# Resilience in Next-Generation Intelligent Optical Networks

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

**1st Annual PI Meeting, Tokyo**
**October 26, 2018**

# 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 in each link

⇨ Large scale optical nodes with many components

Almost constant revenue
Increasing CAPEX

**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).

# Our previous joint research

Team: GWU and NU

Target: Scalability and CAPEX optimization

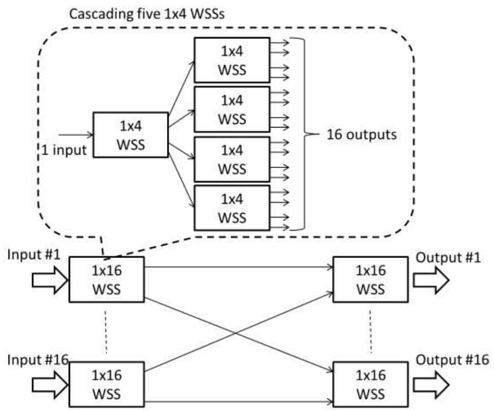
Conventional

Limits the scalability and causes square-order cost increment

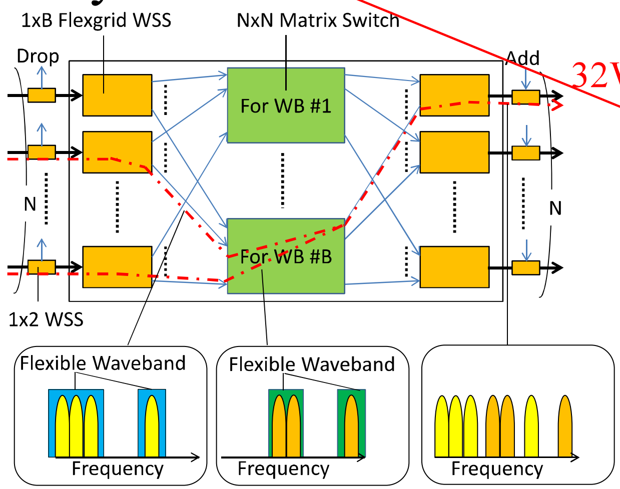
- “Demultiplexing to paths” + “path granularity switching”
- All operations are done by expensive wavelength selective switches (WSSs)

Proposed

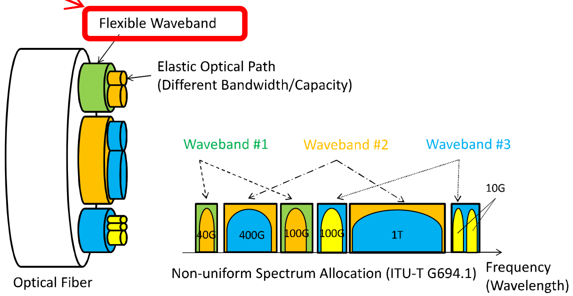
- “Dynamic grouping of paths” + “switching of path groups”
- WSSs are used only for the former operation.
- The latter operation is done by more cost-effective switches.




160WSSs for 16x16




32WSSs for 16x16




Reduction ratio of #{expensive devices (WSSs)} reaches to 80%.

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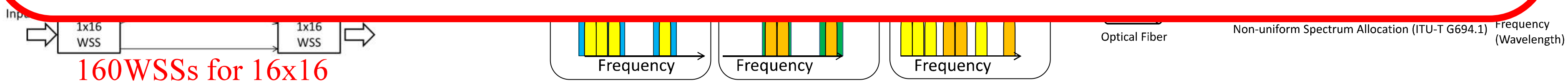
In addition to proposals of novel optical node architectures, we had succeeded in development of network control & design algorithms, routing performance analysis, and transmission experiments on a prototype.

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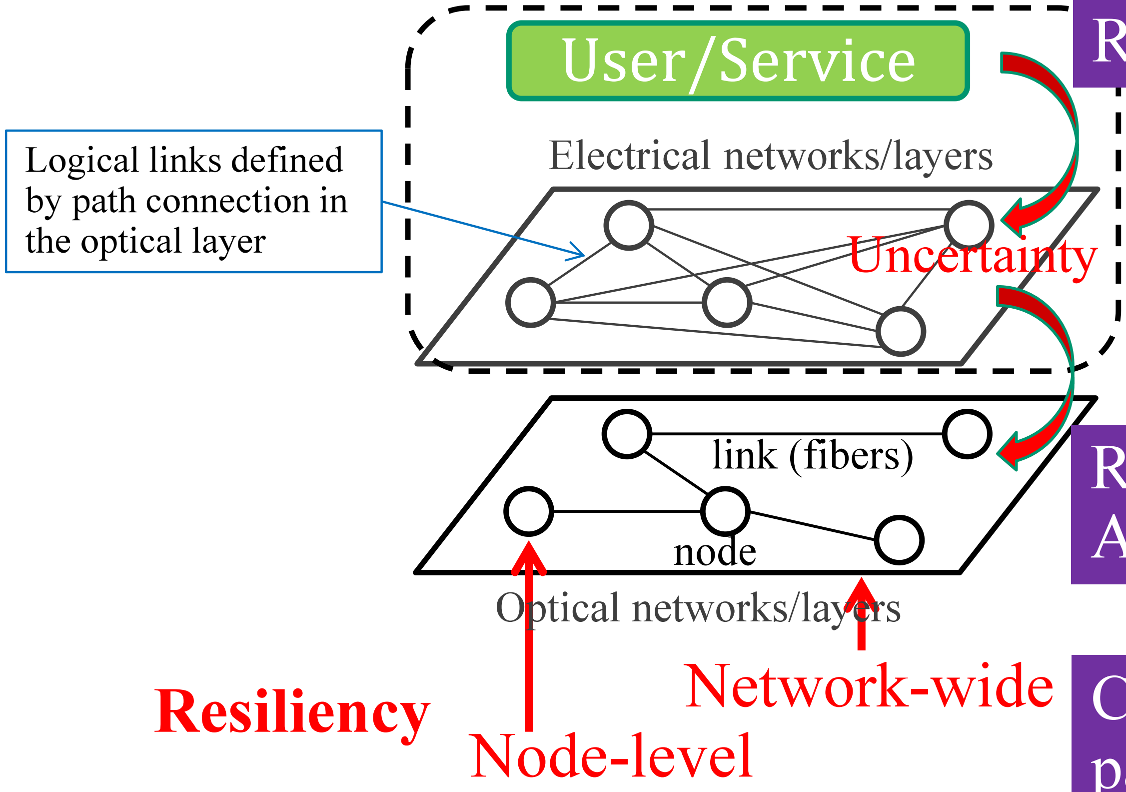
# Trustworthy & “profitable” optical networks




**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

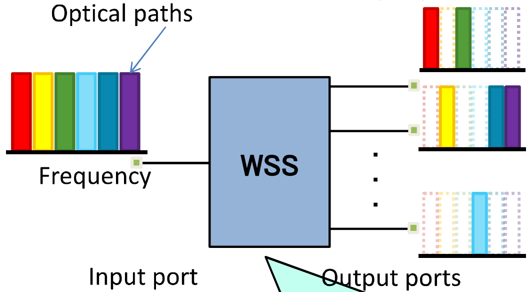
1. Highly reliable optical nodes that consist of unreliable components/functional blocks will be studied. Network design algorithms that take advantage of the switching capability will be also developed.
2. The robustness against multiple node/link failures while avoiding explosive increase of spare network resource is enabled by a hybrid protection/restoration frameworks. The highest possible resilience with "intelligent" algorithms realizes "trustworthy" optical layer while managing the wide diversity of hardware and transmission conditions.
3. Fine-grained connection-level availability (as opposed to network-level survivability) will also be investigated. The developed nodes and other components will be analyzed for their availability, and methods for providing a required level of availability for connections will be created.

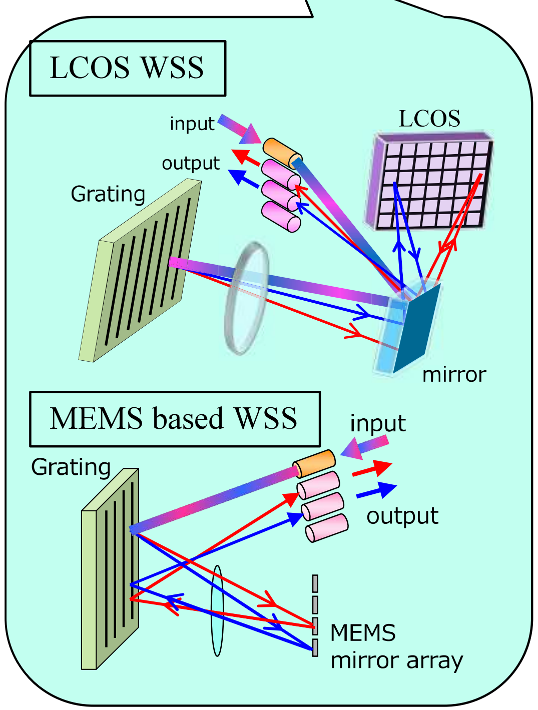
# Survivable and Scalable OXC Node Architecture

Hiroshi Hasegawa (Nagoya University)

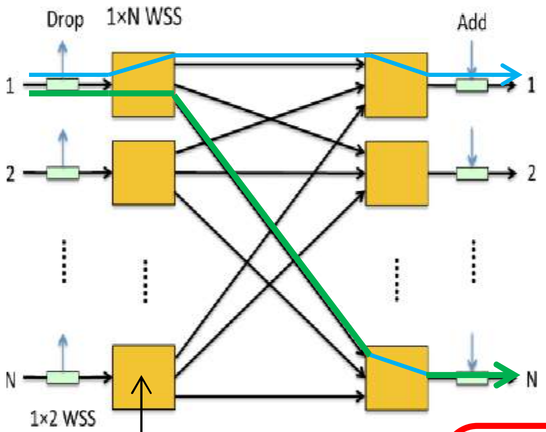
# WSSs and conventional nodes

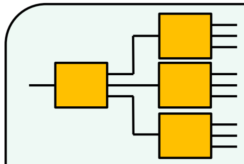
Wavelength selective switch (WSS)



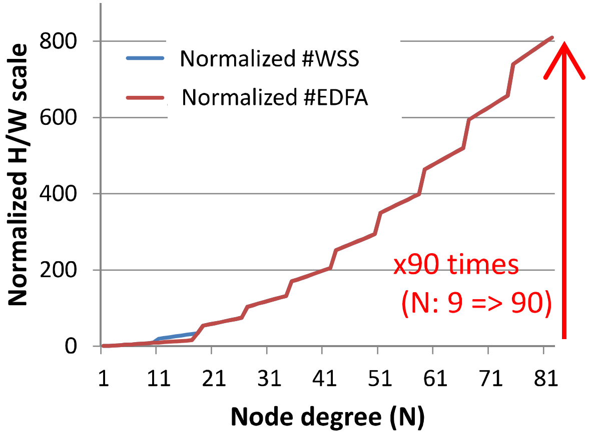




NxN optical cross-connect node



WSSs will be cascaded
if “deg. of WSS > deg. of node”.




Hardware cost explosion at WSS based node

An example of WSS
(santec WSS-100)

165 x 98 x 20 mm


Filtering & Switching

Switching

| | WSS | Optical switch |
|---|---|---|
| Switching granularity | Wavelength/Frequency slots | Fiber |
| Port count (1xn/nxn) | ~20 | ~400(3D MEMS), ~64(PLC) |
| Switching speed | - | Ultra fast (ps) ~ Slow (ms) |
| Adjustment | For all ports and wavelengths | For all ports / None |

# Resiliency enhancement for conventional nodes

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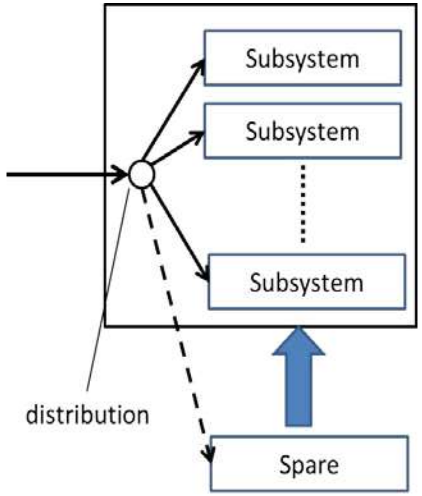
WASHINGTON, DC

NAGOYA UNIVERSITY

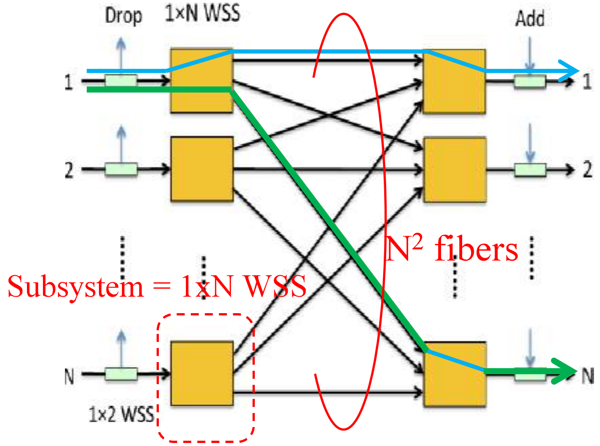
KAGAWA UNIVERSITY

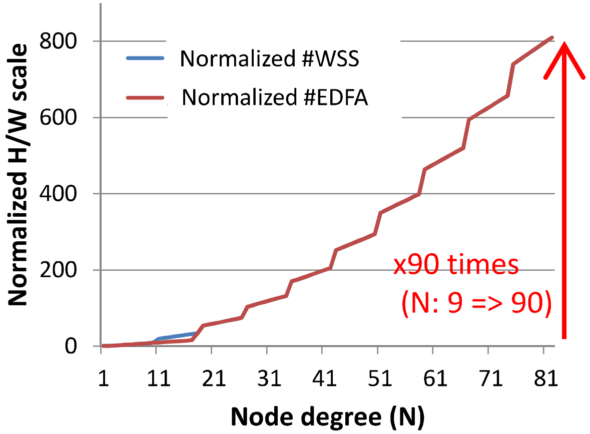
Basic strategy for resiliency enhancement




Ex) RAID: redundantly arrayed inexpensive disks

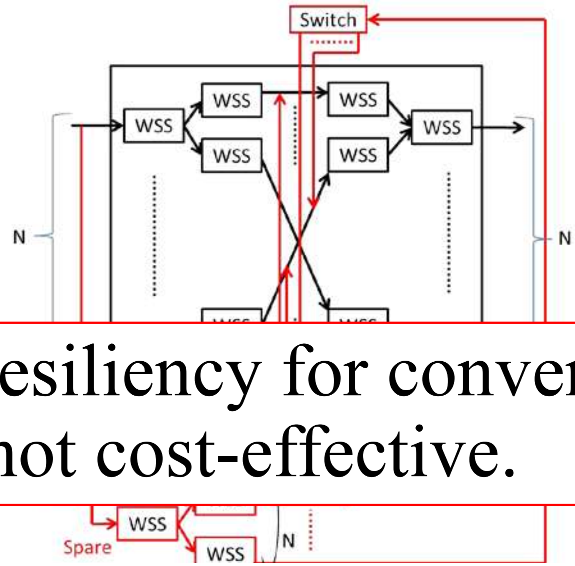
NxN optical cross-connect node




Hardware cost explosion at WSS based node

Installing a spare WSS to conventional node

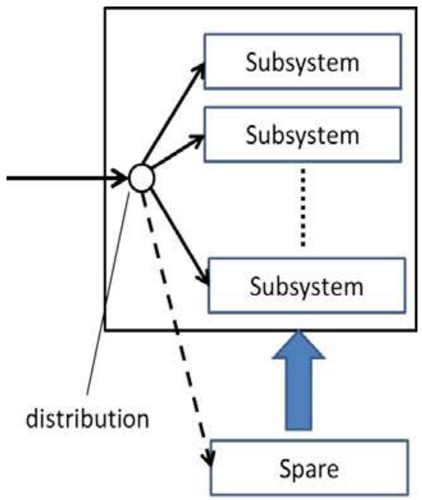



- Massive interconnection between the spare and the node
- WSS cascading increases the risk of failure.
- We need many optical switches: N+1 1xN and $N^2$+N 1x2.

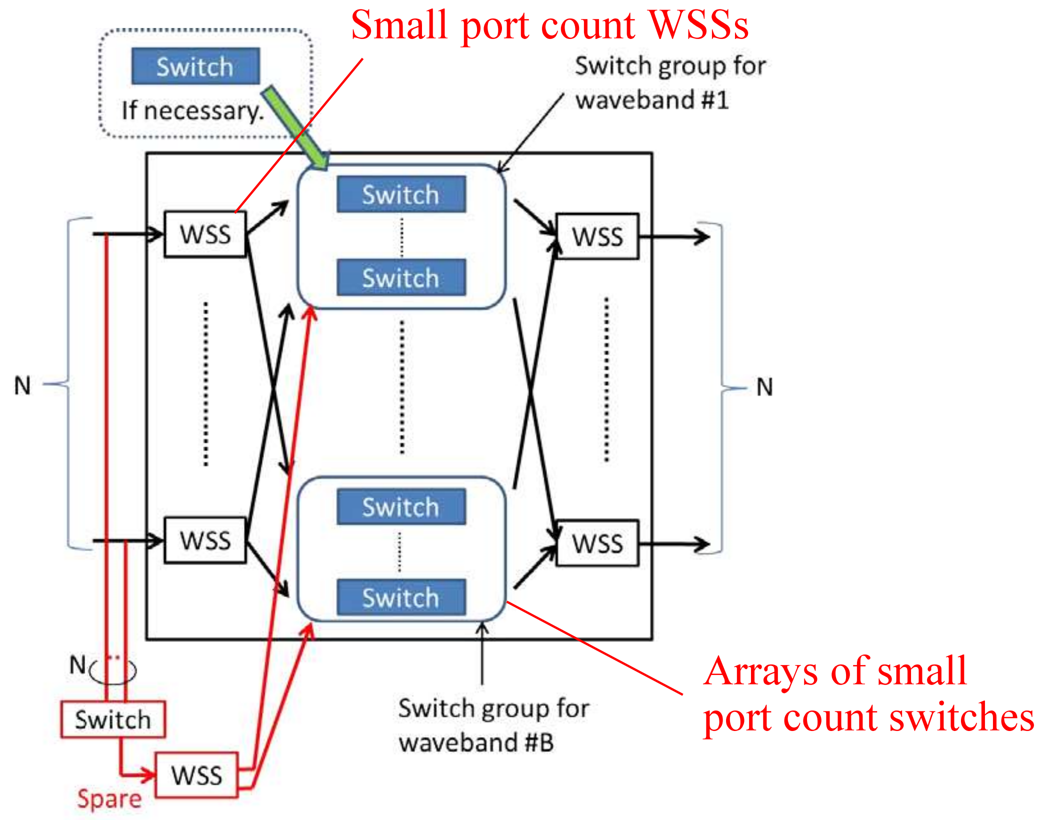
Enhancing resiliency for conventional nodes is hard and not cost-effective.

# Resiliency enhancement for flexible waveband routing nodes

Basic strategy for resiliency enhancement




Ex) RAID: redundantly arrayed inexpensive disks



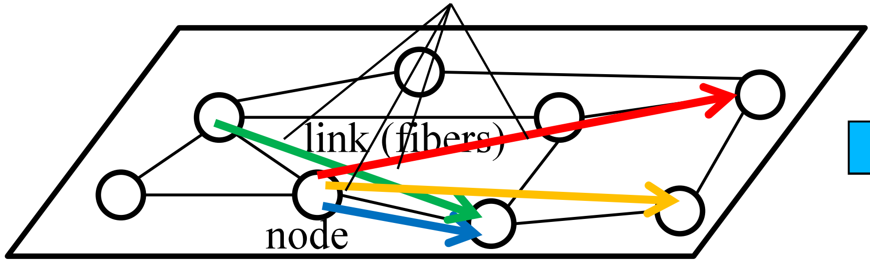

Flexible waveband routing nodes satisfy key requirements:

1. They consist of small port count devices arrayed in parallel
2. Small number of additional fibers/switches is needed

# Difficulty in introducing path redundancy to flexible waveband routing networks

Without redundancy

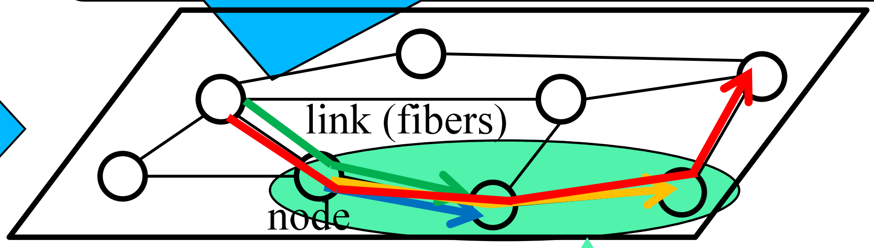
Path connection requests




Optical networks/layers

**A simple path bundling procedure**

1. Draw a line on given topology.
2. Bundle all paths whose edge nodes are on the line.




Optical networks/layers

Grouped path routing can be applied here

Wi

We need network design algorithms that can resolve the trade-offs between CAPEX reduction and resiliency enhancement, in addition to resilient flexible waveband routing nodes.

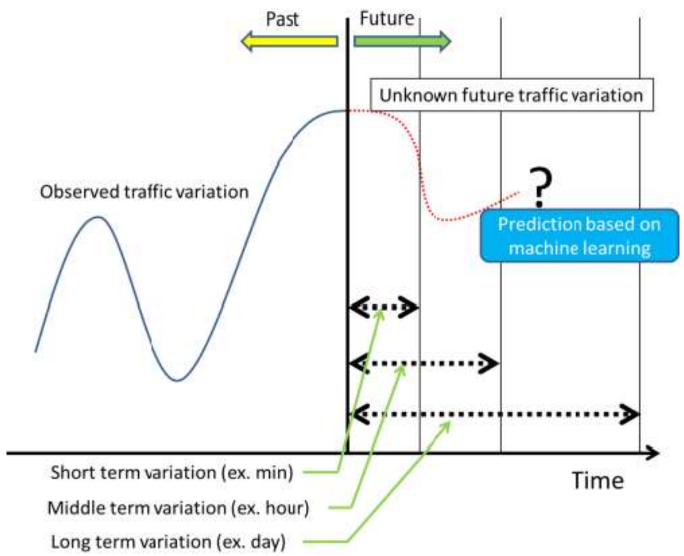
Optical networks/layers

Optical networks/layers

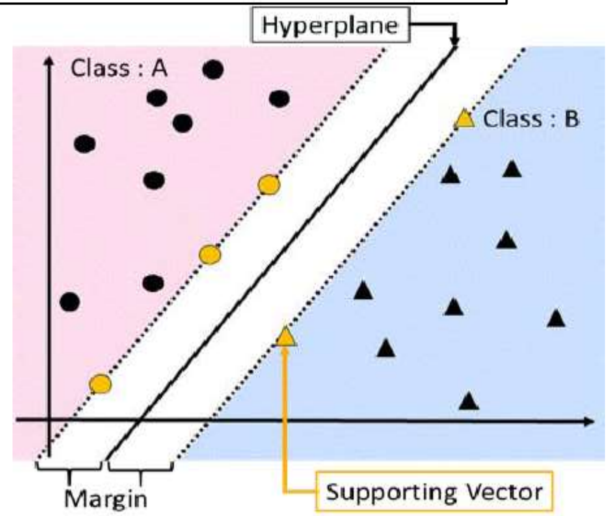
1. Route independence limits the room for optimization.
2. There are several options for switching to backups.

# Intelligence in network control

Machine-learning-based Multi-period traffic prediction and dynamic resource assignment (Sec. 3.2)




Traffic prediction on multiple time-scales




Classification by support vector machines (SVMs)

1. Prediction of traffic variation (i.e. path setup/tear down requests) will be studied.
2. Sufficiently accurate prediction must be done with relatively less data. Fast convergence is necessary.
3. Dynamic network control scheme based on prediction will be developed here.

# Highly survivable protection schemes toward more trustworthy optical networks

**Masahiko Jinno (Kagawa University)**

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

# Motivation of Our Work

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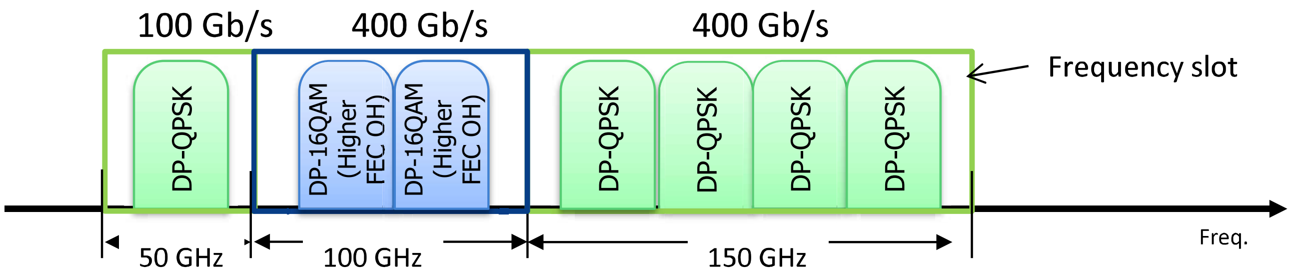
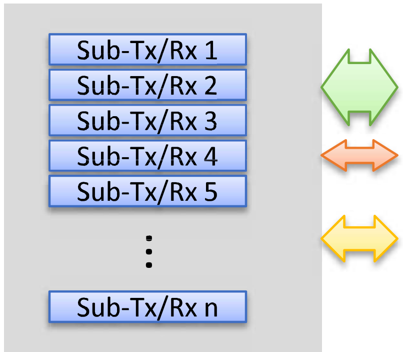
KAGAWA UNIVERSITY

- Two types of fault-recovery mechanisms, protection and restoration. Protection schemes can be dedicated or shared.
- 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 goal of our task:
  - ✓ Develop fault-recovery strategies and algorithms
  - ✓ Enhance connection survivability in the case of multiple link-failures in optical networks, while saving the backup spectral and regeneration resources.

# Resource Virtualization in EON

- Adaptive resource allocation capability of Elastic Optical Networks (EONs) based on optical network resources virtualization
- Spectrum resources in a fiber link
  - ✓ Segmented and seamlessly aggregated to create an optical path with a spectrum width that is just enough to support each traffic demand.
- Sliceable transponder/regenerator (ST/SR)
  - ✓ Comprises arrayed sub-transponders/regenerators
  - ✓ Simultaneously transmits/receives or regenerates optical channels with various bandwidths.
- Such features of link- and equipment-level virtualization
  - ✓ Efficiently accommodate various traffic demands
  - ✓ Enhance connection survivability of optical networks

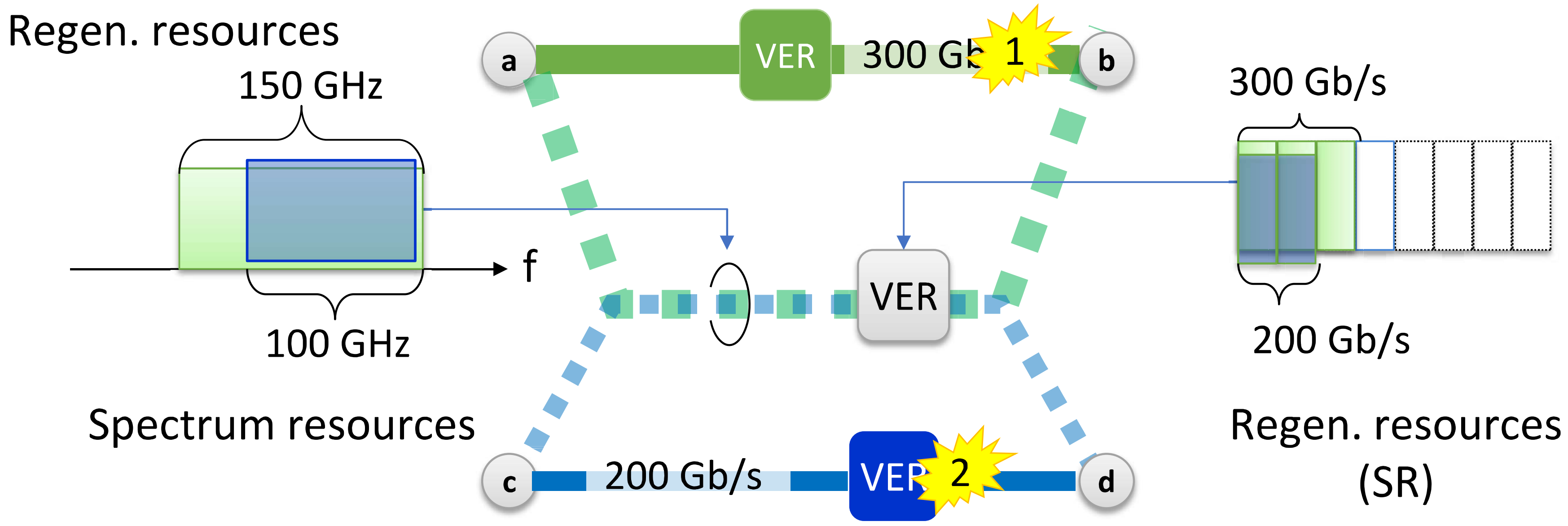



Sliceable Tx/Rx, regen

# Our Approach: Shared Protection with Fall-back

- Fallback operation in spectral width and ST/SR bandwidth when switching-over to backup route
- Fallback operation means to reduce bandwidth for each demand through mutual concessions in the bandwidth
- May be a good compromise in the case of a catastrophic disaster where ensuring connectivity would be the first priority.

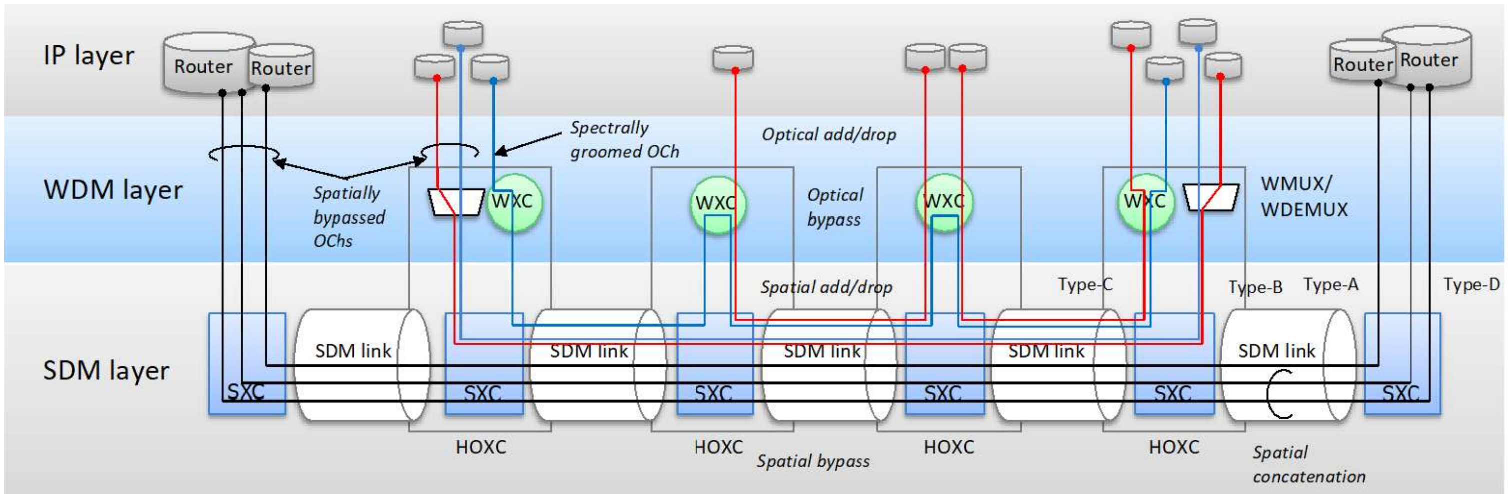


# Our tasks 1/2

1. Design algorithm for large-scale *translucent* EON balancing reliability and cost-effectiveness
   - ✓ Employ shared protection with distance–adaptive modulation format selection and conversion, and sliceable regenerator placement optimization.
2. Resource re-allocation algorithms at fallback switching-over process
   - ✓ Develop strategies and algorithms for efficient use of shared backup resources at fallback switching-over process, considering
     - Backup-resources usage efficiency
     - Fairness criteria
     - Priority of demand etc.

# Our tasks 2/2

3. Extension of shared-protection with fallback (SP-FB) to support spatial channel networks (SCNs) employing parallel SMFs or uncoupled MCFs
   - ✓ In an SCN, a spatial lane, whose physical entity is a core of parallel SMFs or an MCF, can be regarded as sliceable network resources
   - ✓ Investigate a range of SP-EB strategies
     - From single-layer spatial lane level
     - To multi-layer frequency slot and spatial lane level



# Trustworthy Connection Resource Management

**Suresh Subramaniam (George Washington Univ.)**

# Motivation and Goals

- ✓ Network survivability ensures that the entire network remains operational when failures occur
  - Does not differentiate between different connections
- ✓ A one-size-fits-all approach is not desirable
  - May be too expensive or insufficient
- ✓ Goal: Provide availability guarantees at the connection level
- ✓ Tasks
  - Systematically characterize the availability of components, sub-systems, and systems
  - Predict connection availability
  - Develop resource allocation algorithms to meet availability requirements

# Availability Characterization

- ✓ Characterize availability of integrated modules made up of disaggregated and heterogeneous components
- ✓ What is the availability of such a sub-system?
- ✓ Availability, A = 1 – MTTR/MTBF
- ✓ The challenge here is data on availability is not readily available
- ✓ We propose to characterize availability using available data and making reasonable assumptions
  - Fiber failure rate is linear in length of fiber, failure of components within a system are statistically independent, etc.

# Availability Prediction

- ✓ Given the availability of components and sub-systems and a set of resources allocated to a connection, what is its predicted availability?

- ✓ Suppose a connection has a holding time H. Can we find the probability distribution or even average of the up-time of the connection?

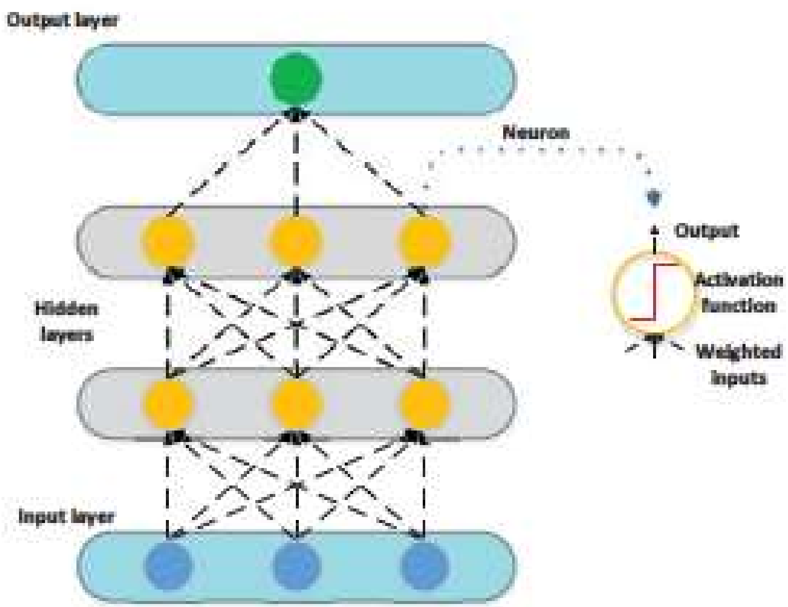
- ✓ We will pursue two approaches
  - Mathematical modeling
  - Machine learning

# Mathematical Modeling

- ✓ The system has $K$ types of components, and $N_j$ components of type $j$
- ✓ The state of the system is a tuple, each element representing the number of components of type $j$ in failure
- ✓ The set of states $S$ is partitioned into two disjoint sets $S_O$ and $S_{F,}$ operational and failed states
- ✓ Model the system as a Markov process with state space $S$ and transition rate matrix $Q$
- ✓ Possible to obtain the cdf of the up-time of a connection during its holding time
- ✓ This approach may not be scalable to 1000s of components

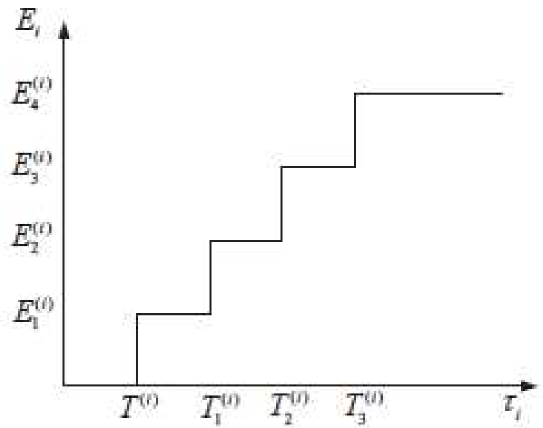
# Machine Learning

- ✓ Train a DNN using a large training data set
  - Simulate lots of connection arrivals and component failures and record connection availability values
  - Let DNN predict the availability of a connection in a given network state



# Connection Resource Management

- ✓ Each connection has an SLA that specifies various objectives and penalties
  - Availability, bandwidth, QoT, etc.
  - Penalty function if a requirement is violated




- ✓ Goal: Allocate sufficient resources to the connection so that a network performance objective is optimized
  - Maximize profit
  - Minimize penalty
  - Minimize cost, etc.
- ✓ Approaches
  - Heuristics
  - Markov Decision Processes

# 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

# Time Table

| Task | Lead | Year 1 | | | | Year 2 | | | | Year 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| GWU: Red, Nagoya: Yellow, Kagawa: Cyan, Joint: Orange | | | | | | | | | | | | | |
| 1. Survivable and scalable optical cross-connect node architecture | | | | | | | | | | | | | |
| 1.1 Cost-effecitive and resilient optical cross-connect node architecture | | | | | | | | | | | | | |
| **1.1.1 Introduction of component level redundancy to flexible waveband routing optical nodes** | **Nagoya** | | | | | | | | | | | | |
| **1.1.2 Seamless node expansion and disruption-free maintenance schemes** | **Nagoya** | | | | | | | | | | | | |
| **1.1.3 Node architecture optimization** | **Nagoya** | | | | | | | | | | | | |
| 1.2 Design algorithms of resilient optical networks with proposed nodes | | | | | | | | | | | | | |
| **1.2.1 Intra-node redundancy aware network design algorithm** | **Nagoya** | | | | | | | | | | | | |
| **1.2.2 Switching methodology to backups in flexible waveband routing networks and design of resilient networks** | **Nagoya** | | | | | | | | | | | | |
| **1.2.3 Network control/management algorithm for node expansion and maintenance** | **Nagoya** | | | | | | | | | | | | |
| 2. Highly survivable protection schemes toward more trustworthy optical networks | | | | | | | | | | | | | |
| 2.1Enhancing survivability based on a concept of sliceable network element | | | | | | | | | | | | | |
| **2.1.1 Design algorithm for translucent elastic optical network supporting shared protection with modulation format selection** | **Kagawa** | | | | | | | | | | | | |
| **2.1.2 Resource allocation algorithms at fallback switching-over process** | **Kagawa** | | | | | | | | | | | | |
| **2.1.3 Extension to support SDM networks** | **Kagawa** | | | | | | | | | | | | |
| 2.2 Multi-period traffic prediction and dynamic network control method | | | | | | | | | | | | | |
| **2.2.1 Machine-learning based traffic prediction** | **Nagoya** | | | | | | | | | | | | |
| **2.2.2 Improvement of prediction accuracy** | **Nagoya** | | | | | | | | | | | | |
| **2.2.3 Development of dynamic network control method** | **Nagoya** | | | | | | | | | | | | |
| 3. Trustworthy connection resource management | | | | | | | | | | | | | |
| 3.1 Characterizaiton of availability | GWU | | | | | | | | | | | | |
| 3.2 Connection availability prediction using analytical models | GWU | | | | | | | | | | | | |
| 3.3 Connection availability prediciton using machine learning | GWU | | | | | | | | | | | | |
| 3.4 Resource provisioning and management | GWU | | | | | | | | | | | | |
| 4. Evaluation Plan | | | | | | | | | | | | | |
| 4.1 Numerical evaluation | | | | | | | | | | | | | |
| **4.1.1 Flexible waveband routing OXC nodes** | **Nagoya** | | | | | | | | | | | | |
| **4.1.2 Protection schemes** | **Kagawa** | | | | | | | | | | | | |
| **4.1.3 Traffic prediction and dynamic network control** | **Nagoya** | | | | | | | | | | | | |
| **4.1.4 Availability characterization and prediction** | **GWU** | | | | | | | | | | | | |
| **4.1.5 Trustworthy connection resource provisioning and management** | **GWU** | | | | | | | | | | | | |
| 4.2 Development of optical cross-connect node prototype performance evaluation | | | | | | | | | | | | | |
| **4.2.1 Estimation of transmission characteristics** | **Nagoya** | | | | | | | | | | | | |
| **4.2.2 Prototype development and transmission experiment** | **Nagoya** | | | | | | | | | | | | |

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

Thank you for your kind attention!!

# Resilience in Next-Generation Intelligent Optical Networks

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**Hiroshi Hasegawa**, Nagoya University
**Masahiko Jinno**, Kagawa University

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

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# General Background & Project Goals

# Background

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Emerging applications: 5G, UHDTV(up to 144Gbps)
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- Offloading from wireless to fiber (ex. 5G, Radio over Fiber (RoF))
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- "Channel capacity enhancement < Traffic growth" : More fibers on each link

Almost constant revenue

⇨ Large scale optical nodes with many components

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.

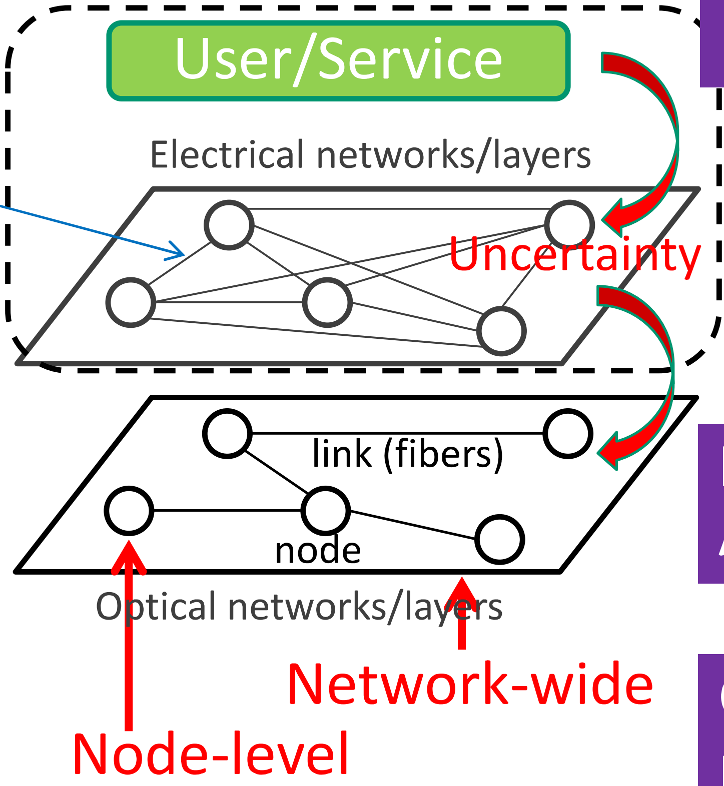
Resiliency / Trustworthyness

## 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.

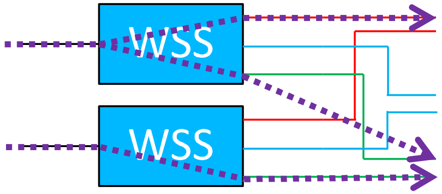
- ✓ Steep traffic growth motivates the introduction of parallelism to optical networks.
  - Fiber cables with many fibers, Multiple-core fibers, Spatial division multiplexing, etc.
  - However, costly large-scale optical nodes will be necessary.

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

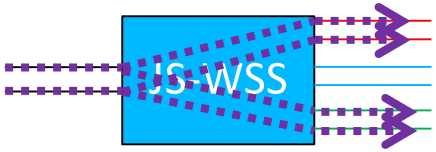
- ✓ Achievement in the past year
  - Cost-effective node architecture that adopts spatially-joint switching and flexible wavebanding
  - ML-based RWA algorithm

# Spatially Jointed Flexible Waveband Routing Optical Node

A pair of conventional WSSs

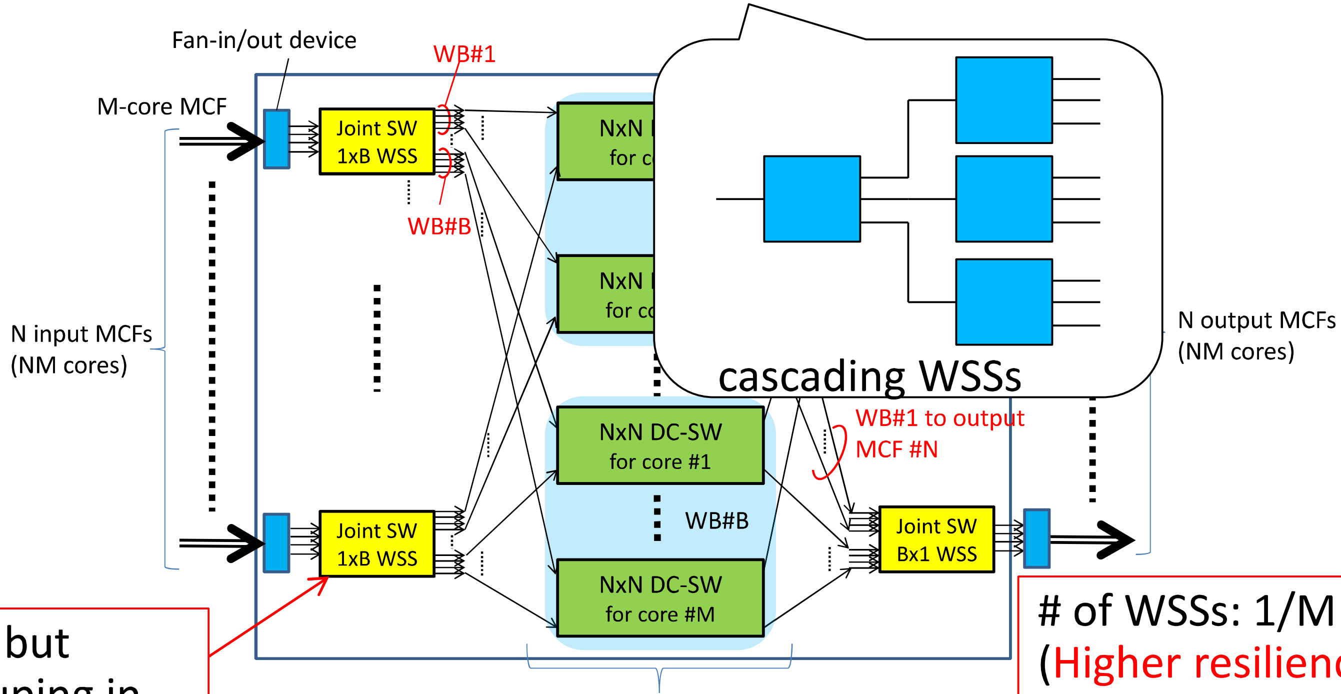



A conventional WSS in the spatial-joint-switching mode




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)

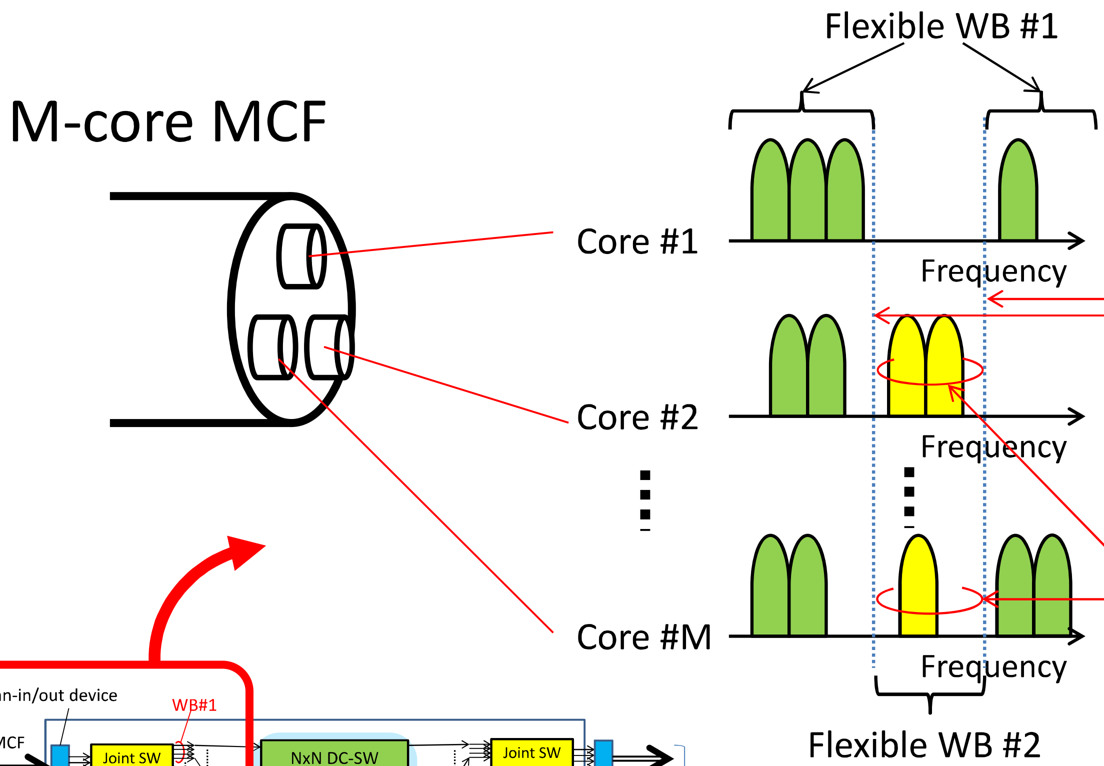



Spatially jointed, but flexible path grouping in the frequency domain

Proposed node architecture

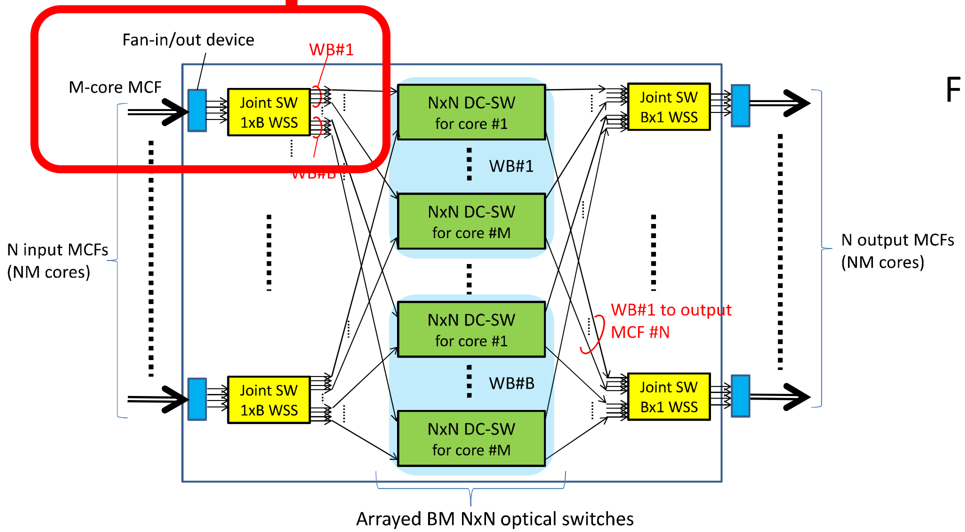
\# of WSSs: 1/M or less (Higher resiliency and better cost-effectiveness)

# 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.



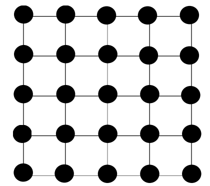

Spatially jointed, however still flexible in the frequency domain

# Performance Evaluation

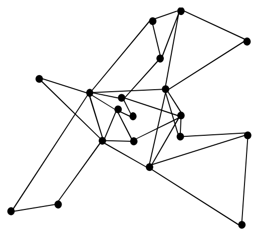
## Parameters

# 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)

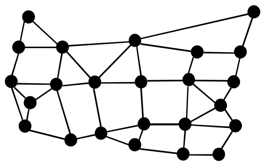
## Topologies



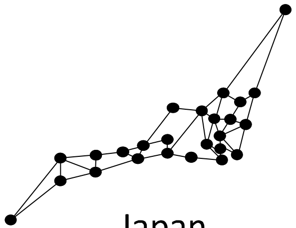
5x5 regular mesh



Pan-European



USA

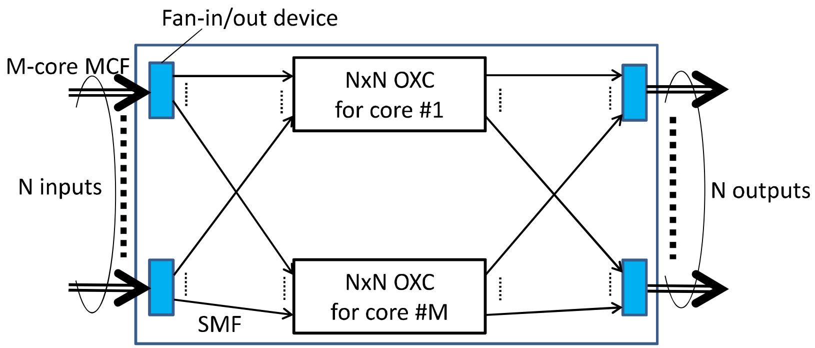


Japan

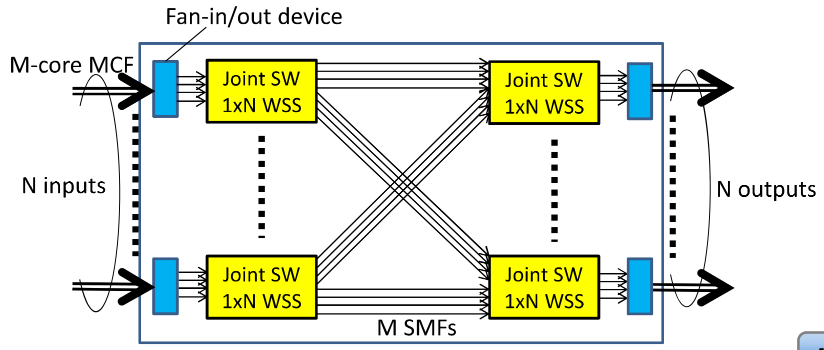
## Metrics

# of fibers necessary
# of WSSs necessary

Normalized by these for conventional core-wise switching



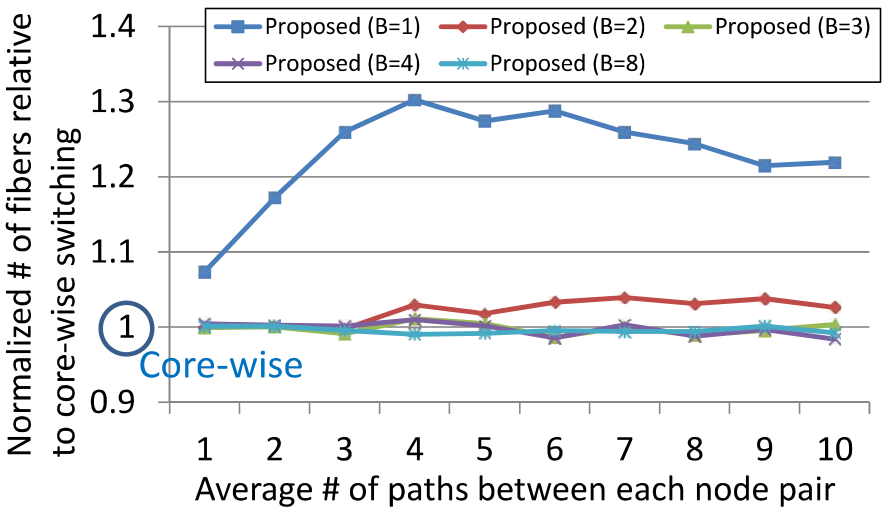

Conventional (Core-wise switching)



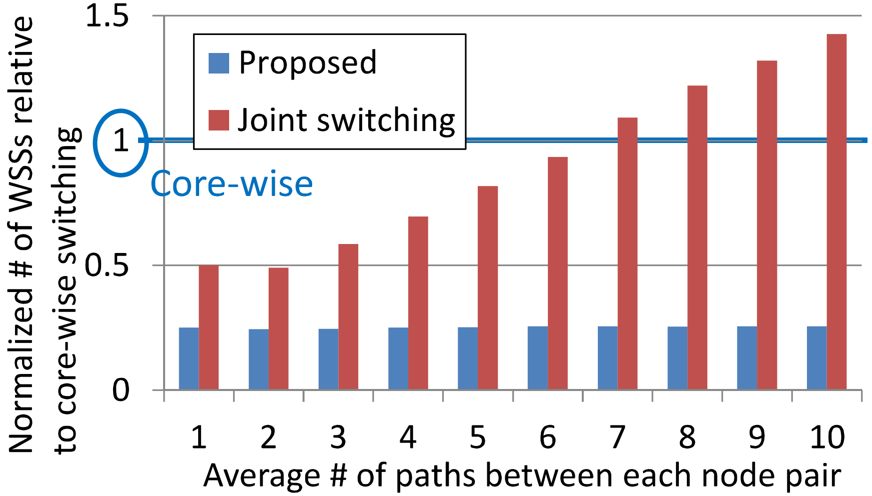

Conventional (Joint switching)

# Results on the 5x5 regular mesh

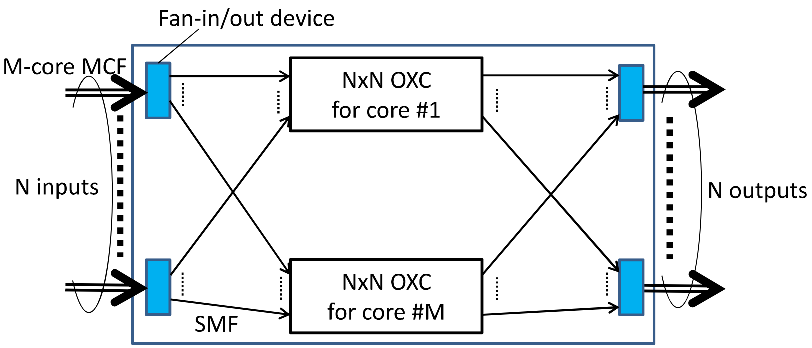
## # of fibers



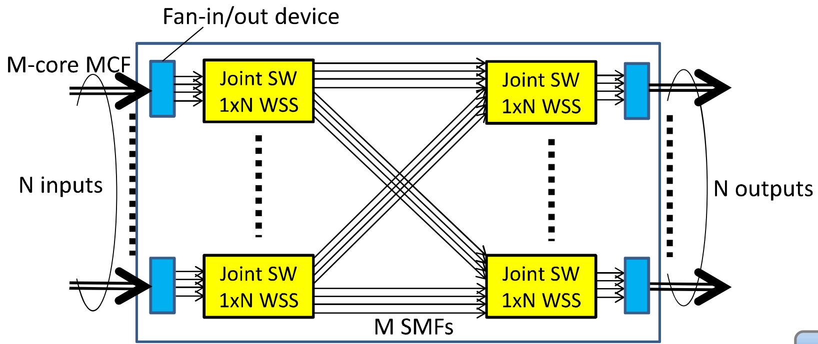

## # of WSSs




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




Conventional (Core-wise switching)




Conventional (Joint switching)

# Machine-Learning based Routing and Wavelength Assignment

**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**

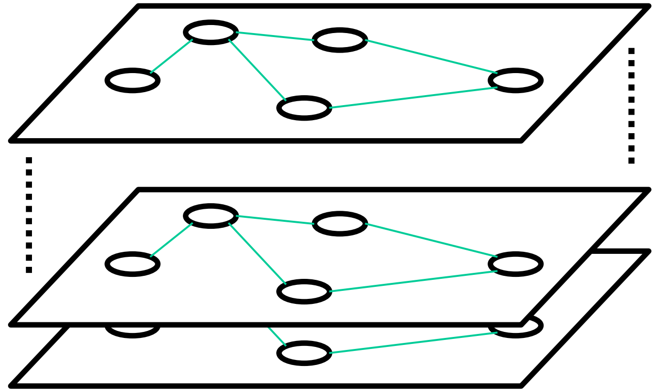
[C. Chun-yen et.al. ECOC2018],[ J.S. Varela et.al. OFC2019]

Proposed

**Dimension Reduction & Relatively Compact NNs**

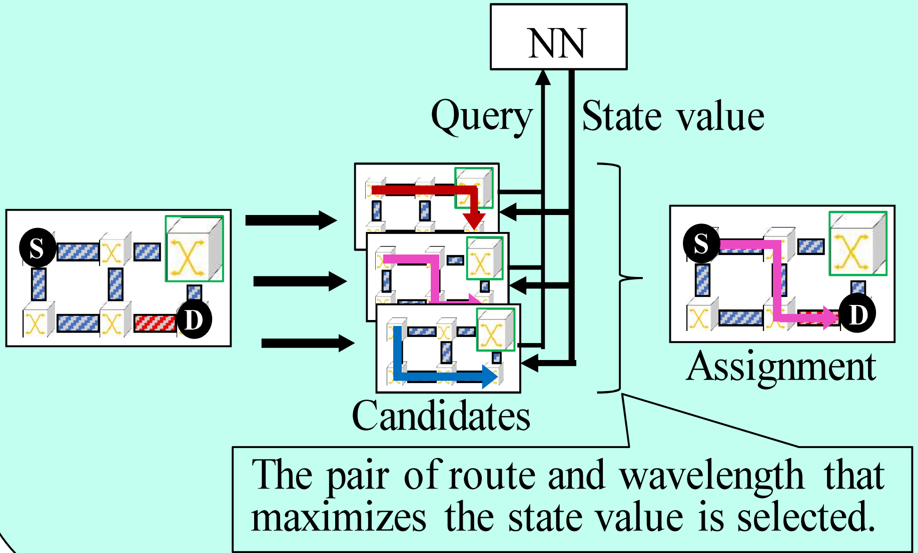
[R. Shiraki et.al. ICTON2019]

# of layers of NN: 3



opology is same for all wavelengths/slots.

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




Blocking ratio

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)

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

# Motivation of Our Work

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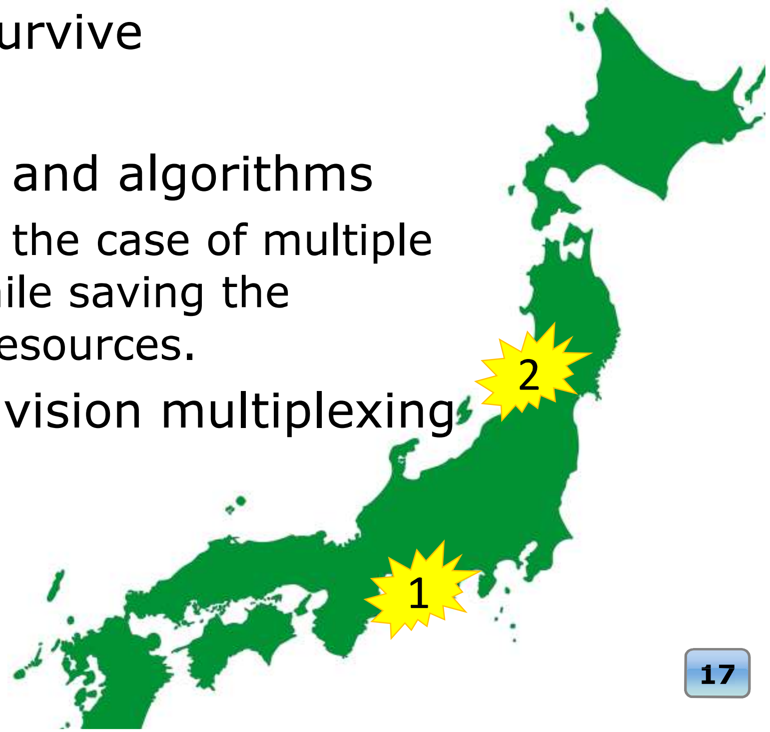
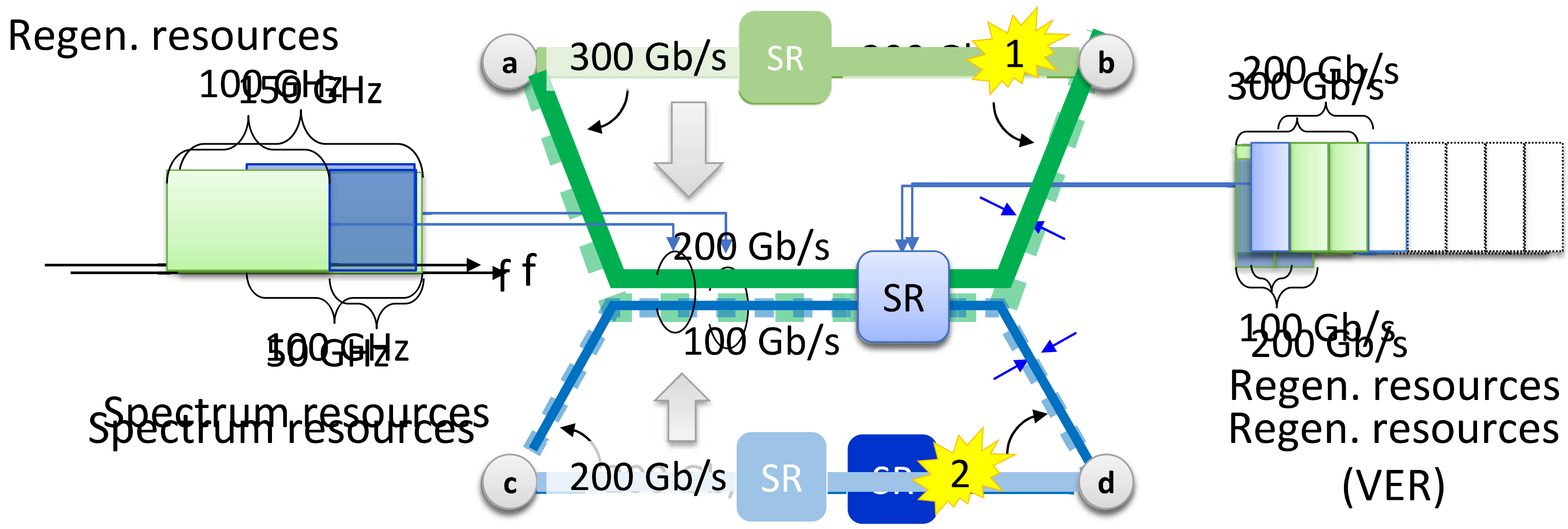
- ✓ Shared protection ensures 100% recovery from an arbitrary single link failure, while saving backup resources by sharing them among link-disjoint working paths.
- ✓ In case of double link failures where working paths that mutually share their backup resources are simultaneously cut due to, *e.g.*, 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



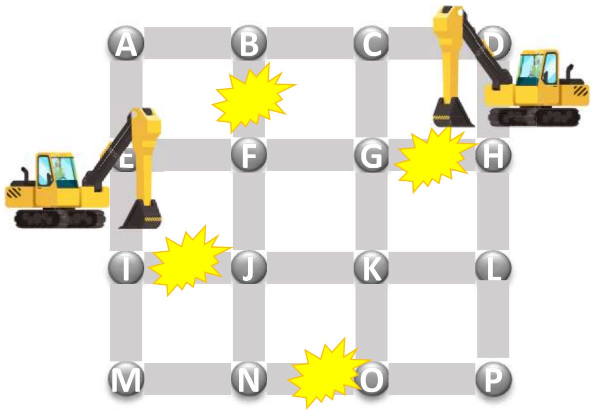
# Shared Protection with Fallback (SP-FB)

- ✓ 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

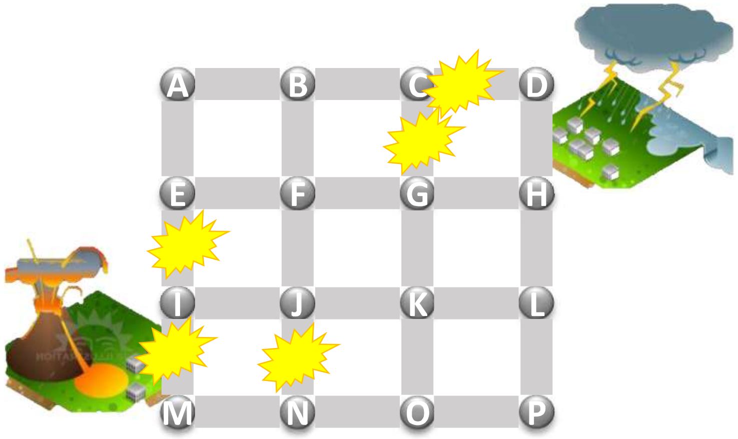


# Effects of geographical distribution of failed links

- ✓ 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



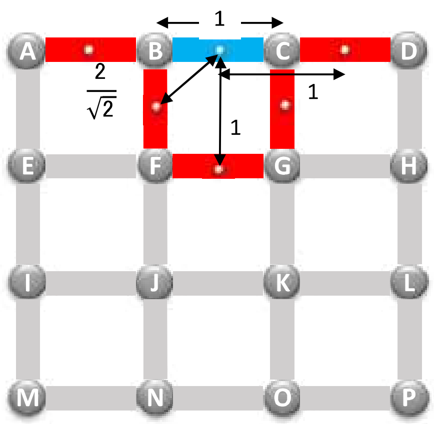

Fiber cut at two points that are not geographically correlated



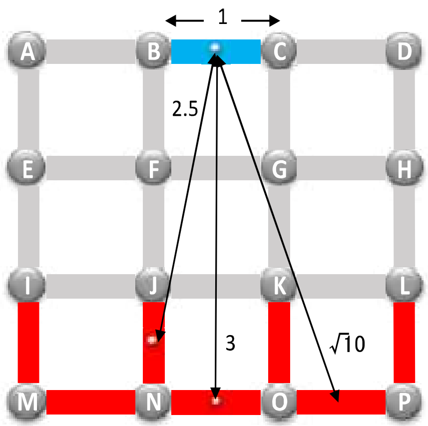

Fiber cut at two points that are geographically close each other

# Achievement (1/2)

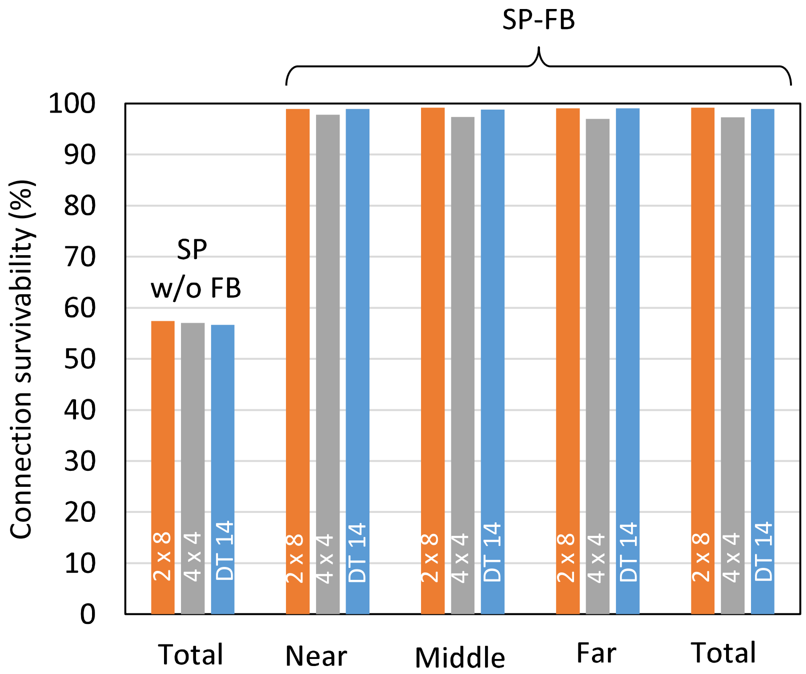
1. Evaluated the effect of geographical distribution of failed links on survivability improvement in translucent EON employing SP-FB
2. Categorize failed link pairs into *near, middle*, and *far* in terms of the distance between link centers
3. Found that SP-FB is effective for double link failures in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




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

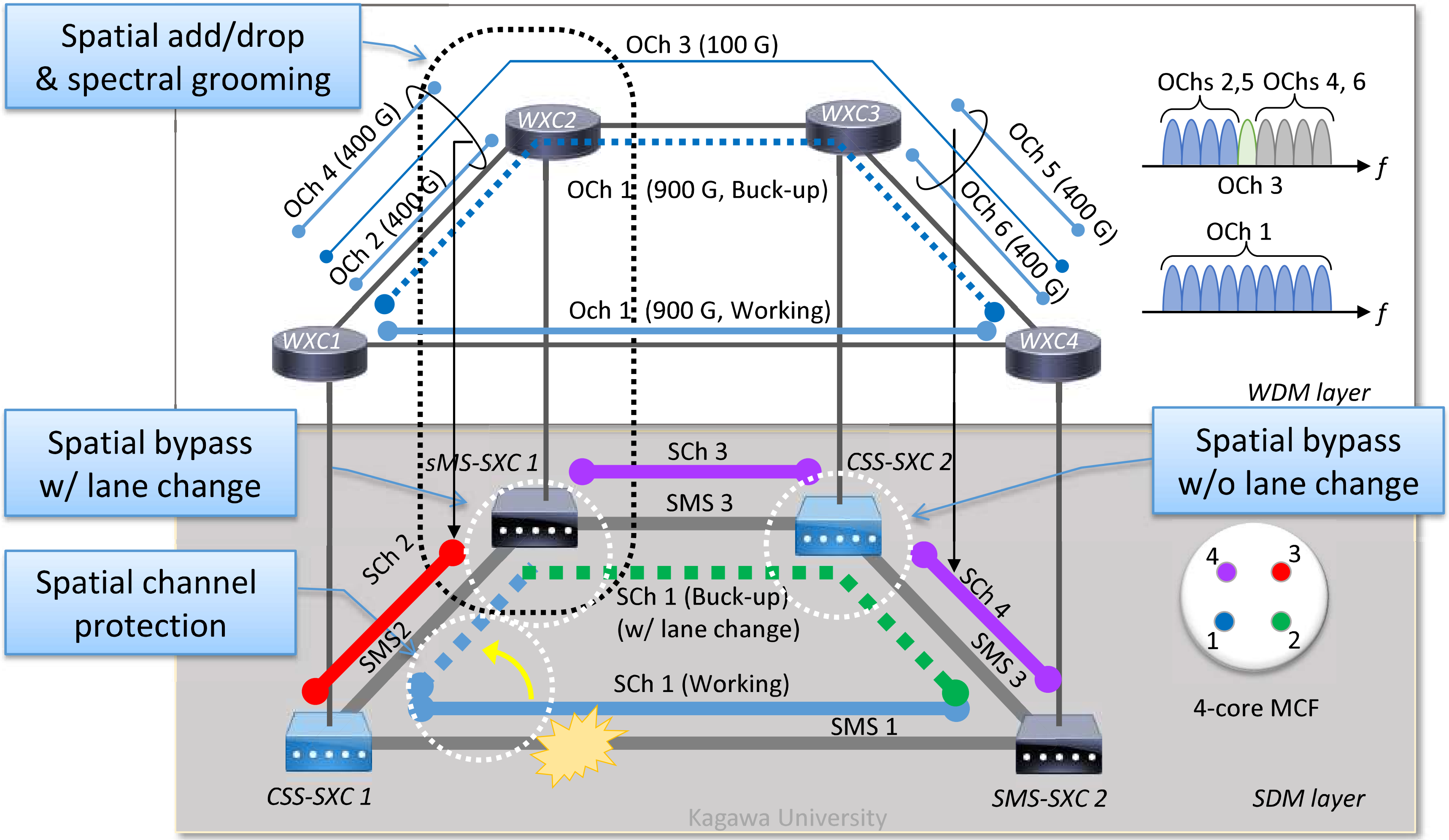



(c) far links
($\sqrt{5} < l_c$)

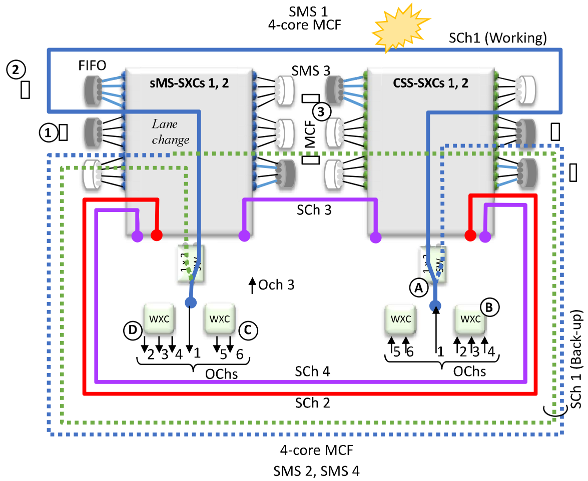


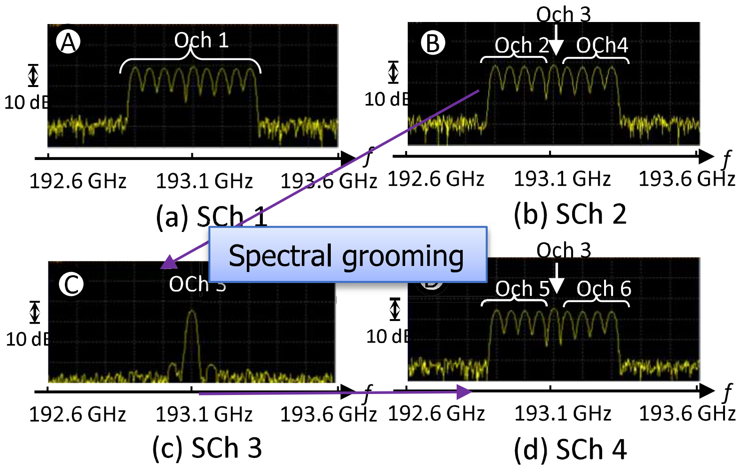
# Spatial Channel Networking Testbed

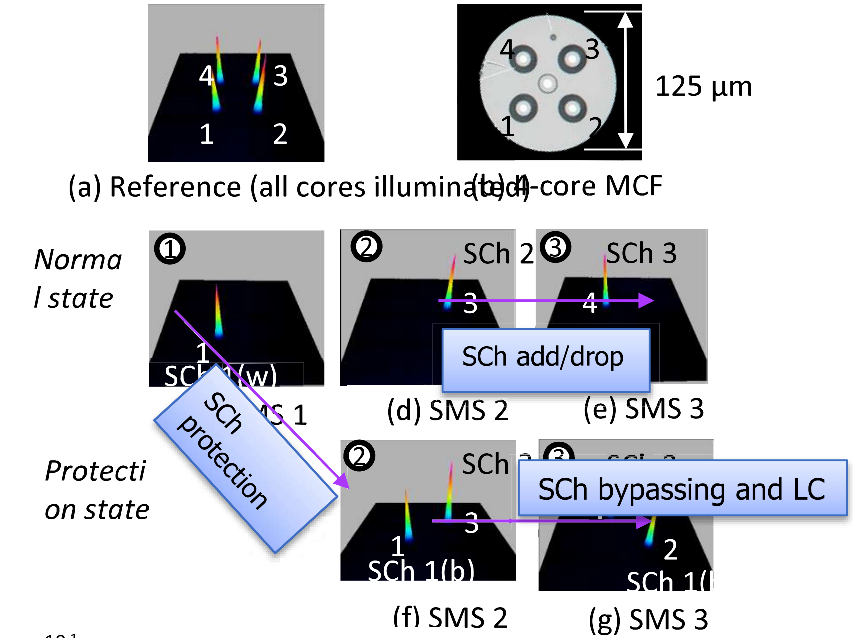
- Preliminary experiment of spatial channel networking with two types of low-loss SXC prototypes, which will be a basis for the demonstration of applying SP-FB to SDM networks.

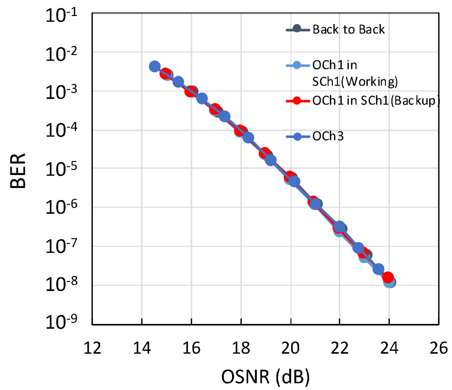


# Achievements (2/2)




- 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*

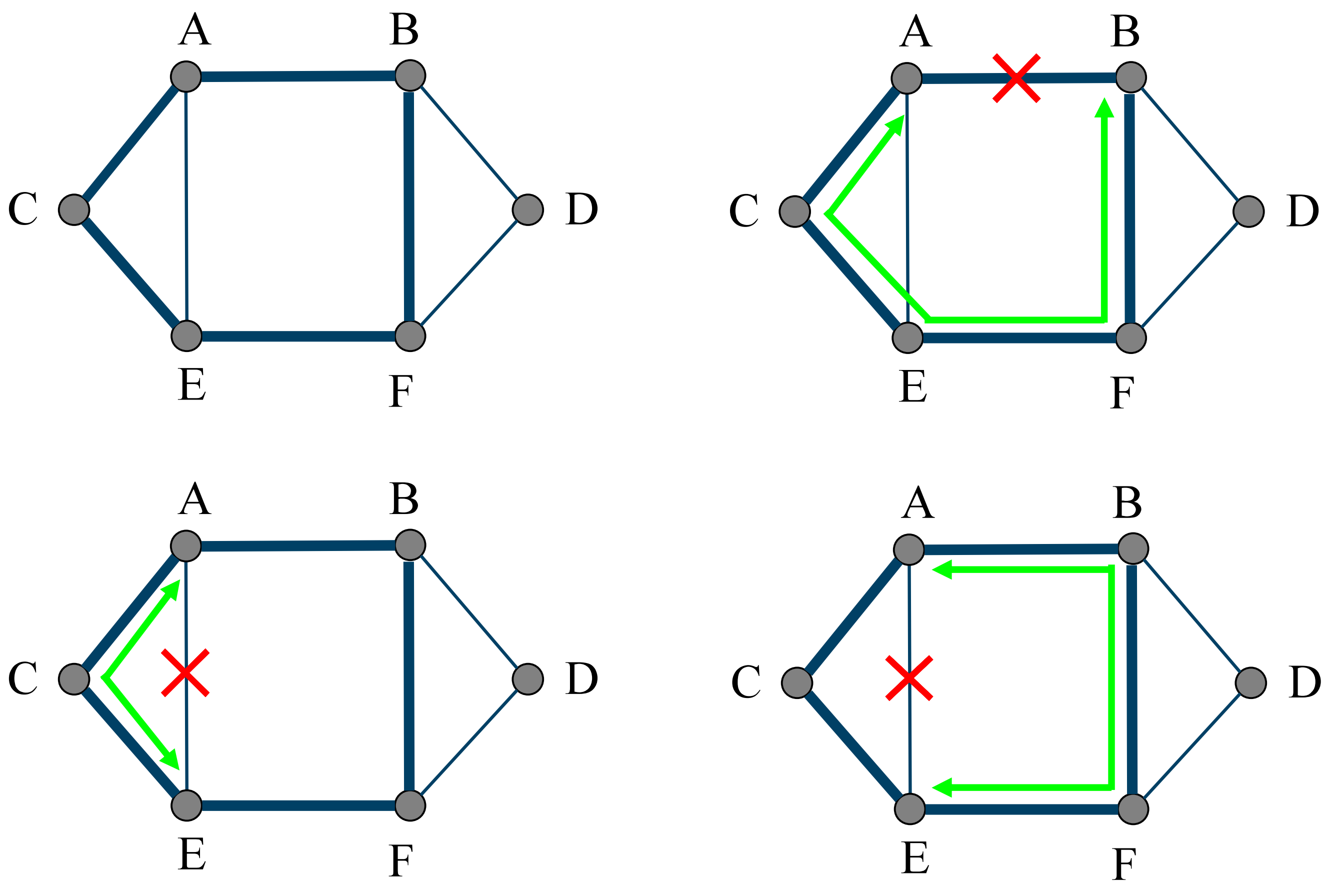
- Built a spatial channel network testbed and conducted preliminary experiment of spatial channel networking , which will be a basis for the future demonstration of applying SP-FB to SDM
  - ✓ *M. Jinno, T. Kodama, T. Ishikawa, K. Yamashita, Y. Asano, R. Nakai, and D. Suzuki, "Demonstration of spatial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

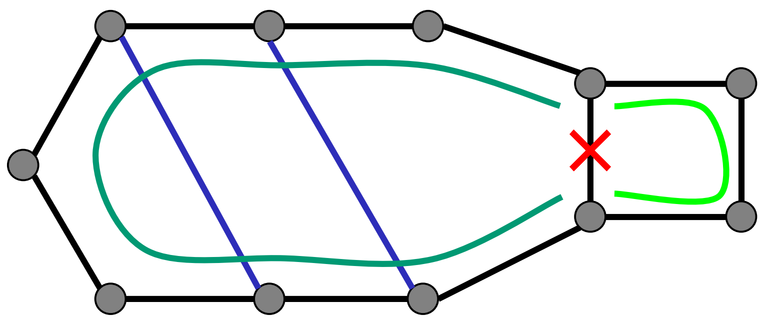
# P-cycle Link Protection



# Problem & Motivation - 1

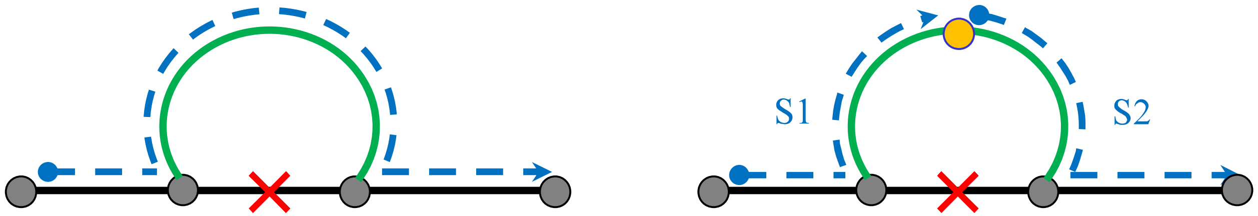
- Generate a set of p-cycles that covers all links and minimizes spectrum usage

- 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

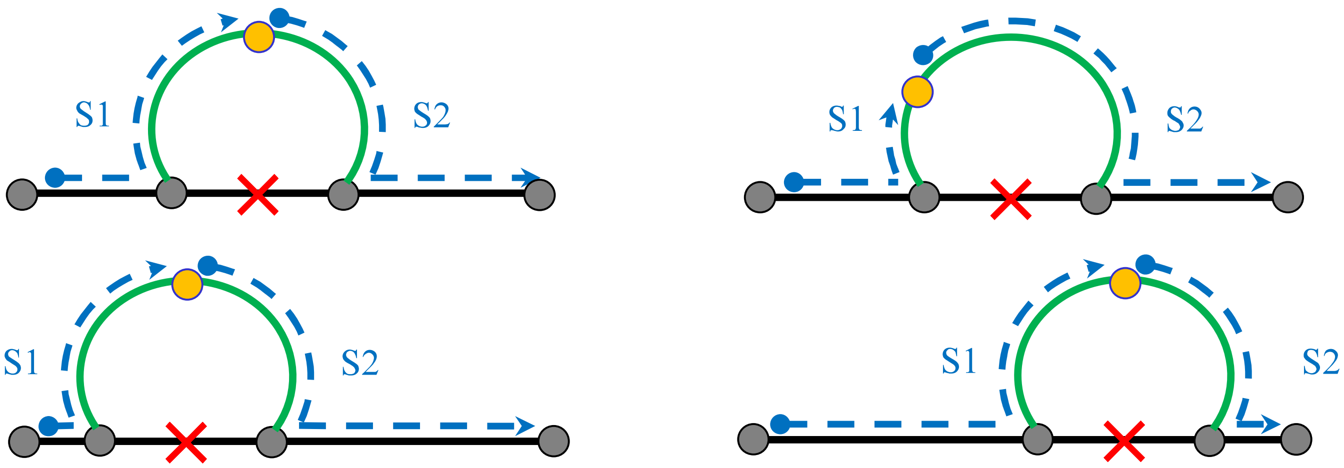


# Problem & Motivation - 2

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



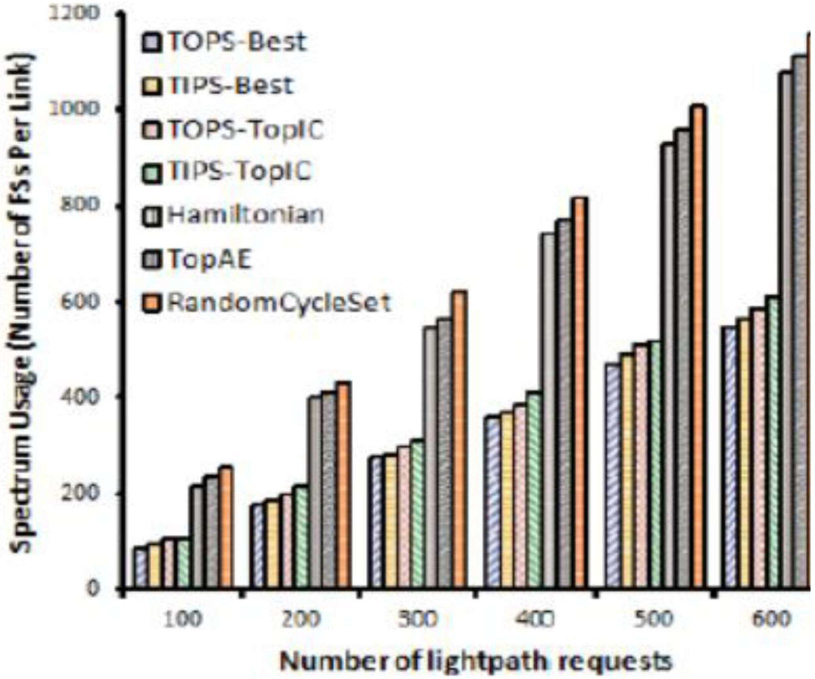

  - ✓ Length of lightpath is determined by relative position between 3R regenerator location and lightpath

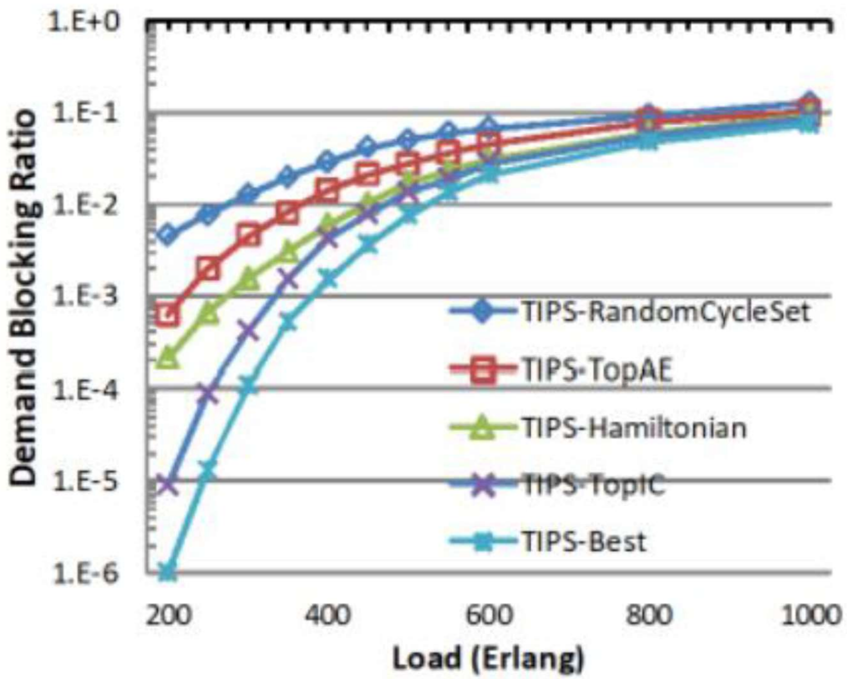


# P-cycles in Transparent EONs

- 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



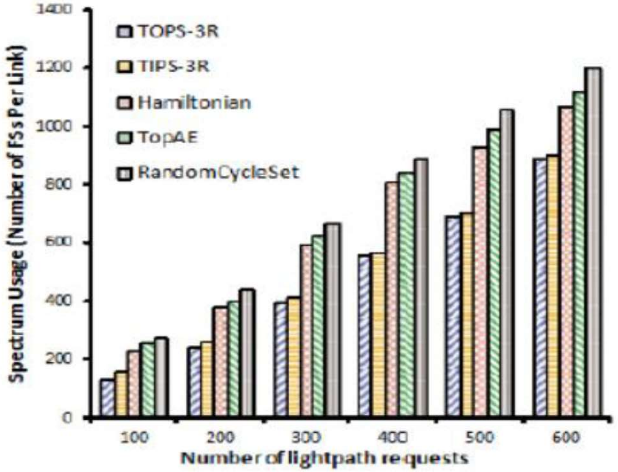



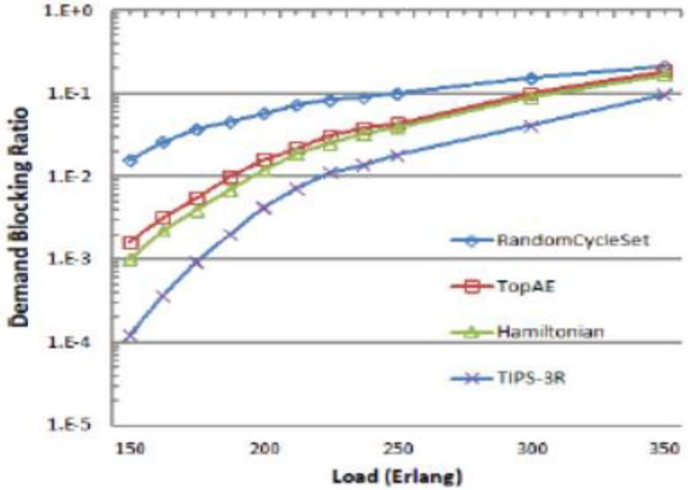

Cost239 Network

# 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

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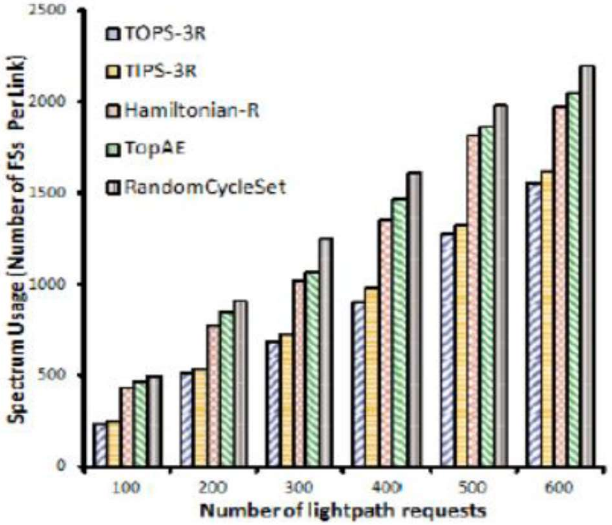


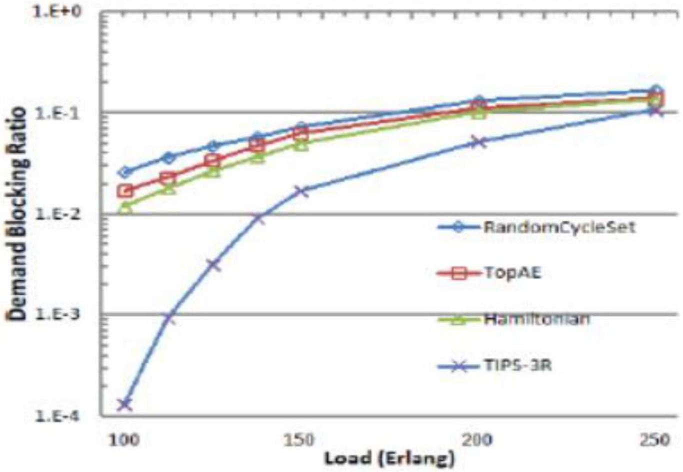


Pan-European

# 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.

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# Other Publications (2/3)

NAGOYA UNIVERSITY
KAGAWA UNIVERSITY

- ✓ 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)**.

NICT

NSF

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

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Thank you for your kind attention!!

名古屋大学

NAGOYA UNIVERSITY

香川大学

KAGAWA UNIVERSITY

Same as the slides used at the PI meeting 2019@Chicago

# Resilience in Next-Generation Intelligent Optical Networks


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


**1st Annual PI Meeting, Tokyo**
**October 26, 2018**

# Outline

- ✓ Ge Same as the slides used at the PI meeting 2019@Chicago

- ✓ 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

Same as the slides used at the PI meeting 2019@Chicago

**General Background & Project Goals**

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# Background

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Same as the slides used at the PI meeting 2019@Chicago

## Extreme

Cisco VNI (Visual Network Index)

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

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

**ICT based society**

In Japan

- +29.7% /year (2017-2018)

## 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

Almost constant revenue

⇨ Large scale optical nodes with many components

**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.

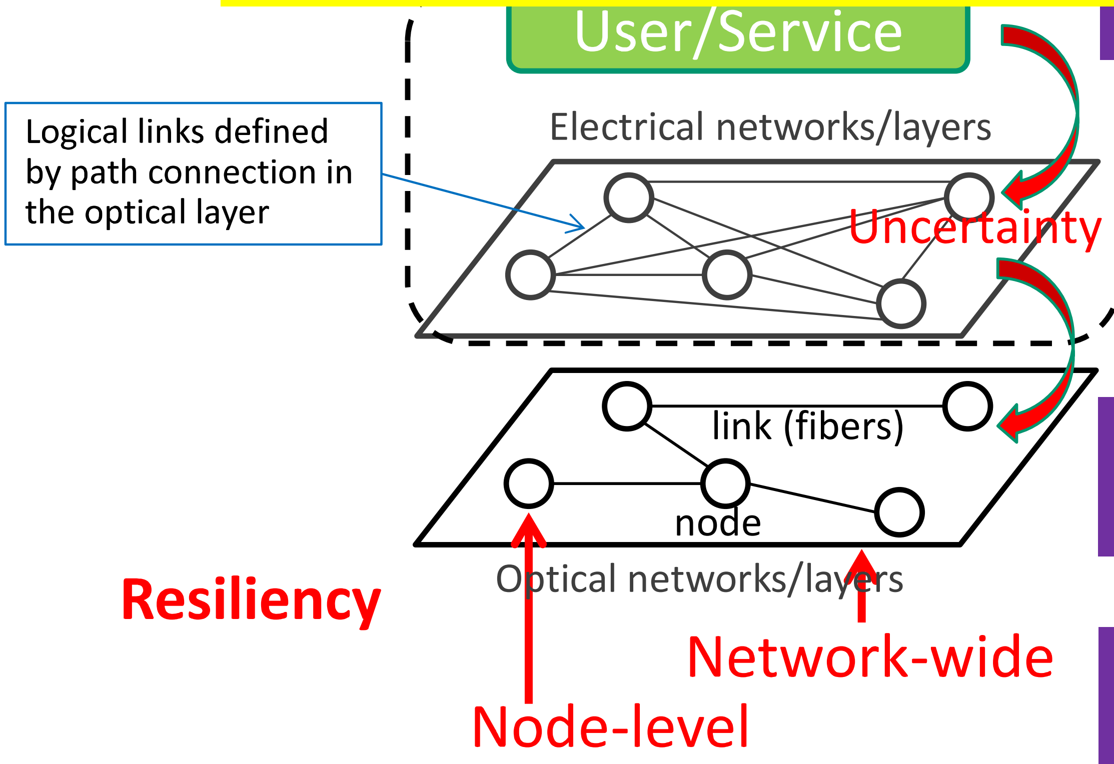
**Resiliency / Trustworthyness**

## Tools

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

# Trustworthy & "profitable" optical networks

Same as the slides used at the PI meeting 2019@Chicago




**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. De Same as the slides used at the PI meeting 2019@Chicago es.

2. Hybrid protection/restoration frameworks for the robustness against multiple node/link failures.

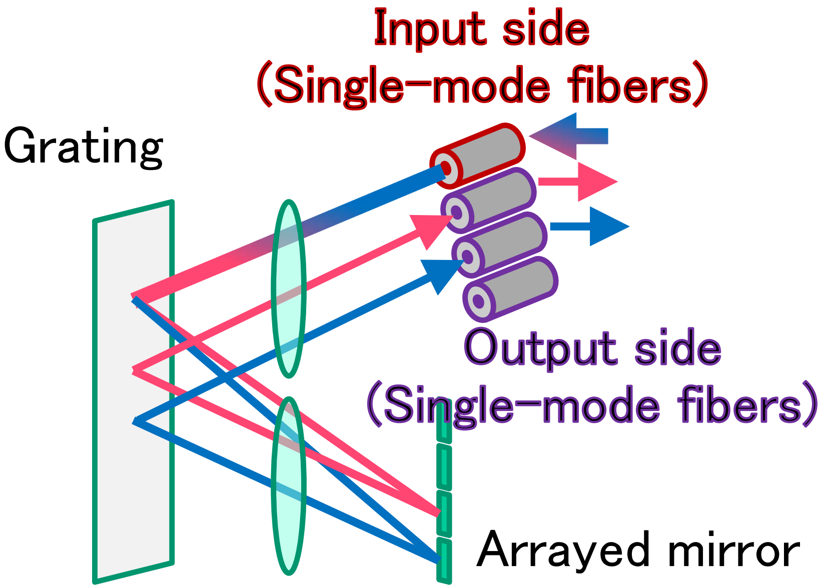
3. Fine-grained connection-level availability (as opposed to network-level survivability) management.

# Survivable and Scalable OXC Node Architecture

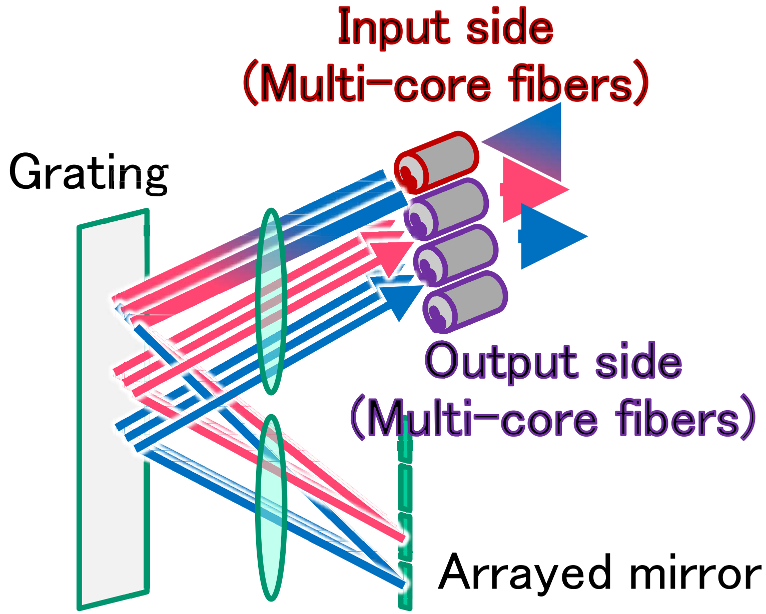
**Hiroshi Hasegawa (Nagoya University)**

# Spatially-jointed switching @ WSSs

MEMS-based WSS

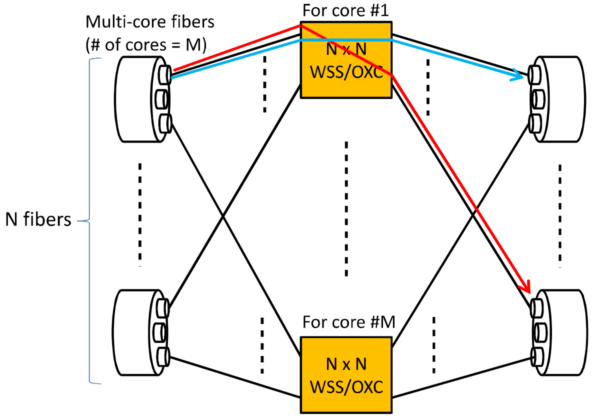



Spatially-jointed switching mode

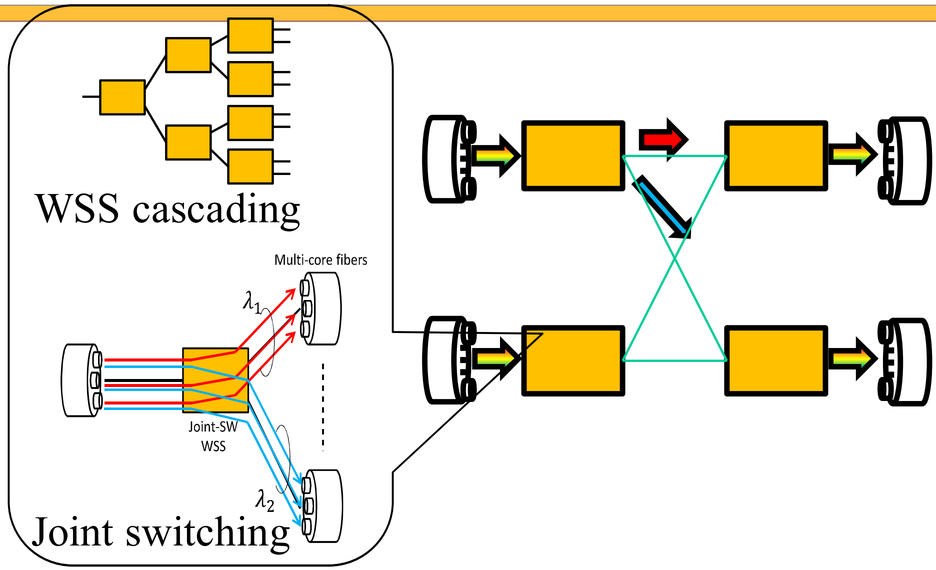



- A WSS can be shared by # of cores.
- The WSS degree will be small. For example, a 1x20 WSS can be used as a 7-core 1x2 joint switching WSS.
- The WSS cascading will be inevitable which substantially increases the number of WSSs.

# Conventional SDM node architectures




Core-wise switching node
[F. Moreno-Muro et.al. JOCN2017]




Spatially-jointed switching node

- # of WSSs/core $\geq$ 1
- Very good routing performance. Comparable to impractical WSS-based node with the full mesh inter-connection.

- # of WSSs/core $\geq$ 1/# of cores/MCF
- Suffered from insufficient WSS degree. The number of WSSs will steeply increase by the WSS cascading.
- Relatively poor routing performance

**There was no proposal that achieves "# of WSSs/core = 1/# of cores/MCF" and comparalbe routing performance to WSS-based node.**

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# Spatially-jointed flexible waveband routing node architecture

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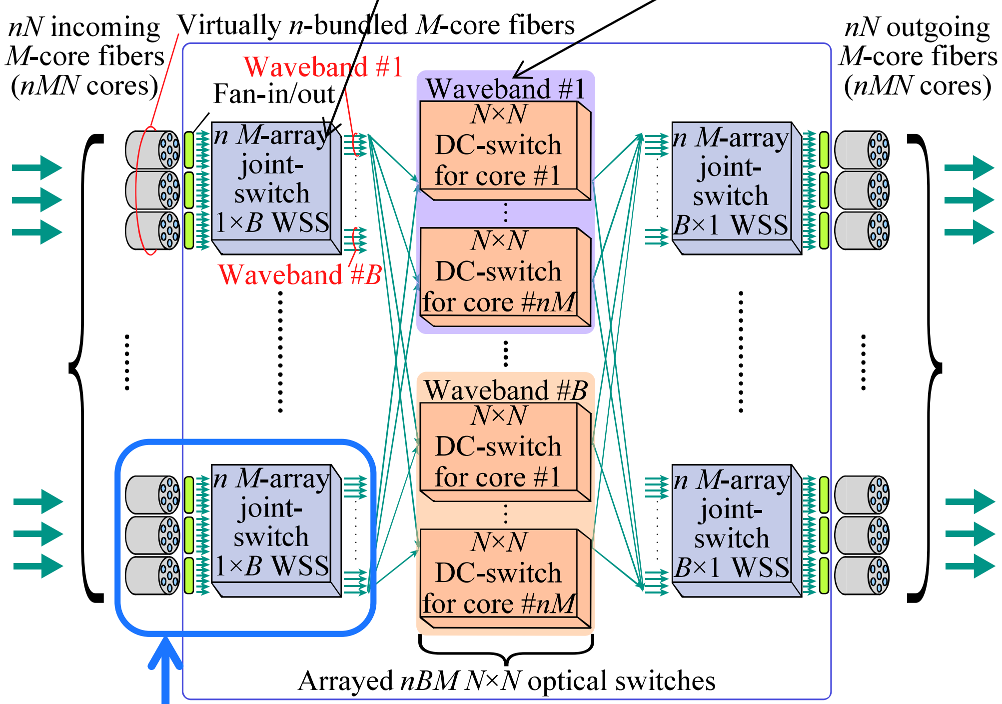
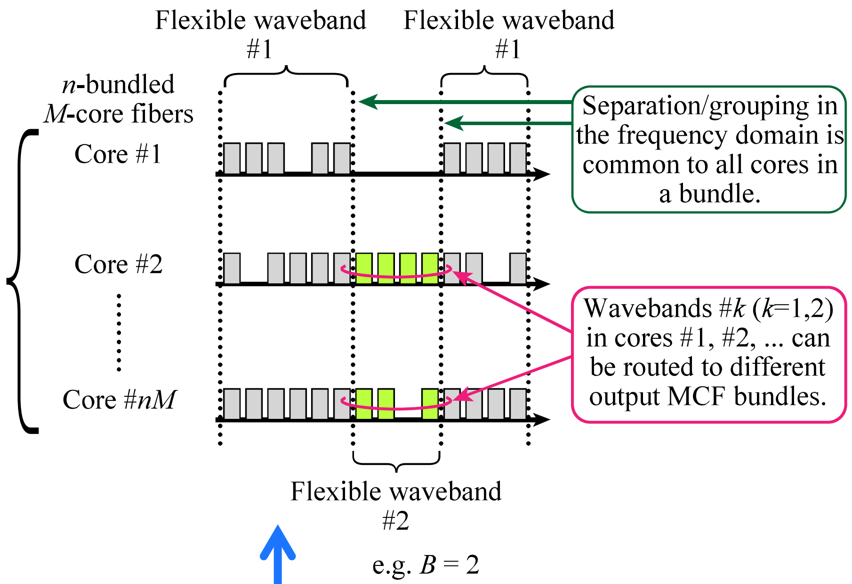
Path grouping and routing are separated and implemented with different devices.

**Flexible waveband routing at JUNO1**




**Spatially-jointed switching at WSSs**

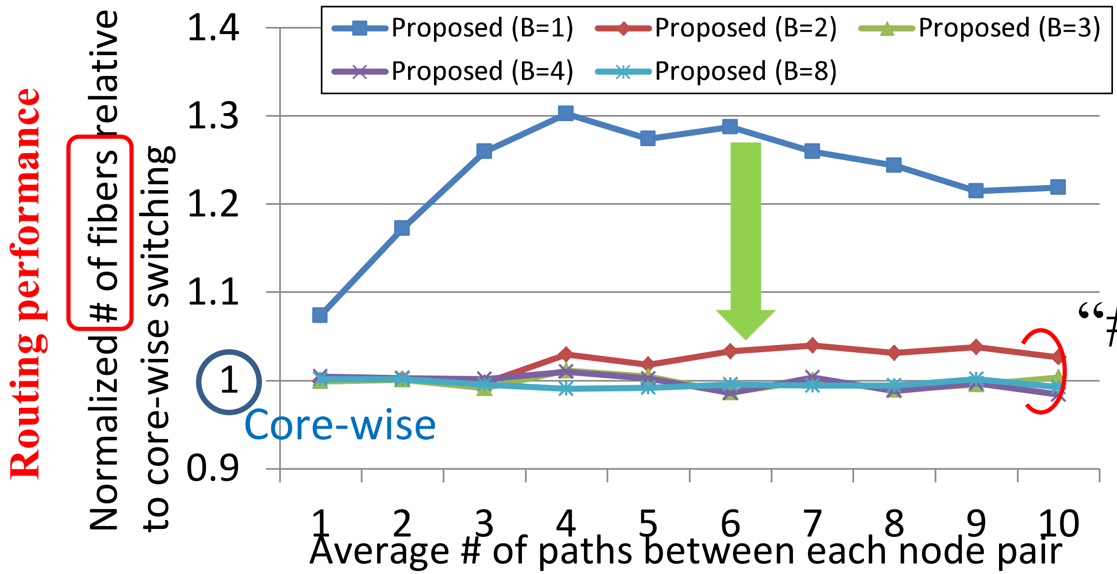
- Cost-effectiveness: "# of WSSs << # of cores"
- Scalability: Increasing the number of arrayed WSSs.
- Reliability: Minimized WSS numbers.

**Spatially-jointed flexible wavebanding**

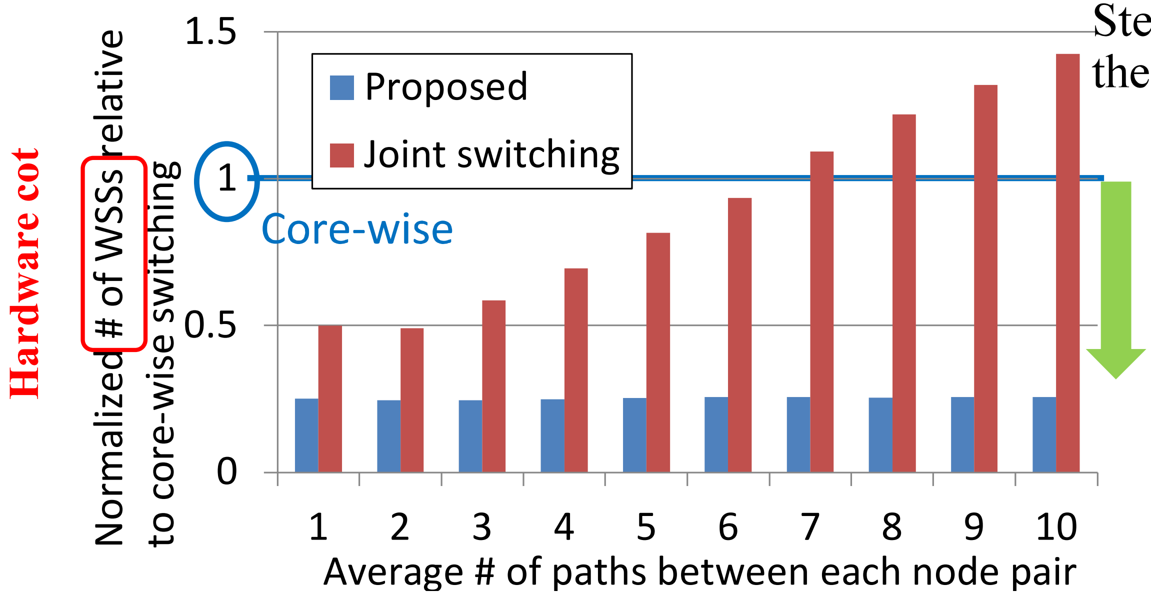
- Wavebanding: Common to all cores.
- Routing wavebands: independent.
- # of wavebands in a core: small

This property enables the use of spatially-joint switching mode.

# Results @ 5x5 mesh with 4-core MCFs



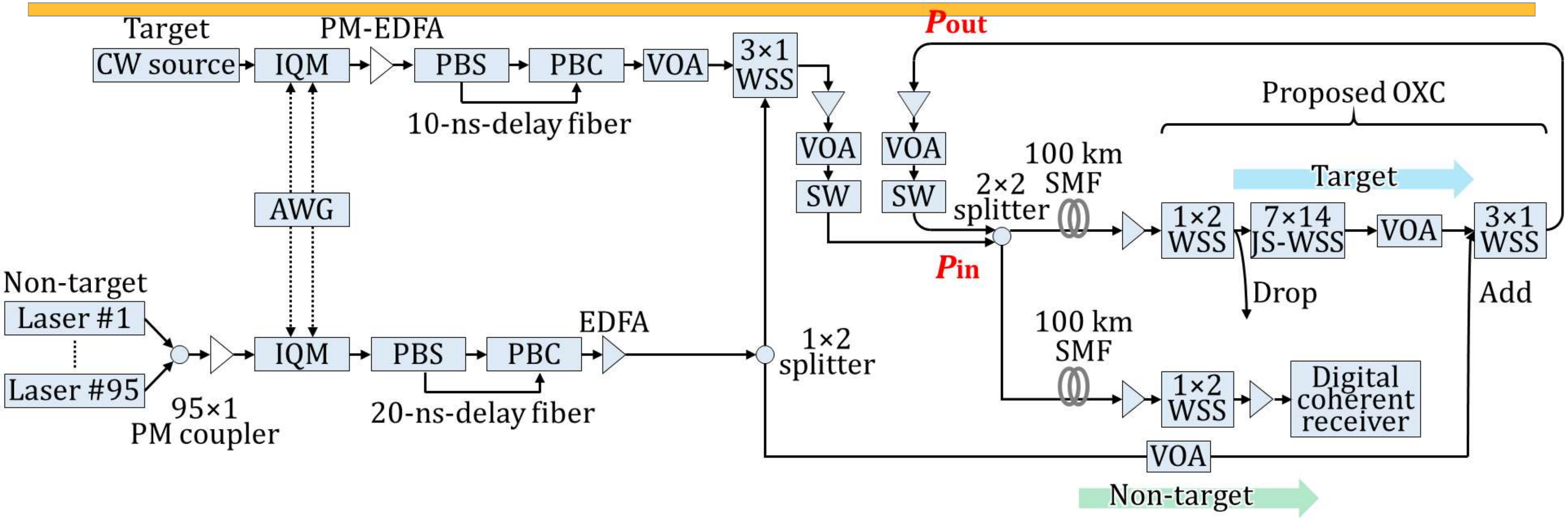

"# of wavebands ≥ 2"




Steep increase by the WSS cascading.

75% reduction

# Transmission experiments




| | | | |
|---|---|---|---|
| IQM | IQ modulator | WSS | Wavelength selective switch |
| AWG | Arbitrary waveform generator | SW | Switch |
| PM-EDFA | Polarization maintain erbium-doped fiber amplifier | EDFA | Erbium-doped fiber amplifier |
| PBS | Polarization beam splitter | SMF | Single mode fiber |
| PBC | Polarization beam coupler | JS-WSS | Joint-switch wavelength selective switch |
| VOA | Variable optical attenuator | | |

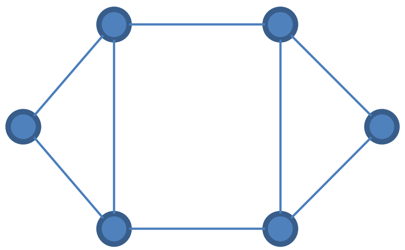
400Gbps × 64 × 84 = **2.15Pbps**

# of paths/fiber    # of ports of the cross-connect

**Best student paper award@ONDM2020, Best paper award@ICP2020**

# Machine-Learning based Network Control

How to parametrize the state of an optical network?



“# of fibers” x “# of slots”=1024

- 6 nodes/ 16 unidirectional links
- # of frequency slots: 64, # of fibers/link: 1

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

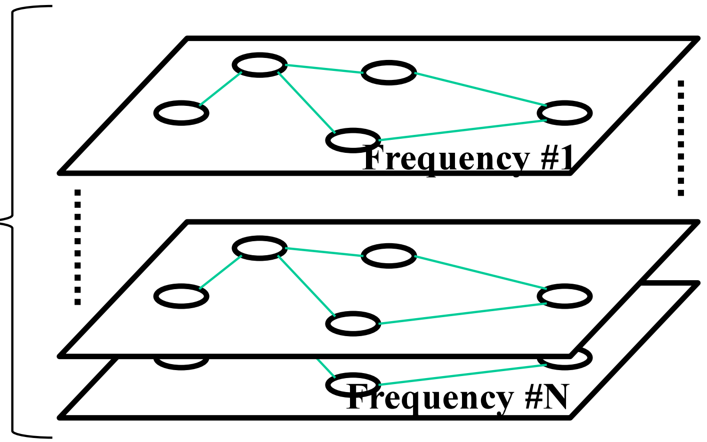
| Topologies | # of nodes | # of links | Size of state vector |
|---|---|---|---|
| 5x5 regular mesh | 25 | 40 | 28160 |
| USA (USNET) | 24 | 43 | 30272 |
| Pan-European (COST239) | 19 | 37 | 26048 |
| Japan (JPN25) | 25 | 43 | 30272 |

The control of typical optical networks would be intractable.

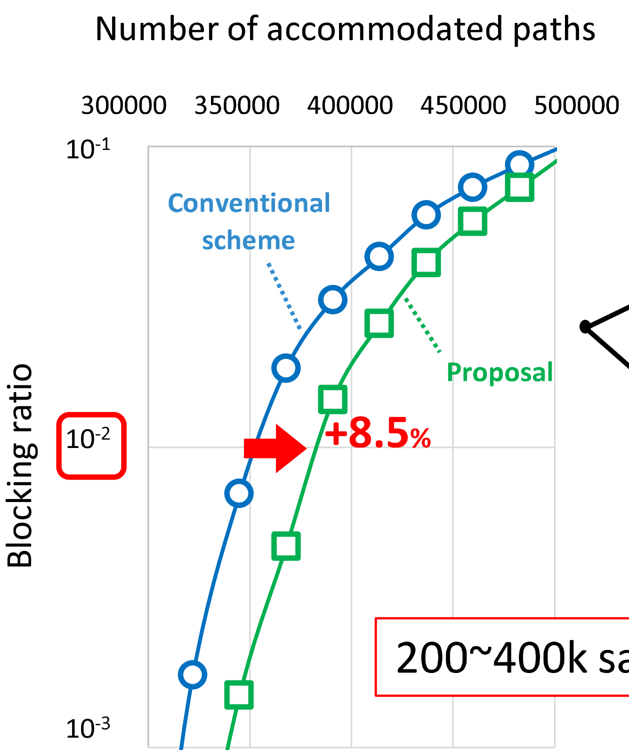
# Proposed Control Algorithm @ Fixed grid

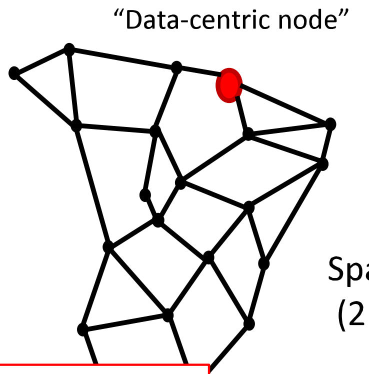
**Our strategy** [R. Shiraki et.al. ICTON2019]
Estimate the "value" of each wavelength layer independently and sum up all values.

Topologies are identical.




a DWDM network (fixed-grid)



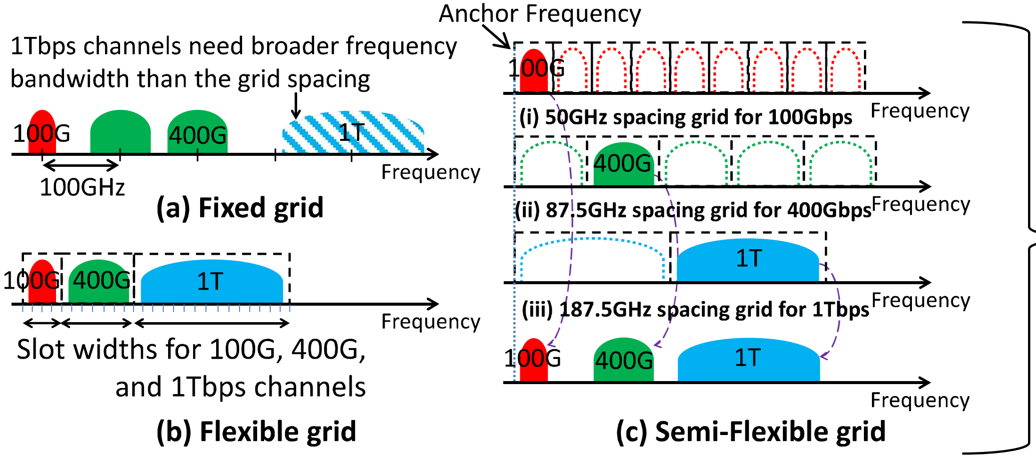




200~400k samples

Spanish Telefónica network
(21 nodes, 70 unidirectional links with multiple fibers)

**Best student paper award@ICTON2019**

# Proposed Control Algorithm @ Flexgrid

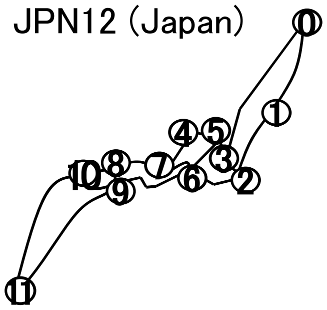



[Z.Shen et.al. ECOC2013]

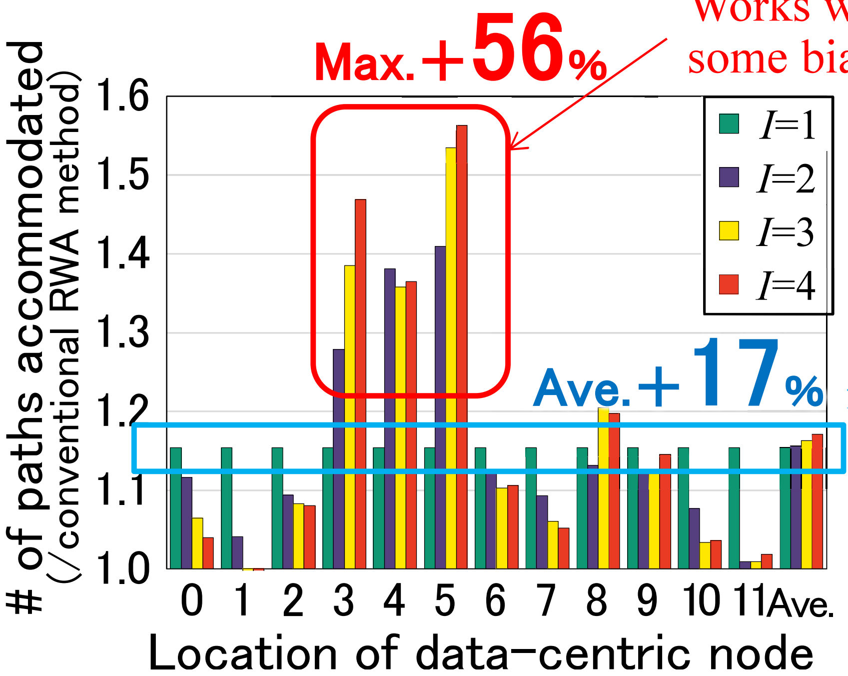
- The "value" at each grid position is estimated in the same way and then combined.
- The use of semi-flexible grid automatically mitigates the frequency slot fragments.

[R. Shiraki et.al. OFC2020]

JPN12 (Japan)




Works well especially for some biased traffic.




Traffic enhancement factor for the selected node

Substantial improvement for the uniform traffic.