Resilience in Next-Generation Intelligent Optical Networks

Suresh Subramaniam, George Washington University

Hiroshi Hasegawa, Nagoya University

Masahiko Jinno, Kagawa University

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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

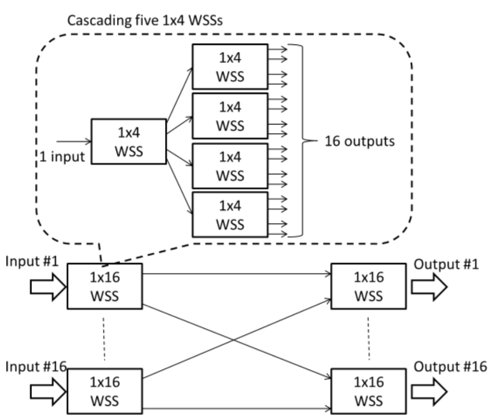
Conventional

Limits the scalability and causes square-order cost increment

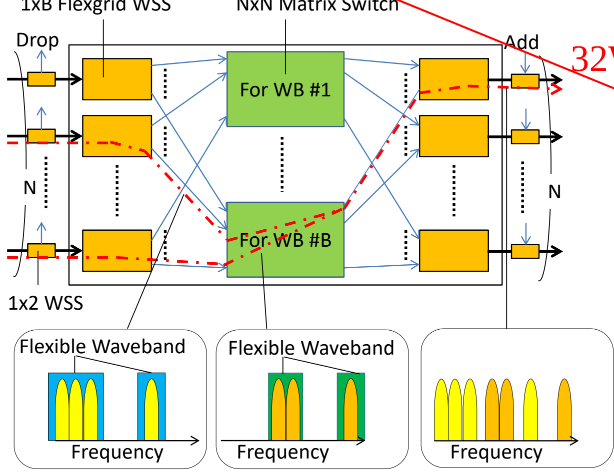
- “Demultiplexing to paths” + “path granularity switching”
- All operations are done by expensive wavelength selective switches (WSSs)

Proposed

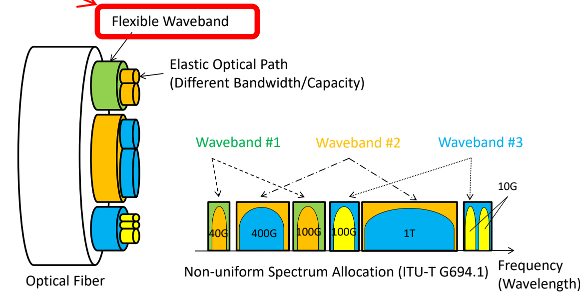
- “Dynamic grouping of paths” + “switching of path groups”
- WSSs are used only for the former operation.
- The latter operation is done by more cost-effective switches.



160WSSs for 16x16



32WSSs for 16x16



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

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Our previous joint research

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KAGAWA UNIVERSITY

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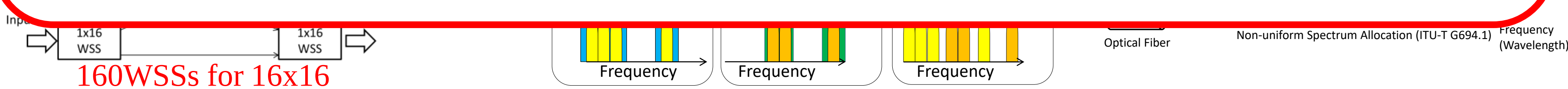
In addition to proposals of novel optical node architectures, we had succeeded in development of network control & design algorithms, routing performance analysis, and transmission experiments on a prototype.



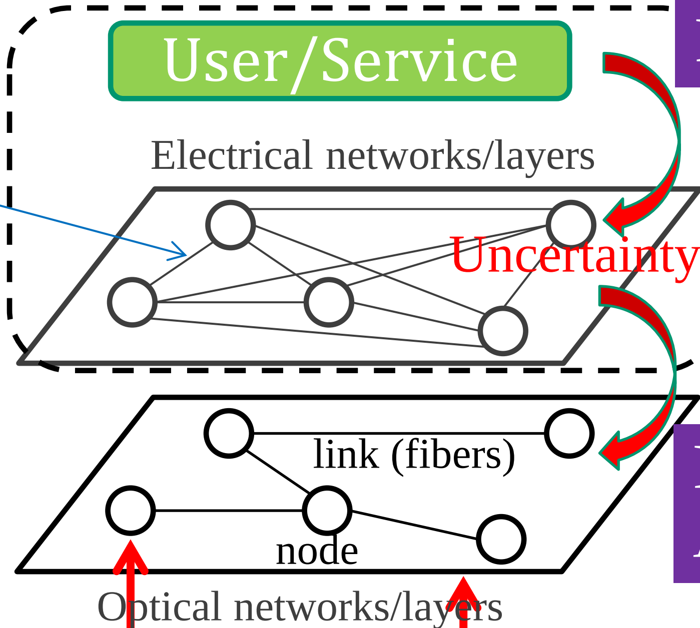
160WSSs for 16x16

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

Trustworthy & "profitable" optical networks

Prediction &
Resource allocation

Logical links defined by path connection in the optical layer



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

Redundancy in networks
Advanced transmission

Resiliency

Network-wide

Node-level

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

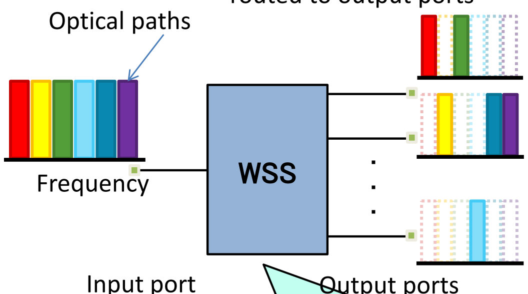
1. Highly reliable optical nodes that consist of unreliable components/functional blocks will be studied. Network design algorithms that take advantage of the switching capability will be also developed.
2. The robustness against multiple node/link failures while avoiding explosive increase of spare 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.

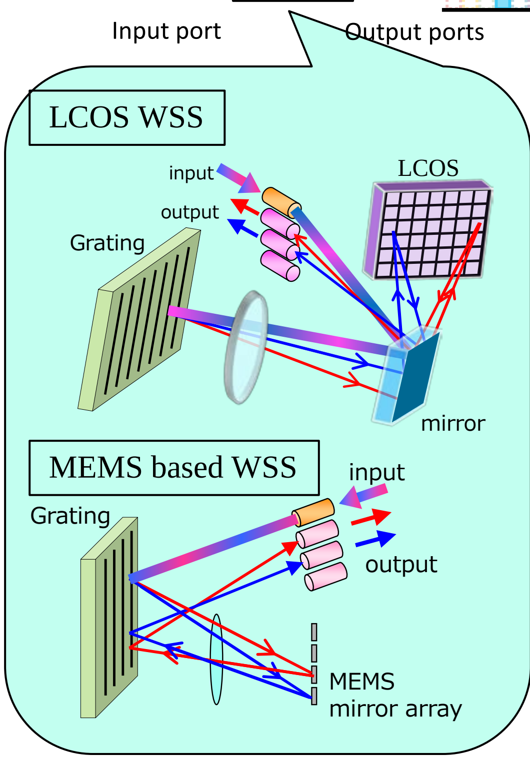
Survivable and Scalable OXC Node Architecture

Hiroshi Hasegawa (Nagoya University)

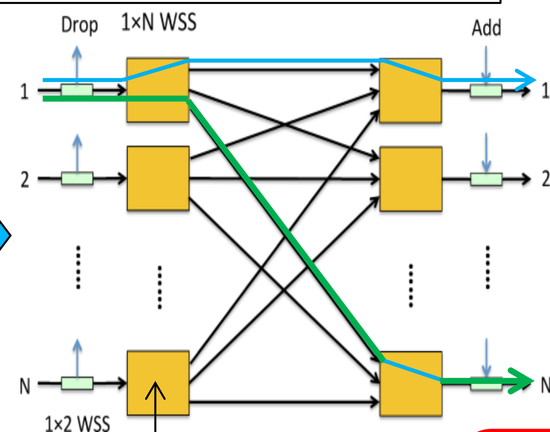
WSSs and conventional nodes

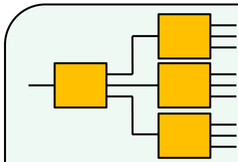
Wavelength selective switch (WSS)



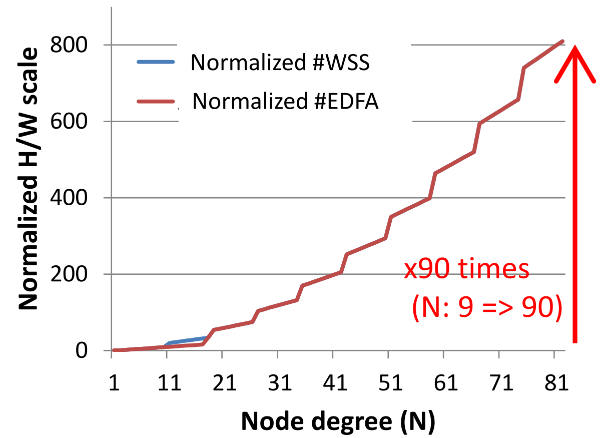


NxN optical cross-connect node





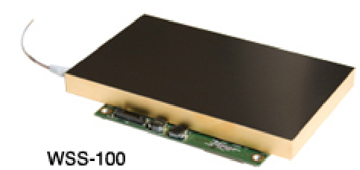
WSSs will be cascaded
if "deg. of WSS > deg. of node".



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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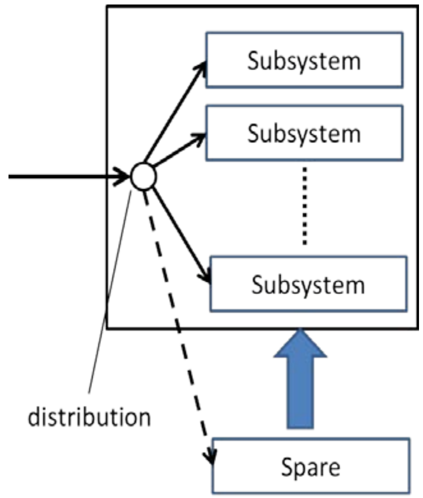
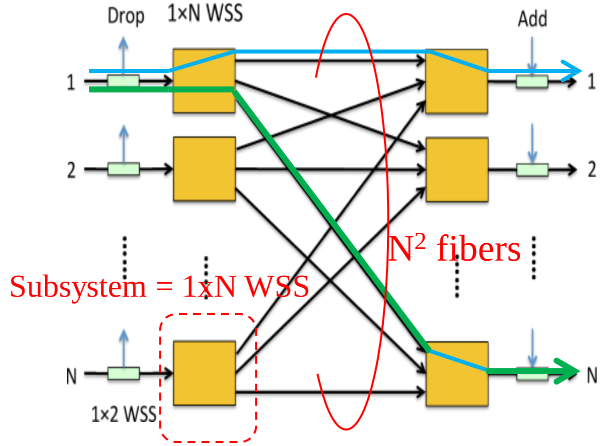
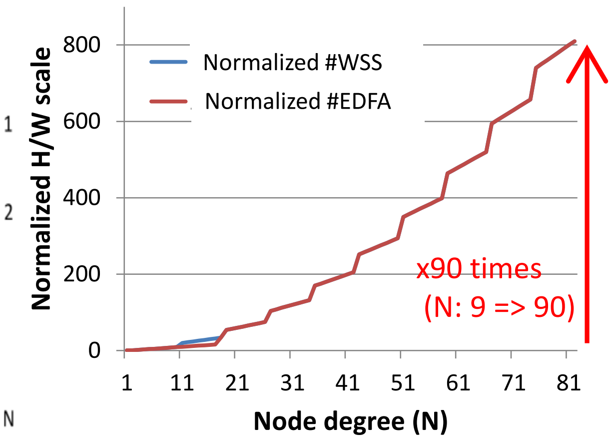
Basic strategy for resiliency enhancement



Ex) RAID: redundantly arrayed inexpensive disks

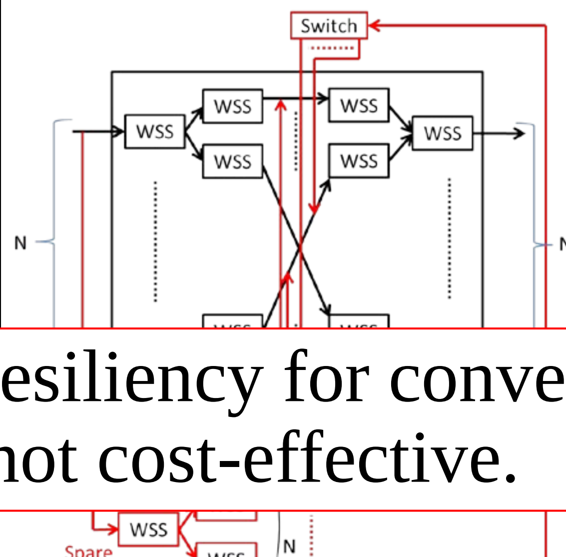
NxN optical cross-connect node





Hardware cost explosion at WSS based node

Installing a spare WSS to conventional node

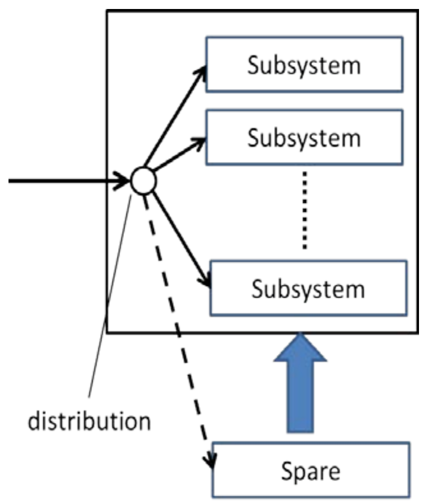


- Massive interconnection between the spare and the node
- WSS cascading increases the risk of failure.
- We need many optical switches: N+1 1xN and N^2+N 1x2.

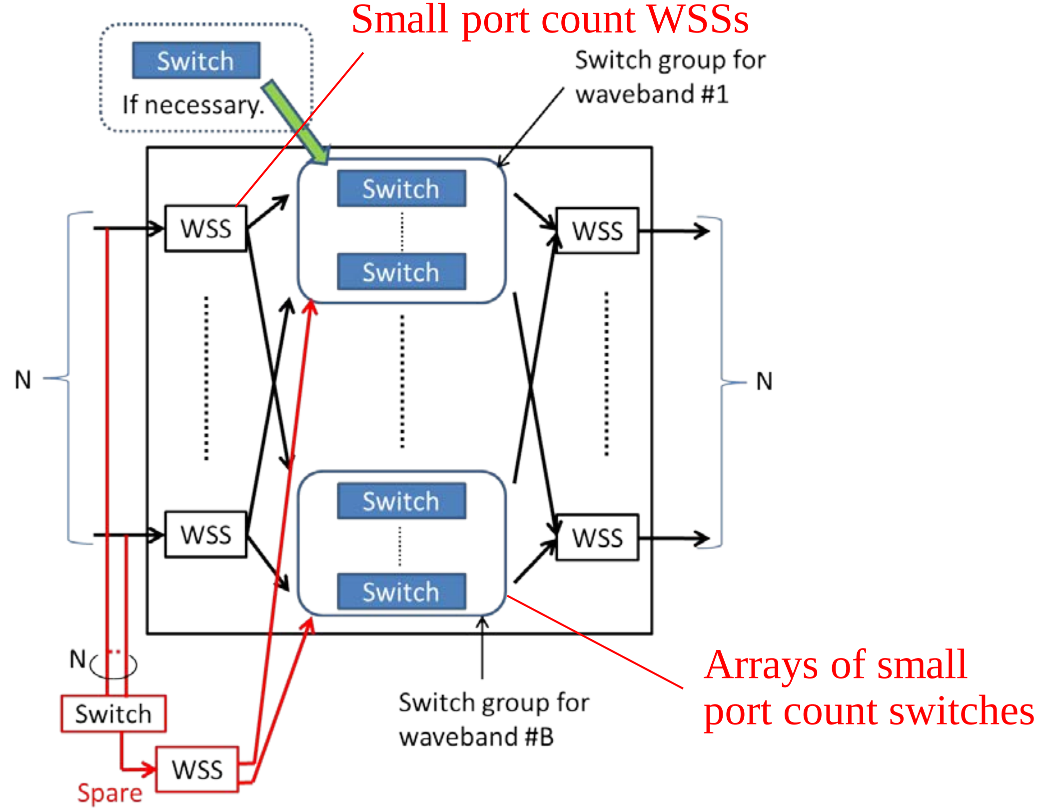
Enhancing resiliency for conventional nodes is hard and not cost-effective.

Resiliency enhancement for flexible waveband routing nodes

Basic strategy for resiliency enhancement



Ex) RAID: redundantly arrayed inexpensive disks



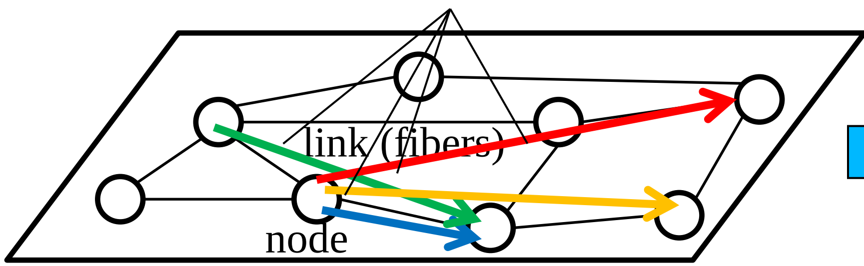
Flexible waveband routing nodes satisfy key requirements:

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

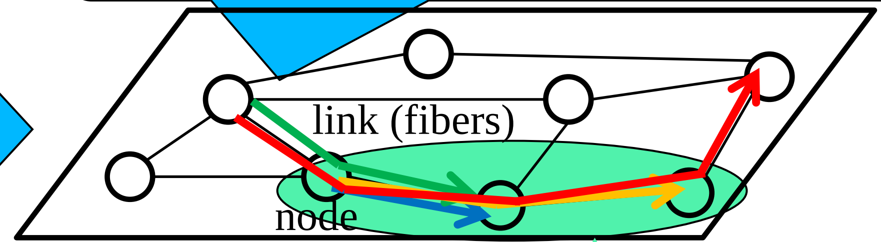
Path connection requests



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.

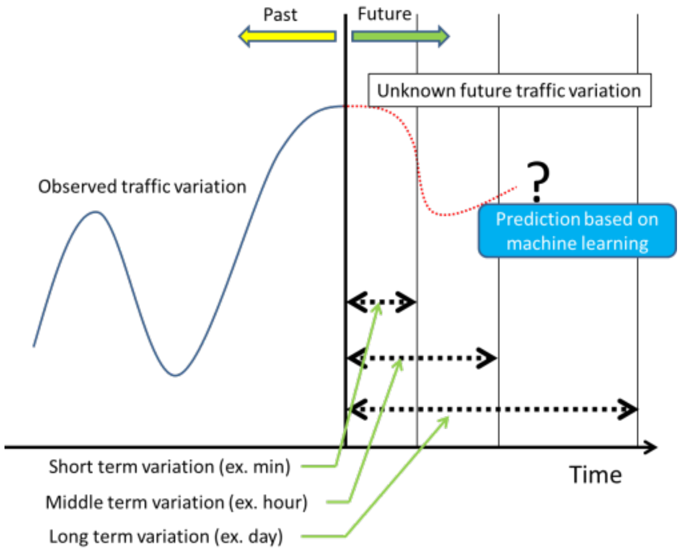
Optical networks/layers

Optical networks/layers

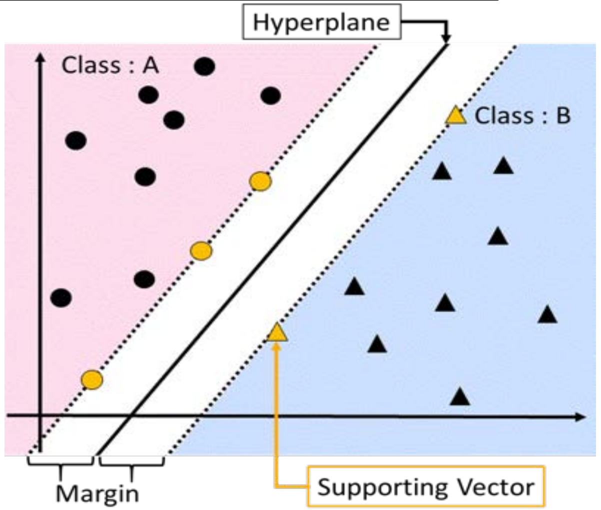
1. Route independence limits the room for optimization.
2. There are several options for switching to backups.

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

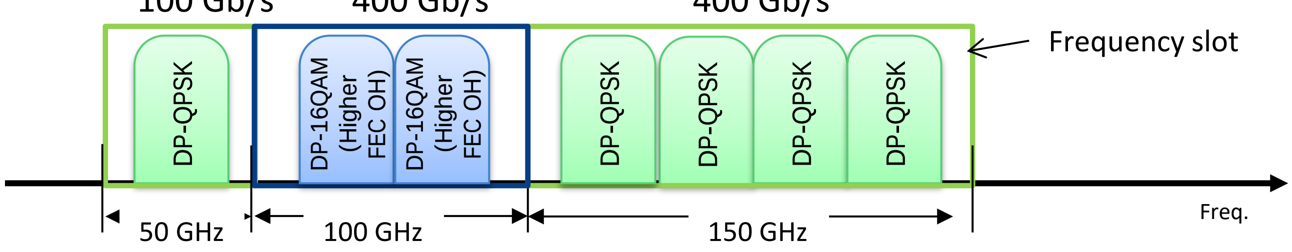
Masahiko Jinno (Kagawa University)

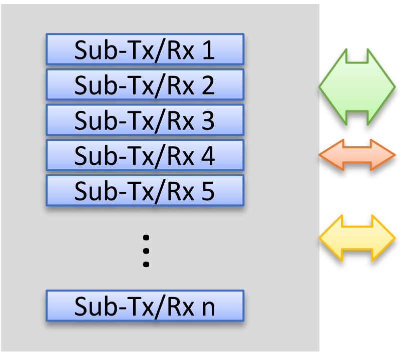
Motivation of Our Work

- 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

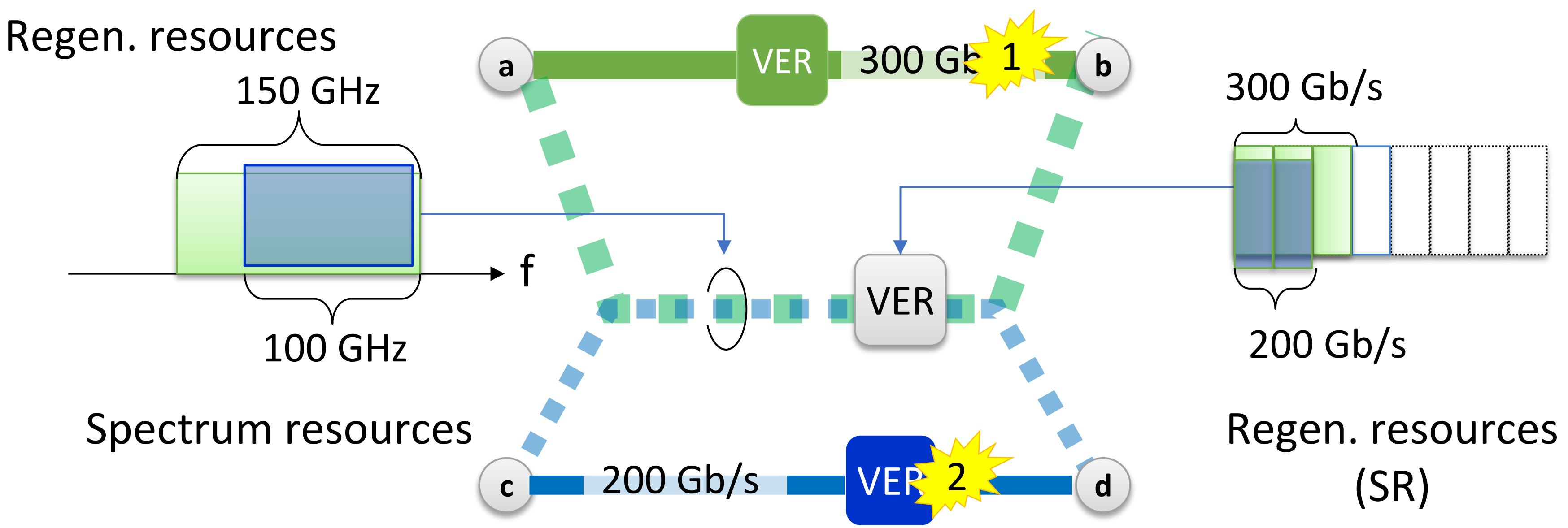




Sliceable Tx/Rx, regen

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.

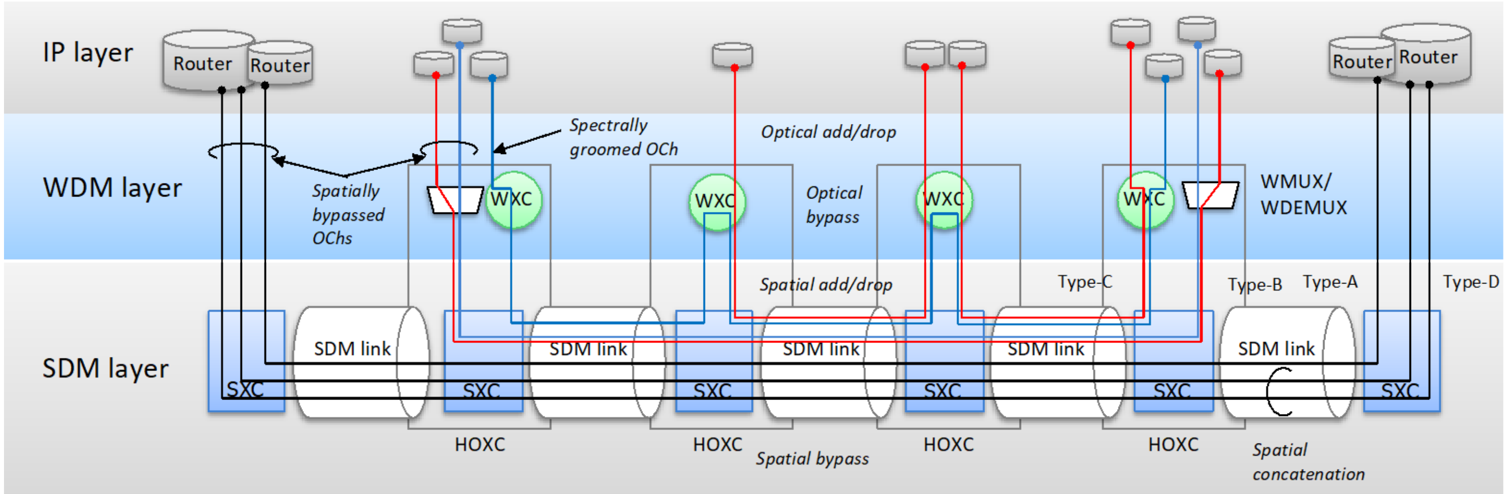


Our tasks 1 / 2

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.)

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Motivation and Goals

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- ✓ 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

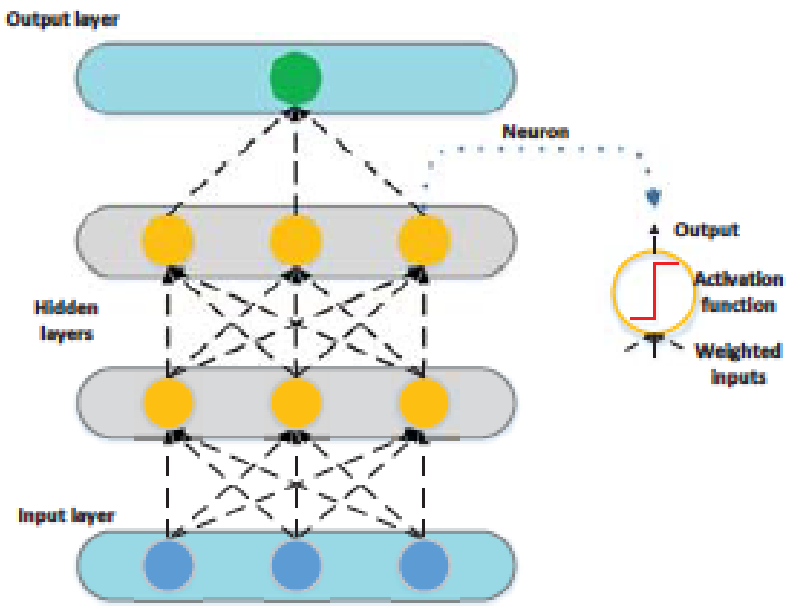
Mathematical Modeling

- ✓ 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

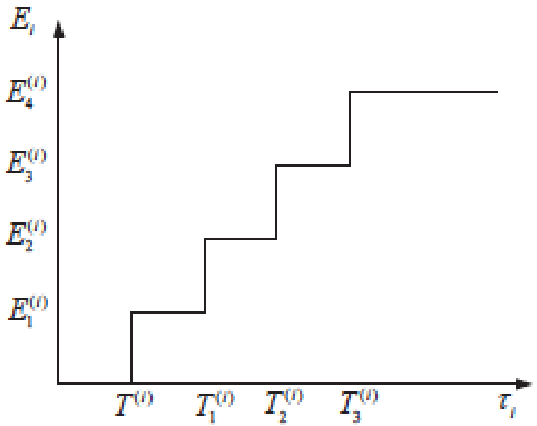
✓ Train a DNN using a large training data set

- 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-effective and resilient optical cross-connect node architecture													
1.1.1 Introduction of component level redundancy to flexible waveband routing optical nodes	**Nagoya**	Yellow	Yellow	Yellow									
1.1.2 Seamless node expansion and disruption-free maintenance schemes	**Nagoya**			Yellow	Yellow	Yellow							
1.1.3 Node architecture optimization	**Nagoya**								Yellow	Yellow	Yellow		
1.2 Design algorithms of resilient optical networks with proposed nodes													
1.2.1 Intra-node redundancy aware network design algorithm	**Nagoya**			Yellow	Yellow								
1.2.2 Switching methodology to backups in flexible waveband routing networks and design of resilient networks	**Nagoya**				Yellow	Yellow							
1.2.3 Network control/management algorithm for node expansion and maintenance	**Nagoya**						Yellow	Yellow	Yellow	Yellow			
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**	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan						
2.1.2 Resource allocation algorithms at fallback switching-over process	**Kagawa**			Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan	Cyan		
2.1.3 Extension to support SDM networks	**Kagawa**							Cyan	Cyan	Cyan	Cyan	Cyan	Cyan
2.2 Multi-period traffic prediction and dynamic network control method													
2.2.1 Machine-learning based traffic prediction	**Nagoya**				Yellow	Yellow	Yellow						
2.2.2 Improvement of prediction accuracy	**Nagoya**								Yellow	Yellow			
2.2.3 Development of dynamic network control method	**Nagoya**						Yellow	Yellow	Yellow				
3. Trustworthy connection resource management													
3.1 Characterizaiton of availability	GWU	Red	Red	Red	Red	Red							
3.2 Connection availability prediction using analytical models	GWU			Red	Red	Red	Red	Red					
3.3 Connection availability prediciton using machine learning	GWU					Red	Red	Red	Red	Red			
3.4 Resource provisioning and management	GWU							Red	Red	Red	Red	Red	Red
4. Evaluation Plan													
4.1 Numerical evaluation													
4.1.1 Flexible waveband routing OXC nodes	**Nagoya**					Orange	Orange	Orange					
4.1.2 Protection schemes	**Kagawa**						Orange	Orange	Orange				
4.1.3 Traffic prediction and dynamic network control	**Nagoya**								Orange	Orange	Orange		
4.1.4 Availability characterization and prediction	**GWU**					Orange	Orange	Orange	Orange	Orange			
4.1.5 Trustworthy connection resource provisioning and management	**GWU**								Red	Red	Red	Red	Red
4.2 Development of optical cross-connect node prototype performance evaluation													
4.2.1 Estimation of transmission characteristics	**Nagoya**									Orange	Orange		
4.2.2 Prototype development and transmission experiment	**Nagoya**											Orange	Orange

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