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Resilience in Next-Generation Intelligent Optical Networks

Suresh Subramaniam, George Washington University
Hiroshi Hasegawa, Nagoya University
Masahiko Jinno, Kagawa University

2nd Annual PI Meeting, Chicago
October 11th, 2019

NSF

NICT

Outline

- ✓ General Background & Project Goals

- ✓ Proposed Research
  - Survivable and Scalable OXC Node Architecture (Nagoya Univ.)
  - Highly Survivable Protection Schemes for Trustworthy Optical Networks (Kagawa Univ.)
  - Trustworthy Connection Resource Management (George Washington Univ.)

- ✓ Collaboration Plan & Time Table

General Background & Project Goals

Background

Extremely fast traffic growth in the Internet

Cisco VNI (Visual Network Index)

- 127 times/16 years (2006-2021)
- 3.2 times (average), 4.6 times (peak) / 5 years (2016-2021)

In Japan

- +29.7% /year (2017-2018)

Because of…

Broadband connection speed: x2 faster (2016-2021)
Emerging applications: 5G, UHDTV(up to 144Gbps)
Cloud based services

ICT based society

Optical networks

- Only optical networks can carry the huge traffic. (10+Tbps/fiber, 1000fibers/cable)
- Offloading from wireless to fiber (ex. 5G, Radio over Fiber (RoF))
- Optical channel capacity: 10Gbps, 40Gbps, 100Gbps ⇨ 200Gbps, 400Gbps, 1Tbps…
- "Channel capacity enhancement < Traffic growth" : More fibers on each link

⇨ Large scale optical nodes with many components

Almost constant revenue

Scalability & CAPEX

Failures

- Disasters: earthquakes, typhoons, tsunami…
- Random failures: # of failures will increase as components in a network will be more.
- Connection disruption has huge impact on our ICT based society.

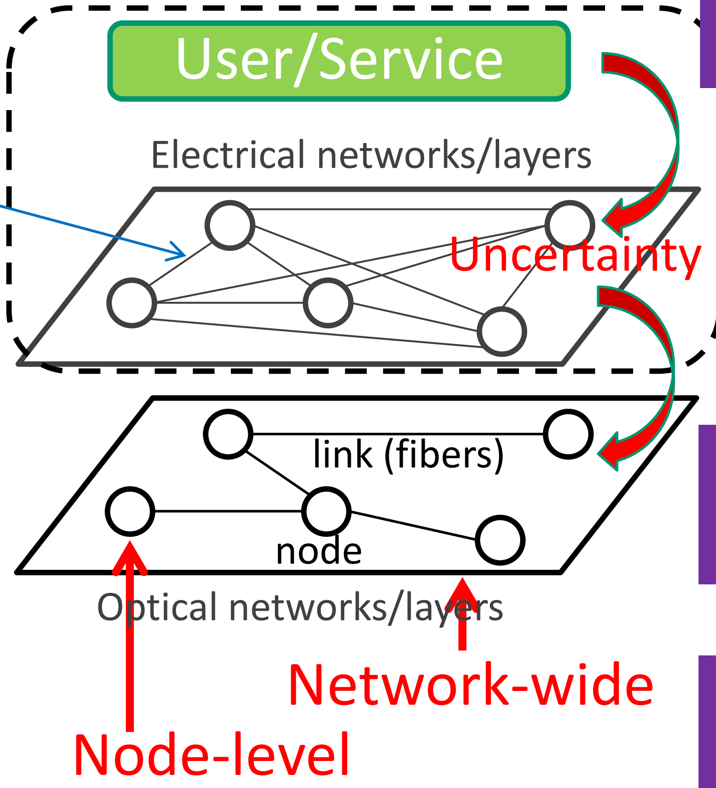
Resiliency / Trustworthyness

Tools

- Recent advancement of machine learning.
- Specialized software and hardware (ex. Google's TPU).

Trustworthy & “profitable” optical networks

Logical links defined by path connection in the optical layer



Resiliency

Prediction & Resource allocation

- Traffic/connection demand
- Service Level Agreement
- **Revenue**

Redundancy in networks Advanced transmission

Cost-effective, scalable, & parallel hardware

Essentially difficult and complex problem

- Optical network design problem is **NP complete** even if we omit the resiliency requirement.
- Trade-offs between CAPEX reduction and resiliency level.
- Revenue is defined in the upper layer and CAPEX (i.e. cost) in the lower layer.

Project Goals

1. Development of highly reliable and cost-effective optical nodes.
2. Hybrid protection/restoration frameworks for the robustness against multiple node/link failures.
3. Fine-grained connection-level availability (as opposed to network-level survivability) management.

Survivable and Scalable OXC Node Architecture

Hiroshi Hasegawa (Nagoya University)

Motivation and Goals

- ✓ Current optical nodes rely on complex components; i.e. WSSs.
  - Less reliable than conventional thermo-optic switches.
  - Limited port count, High cost, Transmission impairment, etc.

- ✓ Steep traffic growth motivates the introduction of parallelism to optical networks.
  - Fiber cables with many fibers, Multiple-core fibers, Spatial division multiplexing, etc.
  - However, costly large-scale optical nodes will be necessary.

- ✓ Goal: Develop a novel highly reliable, scalable, cost-effective optical node architecture.

- ✓ Achievement in the past year
  - Cost-effective node architecture that adopts spatially-joint switching and flexible wavebanding
  - ML-based RWA algorithm

Spatially Jointed Flexible Waveband Routing Optical Node

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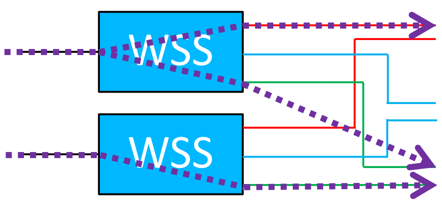
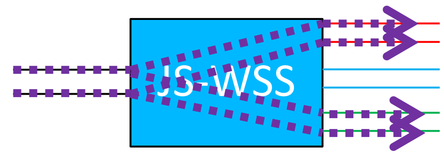
A pair of conventional WSSs

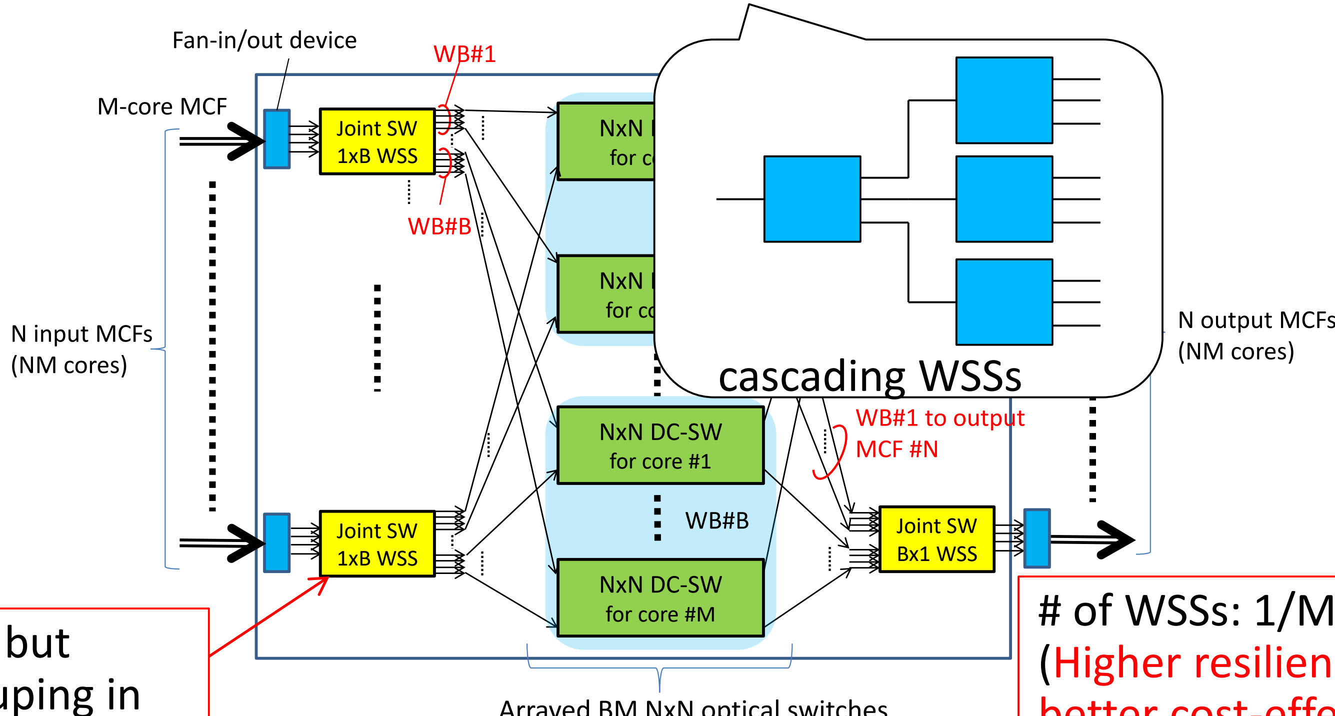


A conventional WSS in the spatial-joint-switching mode



A set of signals of the same wavelength will be routed together to the same output port group

- Reduce the number of WSSs
- Lower degrees of WSSs (ex. 1x20 => 1x2@7core)

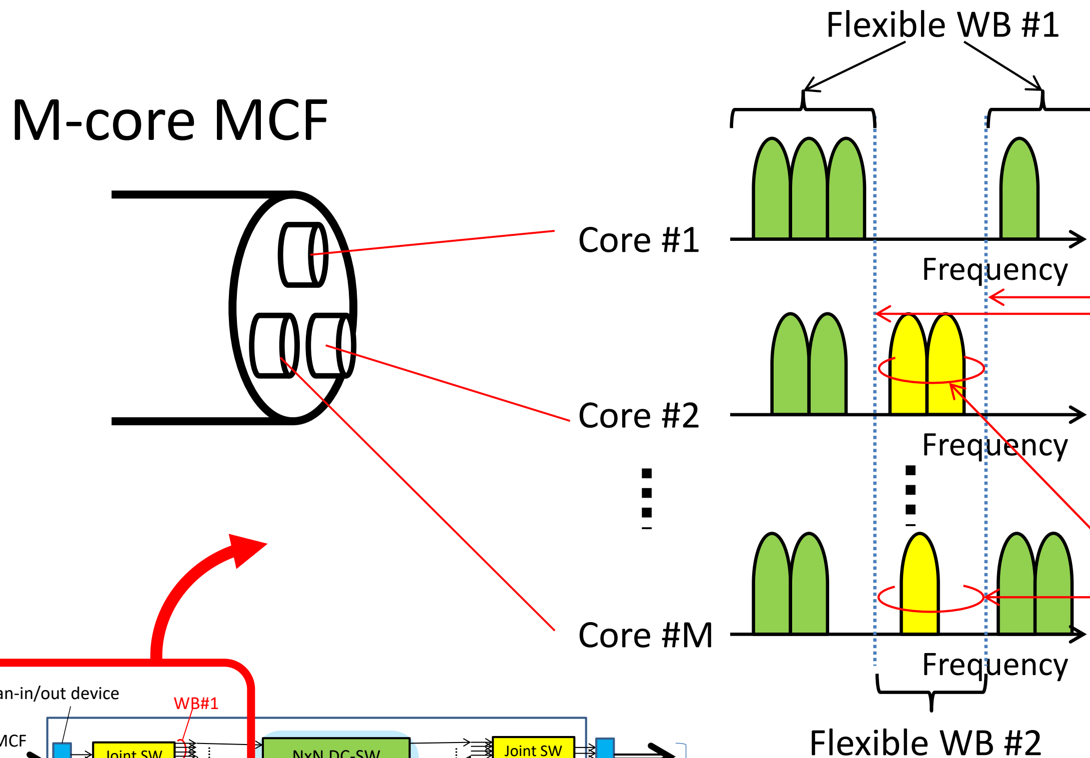


Spatially jointed, but flexible path grouping in the frequency domain

# of WSSs: 1/M or less
(Higher resiliency and better cost-effectiveness)

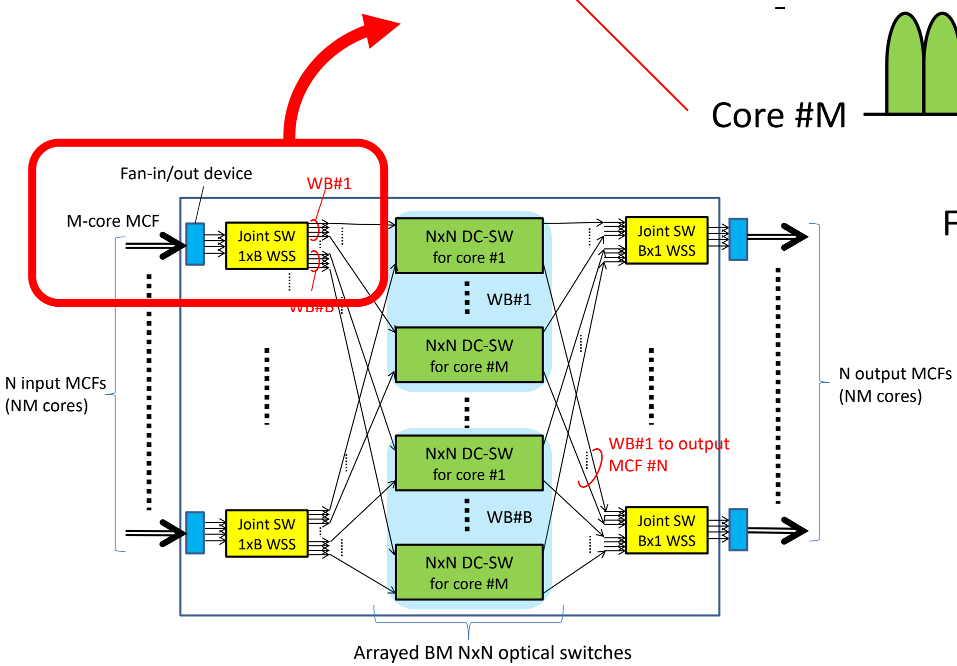
Proposed node architecture

Spatially Jointed Flexible Wavebanding



Separation/grouping in the frequency domain is common to all cores. ("spatially jointed wavebanding")

Wavebands #k (k=1,2) in cores #1,#2,… can be routed to different output MCFs.



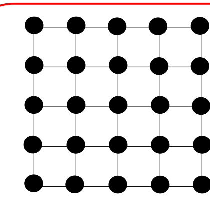
Spatially jointed, however still flexible in the frequency domain

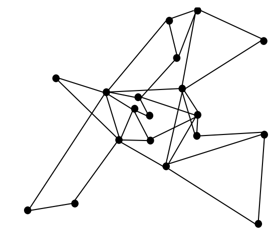
Performance Evaluation

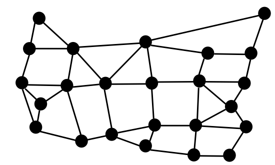
Parameters

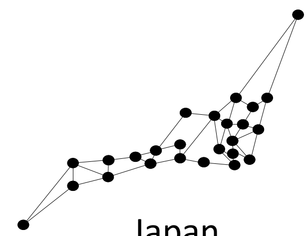
of cores in each MCF: 4
Frequency bandwidth: 4.4THz (352 x 12.5GHz width slots)
Channel types (# of slots): 100Gbps (4), 400Gbps (7), 1Tbps (15)
WSS types: 1x20 (1x4 for joint switching)

Topologies


5x5 regular mesh


Pan-European

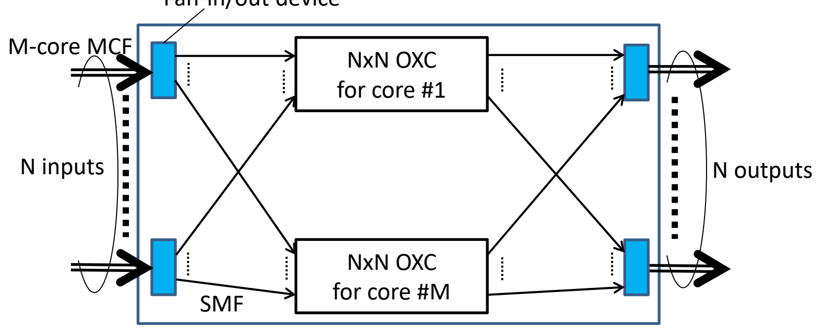

USA


Japan

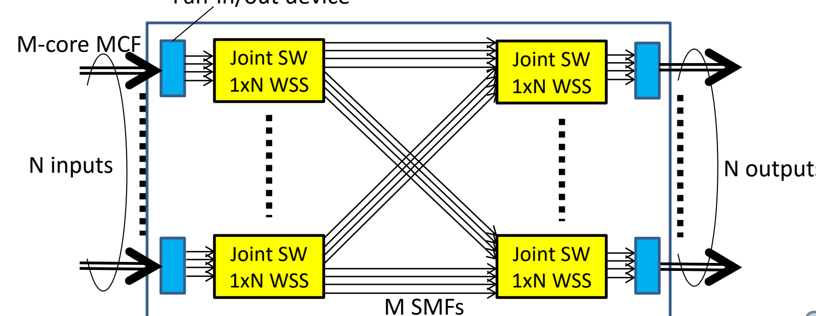
Metrics

of fibers necessary
# of WSSs necessary

Normalized by these for conventional core-wise switching



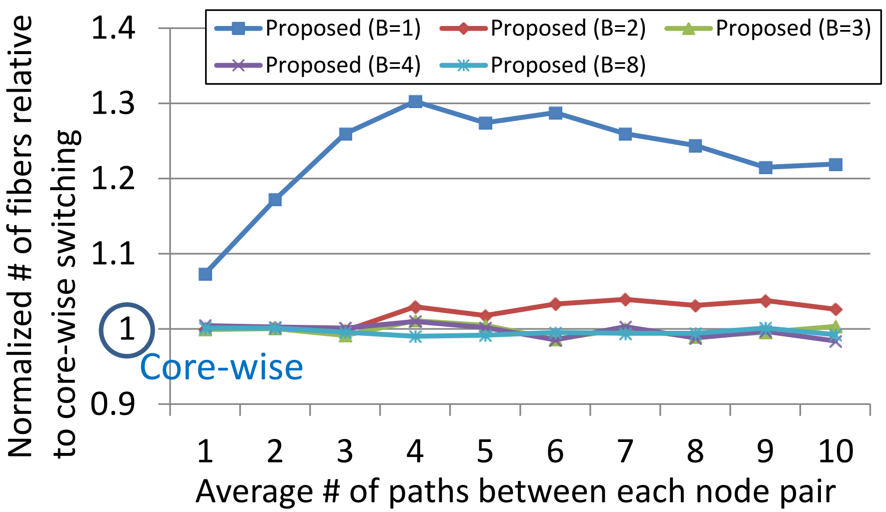
Conventional (Core-wise switching)



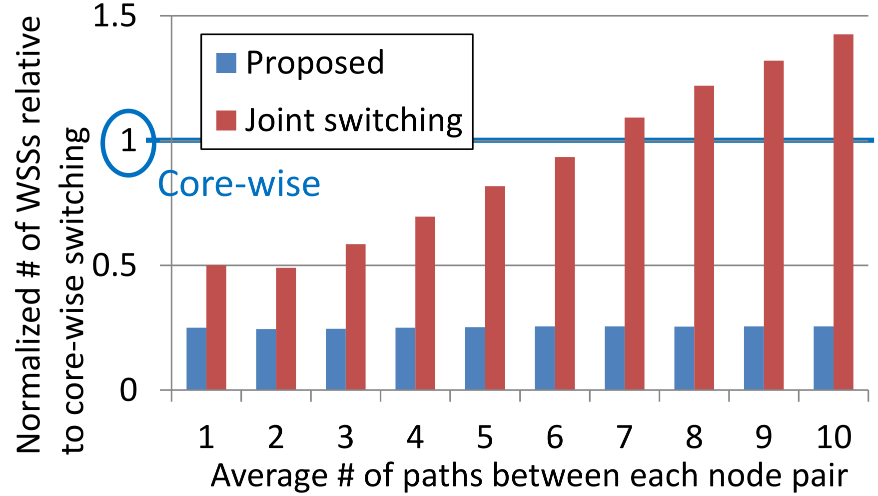
Conventional (Joint switching)

Results on the 5x5 regular mesh

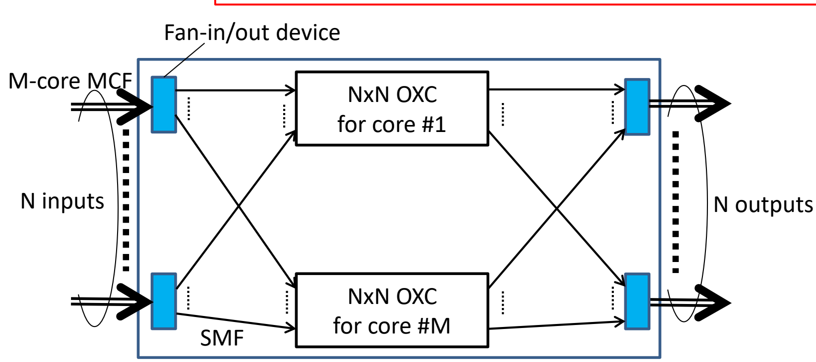
of fibers



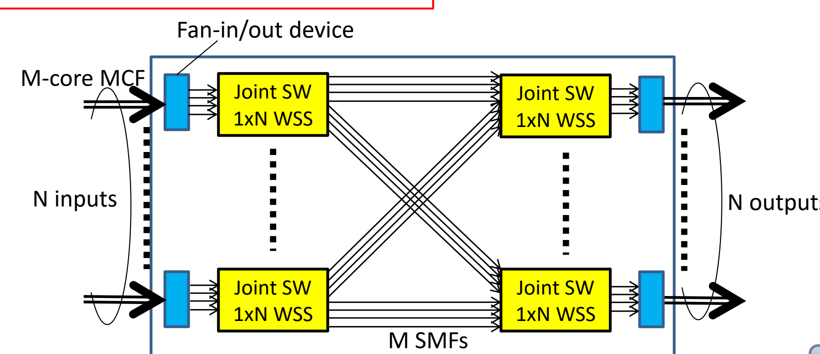
of WSSs



- Almost equivalent routing performance
- WSS number reduction: up to 75%



Conventional (Core-wise switching)



Conventional (Joint switching)

Machine-Learning based Routing and Wavelength Assignment

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Applications of Machine Learning to Optical Networks

- Most of existing studies focus on optical transmissions.
  - → Supervised learning with numerous training data samples.
- However, the application of MLs to the control/management of optical networks is hard.
  - → Many parameters (10000+) will be necessary to describe a status.
- No common metric like BER for the transmission.

Size of the state vector

Deep-RMSA [X.Chen et.al., OFC2018]

“# of fibers” x “# of slots”=1024

- 6 nodes/ 16 unidirectional links

Topologies	# of nodes	# of links	Size of the state vector
5x5 regular mesh	25	40	28160
USA (USNET)	24	43	30272
Pan-European (COST239)	19	37	26048
Japan (JPN25)	25	43	30272

# of frequency slots = 352 (C-band), # of fibers on each link = 1

Learning Efficiency Improvement

"Curse of dimensionality"

Enhancement in Learning Efficiency of Deep NNs

[C. Chun-yen et.al. ECOC2018],[J.S. Varela et.al. OFC2019]

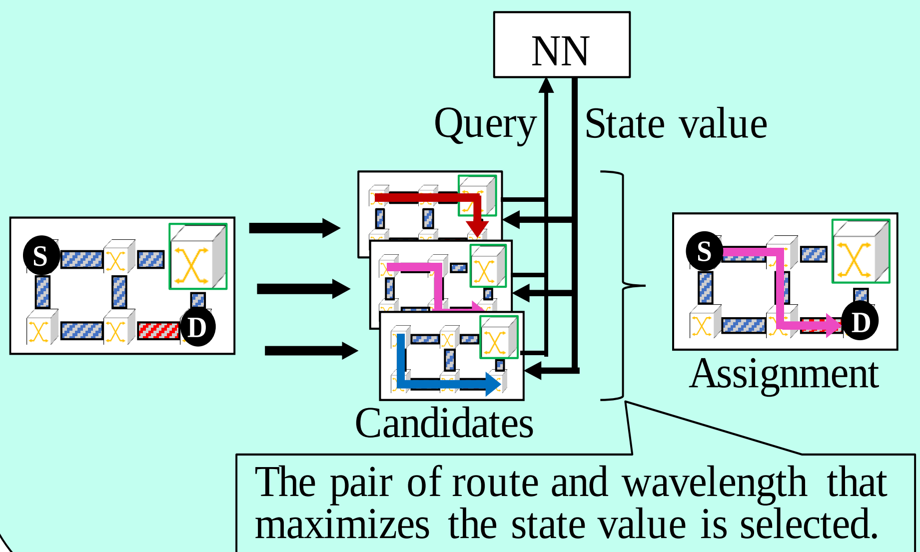
Proposed

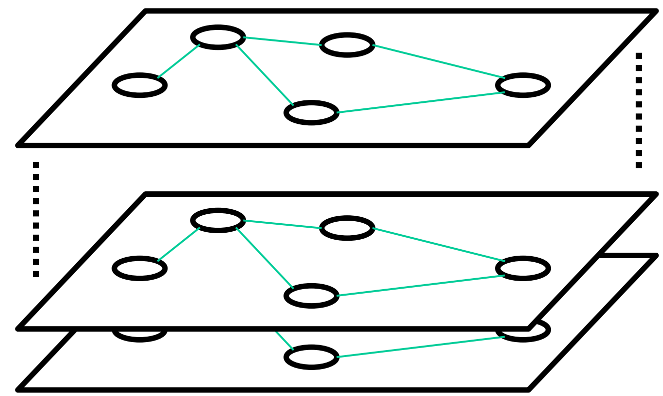
Dimension Reduction & Relatively Compact NNs

[R. Shiraki et.al. ICTON2019]

# of layers of NN: 3

For each wavelength, find a route that is optimal in terms of the proposed metric. Then find the optimal pair of route and wavelength.





...opology is same for all wavelengths/slots.

Blocking ratio

S...

...s with multiple fibers)

Summary

1. We have a novel node architecture “Spatially-jointed flexible waveband routing node”.
   1. The number of costly WSSs is substantially reduced.
   2. It overcomes the limited-port-count issue of joint-switching WSSs.
   3. Better reliability and implementation cost.

   H. Hasegawa, S. Subramaniam, and M. Jinno, “Node Architecture and Design of Spatially Jointed Flexible Waveband Routing Optical Networks,”, ECOC 2019, P63, Dublin, Ireland, Sep. 2019. **Joint publication**

2. A novel reinforcement-learning-based dynamic control algorithm for optical networks has been proposed.

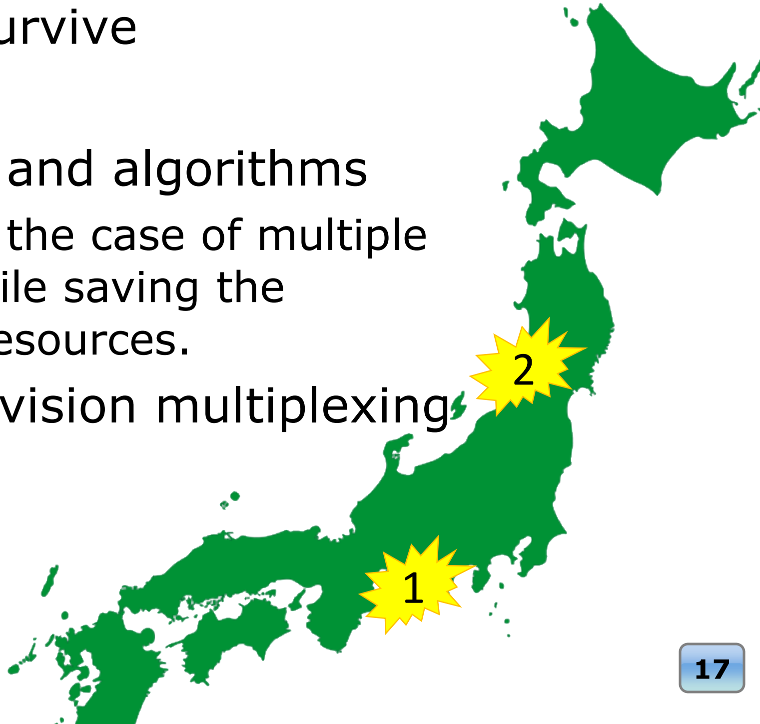
   R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, “Dynamic Control of Transparent Optical Networks with Adaptive State-Value Assessment Enabled by Reinforcement Learning,” International Conference on Transparent Optical Networks (ICTON 2019), paper Sa.A3.4, Angers, France, July 2019. **Best student oral presentation award**

Highly survivable protection schemes toward more trustworthy optical networks

Masahiko Jinno (Kagawa University)

Motivation of Our Work

- ✓ Shared protection ensures 100% recovery from an arbitrary single link failure, while saving backup resources by sharing them among link-disjoint working paths.
- ✓ In case of double link failures where working paths that mutually share their backup resources are simultaneously cut due to, *e.g.*, a catastrophic disaster, only a part of the working paths can survive
- ✓ The goals of our task:
  1. Develop fault-recovery strategies and algorithms
     - ❿ Enhance connection survivability in the case of multiple link-failures in optical networks, while saving the backup spectral and regeneration resources.
  2. Extend them to support spatial division multiplexing (SDM) networks



Shared Protection with Fallback (SP-FB)

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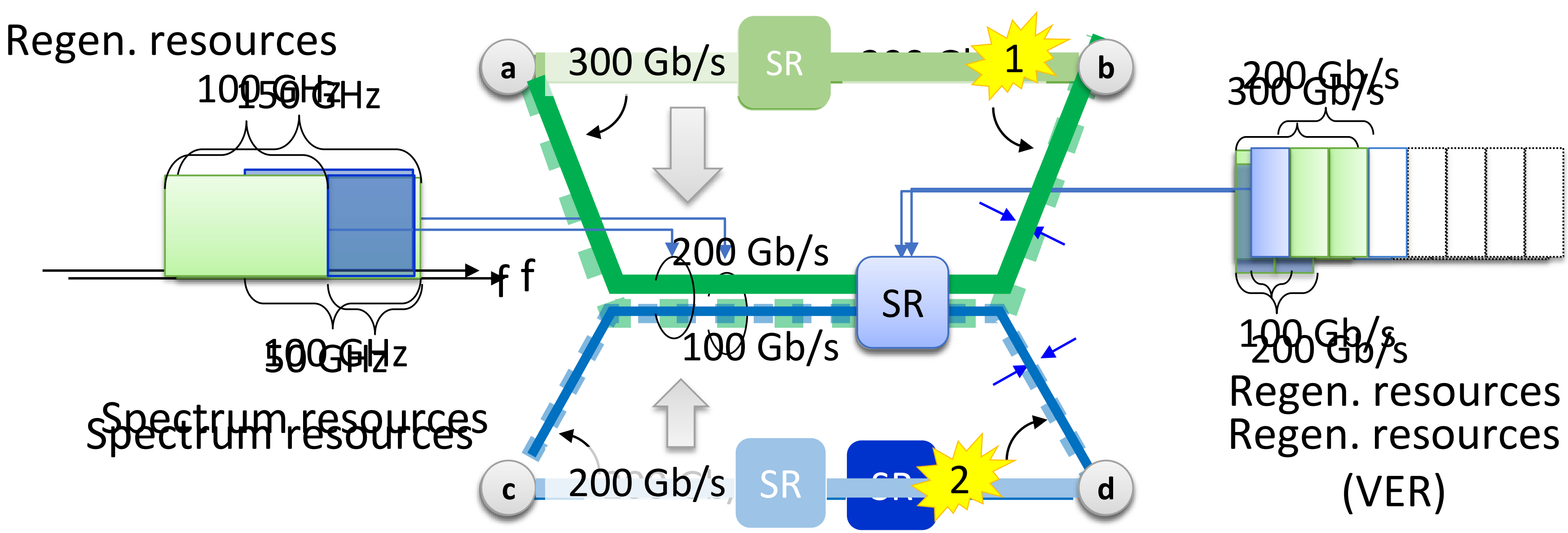
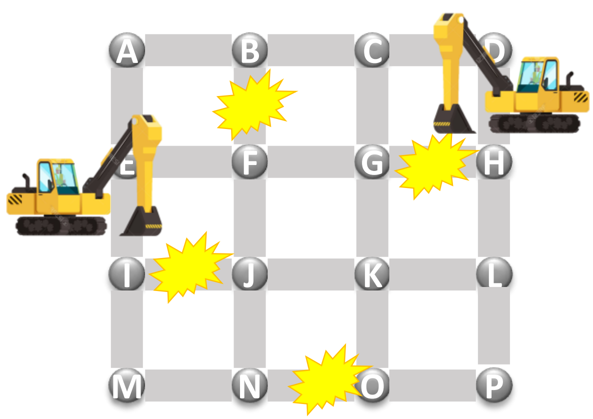
- ✓ Take advantage of sliceable transponders (STs) and sliceable regenerators (SRs)
- ✓ Connection survivability for double link failures significantly increases through mutual concessions in bandwidth of affected demands
  - Shared protection with fallback (SP-FB) operation

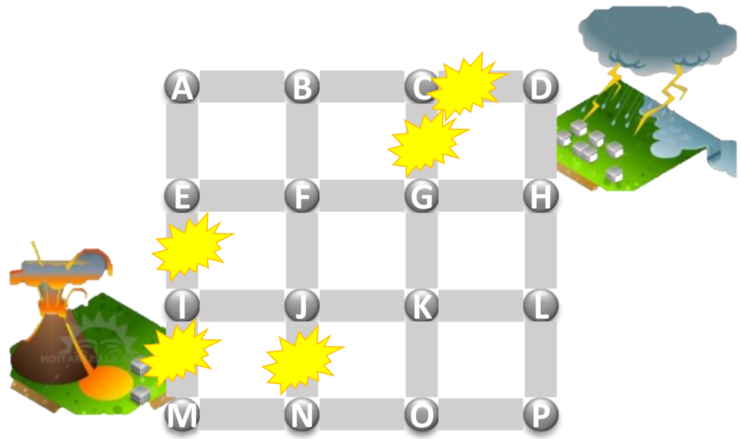


Effects of geographical distribution of failed links

- ✓ Previous study
  - Connection survivability was evaluated for double link failures occurring at two randomly chosen links
  - Corresponds to the case where fiber cuts due to road piping work etc.. occur in different places by chance.
- ✓ In a catastrophic disaster, failed links are most likely geographically close to each other



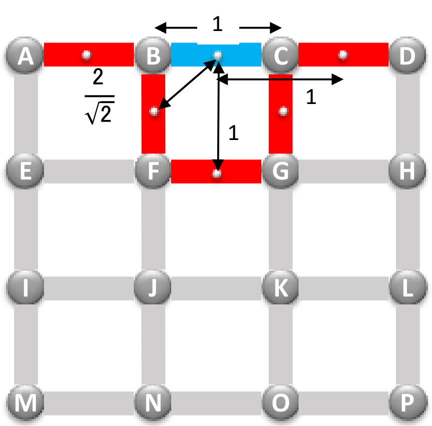
Fiber cut at two points that are not geographically correlated



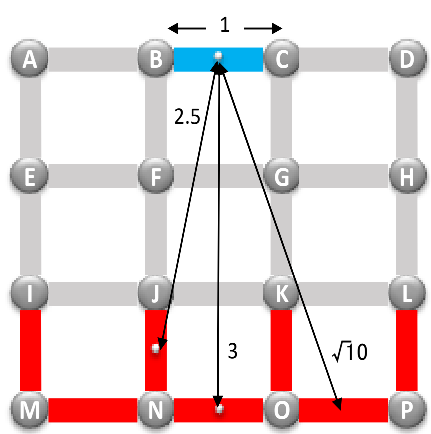
Fiber cut at two points that are geographically close each other

Achievement (1/2)

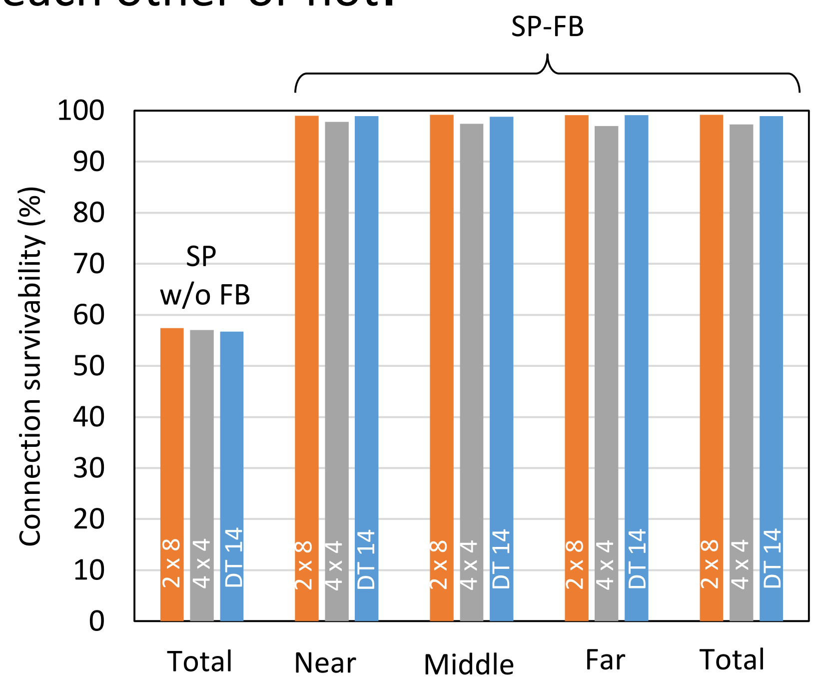
1. Evaluated the effect of geographical distribution of failed links on survivability improvement in translucent EON employing SP-FB
2. Categorize failed link pairs into *near, middle*, and *far* in terms of the distance between link centers
3. Found that SP-FB is effective for double link failures in both cases that failed links are geographically close each other or not.



(a) Near links
($l_c \leq 1$)



(c) far links
($\sqrt{5} < l_c$)



Spatial Channel Networking Testbed

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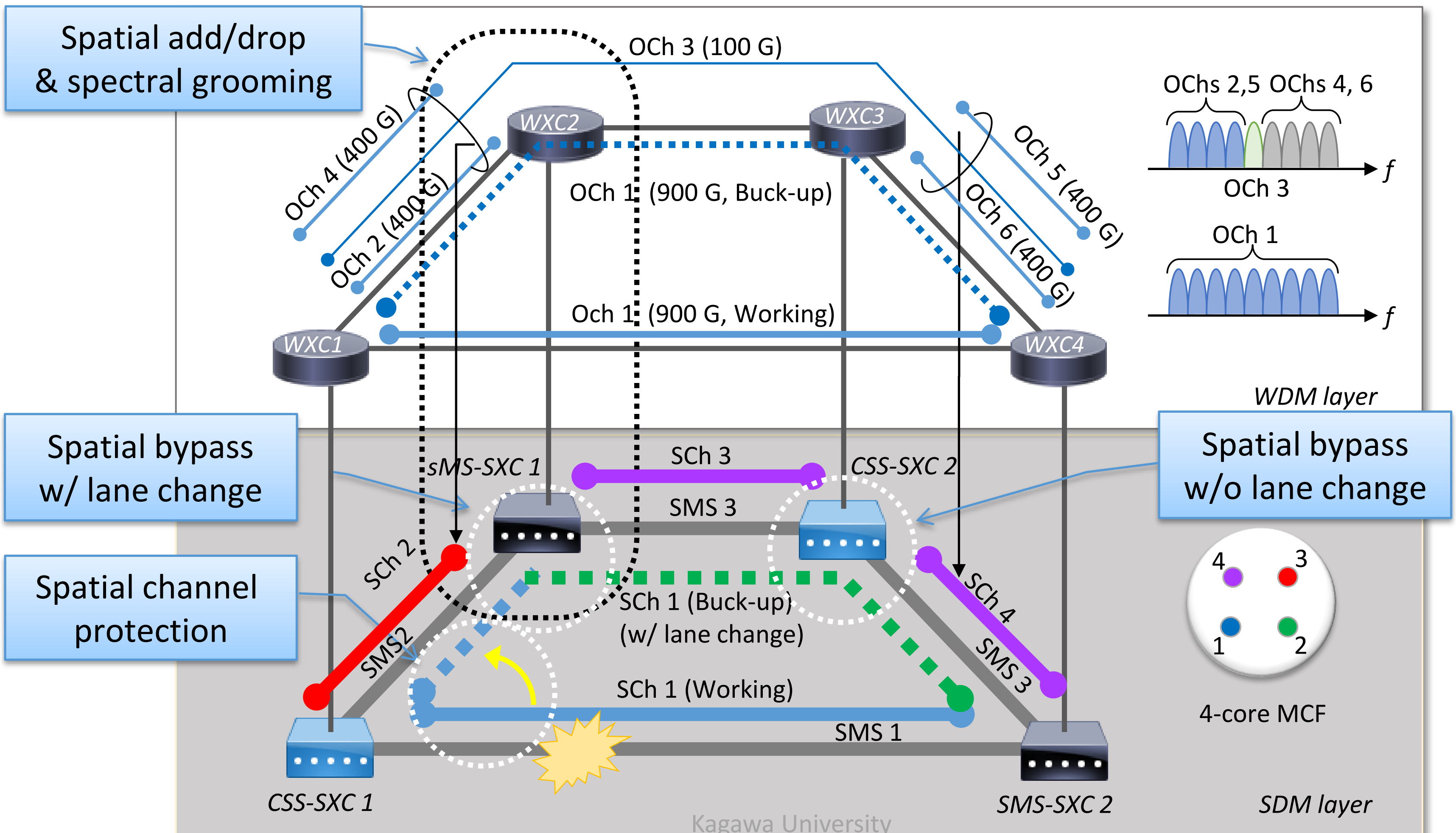
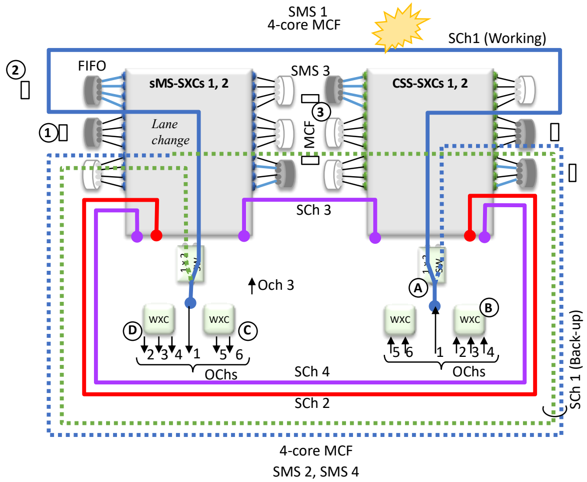
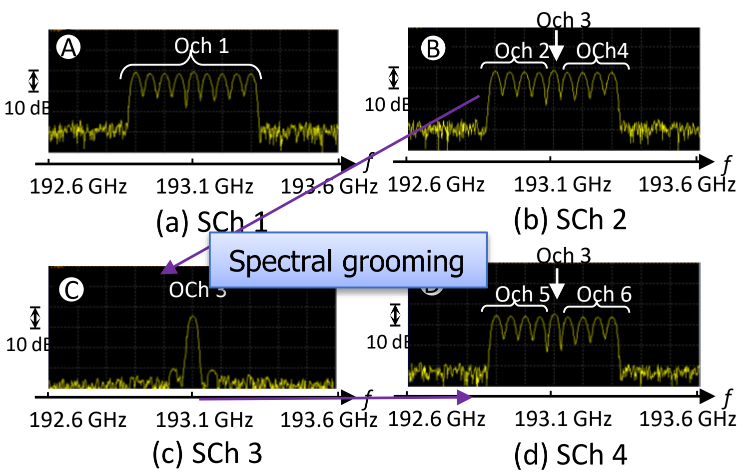
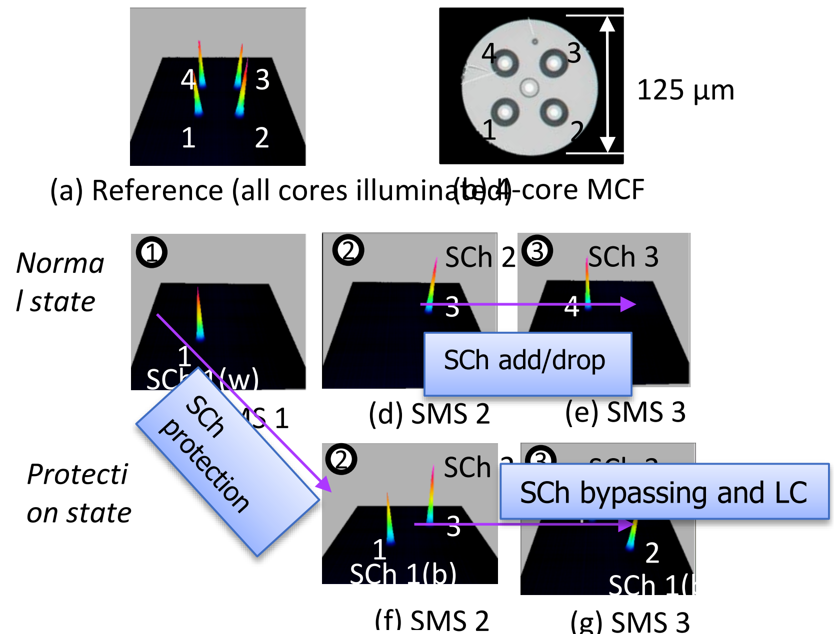
- Preliminary experiment of spatial channel networking with two types of low-loss SXC prototypes, which will be a basis for the demonstration of applying SP-FB to SDM networks.

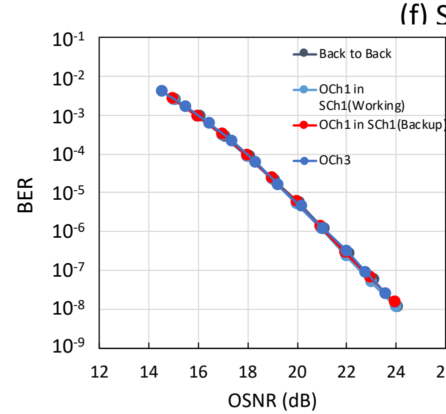


Achievements (2/2)









- Real-time pre-FEC BER measurements confirmed that there is no OSNR penalty

Summary

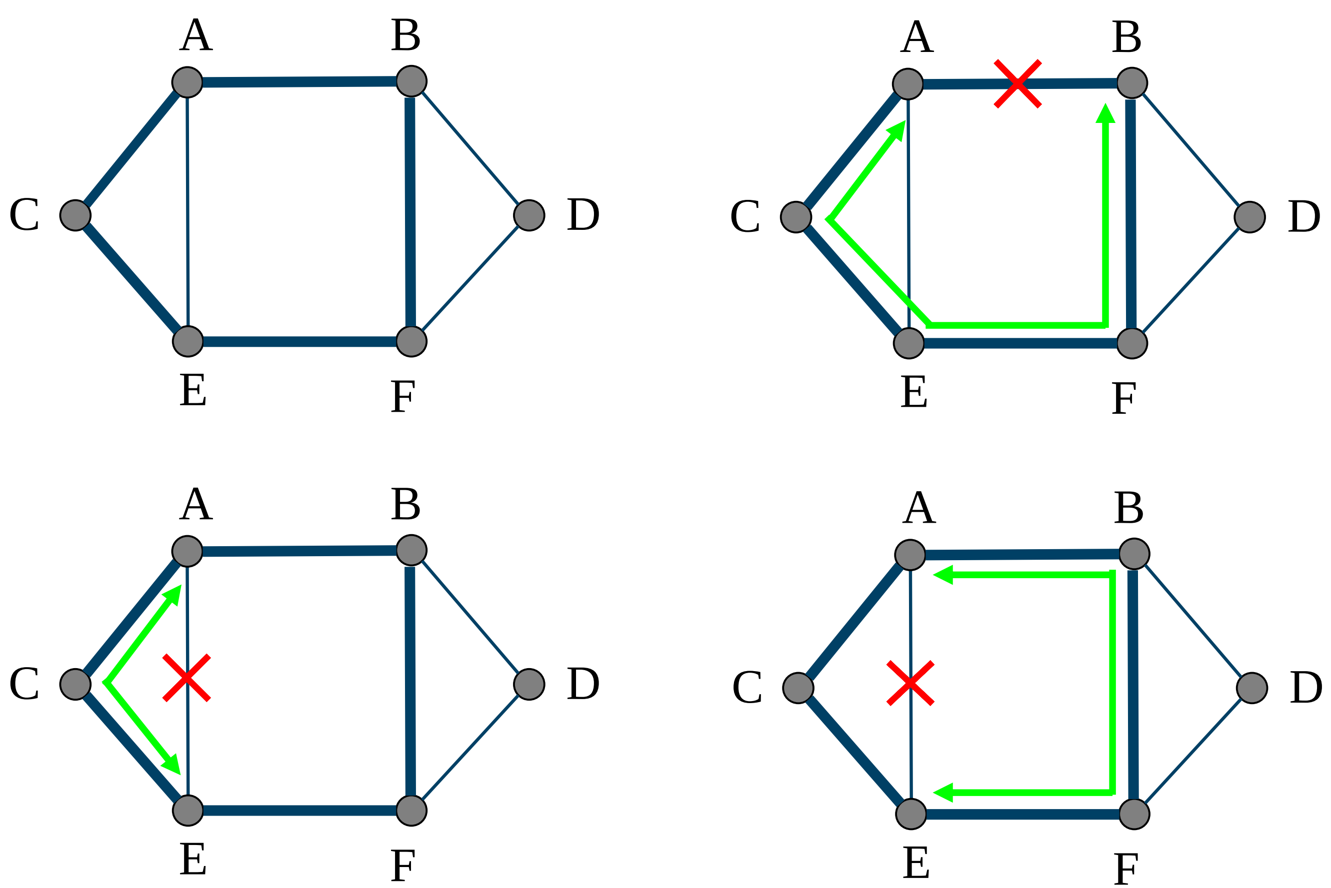
- Investigated how geographical distribution of failed links affect the extent of survivability improvement when employing SP-FB in translucent EONs. Found that SP-FB is effective for double link failures in both cases that failed links are geographically close each other or not.
  - ✓ *Y. Azuma, T. Kodama, M. Jinno, H. Hasegawa, and S. Subramaniam, "Effect of geographical distribution of failed links on survivability improvement in translucent elastic optical network employing shared protection with fall back," ACP 2019*

- Built a spatial channel network testbed and conducted preliminary experiment of spatial channel networking , which will be a basis for the future demonstration of applying SP-FB to SDM
  - ✓ *M. Jinno, T. Kodama, T. Ishikawa, K. Yamashita, Y. Asano, R. Nakai, and D. Suzuki, "Demonstration of spatial channel networking using two types of hierarchical optical cross-connects," ECOC 2019*

P-Cycle Design in Elastic Optical Networks

Suresh Subramaniam
(The George Washington University)

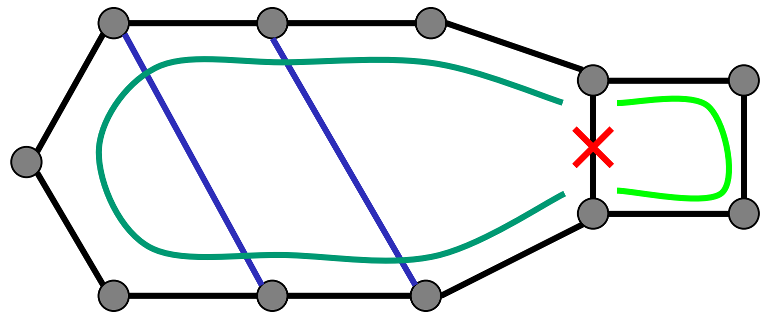
P-cycle Link Protection



Problem & Motivation - 1

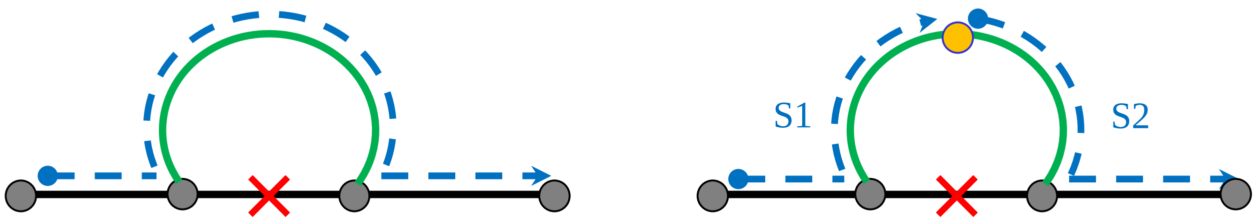
- Generate a set of p-cycles that covers all links and minimizes spectrum usage

- Factors that influence the performance of p-cycles:
  - ✓ Hop Length of p-cycle → Protection Cost
  - ✓ The number of links that can be protected by the p-cycle → Sharing Protection
  - ✓ Physical length of p-cycle → Modulation Format

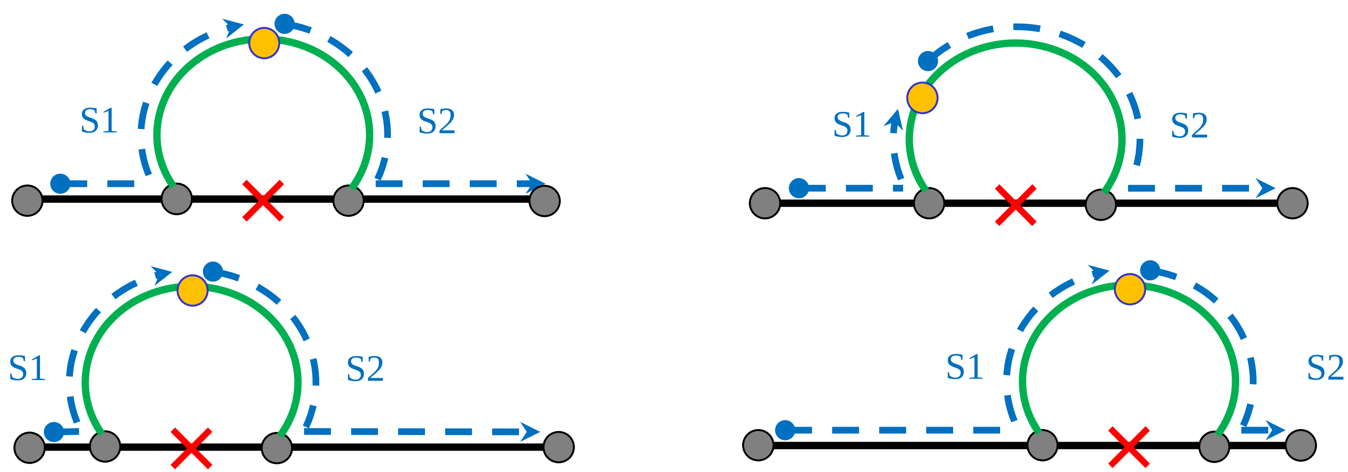


Problem & Motivation - 2

- P-cycle design with 3R regenerators in EONs
  - ✓ 3R regenerator can reduce transparent transmission distance (i.e., reduce segment length) → Higher level modulations



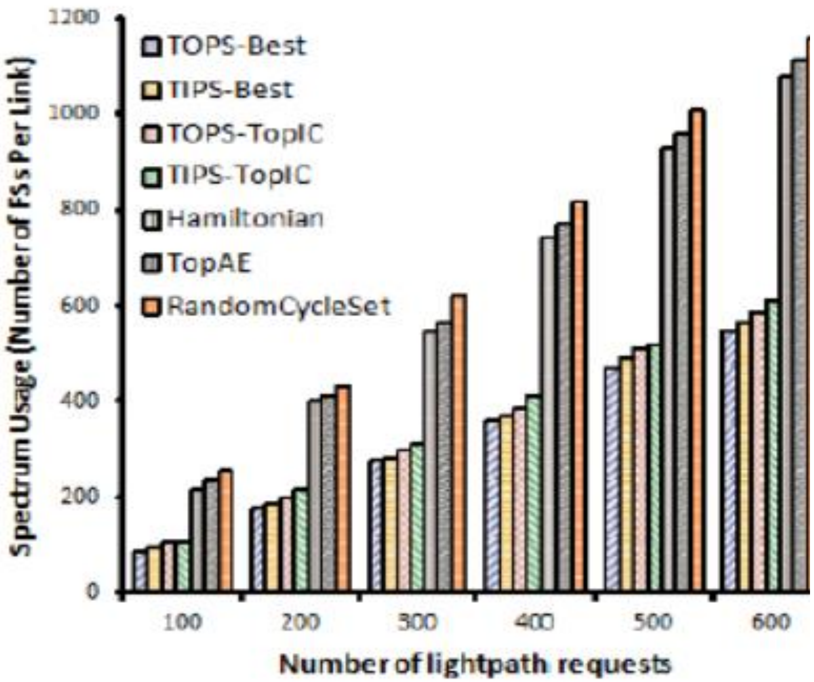
  - ✓ Length of lightpath is determined by relative position between 3R regenerator location and lightpath

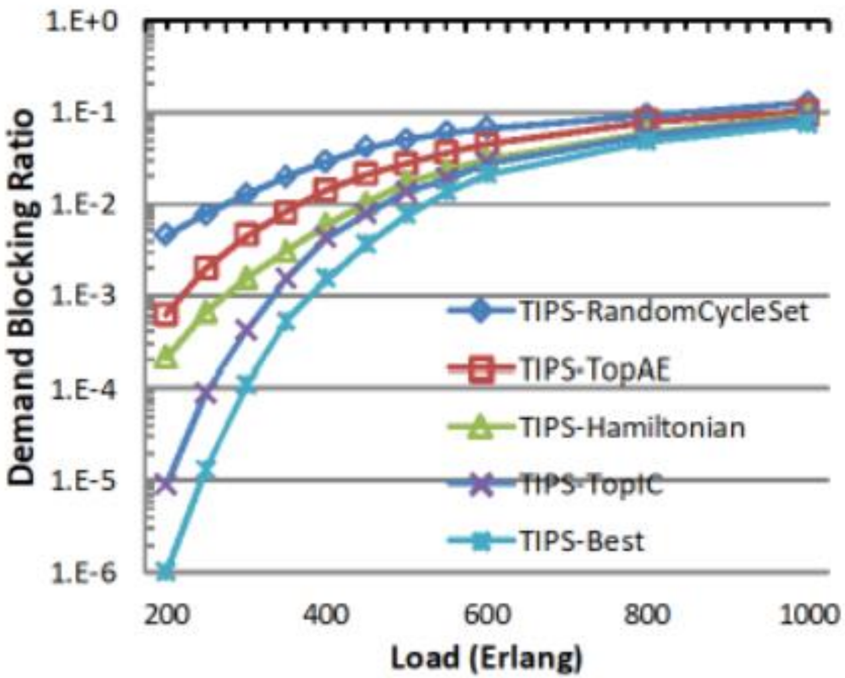


P-cycles in Transparent EONs

- P-cycle Evaluation & Selection
  - ✓ Proposed two novel link-based p-cycle evaluation methods: individual p-cycle selection (IC) and p-cycle set selection (SC) for EONs
  - ✓ Proposed Traffic Independent P-cycle Selection (TIPS) and Traffic Oriented P-cycle Selection (TOPS)
- P-cycle Set Generation
  - ✓ Find a set of p-cycles based on IC and SC.
  - ✓ Form a random p-cycle → Expand p-cycle → Form additional p-cycles if needed
- Routing and Spectrum Assignment
  - ✓ Shortest distance working path
  - ✓ Select modulation index based on the total physical distance of the protection path
  - ✓ First-fit spectrum assignment

P-cycles in Transparent EONs



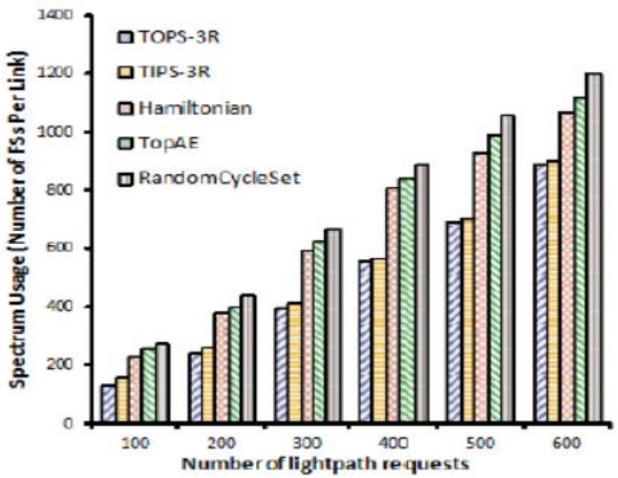


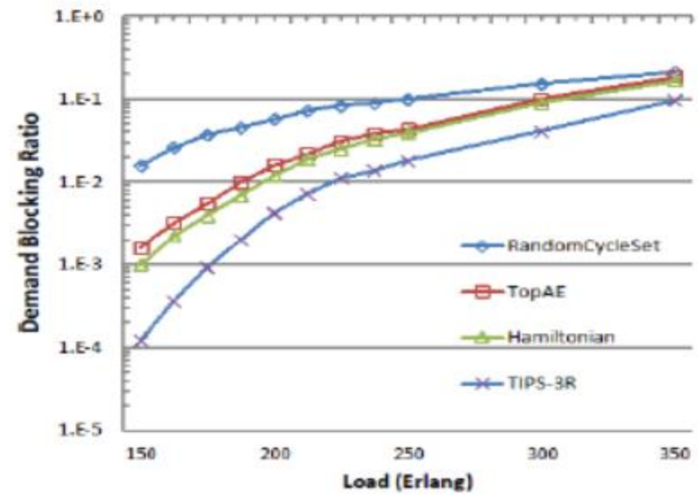
Cost239 Network

P-cycles in Translucent EONs

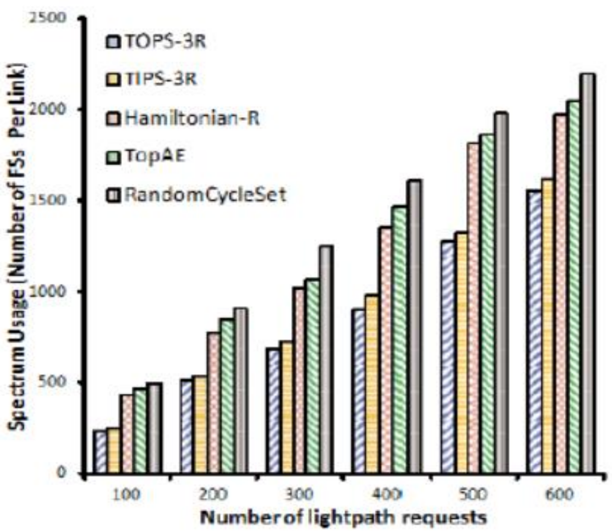
- P-cycle Evaluation & Selection
  - ✓ The individual p-cycle selection (IC) and p-cycle set selection (SC) for translucent EONs are designed with the placement of 3R regenerators
  - ✓ Traffic Independent P-cycle Selection (TIPS) and Traffic Oriented P-cycle Selection (TOPS) are designed in translucent EONs
- P-cycle Set Generation (same as for transparent EONs)
- Routing and Spectrum Assignment
  - ✓ Shortest longest segment working path

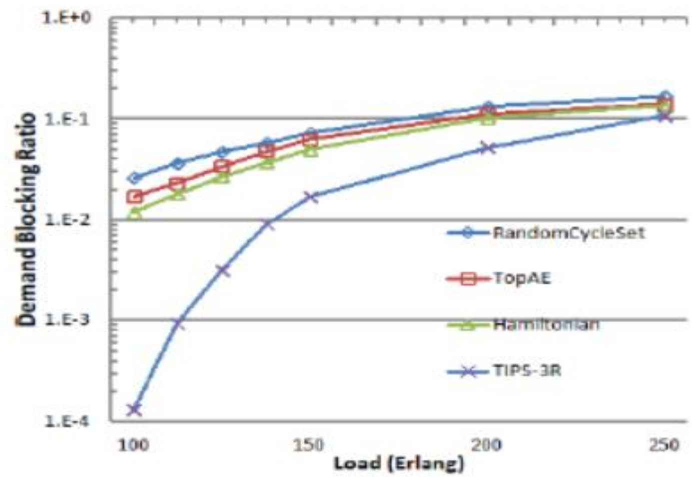
P-cycles in Translucent EONs





Cost239





Pan-European

Summary

- P-cycle Design in Transparent EONs
  - ✓ Traffic-Independent P-cycle Selection (TIPS)
  - ✓ Traffic-Oriented P-Cycle Selection (TOPS)

R. Zou and S. Subramaniam, "Novel p-Cycle Selection Algorithms for Elastic Optical Networks," in Proc. ONDM, May 2019. **Best Paper Award.**

- P-cycle Design in Translucent EONs
  - ✓ Traffic-Independent P-cycle Selection with 3R regenerators
  - ✓ Traffic-Oriented P-Cycle Selection with 3R regenerators

R. Zou, S. Subramaniam, H. Hasegawa, and M. Jinno, "P-cycle Design for Translucent Elastic Optical Networks ," in Proc. Globecom, Dec. 2019.

Collaboration Plan & Time Table

Collaboration

- ✓ Regular Skype meetings
- ✓ Face-to-face meetings
  - PI meetings in Tokyo (2018) and future meetings in US and Japan
  - Conferences: ICC, Globecom, OFC
  - Visit by GWU PI to Nagoya U in 2015 and 2017
- ✓ Education
  - NU PI served on the dissertation committee for a GWU student on the JUNO project
  - A GWU student is attending today's meeting

Joint Publications

- ✓ H. Hasegawa, S. Subramaniam, and M. Jinno, “Node Architecture and Design of Spatially Jointed Flexible Waveband Routing Optical Networks,”, ECOC 2019, P63, Dublin, Ireland, Sep. 2019.
- ✓ Y. Azuma, T. Kodama, M. Jinno, H. Hasegawa, S. Subramaniam, “Effect of Geographical Distribution of Failed Links on Survivability Improvement in Translucent Elastic Optical Network Employing Shared Protection with Fall-back,” ACP 2019, Sichuan, China, T4C.7, Nov. 2019.
- ✓ R. Zou, S. Subramaniam, H. Hasegawa, and M. Jinno, "P-cycle Design for Translucent Elastic Optical Networks ," in Proc. Globecom, Dec. 2019.

Other Publications (1/3)

- ✓ M. Jinno, "Spatial Channel Network (SCN) Architecture Employing Growable and Reliable Spatial Channel Cross-Connects Toward Massive SDM Era," PSC 2018, Fr3C.5, Jul. 2018.
- ✓ M. Jinno, "Added Value of Introducing Spatial Bypass Into WDM/SDM Networks: Gaussian-Noise Model Analysis for Spatially-Bypassed and Spectrally-Groomed Optical Channels," ECOC 2018, We3D.6, Sep.2018.
- ✓ Y. Asano and M. Jinno, “Cost Comparison of Hierarchical Optical Cross-Connect Architectures for Spatial Channel Networks (SCNs),” ACP2018, Nov.2018.
- ✓ R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, "Novel Network Architecture Enabling Quasi-Nyquist Wavelength-Division Multiplexing," Photonics West 2019, Feb. 2019.
- ✓ R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, "Demonstration of Quasi-Nyquist WDM Networks Using Widely Deployed Wavelength-Selective Switches," OFC2019, Mar. 2019.

Other Publications (2/3)

- ✓ M. Jinno and Y. Asano, "Required Link and Node Resource Comparison in Spatial Channel Networks (SCNs) Employing Modular Spatial Channel Cross-Connects (SXCs)," OFC 2019, M1A.1, Mar.2019.
- ✓ K. Itakura, Y. Mori, H. Hasegawa, and K. Sato, "Design of and Resiliency Enhancement in Coarse/Fine Hybrid Granular Routing Optical Networks Based on Iterative Path-Pair-Loop Inflation," DRCN2019, Mar. 2019.
- ✓ R. Zou and S. Subramaniam, "Novel p-Cycle Selection Algorithms for Elastic Optical Networks," in Proc. ONDM, May 2019. **Best Paper Award.**
- ✓ R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, "Quasi-Nyquist WDM Networks Using Widely Deployed Wavelength-Selective Switches," EXAT2019, P.24, May 2019.
- ✓ R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, "Design and Evaluation of Quasi-Nyquist WDM Networks Utilizing Widely Deployed Wavelength-Selective Switches," *OSA Optics Express*, vol.27, no.13, Jun. 24, 2019.

Other Publications (3/3)

- ✓ H. Hasegawa, "WS1: Machine Learning for Optical Network and Transmission - Why and Where?," OECC/PS2019 Workshop WS1, Jul. 2019 **(invited)**.
- ✓ R. Shiraki, Y. Mori, H. Hasegawa, and K. Sato, "Dynamic Control of Transparent Optical Networks with Adaptive State-Value Assessment Enabled by Reinforcement Learning," International Conference on Transparent Optical Networks (ICTON 2019), paper Sa.A3.4, Angers, France, July 2019. **Best student oral presentation award**
- ✓ M. Jinno, "Opportunities, Challenges, and Solutions for Spatial Channel Networks (SCNs) Toward The SDM Abundant Era," OECC/PS2019, TuA1-1, Jul. 2019 **(invited talk)**.

NeTS: JUNO2: Resilience in Next-Generation Intelligent Optical Networks

Thank you for your kind attention!!