End-to-end Network Slicing and Orchestration in Future Programmable Converged Wireless-optical Networks

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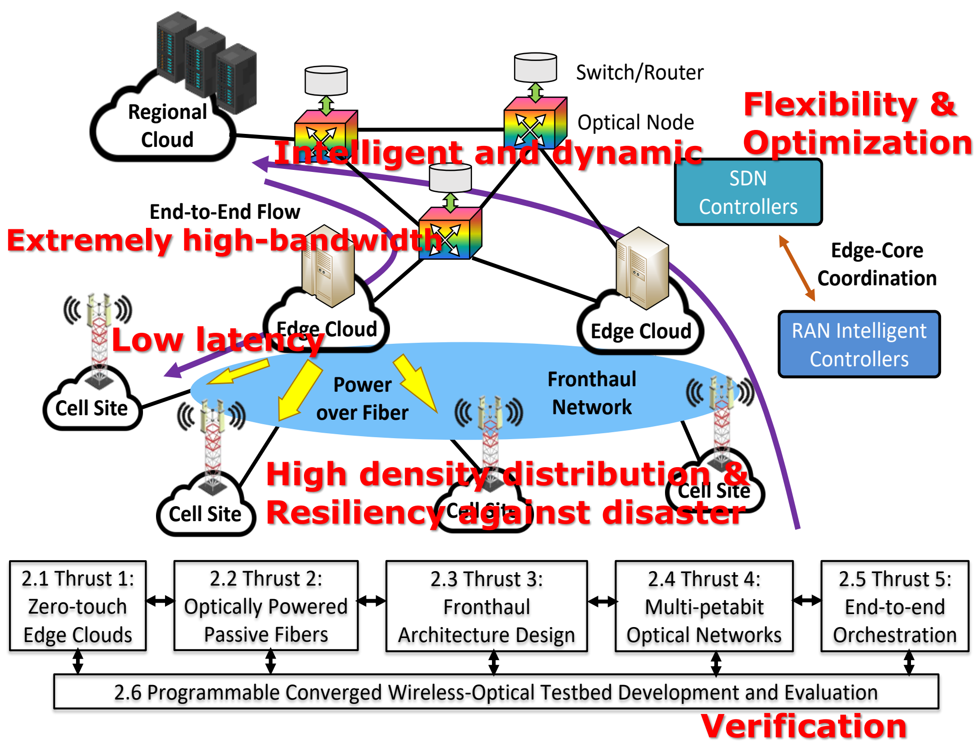
INTRODUCTION

Outline

- ✓ General Background & Project Goals
- ✓ Proposed Research
  - Zero-touch edge clouds and resource management (Lead: NCSU)
  - Optically-powered PONs (Lead: Univ. of Electro-Communications)
  - Front-haul network architecture and design (Lead: GWU)
  - Programmable Multi-petabit Optical Networks (Lead: Nagoya Univ.)
- ✓ Collaboration Plan & Time Table

General Background



- Traffic growth ratio: +30%/year (x13.8 / 10years)
- Introduction of optical transmission to broad area is mandatory
- Broad bandwidth & low-latency communication between user-edge & edge-regional cloud.
- Severe requirements by 5G/Beyond 5G
- Emerging applications: Autonomous driving, Remote surgery, Remote machinery, AR/VR

- “Capacity crunch” in optical fiber
- Fast traffic volume variation
- Deployment of new fibers is hard
- Collaboration and integration between optical and wireless
- Fast progress in ML

- E2E Network slicing and orchestration
- Information exchange between edge-core networks and intelligent multi-domain network control
- Optimal antenna distribution and data/power transmission on newly developed optical fibers for high resiliency against disaster
- Broad-bandwidth optical network infrastructure

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NC STATE UNIVERSITY

Collaboration and Tasks/Techniques

NAGOYA UNIVERSITY

UEC 電気通信大学 The University of Electro-Communications

Network slicing and orchestration

NC STATE UNIVERSITY

Fine-grained and flexible electrical processing

Machine Learning

Flexibility in networks
Network optimization

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC

Integer Linear Programming

Highly dense distribution of survivable optical front-haul

Intelligent network control

NSF

This project

NICT

Graph Theory

Novel fiber architecture

東海国立大学機構 名古屋大学

Ultra high-bandwidth
optical network infrastructure

UEC 電気通信大学 The University of Electro-Communications

Peta-bit class optical networking

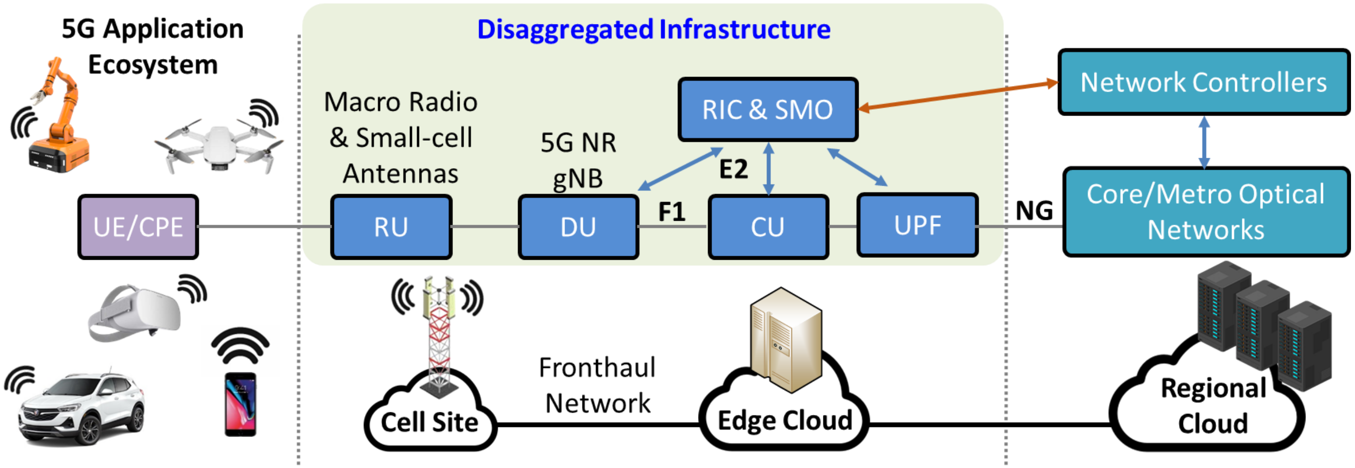
Transmission performance improvement

ZERO-TOUCH EDGE CLOUDS AND RESOURCE MANAGEMENT

Zero-Touch Edge Clouds and Resource Management

Automatically manage networked edge resources via programmable disaggregated infrastructure (*middle* sited for ensuring E2E SLAs)

- ✓ Manage underlying access & edge
- ✓ Orchestrate with optical core/metro networks



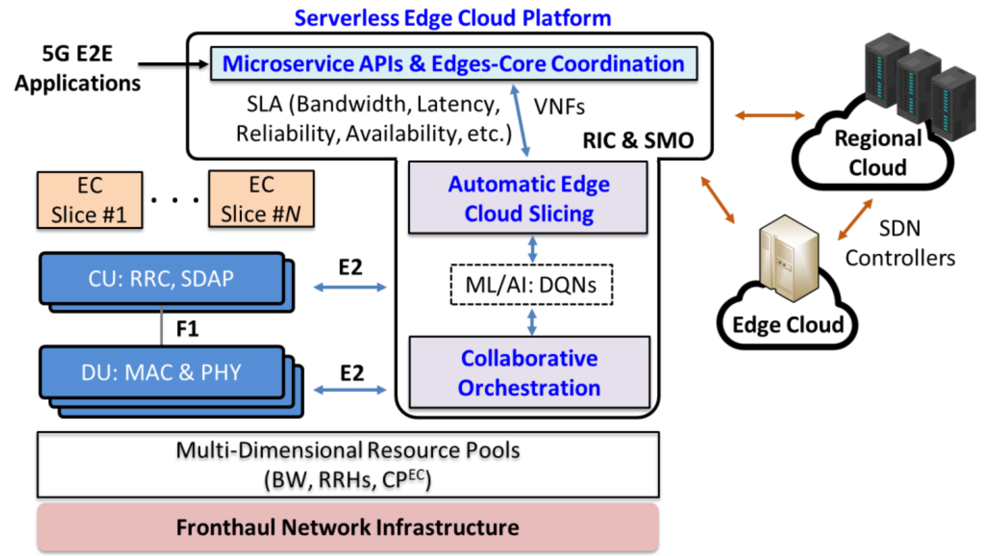
Current limitations:

- ✓ App developers – explicitly manage multi-domain resources; handle complicated scalability, load balancing
- ✓ Pre-allocation designs – underutilize limited edge, wireless resources

a. Automatic Edge Resource Slicing

Our serverless EC platform

- ✓ Abstract resource mgmt. from developers
- ✓ Meet diverse SLA in resource-constrained ECs
- ✓ Orchestrate heterog. infra components for on-demand, flexible resource supply



Automatic EC slicing management

- ✓ Receive SLAs & VNFs from microservice APIs, E2E requests
- ✓ Abstract, allocate, and initiate EC slices on access/edge infra while minimize OPEX (function of power, bandwidth)
- ✓ Automation – plan to use DQNs for effective EC slicing
  - Quickly adapt to environmental/system parameter changes
  - Continuous-state; off-policy setup for proactive decisions at non-RT RIC

b. Joint Scheduling and Clustering

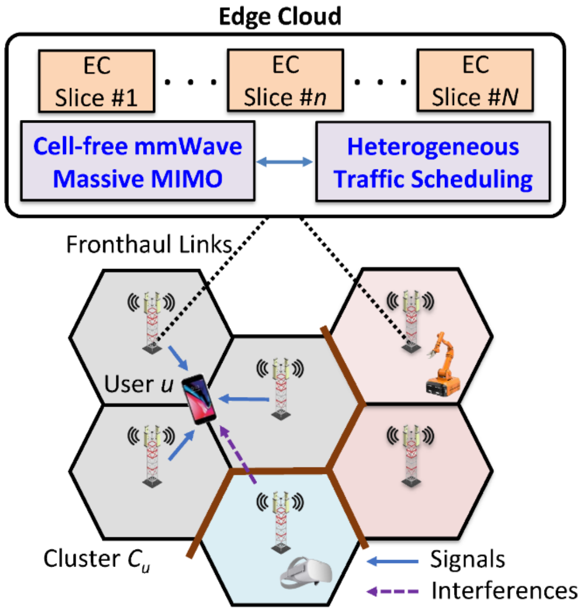
Execute EC slicing results through collaborative scheduling (MAC) & clustering (PHY) orchestration

- ✓ PHY: multiple RRHs cooperatively serve user $r_u(C), C := \bigcup_{u \in \mathcal{U}} C_u$ via software programmability in the FH network
- ✓ MAC: decide transmission status $H_u(t) \in \{0,1\}$; consider traffic queue and packet delay

Find optimal transmission schedule & clustering pattern: (i) total user data rates are maximized; (ii) each user has bounded average delay

$$(\{H_u^*(t)\}, C^*) = \mathrm{argmax}_{\{H_u(t)\},C} \sum_{u \in \mathcal{U}} H_u(t) r_u(C) [D_u(t)]^{\beta_u}$$

instantaneous data rate — traffic serving priority



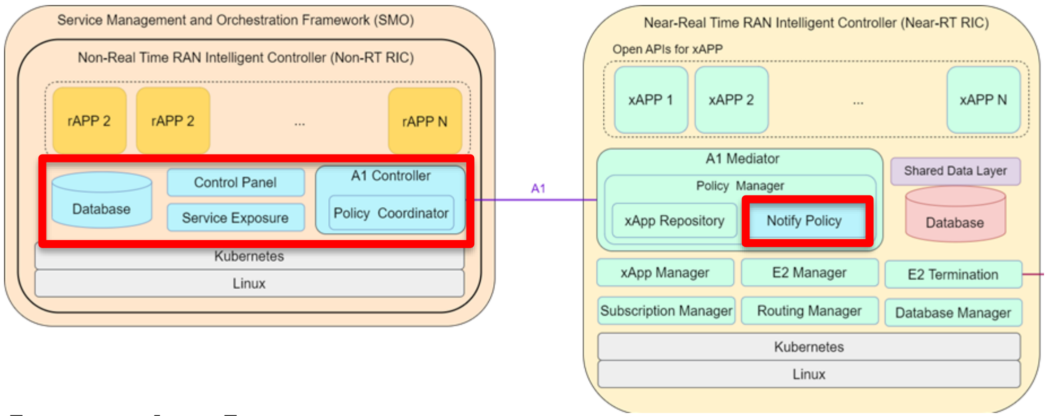
- Two-timescale DQN for hybrid heterogeneous traffic scheduling & dynamic RRH clustering
- Realize cell-free mmWave massive MIMO

A1 Interface and 5G RACH Slicing

Near-RT & non-RT RICs coordination

✓ Implement ORAN-A1 Policy management to query/create/update/delete/feedback policy procedure (JSON format)

client (*consumer*)

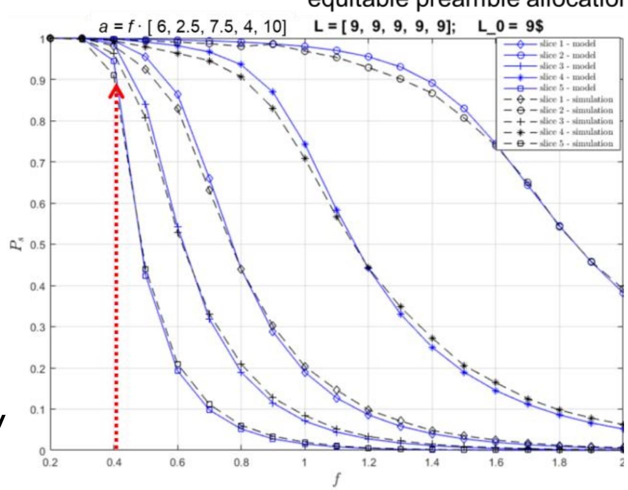


server (*producer*)

Uplink RACH [CSCI'22]: slice-based RA

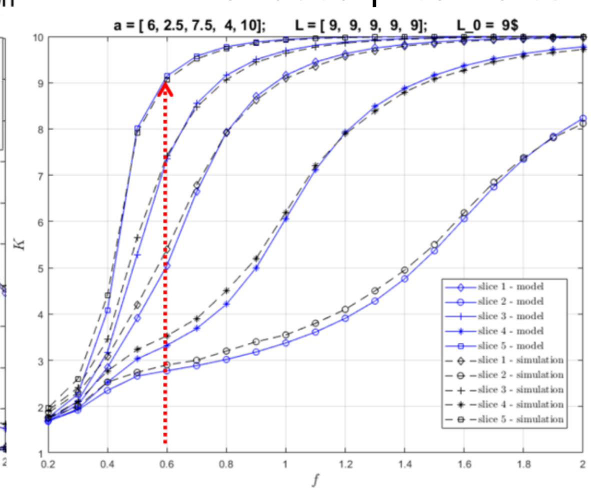
✓ Slice load ↑ , *Ps* ↓ ; more retrans. for each access attempt

equitable preamble allocation



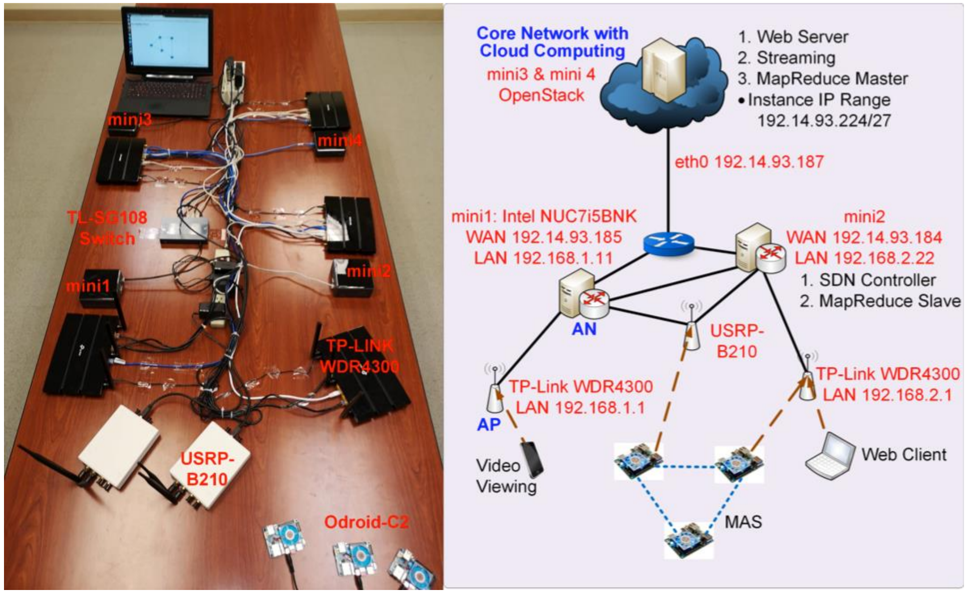
success probability

# of used preambles



E2E Orchestration and Next Steps

Fully-functional prototype: with 128 MB data chuck and Hadoop application, an experimental testbed gives 53% reduction in average read/write time



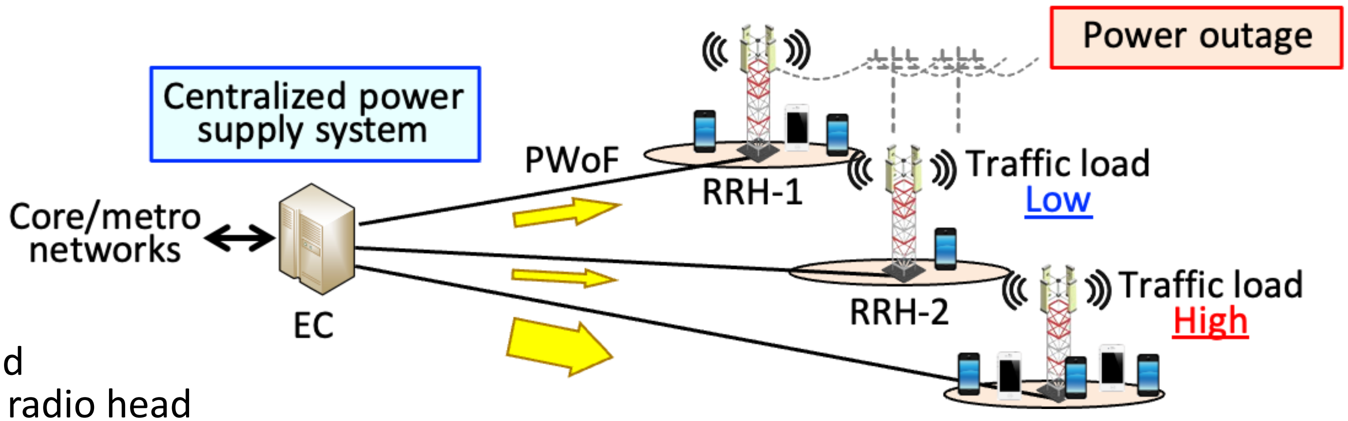
WINE testbed: software-defined wireless intelligent networked edges

Planned tasks:

- ✓ Core network SDN controllers and EC RICs jointly manage VNFs & resource pools via edge-core coordination
- ✓ ECs retains FH resilient connectivity via GNNs with time series
- ✓ Cache and distributed contents into far edges; proactive caching & capacity reservation via experiential AI

OPTICALLY POWERED PASSIVE OPTICAL NETWORKS

Optically Powered Optical Networks



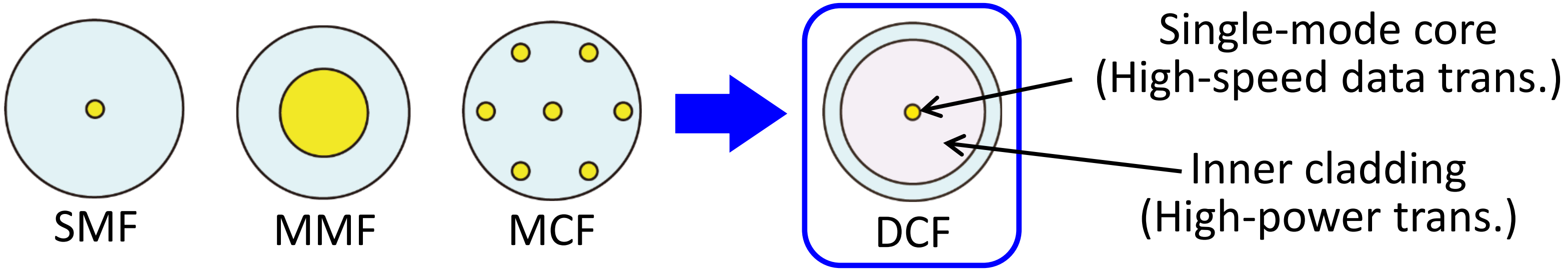
EC: Edge Cloud
RRH: Remote radio head

- ✓ **High availability:** In mobile networks, the power required for RRHs is generally supplied from neighboring public power lines; however, when a power failure occurs during natural disasters, mobile service also stops. By installing power-over-fiber to supply emergency power to RRHs, the network can be made more robust.
- ✓ **Ease of deployment:** If RoF links can always supply power to RRHs, there is no need to install electric power supply facilities and power lines. Each RRH is connected solely to an RoF link, which makes the installation work much easier. In addition, RRHs can be easily installed in places where there are no electric power facilities and power lines nearby.
- ✓ **Power saving in networks:** RRHs are always supplied with a maximum amount of power, regardless of the data traffic. If the power supplied to each RRH corresponds to the data traffic, it is possible to minimize the power required to drive the RRHs, and the power consumption of the entire network will be greatly reduced.

Motivation

➢ Power supply capacity that enables RRH to be driven independently

- Power supply with electrical power exceeding 10 W
- Simultaneous transmission of power/signal as space-saving feature of optical links



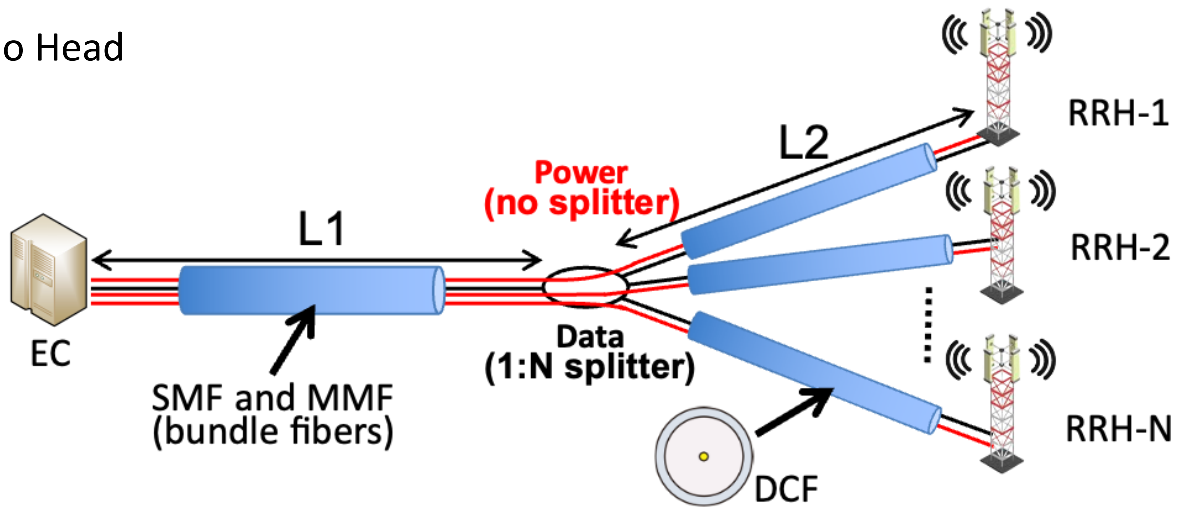
- Achieved simultaneous power/signal transmission of 43.7 W of electric power
- Applicability to networks has not yet been studied

➢ Application to networks for Beyond 5G/6G

- Passive optical network (PON) configuration with high practicability for future front-haul (FH) networks
- Clarify the feasibility of power-over-fiber in PON
- Experimental demonstration of optically powered PON

Optically Powered PON (Proposed)

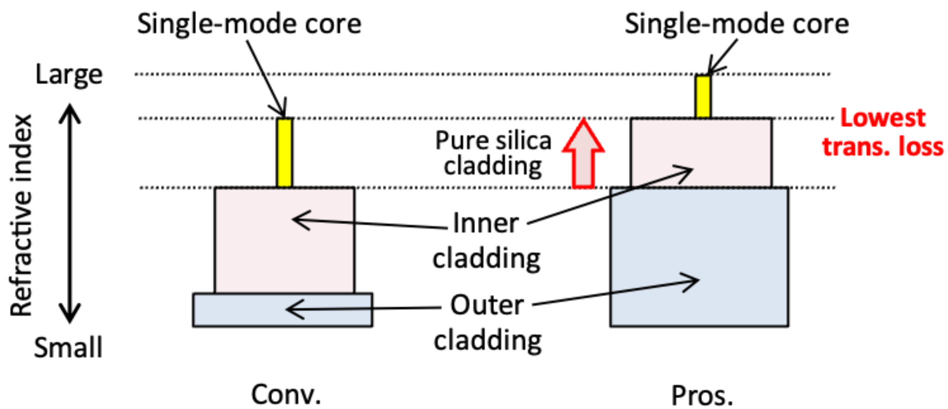
EC: Edge Cloud
RRH: Remote Radio Head



- Pre-branch link: Simultaneous data/power transmission using bundle fibers
- Post-branch link: Simultaneous data/power transmission using DCF
  - DCF transmission that enables <u>simpler combiner/divider configuration</u> of data and power lights
  - Improvement of power transmission efficiency through <u>low-loss DCF</u>

Achievements (to March 2023)

➢ Low-loss double-clad fibers (DCF) [Patent]

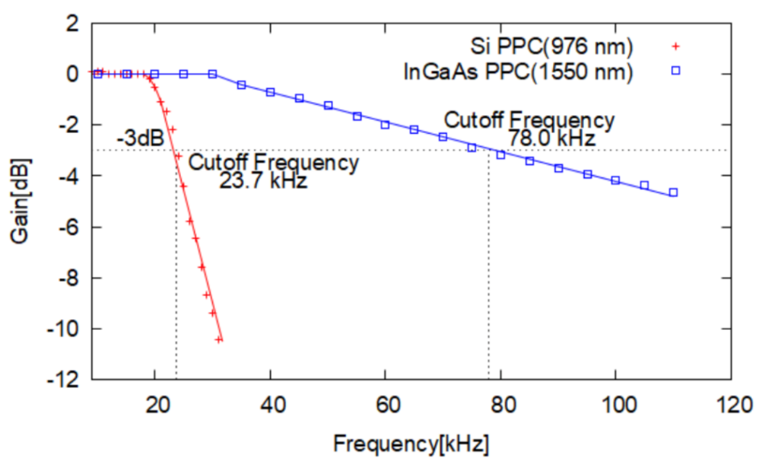


Transmission loss in inner cladding

	976 nm (dB/km)	1550 nm (dB/km)
Conv.	11.3	67.8
Pros.	1.46	1.24

Succeeded in significantly improving power transmission efficiency

➢ Response time for dynamic power control

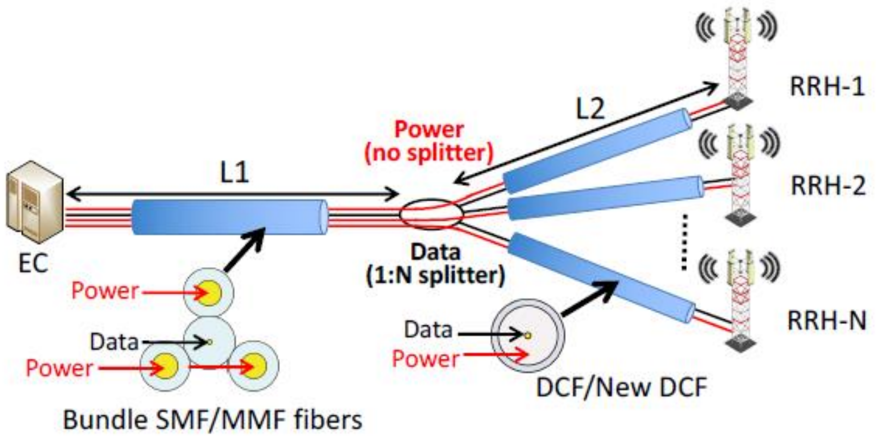


Frequency response of photovoltaic power converters (PPCs)

- The response time of commercially available PPCs (Si and InGaAs) was less than 15 μs.
- The overall response time is expected to be less than 100 μs, which is sufficient for dynamic power control of RRHs in networks

FRONT-HAUL NETWORK ARCHITECTURE AND DESIGN

Fiber Cost and Loss Analysis



	Cost	Loss (previous)	Loss (this work)
Single-mode fiber (SMF)	1	-	-
Multimode fiber (MMF)	1.5	2.0 dB/km (808 nm)	1.0 dB/km (980 nm)
Double-clad fiber (DCF)	3	4.4 dB/km (808 nm)	11.3 dB/km (980 nm)
New double-clad fiber	3	3.15 dB/km (808 nm)	1.46 dB/km (980 nm)

Example: 3 RRH network cost

L1 cost: 1 SMF + 3 MMF
L2 cost: 3 DCF

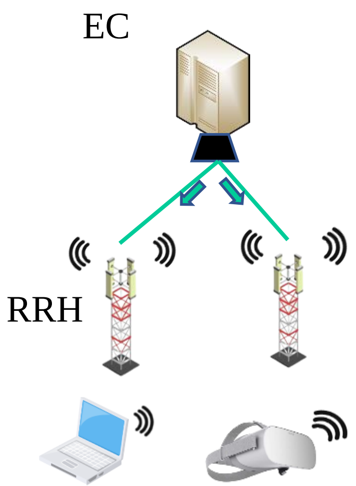
Transmission wavelength

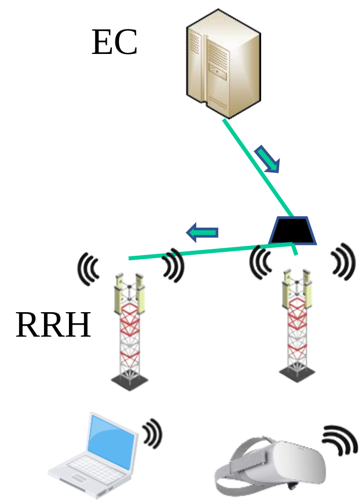
Data: 1550 nm
Power: 808 nm (Previous)
980 nm (This work)

Example: Two Special Cases

1) Splitter at EC

2) Splitter at RRH 2





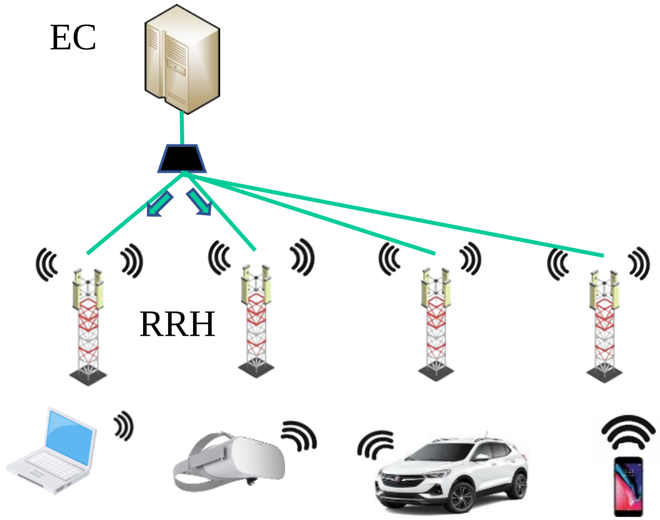
Fiber cost: 2(1.5)(Sum of dist of links from EC to RRHs)
Power loss: 1.46(Sum of dist of links from EC to RRHs)

Fiber cost: (1 + 2(1.5)) . (EC-RRH_2 distance) +
3 . (RRH_2-RRH_1 distance)
Power loss: 1 . (EC-RRH_2 distance) + 1.46(RRH_2-RRH_1 distance)

Depending on the locations of the RRHs and the EC, case 1 or 2 could be better in either or both of fiber cost and power loss

An Example Design Optimization Problem

- 1 EC, 1 splitter, multiple RRHs
- The link between EC and the splitter is bundle of SMF and multiple MMFs
- The fiber between splitter and RRHs is DCF
- Objective: Minimize sum of the fiber cost and power generation



PROGRAMMABLE MULTI-PETABIT OPTICAL NETWORKS

Tasks

4.1 Proactive switching status management in optical core-edge networks.

4.2 Optical networks with variable multiplexing density and mixed routing granularity

4.3 Cost-effective multi-petabit class optical nodes with sparse intra-node interconnection

6.3 OXC prototype development and transmission experiment

Presented at OFC2023
(Today I will focus on this achievement)

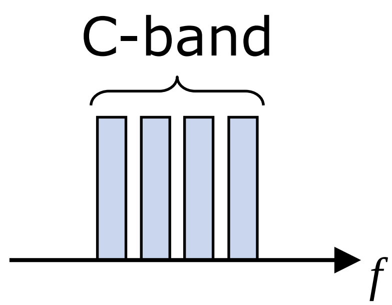
(Resilient network architecture : RNDM2022)

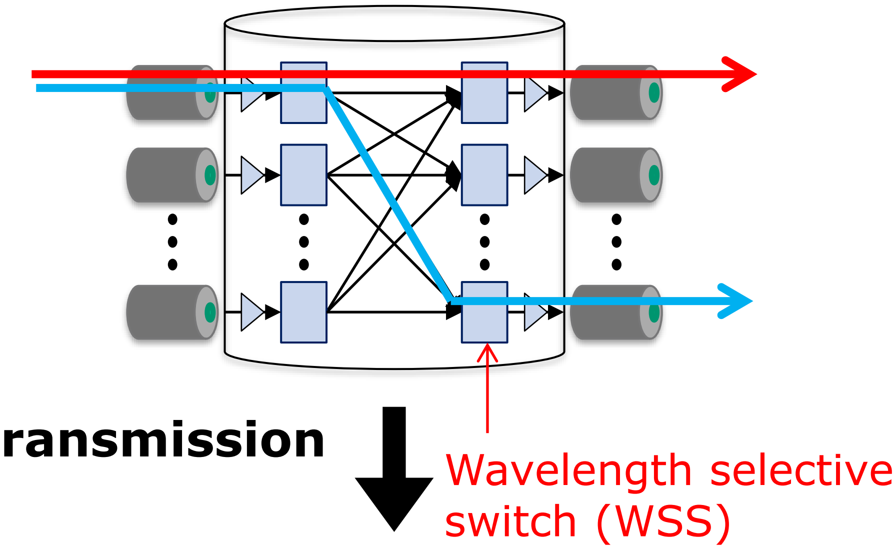
Introduction of multi-band transmission

Optical cross-connect (OXC)

Present

C–band transmission

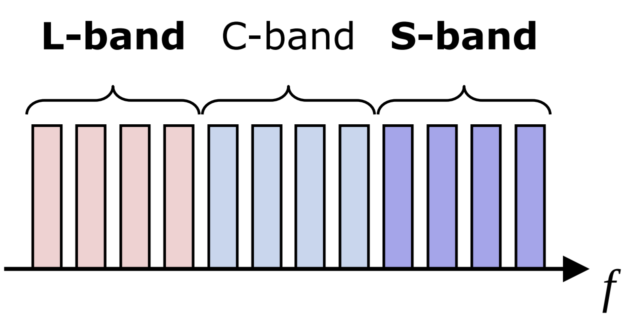


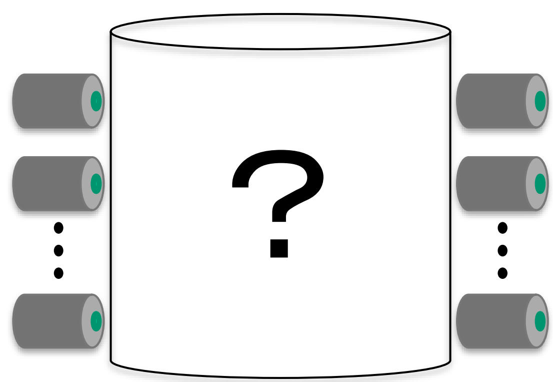


Multi-band transmission

Future

C+L+S–band transmission



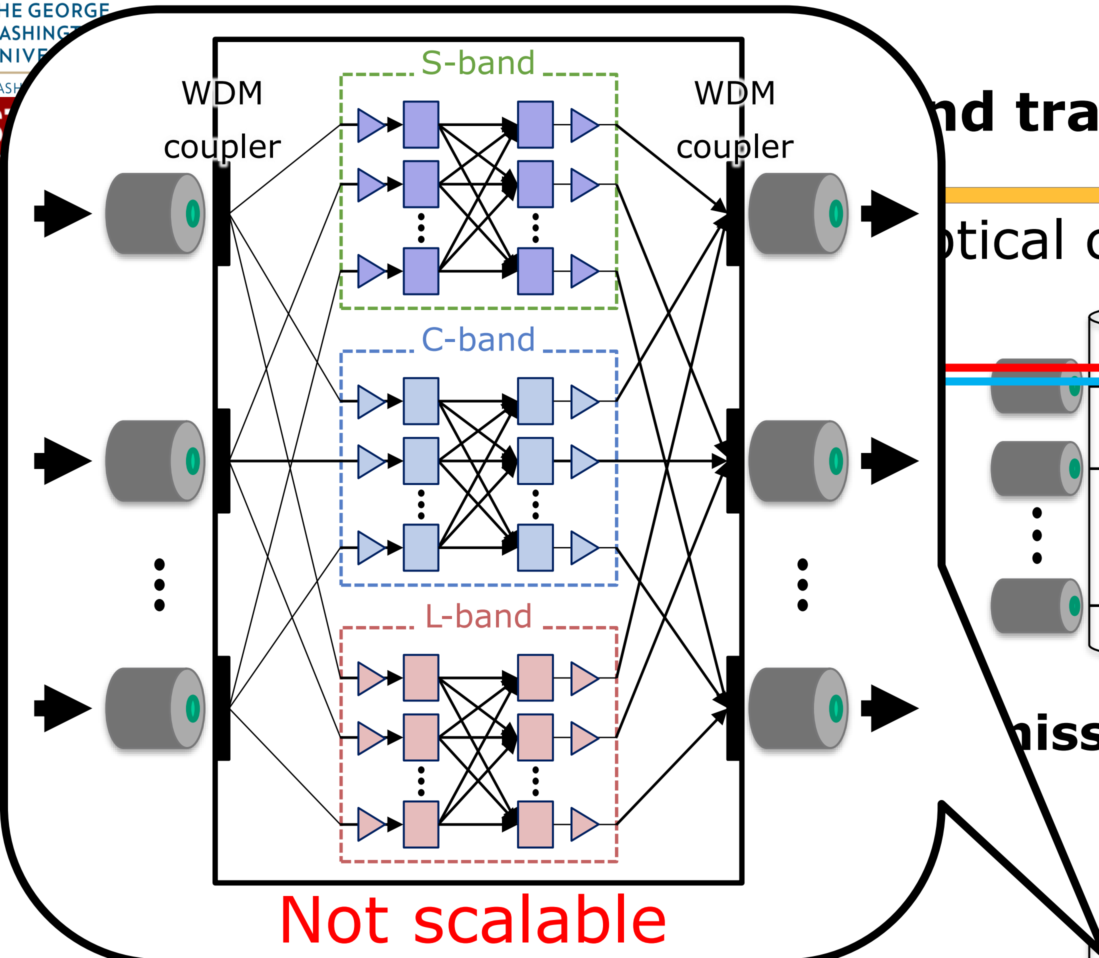


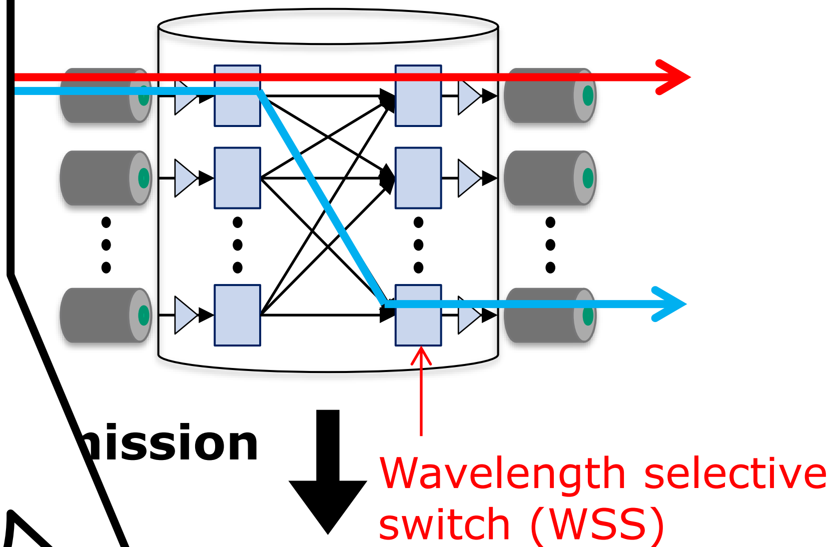
OXC for multi–band networks is needed.

…nd transmission

…ptical cross-connect (OXC)

Pre…





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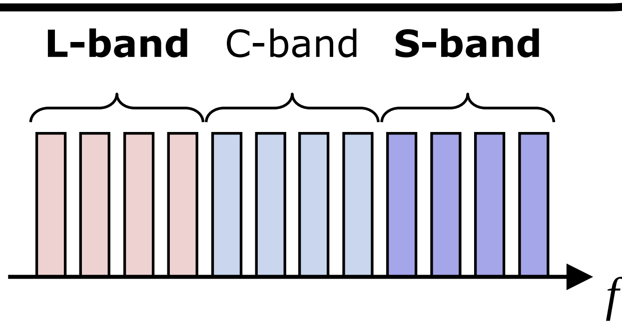
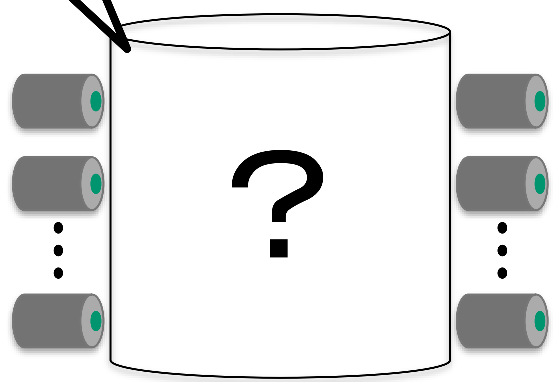
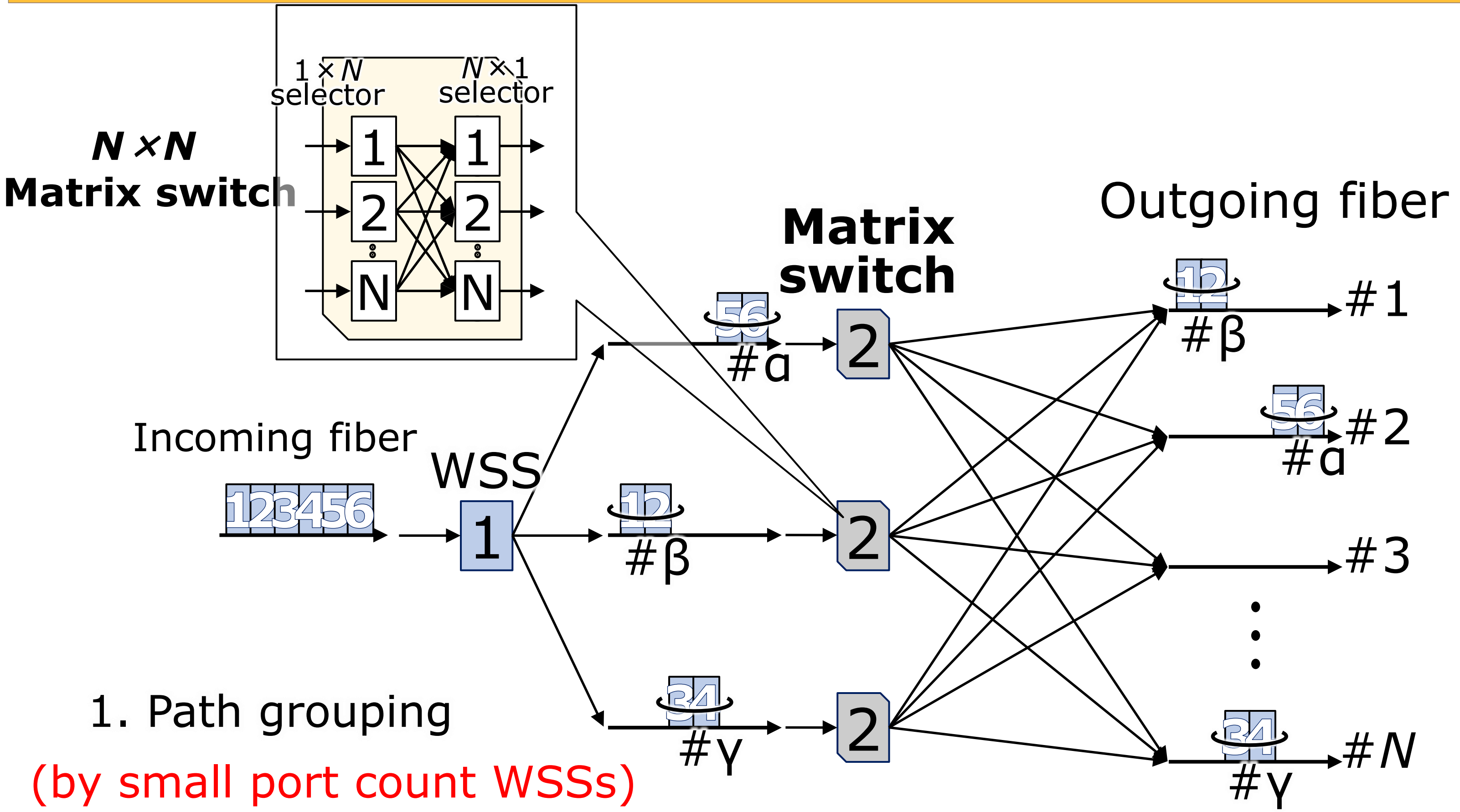
Future





OXC for multi-band networks is needed.

Our Proposal: Two-stage Path Routing

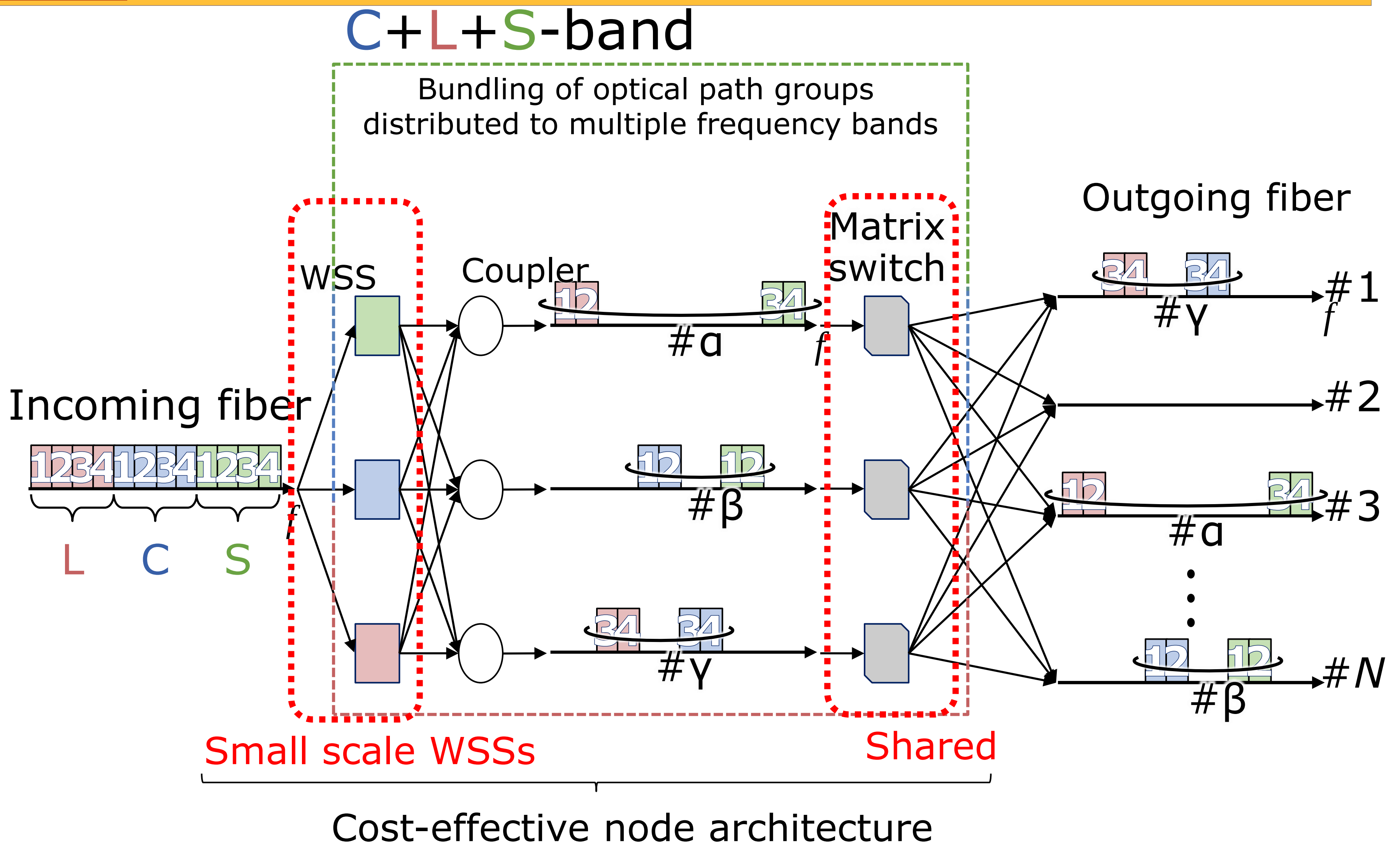


1. Path grouping
(by small port count WSSs)

2. Grouped path routing
(by Optical Switch)

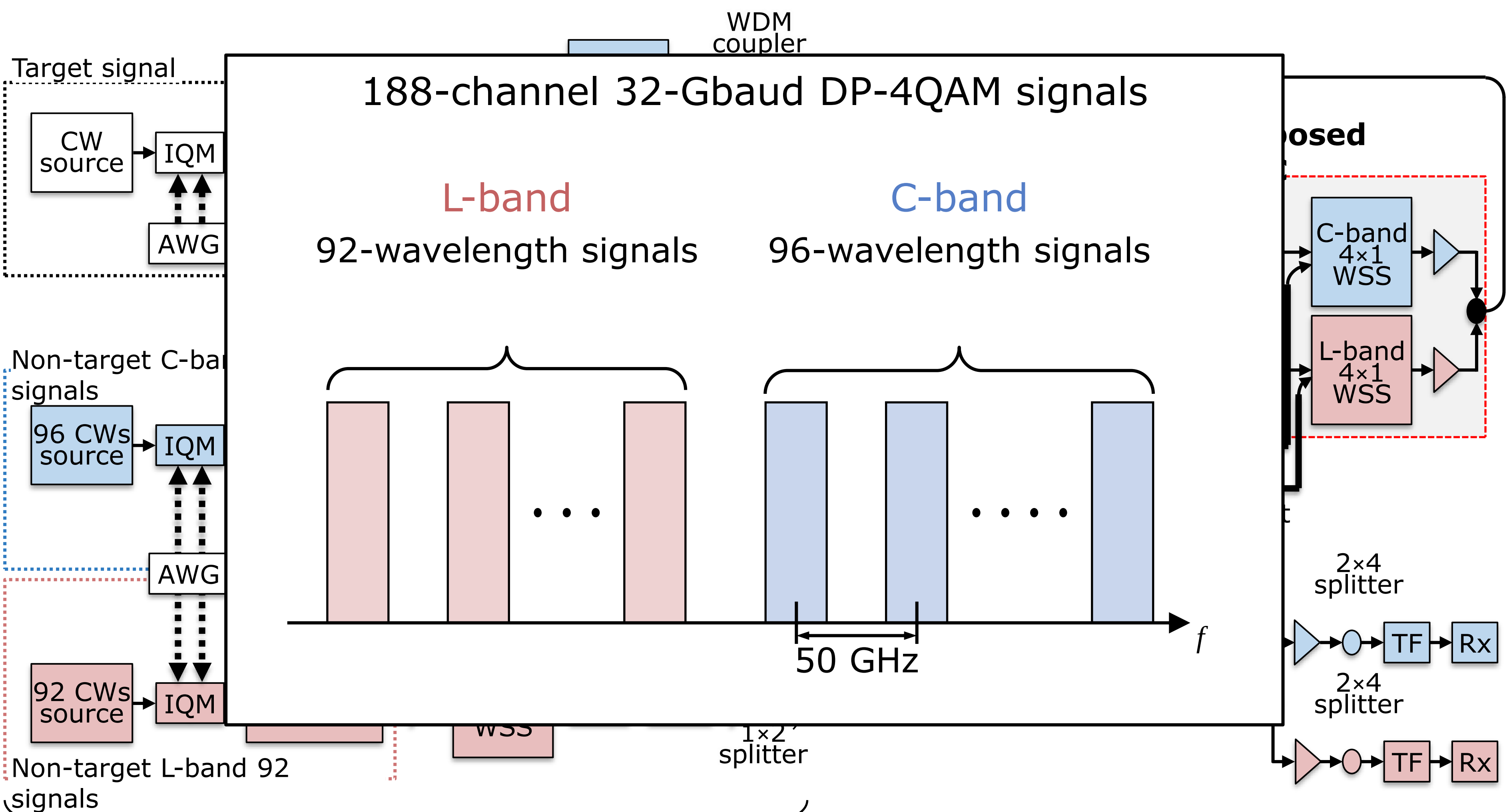
Thanks to the two-stage path routing, WSS port count can be small.

Novel Node Architecture for Multi-band Optical Networks [OFC2023]



Numerical simulations: routing performance verification
Transmission experiments: demonstrating transmission characteristic

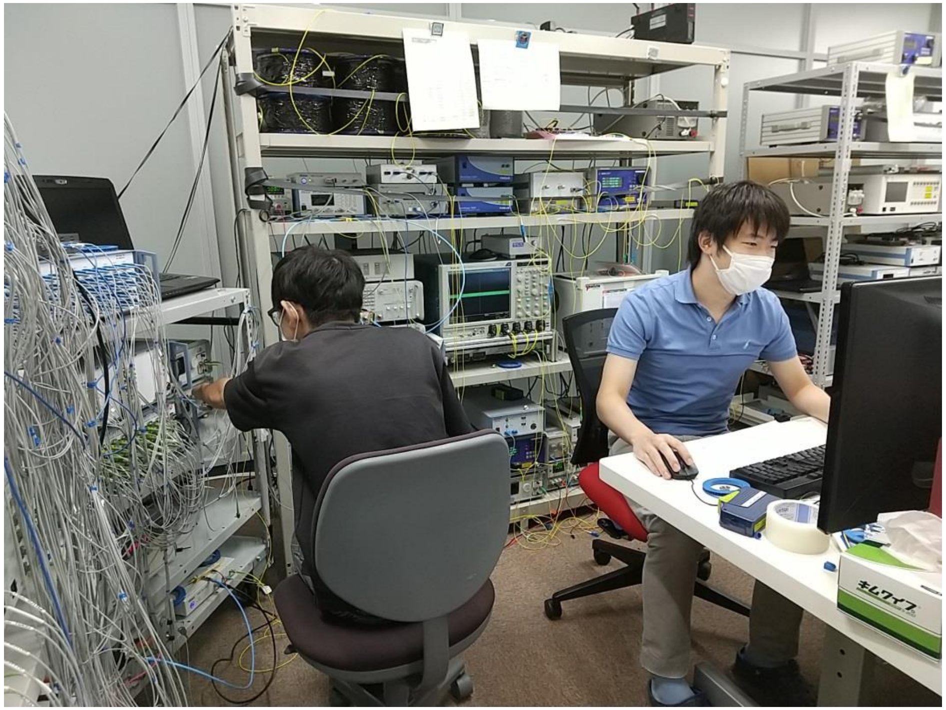
Transmission experiments (16x16 node, 188 wavelengths/fiber)



188-channel 32Gbaud DP-4QAM signals are generated.

Total throughput : **300.8 Tbps**

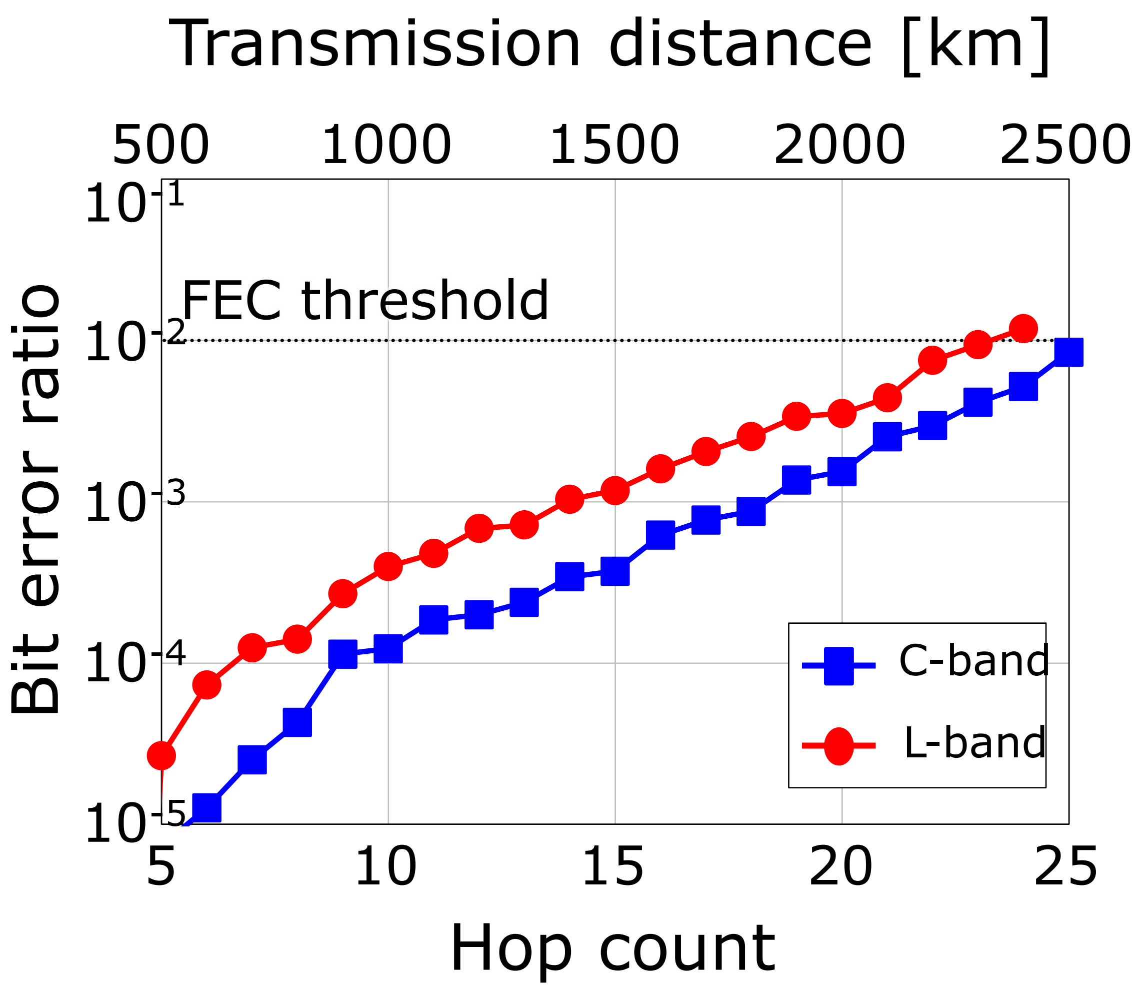
Transmission experiments



Multi-band path grouping

- Front: L-band WSS
- Back: C-band WSS

BER vs. hop count



Succeeded in transmission over 2000+ km.

RMCSA Problem and TRA Algorithm

- Resource allocation in SDM-EONs: RMCSA problem
- Tradeoff: Higher-level modulations require less spectrum but have more stringent inter-core XT tolerances
- We have developed an algorithm called Tridental Resource Allocation (TRA) that balances this tradeoff
- Tridental Resource Assignment Algorithm
  - R - Offline planning
  - MCS - Heuristics based on Tridental Coefficient

[1] Petale, Shrinivas, Juzi Zhao, and Suresh Subramaniam. "TRA: an efficient dynamic resource assignment algorithm for MCF-based SS-FONs." Journal of Optical Communications and Networking 14.7 (2022): 511-523.

Tridental Resource Assignment Algorithm (contd):

- TRA is based on Capacity Loss calculations

- Tridental Coefficient:

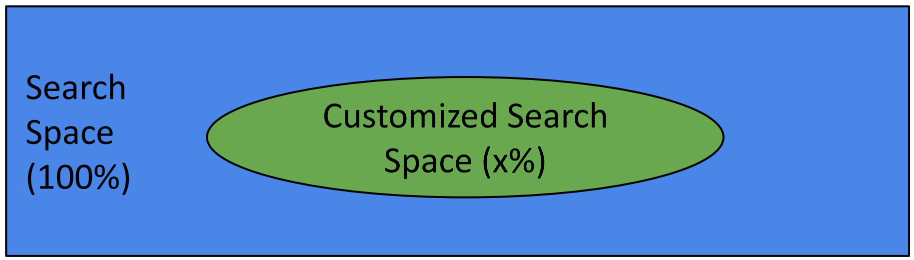
Capacity Loss — Spectrum Utilization — Spectrum Location

$$\Psi(l_{\Delta(r,m)}) = \boxed{\frac{\psi'(l_{\Delta(r,m)})}{max\psi'(l_{\Delta(r,m)})}} + \boxed{\frac{\beta_d^m}{\beta_1^m}} + \boxed{\frac{n}{S - \beta_d^m + 1}}$$

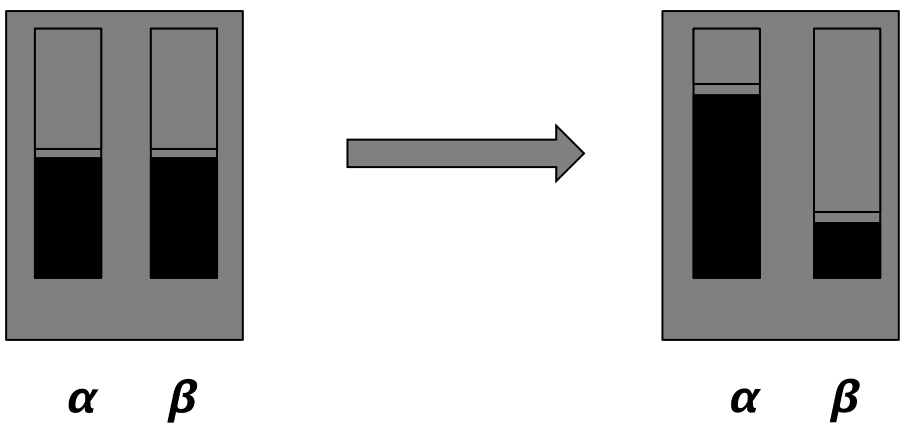
[2] S. Subramaniam and R. A. Barry, “Wavelength assignment in fixed routing WDM networks,” in IEEE Int. Conf. on Communications (ICC), 1997, vol. 1, pp. 406–410.

Proposed Optimizations

A. Reducing the Computational Complexity: Limiting Search Space



A. Weighted Tridental Coefficient: Weight Optimization

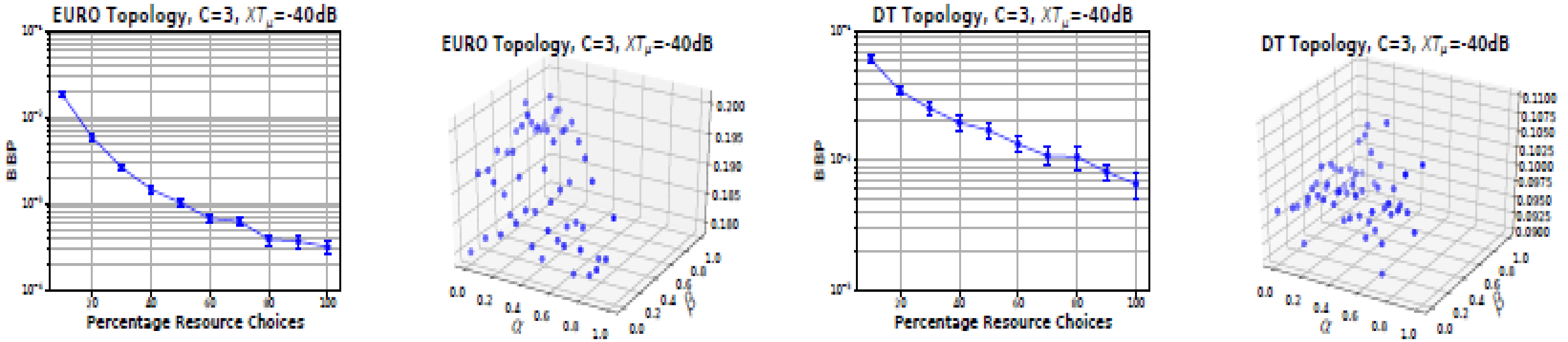


Results - Three Stage Optimization:

- Variation of BBP wrt to resources and scatter plot of $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and bandwidth blocking probability (BBP)

Table I: Sets of (α, β) corresponding to lowest BBP at C=3 and XT_{μ}=-40(dB).

Topology	Load(Erlang)	(α, β)	B_I	B
EURO	2000	(0.77, 0.11)	0.179394	0.192362
DT	2250	(0.66, 0.11)	0.0905354	0.0996859

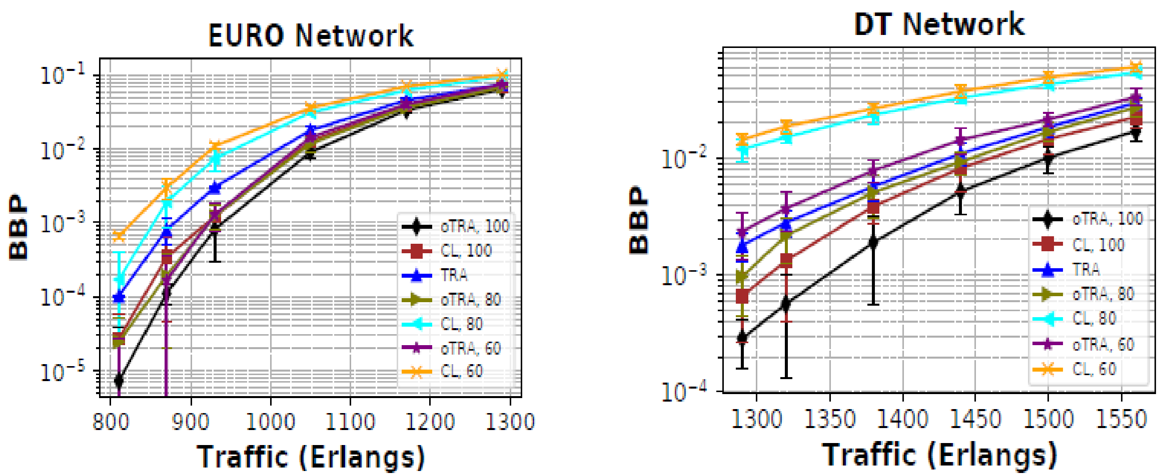


(a) (b) (c) (d)

Figure 1: Variation in BBP for limited percentage of RCs for XT_{μ}=-40dB and for different values of α and β for EURO topology in Fig.1a and Fig.1b, respectively, and for DT topology in Fig.1c and Fig.1d, respectively.

Results (contd):

- 60% resources in EURO and 80% resources in DT lead to acceptable performance.



(a) (b)

Figure 2: Variation in BBP of different versions of TRA for different loads for (a) EURO topology, (b) DT topology.

COLLABORATION PLAN & TIME TABLE

Collaboration

- ✓ Regular online meetings so far

- ✓ Face-to-face meetings
  - Not yet in this project, but hopefully soon!
  - Conferences: ICC, Globecom, OFC, ECOC, ICTON
  - Nagoya PI and GWU PI have collaborated on JUNO1 and JUNO2 as well with multiple visits to others' institution by both PIs

- ✓ Education
  - NU PI is serving on the dissertation committees for 2 GWU students on the JUNO projects

List of Publications

1. R. Munakata, Y. Mori, S. Subramaniam, M. Jinno, H. Hasegawa, "Spatially-Jointed Flexible Waveband Routing Optical Networks Adopting Shared Path Protection," 12th International Workshop on Resilient Networks Design and Modeling (RNDM2022), Compiegne, France, Technical Session II, no.1, Sep. 2022.
2. D. Haro-Mendoza, L. Tello-Oquendo, V. Pla, J. Martinez-Bauset, L. Marrone, S.-C. Lin, "Modeling the Resource Allocation in 5G Radio Access Networks with Network Slicing," in CSCI, Las Vegas, USA, Dec. 2022.
3. M. Matsuura, "Power-over-fiber technologies using double-clad fibers for remote antenna units in mobile networks," SPIE Photonics West 2023, Next-Generation Optical Communication: Components, Sub-Systems, and Systems XII, Session 11, pp.12429-50, San Francisco/Moscone Center, Feb. 2023. (Invited Talk)
4. R. Munakata, T. Kuno, Y. mori, S.-C. Lin, M. Matsuura, S. Subramaniam, and H. Hasegawa, "Architecture and Performance Evaluation of Bundled-path-routing Multi-band Optical Networks," Optical Fiber Communication Conference (OFC 2023) San Diego, USApaper M4G.8, Mar.2023.
5. K. V. S. Rohit, S.-C. Lin, and L. C. Chu, "SPELS: Scalable and Programmable Testbed for Evaluating LEO Satellite Swarm Communications," in Proc. of IEEE INFOCOM Workshop, New York area, USA, May 2023.
6. S. Petale and S. Subramaniam, "Efficient and Optimized TRA Algorithm For MCF-based SDM-EONs", in Proc. ONDM 2023, May 2023.

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