter (Client layer))
Optical Supervisory Ch. with Performance Monitoring

- Mapping between low speed supervisory channel BER and high speed signal (360Gb/s) BER
- The FPGA supervisory channel
  1.25 Gb/s PRBS 2^{31}-1 NRZ OOK
  - BER monitoring at FPGA
  - If BER fails to meet QoT requirement, modulation format is adjusted

Spread Spectrum Optical Supervisory channel: 2^{31}-1 PRBS
Real-time, Automatic Adaptive SDN-EON
**Inter-domain control framework**

Broker-based solution: using a broker to coordinate inter-domain path calculation and provisioning

1. Request
2. Request
3. Reply
4. Configure domain A
5. Configure domain B

Market-driven brokers

Broker A

Broker B

Broker C

NOX for Domain A

NOX for Domain B

NOX for Domain C

Domain A

Domain B

Domain C
Domain Virtualization

• Domain manager provides virtualized resources:
  - Spectral resources
  - Path resources including gateways
  - Time resources

• Broker selects domains and gateways for setting up path

Can this FlexGrid path be setup?
Domain Virtualization for EON

• Broker provides domain controllers with time interval associated with new request

• Domain manager
  ▪ Defines virtual links between gateway pairs
  ▪ Finds path(s) between each pair of gateways
  ▪ Determines spectral channel availability on each path between gateway pairs
  ▪ Reports availability on a per-virtual link basis

• Broker uses virtual links to
  ▪ Determine which domains to use
  ▪ Determine which gateways to use when setting up an end-to-end circuit
SDN experiments across UC Davis - CENIC (COTN) - ESnet

UC Davis Campus Network and its Connectivity
Dynamic end-to-end multi-domain path creation and flow transmission by using our broker-based inter-domain control framework
Next Steps

• Integrate algorithms for defragmentation in spectral-spatial-temporal domains
• Extend RSMA to incorporate cross-layer optimization
• More on Resource and Domain Virtualization
• Implement FlexGrid RSMA within OSCARS
• Develop multi-domain FlexGrid RSMA using virtualized resource model and brokers
• Testbed experiments with multi-domain OpenFlow controller with brokers and resource virtualization
What question does your research motivate you to now ask?

• What is the DoE’s requirements/specs for multi-domain optical networking?
• Can application-network integration achieved with our distributed resource control tools?
• Can end-to-end performance effectively enhanced across multiple administrative domains?