2018 Japan-US Network Opportunity 2 (JUNO2)

Project Title: *Disaster-Resiliency Strategies for Next-Generation Metro Optical Networks*

ATN: 1818972

Speakers:

Dr. Yoshinari Awaji

Dr. Massimo Tornatore

October 26, 2018

Principal Investigator Meeting @NICT Innovation Center, Tokyo, Japan

UCDAVIS

NICT

Project Team

- **PIs**
  - Massimo Tornatore; University of California, Davis; PI
  - Biswanath Mukherjee; University of California, Davis; Co-PI
  - Yoshinari Awaji; NICT (Japan); Team leader (PI Japan side)

- **Collaborators**
  - Sugang Xu; NICT (Japan); Collaborator
  - Yusuke Hirota; NICT (Japan); Collaborator
  - Masaki Shiraiwa; NICT (Japan); Collaborator

- **Students**
  - Dr. Sifat Ferdousi; University of California, Davis; PDF
  - Tanjila Ahmed; University of California, Davis; GSR
  - Priyesh (Phoenix) Shetty; University of California, Davis; GSR

Motivation

A new generation of optical metro networks is needed to turn the vision of "Smart Cities" into reality

- Future metro networks: from a rigid ring-based aggregation infrastructure to a composite network-and-computing ecosystem to support critical 5G services (e.g., autonomous driving)

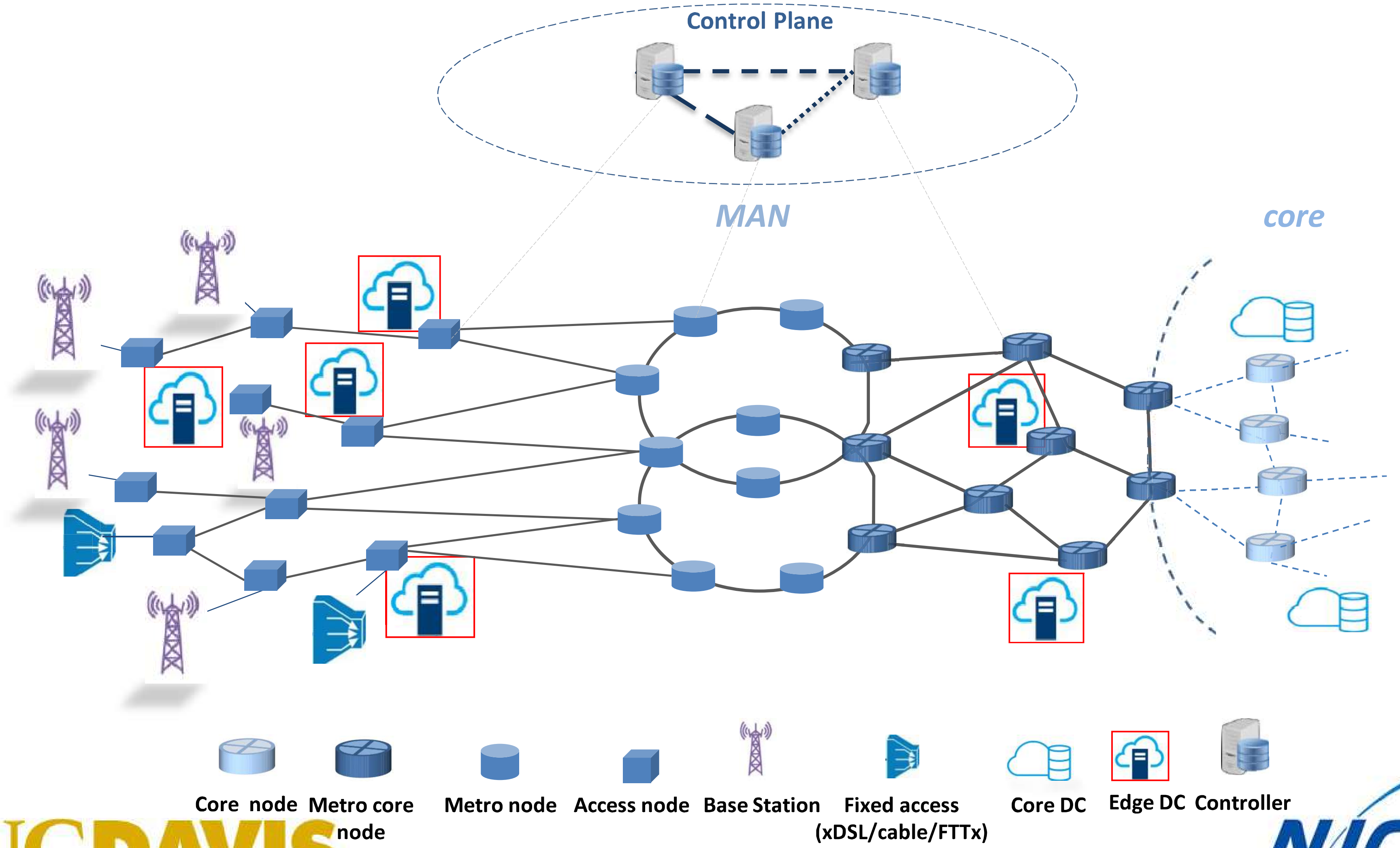
- Several technical enablers:
  - Increased reconfigurability enabled by **SDN**
  - **Integration of optical and wireless** access networks
  - Metro nodes becoming edge data centers (**edge computing**)
  - **Network slicing** to logically partition network, computing, and storage resources
  - …

UCDAVIS

NICT

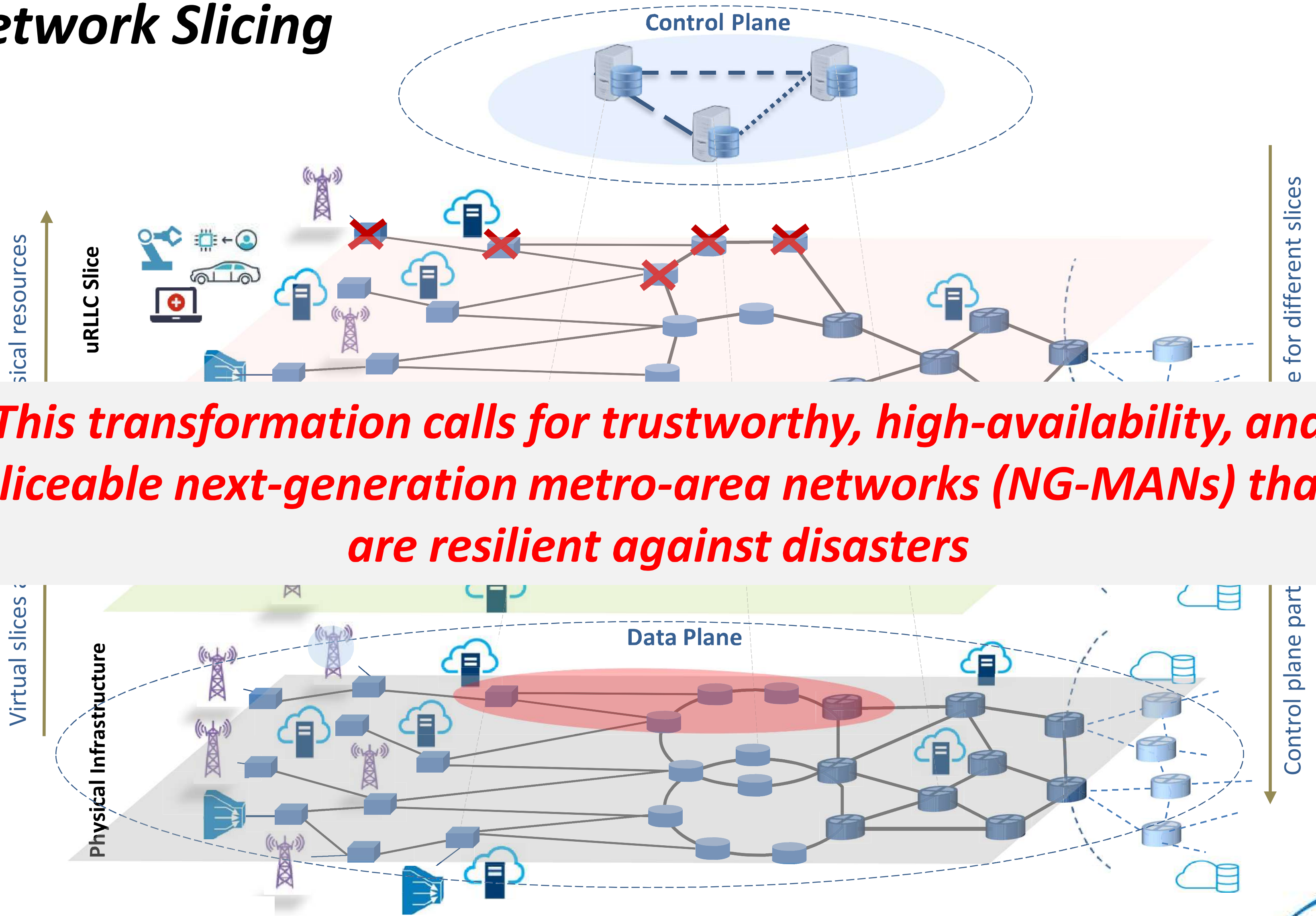
Evolution of Metro Access Networks (I)

Edge computing and SDN



Evolution of Metro Access Networks (II)

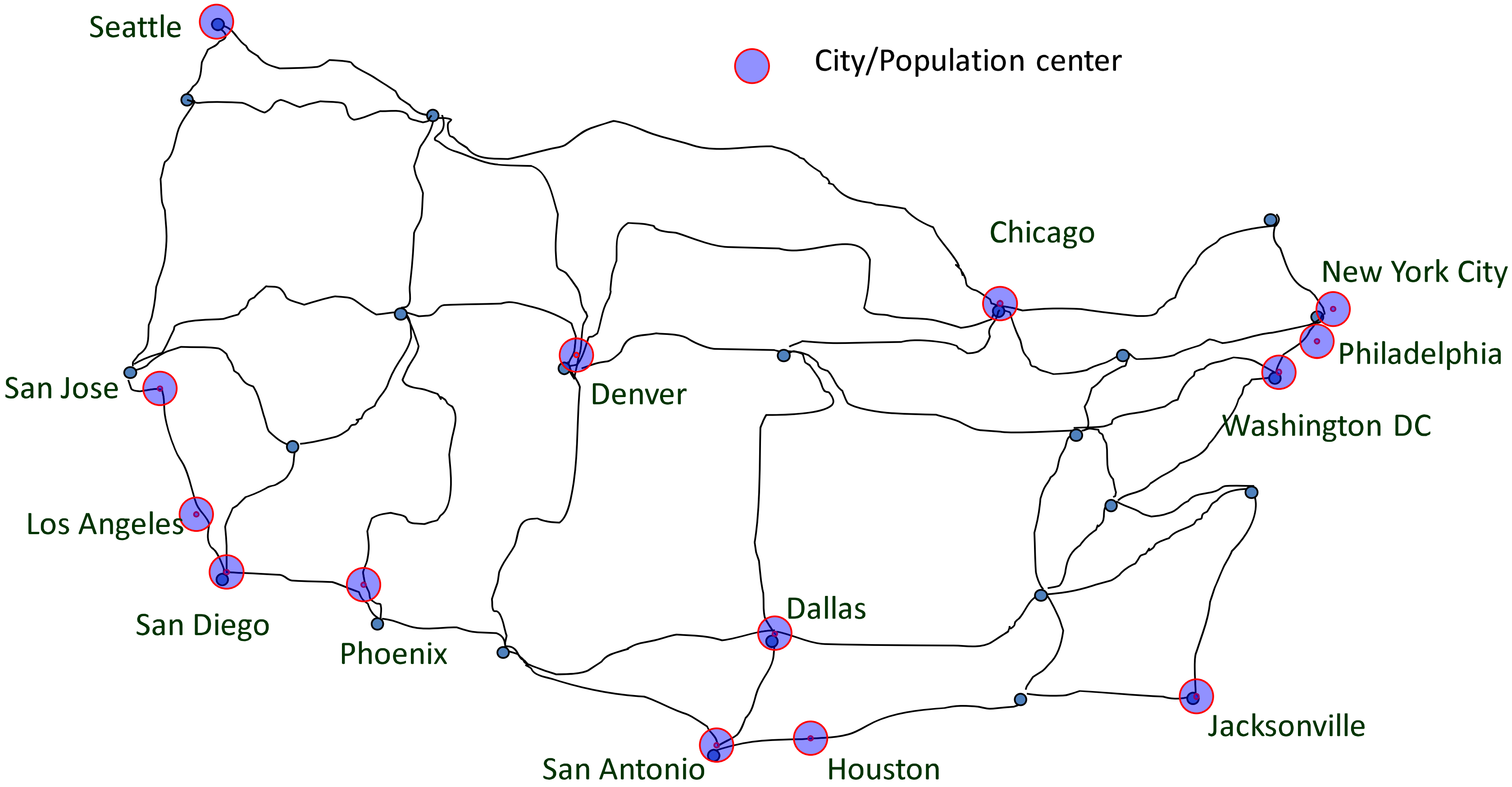
Network Slicing



This transformation calls for trustworthy, high-availability, and sliceable next-generation metro-area networks (NG-MANs) that are resilient against disasters

Disaster affecting underlying NG-MAN

Traditional Core Optical Network

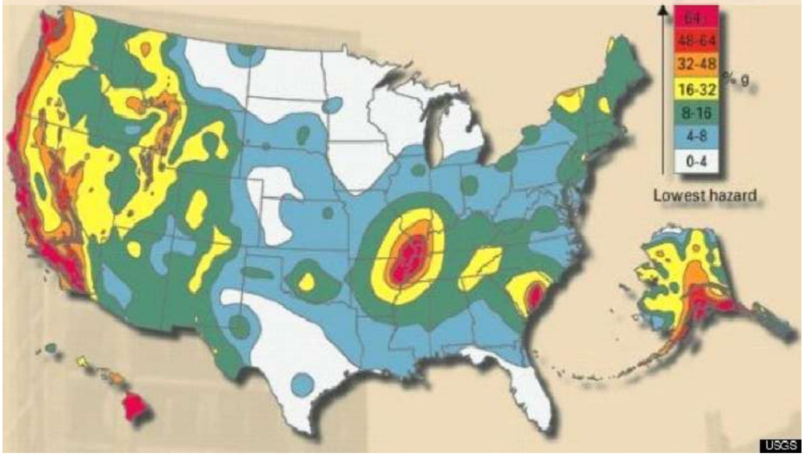


UCDAVIS

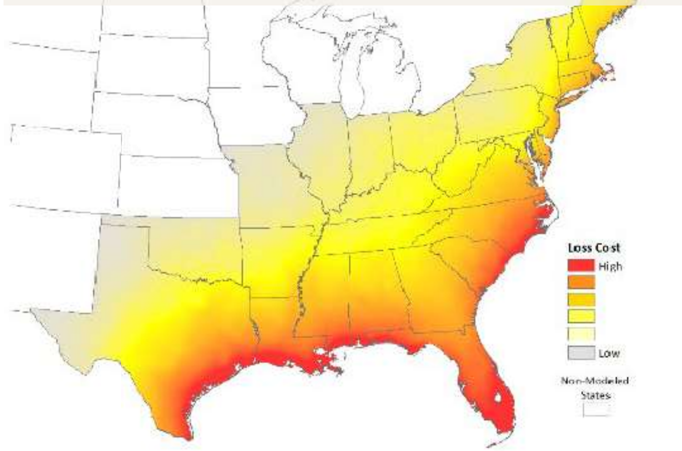
NICT

Disaster Maps

Seismic hazard map

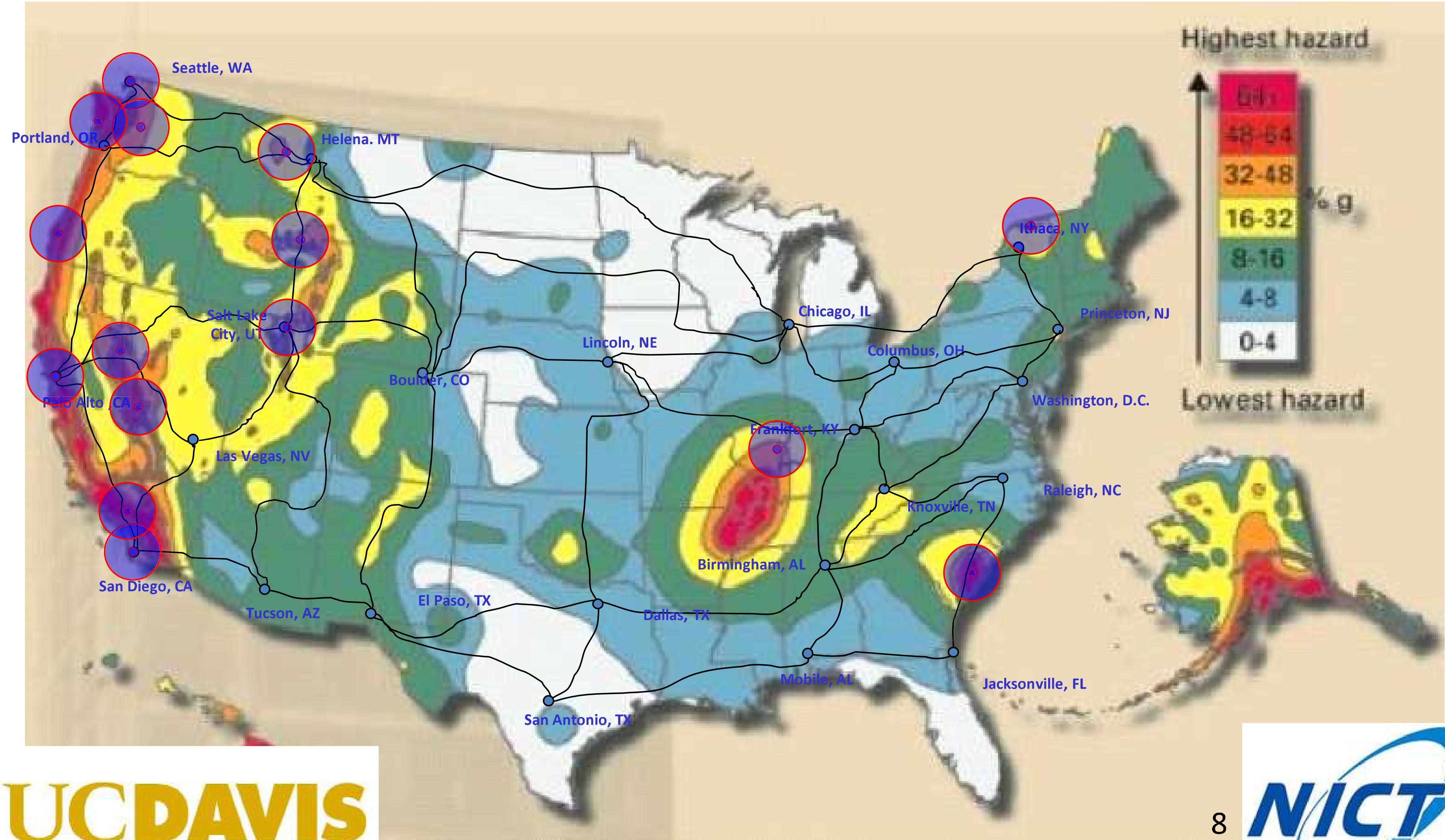


Hurricane risk map



Risk maps **of such disasters can be obtained and matched with the** ***physical topology of a network*** **to help design a disaster-resilient network.**

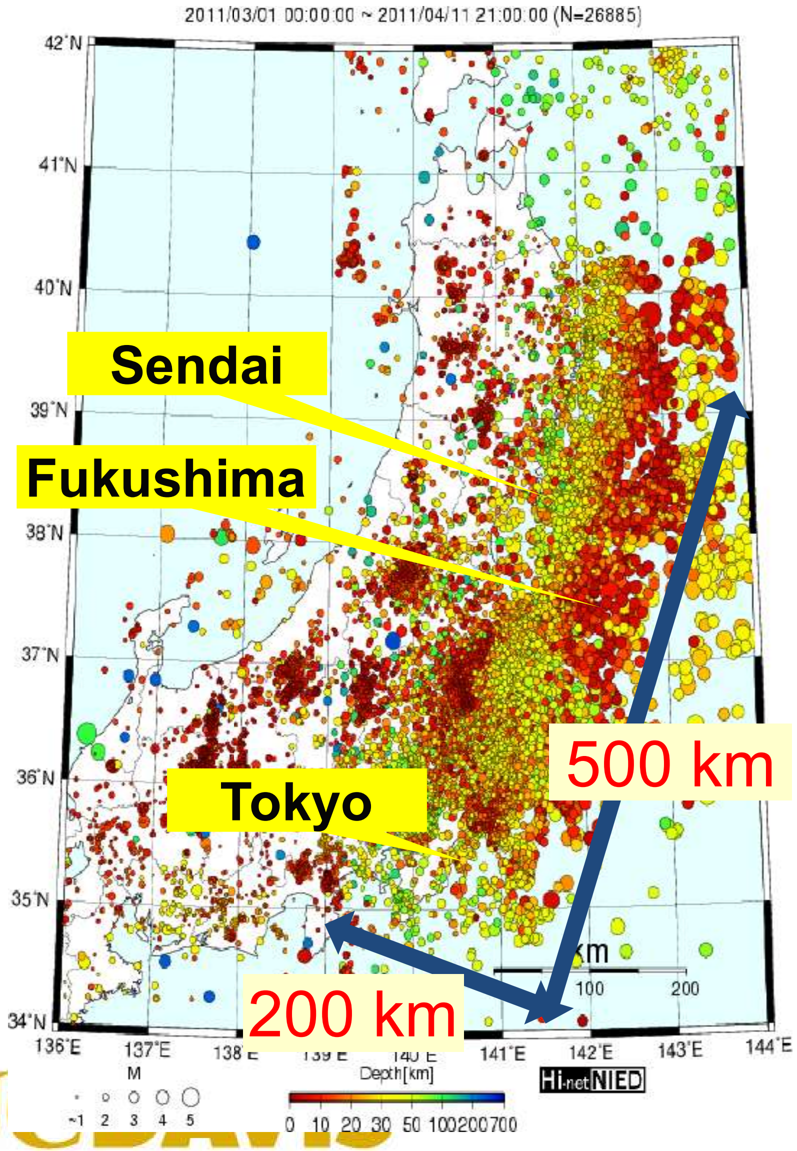
Determination of Disaster Zones



UCDAVIS

NICT

Recent crisis – Disasters in Japan



Types of Failure/breakdown

- General (common) types of failure/breakdown
  - Interface failures
  - Link failures
  - Node failures
  - Misconfigurations

- Failures/breakdown depends on optical communication networks
  - QoT degradation, throughput degradation, increasing electrical buffering delay

- Failures/breakdown in disaster
  - Power blackout
  - Fiber-cut
  - Contact damage by quake

⇒ Redundancy of equipment needs expensive cost.
In a disaster case, redundancy against normal equipment failures is insufficient.

Impact of Disaster-Resilient NG-MAN

- Repair communication network ASAP
  - Prompt and accurate grasp of information of damaged area
  - Immediately create reconstruction plan and execute it.

People

Life saving: It can reduce victims
Safety confirmation: Psychological care of people inside and outside the disaster area

Society

Protection of property (especially information database)
Maintain critical network services
Reconstruction of economic society

Other ripple effects

Maintaining national strength
Prevent the decline of brand power of country/region (damage on rumor)

- Rapid recovery such as communication environment of disaster area
- Continuation of social life in areas other than afflicted areas

Motivation

How we protect metro optical network from disaster?
What should we prepare for disaster resiliency?

Difficult to obtain latest information on affected areas.
Difficult to appropriately distribute/assign resources
Increase psychological burden of disaster victims
Anxiety redundancy of unaffected people

Power loss
features' failure
Fiber cut
etc.

+

Road closed
Lack of repair workers
High cost

Current Technologies

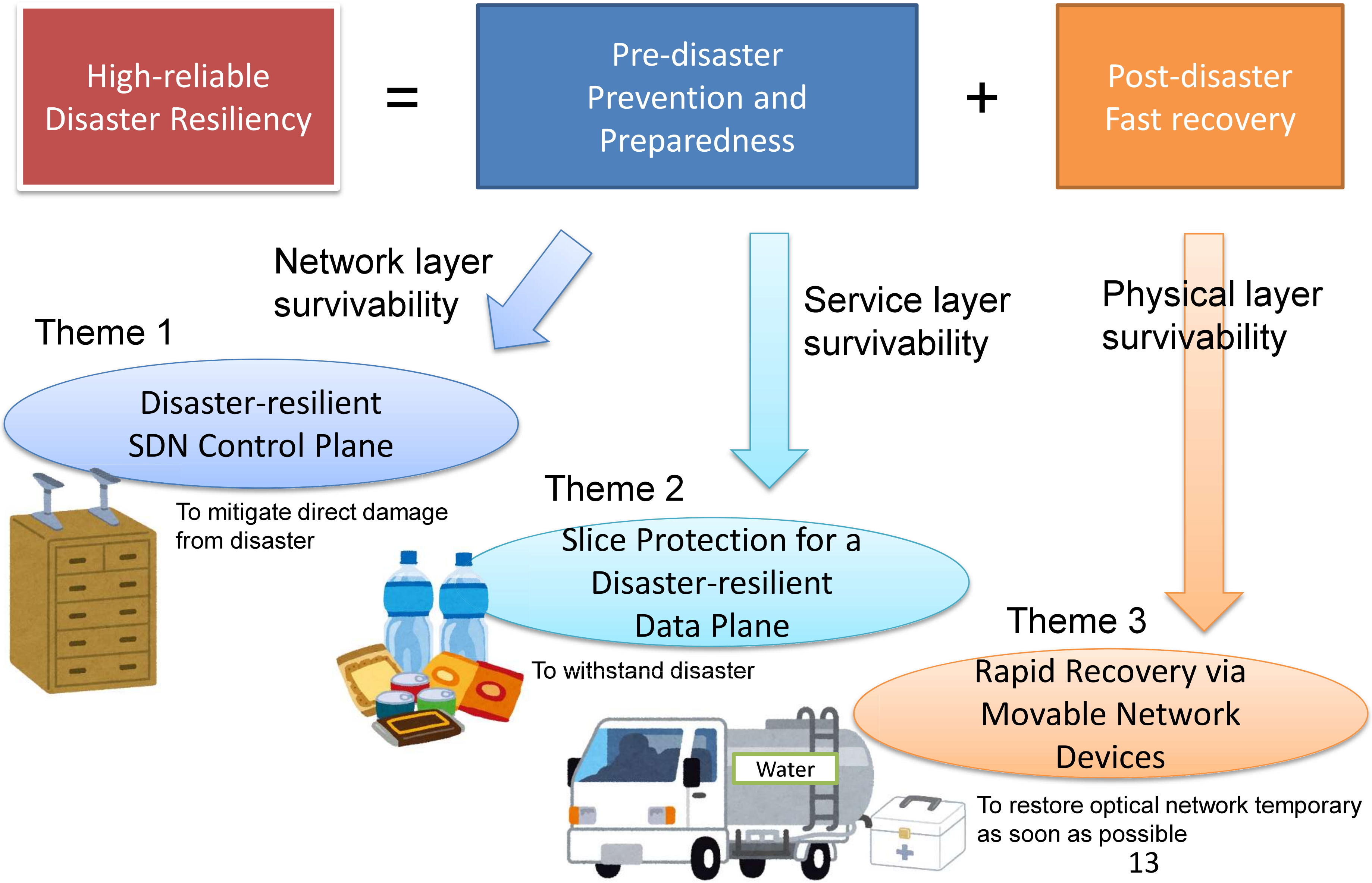
- Satellite communication
- Mobile telecommunication station

After disaster, communication is disconnected.
It takes longer time to repair optical fiber communications.

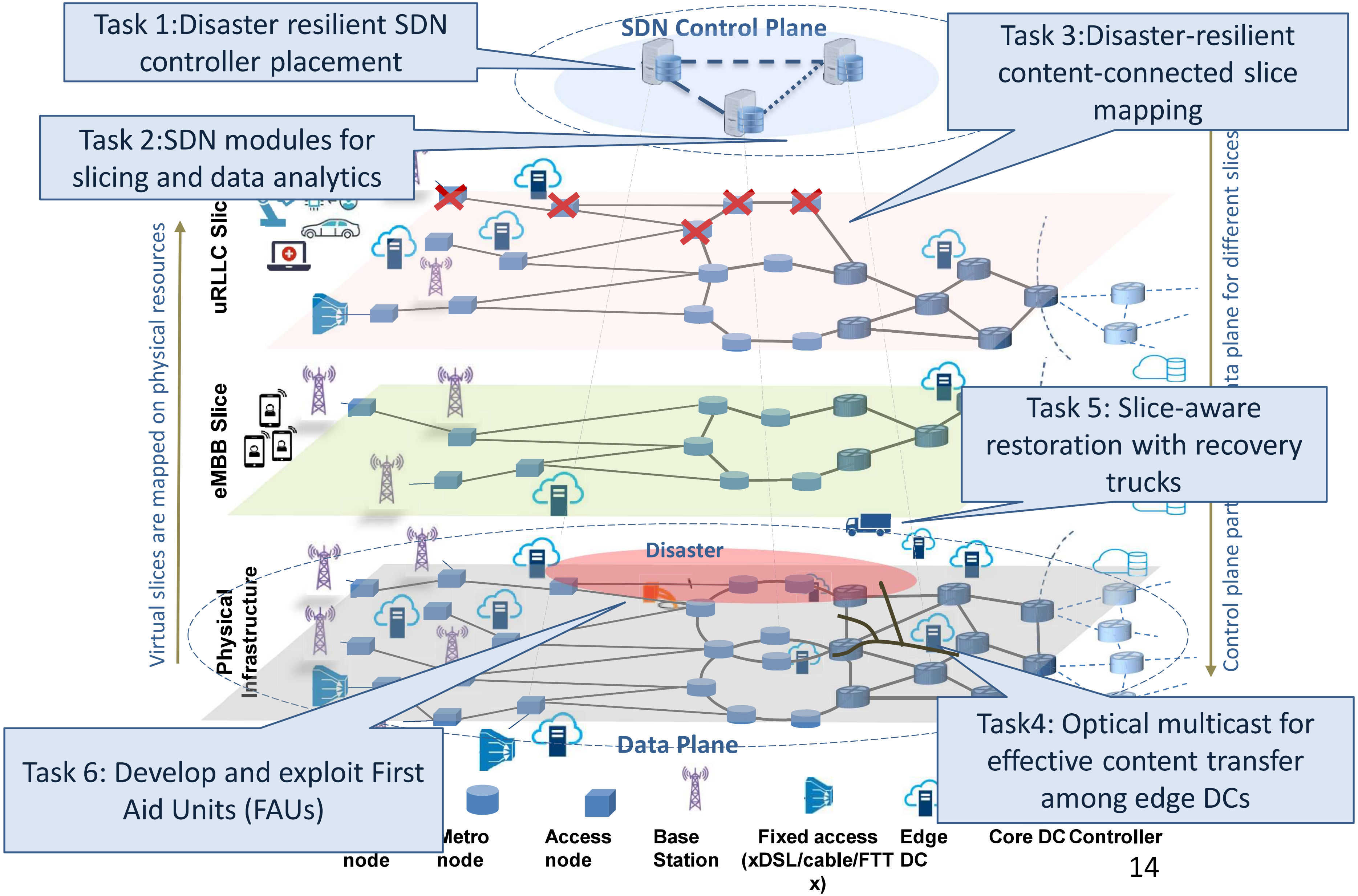
Motivation: To realize a metro optical network that can quickly restore disaster-areas and maintain normal network services outside the affected areas.

Construction of robust control network, rapid failure detection, emergency restoration of optical networks, development of portable optical devices for disaster restoration

Towards Future Disaster-Resilient NG-MAN



Project Overview (1)



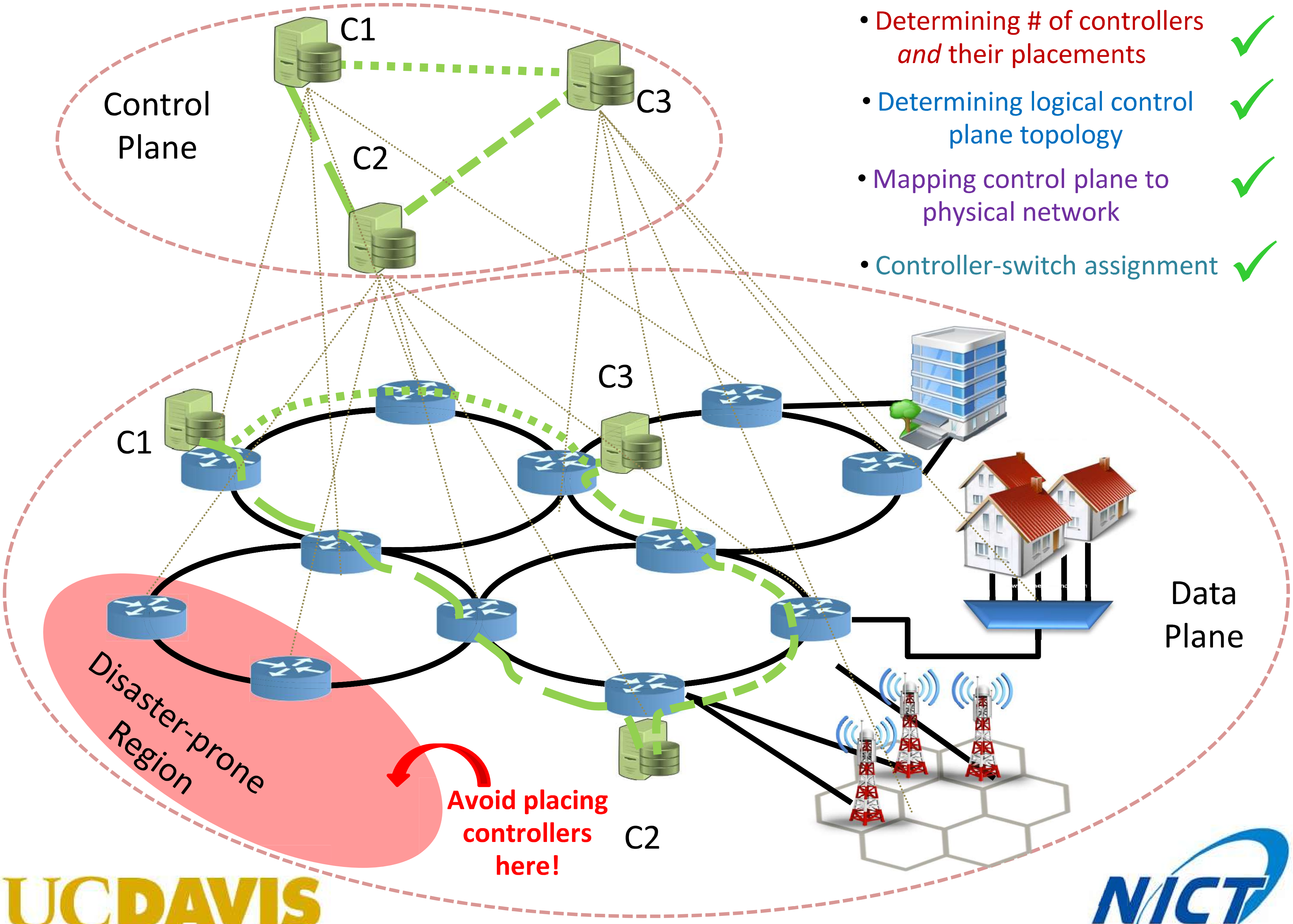
Overall Topics

	Disaster-resilient NG-MANs		
Phase	Pre-disaster phase		Post-disaster phase
Theme	Theme 1: Prevention Disaster-resilient design of the SDN control plane	Theme 2: Preparedness Protection strategies for sliceable NG-MANs	Theme 3: Fast recovery Recovery strategies with portable devices in NG-MANs
Target	AI-assisted Control plane survivability	Content-centric D-plane survivability	Emergency restoration for physical layer survivability
UC Davis	Task 1 Disaster-resilient SDN controller placement	Task 3 Disaster-resilient content-connected slice mapping	Task 5 Slice-aware restoration with recovery trucks for NG-MAN
NICT	Task 2 SDN modules for network slicing and data analytics	Task 4 Optical multicast for effective content transfer among edge DCs	Task 6 Develop and exploit First Aid Unit (FAU)
Key technologies	SDN/NFV, Machine learning	Flexible grid & multicast transmission	Novel portable/movable disaster recovery systems

Task 1: Disaster-Resilient SDN Controller Placement in NG-MANs

- Making the control plane resilient means introducing redundancy through distributed controllers
  - *How many controllers?*
  - *Where to place them?*
  - *Consider delay, survivability, capacity requirements, synchronization overhead, etc.*

- Determining # of controllers *and* their placements
- Determining logical control plane topology
- Mapping control plane to physical network
- Controller-switch assignment



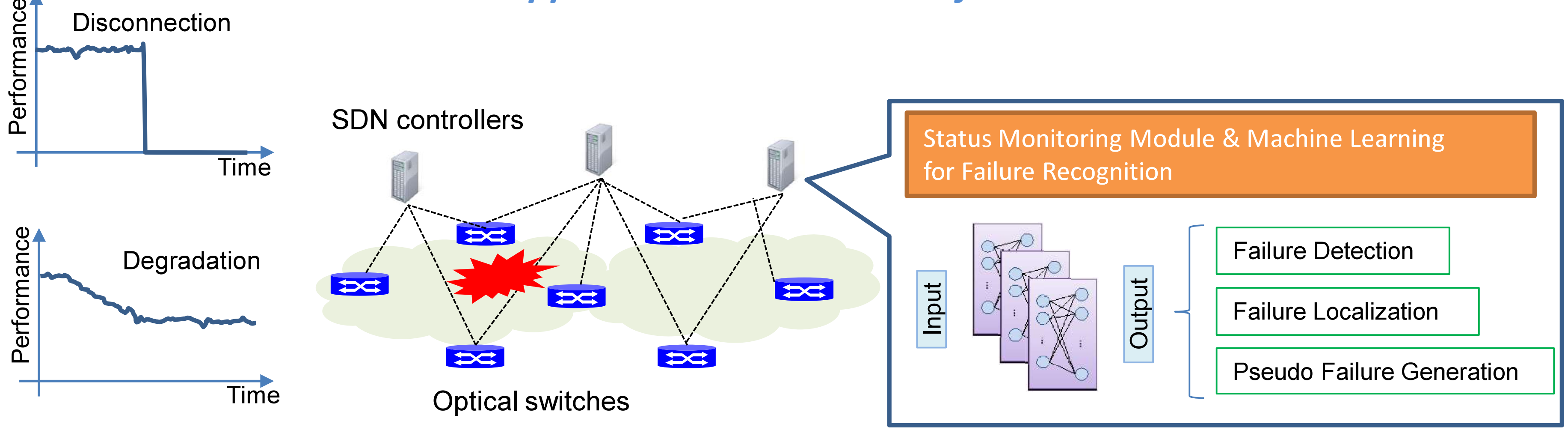
UCDAVIS

NICT

Task 2: SDN Modules for Network Slicing and Data Analytics

Theme: Disaster-resilient design of SDN control plane

SDN to support advanced network functionalities



- ***SDN Control Plane and Slicing***: Assignment of SDN controllers to slices with different requirements - how one or multiple controllers can manage different slices (e.g., one controller per slice or multiple slices per controller).
- ***SDN-Based monitoring for Detecting Failures***: Failure detection mechanisms that make use of the global network view provided by SDN to promptly correlate disaster failures.
    - Detection mechanism for disconnected links and failed nodes
    - Machine Learning based failure recognition mechanisms for incomplete network connectivity

Task 2: SDN Modules for Network Slicing and Data Analytics

- Topic 2-1: （Support advanced network functionalities）
  - How to collect D-plane information and manage slices.
    - Prepare evaluation model

- Topic 2-2: （Suppress performance degradation)
  - How to detect/localize various failures in NG-MANs?
  - How to collect Training Data?
    - LLDP or ML based Failure Recognition approaches
    - Pseudo failure generation

- Goal:
  - With the distributed SDN controllers, perform the resilient slice management, and, failure detection and analytics ➡ Support advanced network functionalities, quick response to failures suppressing performance degradation

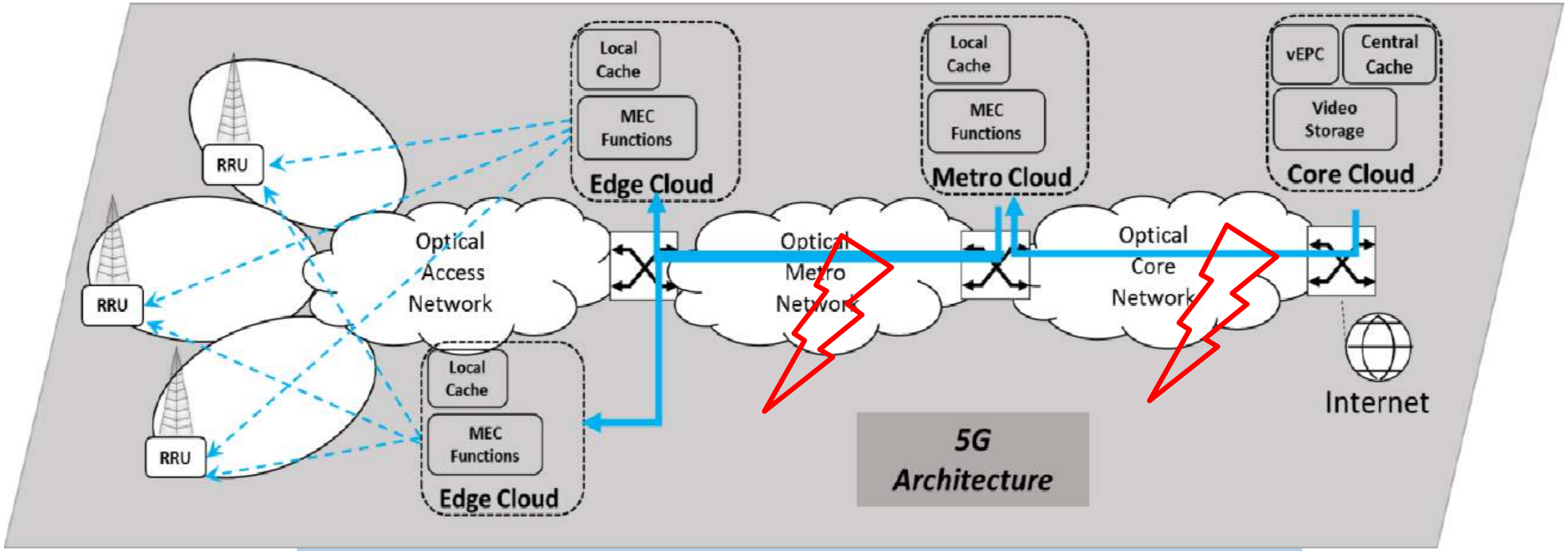
UCDAVIS

NICT

Intro to Theme 2
From Cloud to Edge Computing

- How to guarantee 99,999(9)% service availability [1] in 5G
  - Enabler: Fog/Edge Computing, Mobile Edge Computing (MEC)

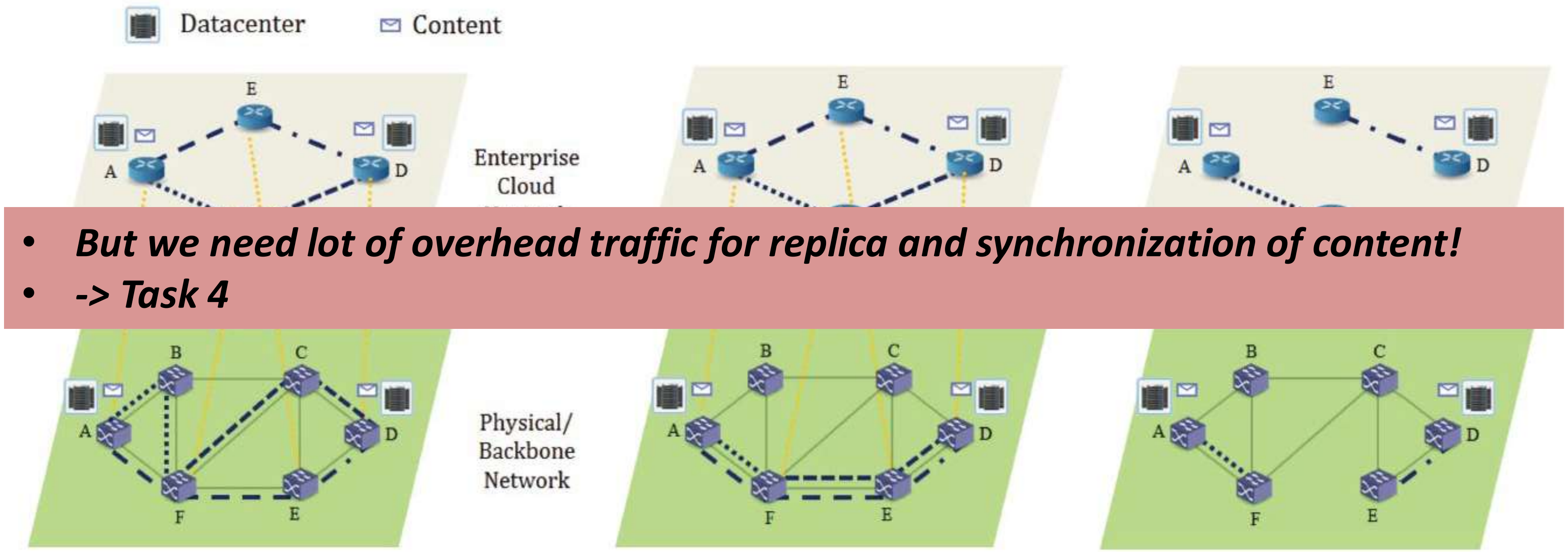
Several cloud services can be replicated and accessed even in case of network disconnection!



[1] NGMN Alliance "5G white paper." *Next generation mobile networks, white paper* (2015).

Task 3: "Content Connectivity" for Disaster Resiliency in NG-MANs

Content Connectivity - **ensure reachability of content from any point of a network (end-to-content) even in case of a disaster partitioning the network**



- ***But we need lot of overhead traffic for replica and synchronization of content!***
- ***-> Task 4***

Task 4: Optical Multicast for Effective Content Transfer among Edge DCs

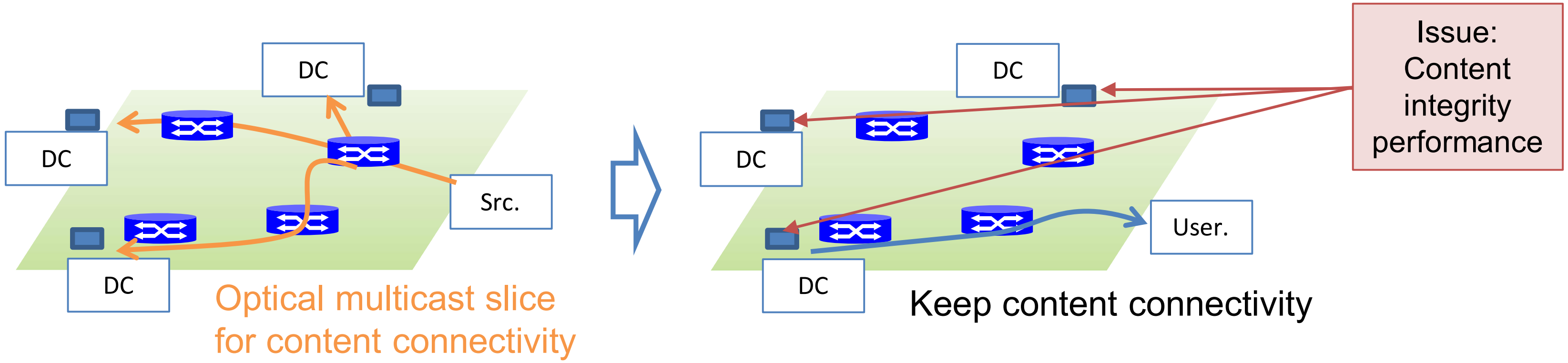
"Content connectivity" can be realized only if relevant data is replicated in several edge DCs

- *Constant and intensive synchronization and backup procedures among edge DCs via optical multicasting (Verification on OPCI network testbed)*

- ***Selection of multicast tree leaves for disaster resiliency*** - How do we determine which nodes receive the synchronization data of the multicast tree?
- ***Slicing and multicasting*** - How to slice network resources for multicast transmissions?
- ***Verification of optical multicasting with SDN control in Sendai testbed*** - SDN controllers need to monitor transmitted data and to construct multicasting slices considering the locations of edge DCs.

OPCI network testbed @Sendai NICT branch

Task 4: Optical Multicast for Effective Content Transfer among Edge DCs

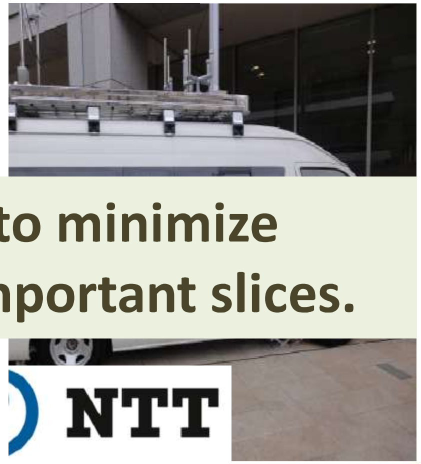


- Topic 4-1: （Efficient data replication via optical multicasting ）
  - Multicast slicing and load balancing
- Topic 4-2: （Verification over OPCI network testbed)
  - Experiment of optical multicasting @ Sendai testbed
    - Verify the content connectivity maintenance in case of network failures
  - Verify distributed content integrity with optical multicast.

Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs (I)

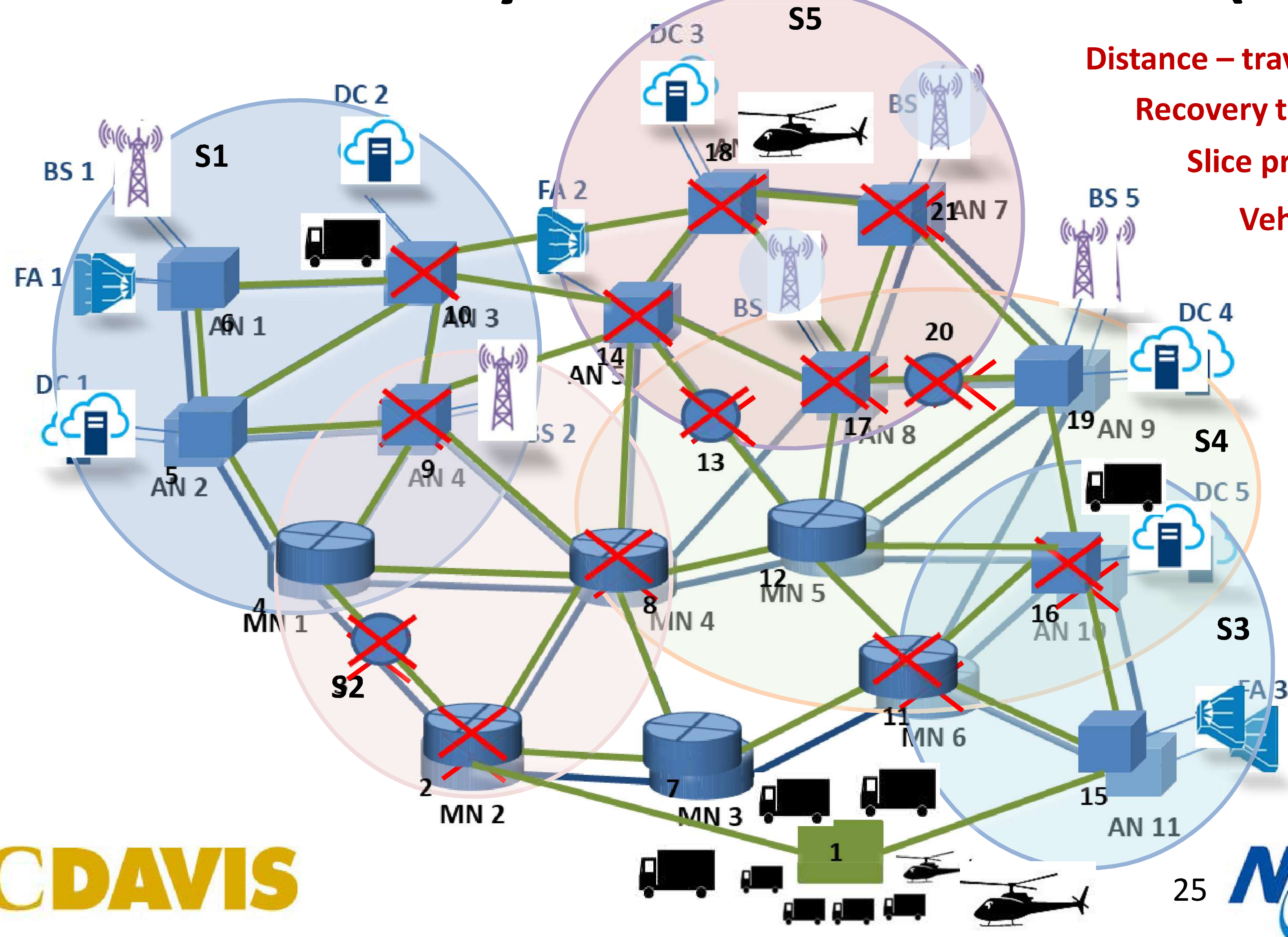
Rapid net… …nits

- In the post… …ide both repair and t… …going on



"Slice-aware" routing and deployment strategy to minimize downtime penalty and ensure fast restoration of important slices.

Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs (II)



Distance – travel time

Recovery time

Slice priority

Vehicle type

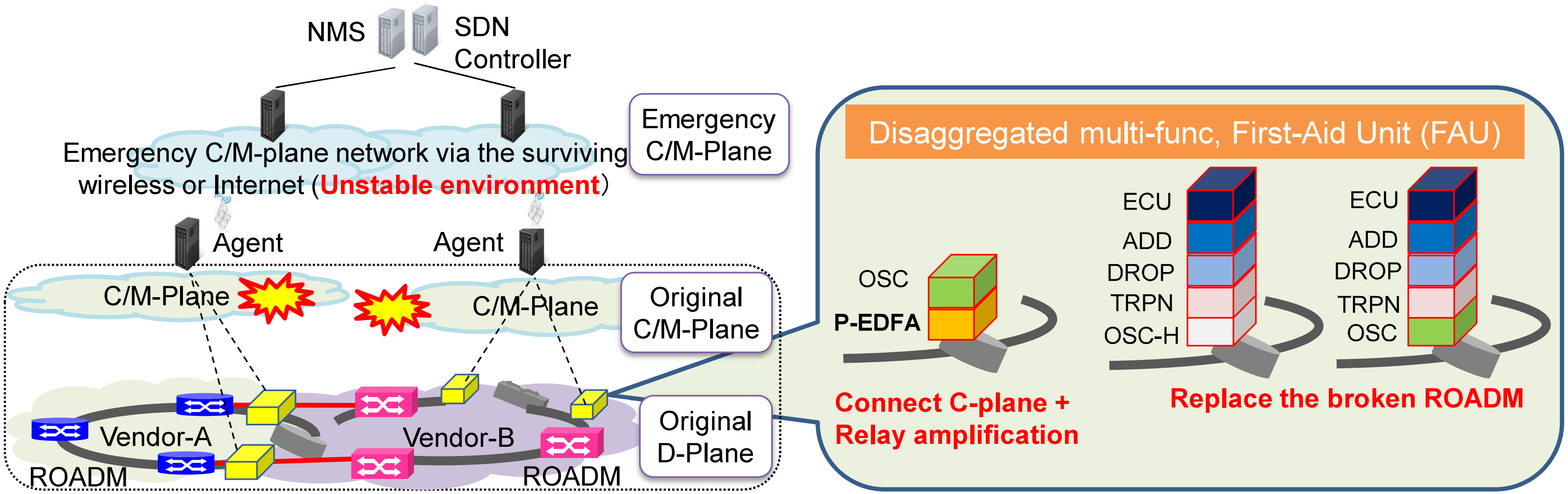
Task 6: Develop and exploit First Aid Unit (FAU)

Interconnection of surviving facilities and FAU to restore network connectivity

- *Impairment information collection utilizing monitoring systems*
- *Impairment-aware emergency optical network planning*
- *Development of supportive hardware and control system*

Task 6: Develop and exploit First Aid Unit (FAU)

Interconnection of surviving facilities and FAU to restore network connectivity



Surviving optical network resources, e.g., ROADM, fibers

+

Emergency resources, e.g., FAUs

- *Impairment information collection utilizing monitoring systems*
- *Impairment-aware emergency optical network planning*
- *Development of supportive hardware and control system*

UCDAVIS

NICT

Task 6: Develop and exploit First Aid Unit (FAU)

- Topic 6-1: *Impairment information collection*
  - Employ emergency optical performance monitoring (OPM) subsystem in FAU
  - Create emergency telemetry platform using outside surviving network resources (e.g., wireless/Internet)

- Topic 6-2: *Impairment-aware emergency optical network planning*
  - Optimization of portable EDFA placement
  - Optimization of the surviving multi-vendor network interconnection

- Topic 6-3: *FAU upgrade*
  - Portable EDFA (C- and L-band)
  - External optical supervisory channel (OSC) unit
  - Disaggregated functions from ROADM
  - Other communication link (LTE/satellite etc.)

UCDAVIS

NICT

Integration (I)

- Complementary expertise
  - Dr. Awaji and Dr. Xu, and Dr. Shiraiwa have long-term R&D experience on optical resilient communication systems
  - Dr. Hirota brings expertise in future network and optical network architecture
  - Dr. Tornatore has extensive research experience in network flow optimization and traffic engineering
  - Dr. Mukherjee brings expertise on optical network design and survivability
- Research exchanges
- Sendai testbed
  - Data generation (for AI) and solution verification (for UCDavis design approaches)

Integration (II)

- **Integrated US and Japan Team responsibilities (per task)**
  - Dr. Tornatore and Mukherjee: Tasks 1, 3 and 5
  - Dr. Awaji: Tasks 2, 4 and 6

  - Practical examples of research integration (a summary):
    - Task 1-2: UC Davis will investigate how to design a disaster-resilient SDN control plane, and NICT will cover the following operational aspects (e.g., forecast traffic intensity and requirements)
    - Task 3-4: UC Davis will provide estimation of synchronization and backup traffic for content connectivity. Based on such inputs, NICT will investigate optical multicast trees inter-DC data synchronization leveraging SDN testbed in Sendai
    - Task 5-6: Common topic is "Post-disaster recovery mechanisms involving movable recovery units". UCDavis on scheduling aspects, NICT on FAU development of the units

Thank you for your attention!

Gantt chart

Duration	**Year 1**			**Year 2**			**Year 3**		
Task # **Months**	4	8	12	16	20	24	28	32	36
1: Disaster-resilient SDN controller placement									
2: SDN modules for network slicing and data analytics									
3: Algorithms for dis.-resilient content-connected slice mapping									
4: Optical Multicast for effective content transfer among edge DCs									
5: Slice-aware restoration with recovery trucks									
6: Deployment planning and development of portable burst-mode optical amplifiers									
Progress Reports (J is to JST and X is to NSF)	**J**		**X**	**J**		**X**	**J**		**XJ**

2019 Japan-US Network Opportunity 2 (JUNO2)

Project Title: *Disaster-Resiliency Strategies for Next-Generation Metro Optical Networks*

ATN: 1818972

Speakers:
Dr. Yoshinari Awaji (NICT)
Dr. Massimo Tornatore (UCDavis)

October 11, 2019
Principal Investigator Meeting @ Chicago (IL)

UCDAVIS

NICT

Project Team

- **PIs**
  - Massimo Tornatore; University of California, Davis; PI
  - Biswanath Mukherjee; University of California, Davis; Co-PI
  - Yoshinari Awaji; NICT (Japan); Team leader (PI Japan side)

- **@NICT**
  - Sugang Xu; NICT (Japan); Collaborator
  - Yusuke Hirota; NICT (Japan); Collaborator
  - Masaki Shiraiwa; NICT (Japan); Collaborator

- **@UCD**
  - Dr. Sifat Ferdousi; University of California, Davis; PDF
  - Andrea Marotta; University of L'Aquila, Italy; Visiting Student
  - Giap Le; University of California, Davis; GSR

- **International Collaborators**
  - Prof. Francesco Musumeci; Politecnico di Milano, Italy
  - Prof. Gustavo Bittencourt; University of Bahia, Brasil

UCDAVIS

NICT

Two in-person meetings

- Davis, Feb 27th to Mar. 1st
  - Pre-OFC visit by Dr. Awaji and Dr. Hirota
- Sendai, July 4th and 5th
  - Pre-OECC visit by Dr. Tornatore
- Several other interactions via email and telco

Massimo Tornatore
@MaxTornatore

Two intense days discussing disaster resiliency for next generation optical metro networks in our JUNO2 #NSF project . Thanks to Dr. Yoshinari Awaji and Dr. Yusuke Hirota from #NICT for visiting us in #UCDavis. @dmedhi

Massimo Tornatore
@MaxTornatore

Visiting #NICT in Sendai, Japan, to discuss disaster resiliency in next generation optical networks for our #JUNO2 #NSF project. Inter-carrier recovery, #MachineLearning for failure management, and several other research directions can be explored over NICT's #OPCI testbed

1:14 AM - 5 Jul 2019

Motivation

A new generation of optical metro networks is needed to turn the vision of "Smart Cities" into reality

- From a **rigid ring-based aggregation infrastructure** to a **composite network-and-computing ecosystem** to support critical 5G services (e.g., autonomous driving)

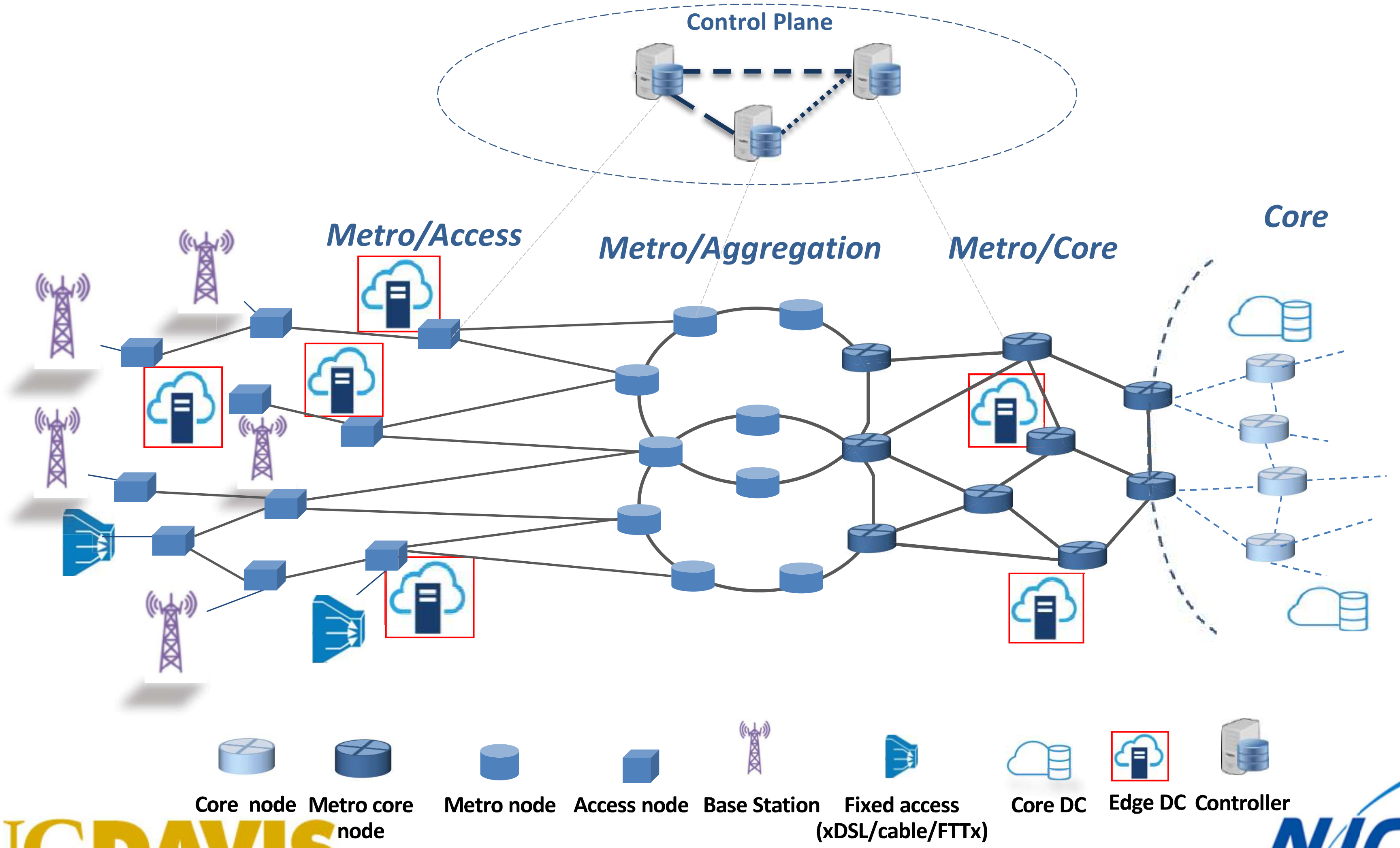
- Several technical enablers:
  - Increased reconfigurability enabled by **SDN**
  - **Integration of optical and wireless** access networks
  - Metro nodes becoming edge data centers (**edge computing**)
  - **Network slicing** to logically partition network, computing, and storage resources
  - …

UCDAVIS

NICT

Evolution of Metro Access Networks (I)

Edge computing and SDN

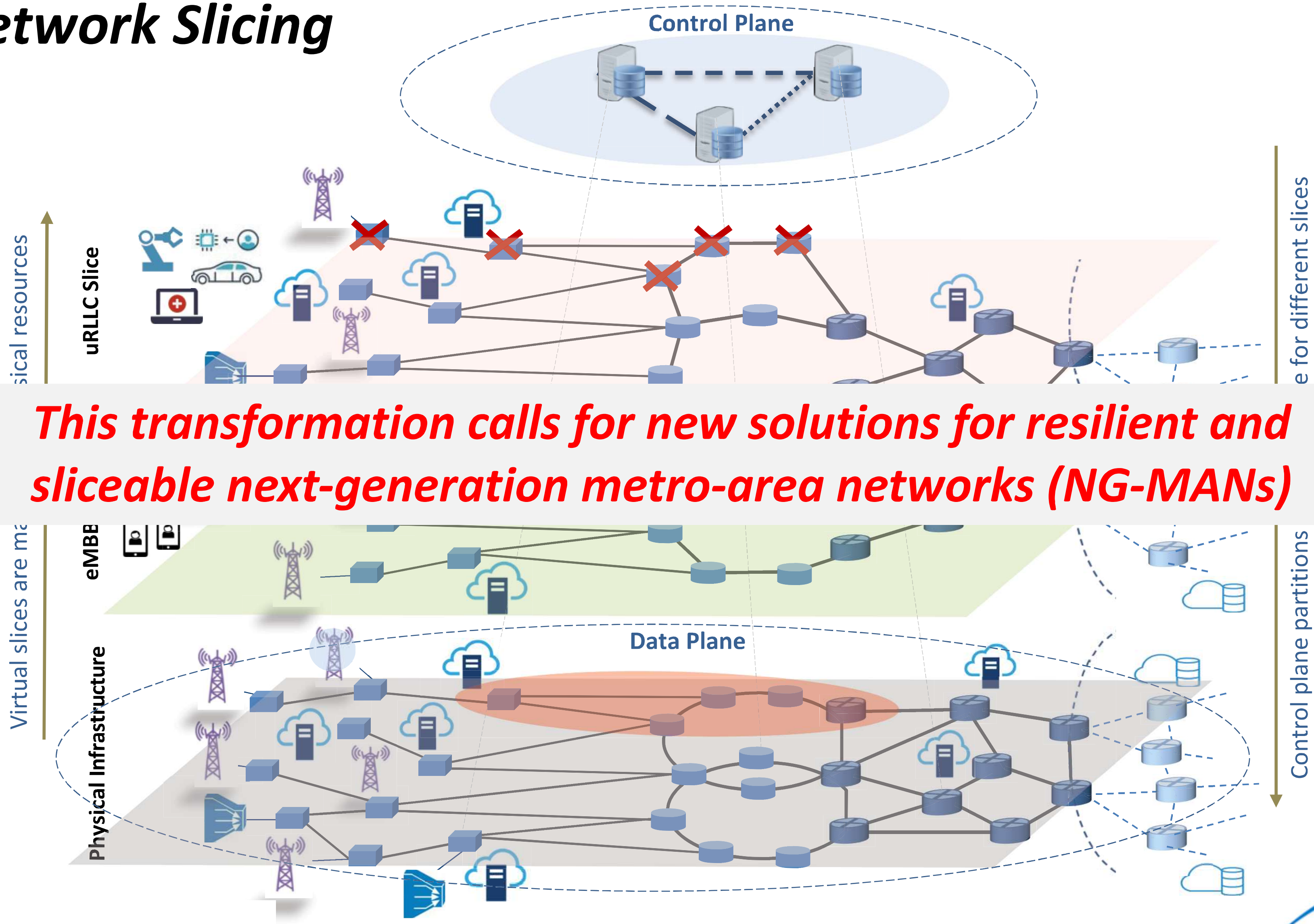


UCDAVIS

NICT

Evolution of Metro Access Networks (II)

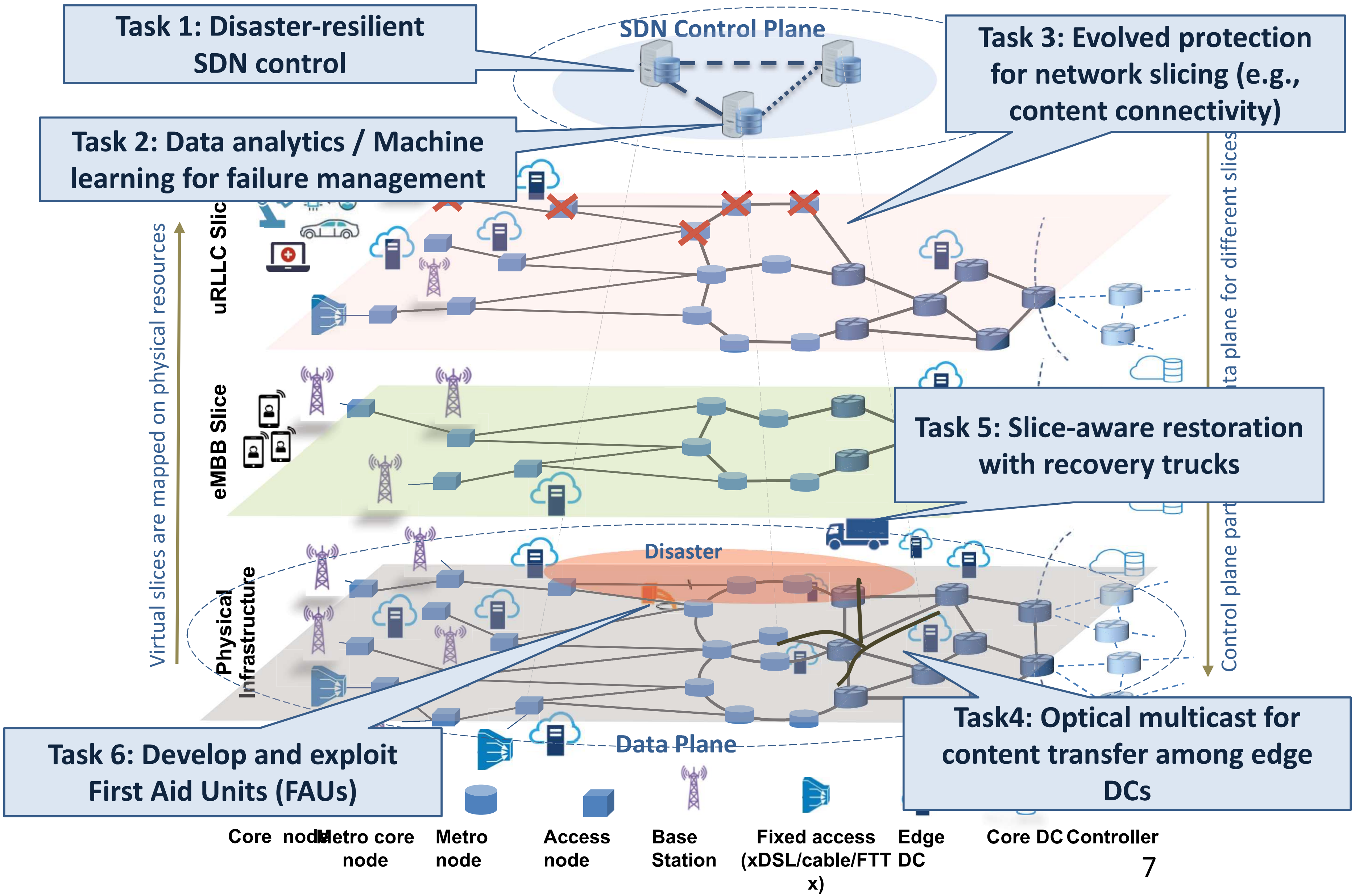
Network Slicing



This transformation calls for new solutions for resilient and sliceable next-generation metro-area networks (NG-MANs)

Disaster affecting underlying NG-MAN

Project Overview



Overall Topics

	Disaster-resilient NG-MANs		
Phase	Pre-disaster phase		Post-disaster phase
Theme	Theme 1: Prevention Disaster-resilient design of the SDN control plane	Theme 2: Preparedness Protection strategies for sliceable NG-MANs	Theme 3: Fast recovery Recovery strategies with portable devices in NG-MANs
UC Davis	Task 1 Disaster-resilient SDN controller placement	Task 3 Disaster-resilient content-connected slice mapping	Task 5 Slice-aware restoration with recovery trucks for NG-MAN
NICT	Task 2 SDN modules for network slicing and data analytics	Task 4 Optical multicast for effective content transfer among edge DCs	Task 6 Develop and exploit First Aid Unit (FAU)
Key technologies	SDN/NFV, Machine learning	Flexible grid & multicast transmission	Novel portable/movable disaster recovery systems

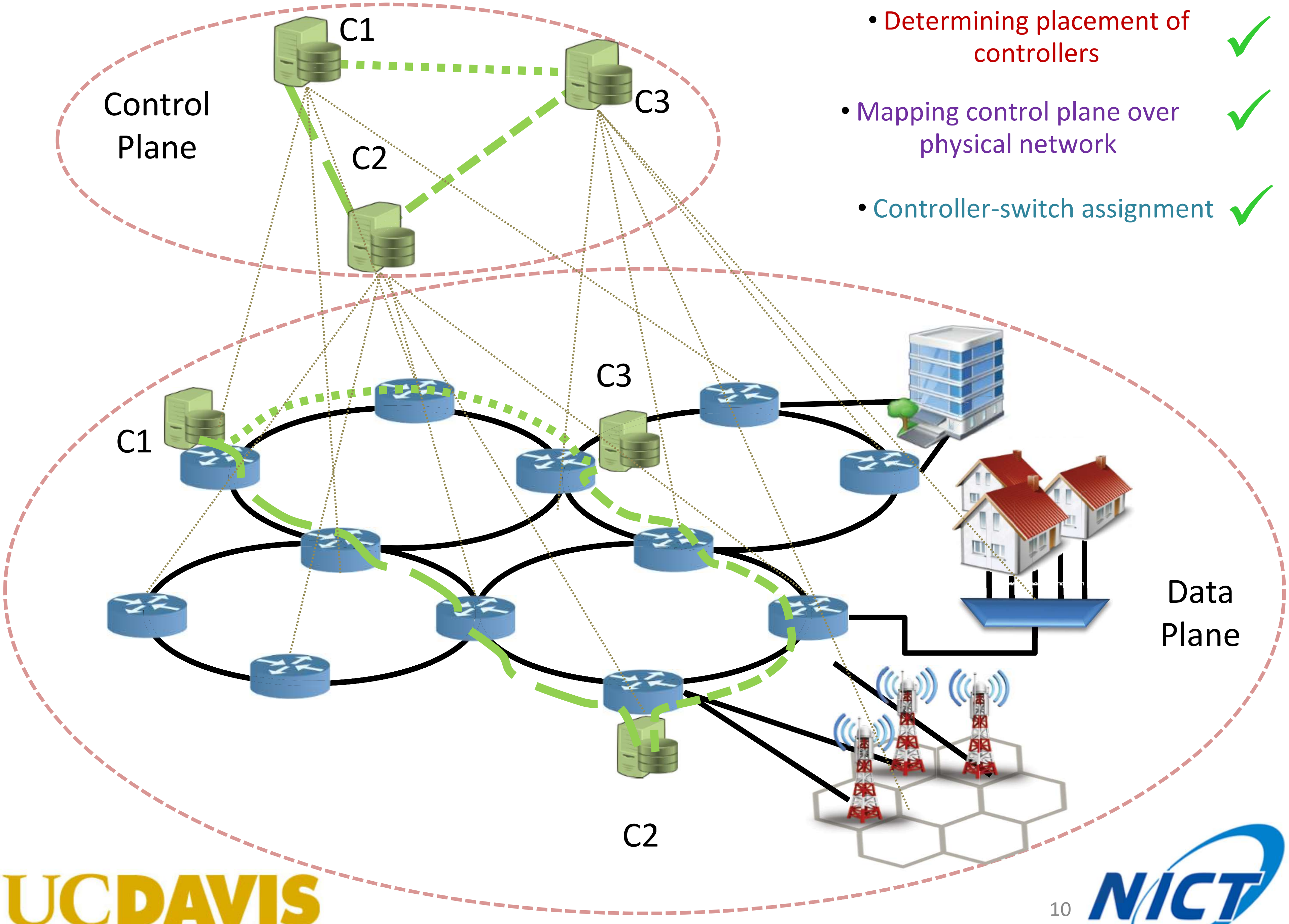
UCDAVIS

NICT

Task 1

Disaster-resilient SDN controller placement

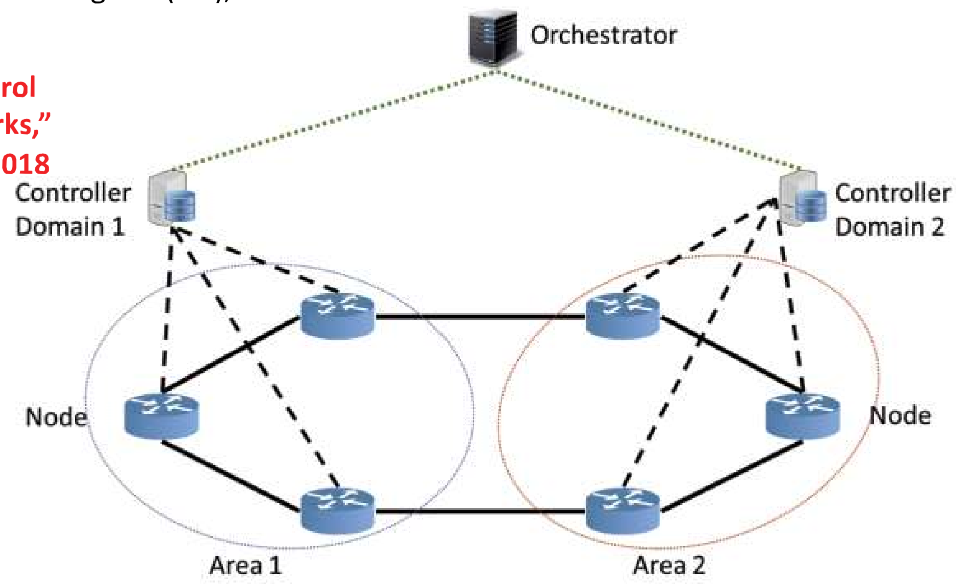
- Mostly concluded activity
  - S. Savas, M. Tornatore, F. Dikbiyik, A. Yayimli, C. Martel, and Biswanath Mukherjee, "RASCAR: Recovery-Aware Switch-Controller Assignment and Routing in SDN," in *IEEE Transactions on Systems and Network Management*, vol. 15, no. 4, pp. 1222-1234, Dec. 2018
  - R. Lourenco, S. Savas, M. Tornatore, B. Mukherjee, "Robust Hierarchical Control Plane for Transport Software-Defined Networks", in *Optical Switching and Networking*, Vol. 30, pp. 10-22, Nov. 2018



- Determining placement of controllers ✓
- Mapping control plane over physical network ✓
- Controller-switch assignment ✓

Our contribution on fault-tolerant controller placement (CP)

- **[Pre-planned controller replicas]** F.J. Ros, P.M. Ruiz, Five nines of southbound reliability in software-defined networks, in: Proc. of the ACM HotSDN, New York, NY, USA, 2014 & (B. Killi, et al., Capacitated next controller placement in software defined networks, IEEE Trans. Netw. Service Manage. 14 (3) (2017) 514–527)
- **[Path diversity]** F. Müller, et al., Survivor: an enhanced controller placement strategy for improving SDN survivability, in: Proc. of the IEEE GLOBECOM, 2014
- **[Disaster awareness]** S. Savas, et al., "Disaster-resilient control plane design and mapping in Software-Defined Networks," *In Proc. of HPSR,* Budapest, Hungary, July 2015
- **[Malicious Attacks]** D. Santos, A. de Sousa, C.M. Machuca, Robust SDN controller placement to malicious node attacks, in: Proc. of IEEE DRCN, 2018.
- **[Several types of failures]** D. Hock, et al., Pareto-optimal resilient controller placement in SDN-based core networks, in: Proc. of the 25th International Teletraffic Congress (ITC), 2013.
- **[T-SDN (Orchestrator+Controllers)]**
  - **R. Lourenço, et. al, "Robust hierarchical control plane for transport software-defined networks," Optical Switching and Networking, vol. 30, 2018**



- Ok controller has been properly placed…

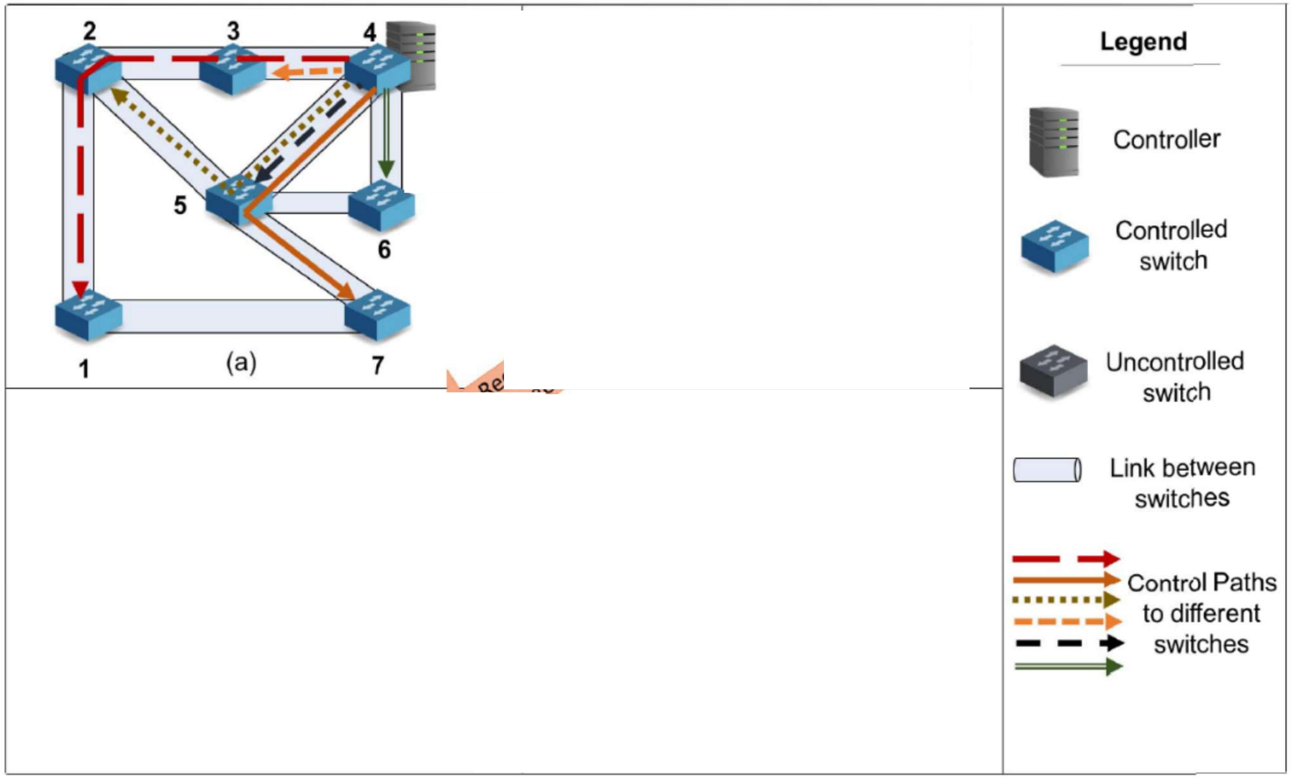
- .. still *how we interconnect controllers to switches* is crucial to minimize recovery time!

S. Savas et. al, "RASCAR Recovery-Aware Switch-Controller Assignment and Routing in SDN", *IEEE Transactions on Network and Service Management*, vol. 15, no. 4, pp. 1222-1234, Dec. 2018

Looking at “controller to switch” paths!

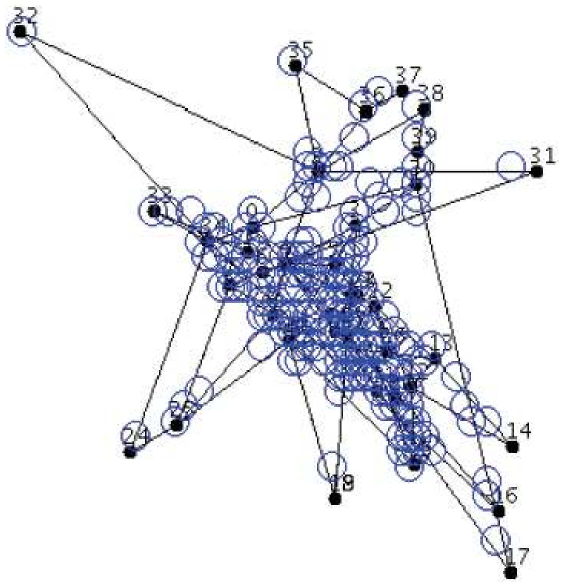
Multi-stage recovery

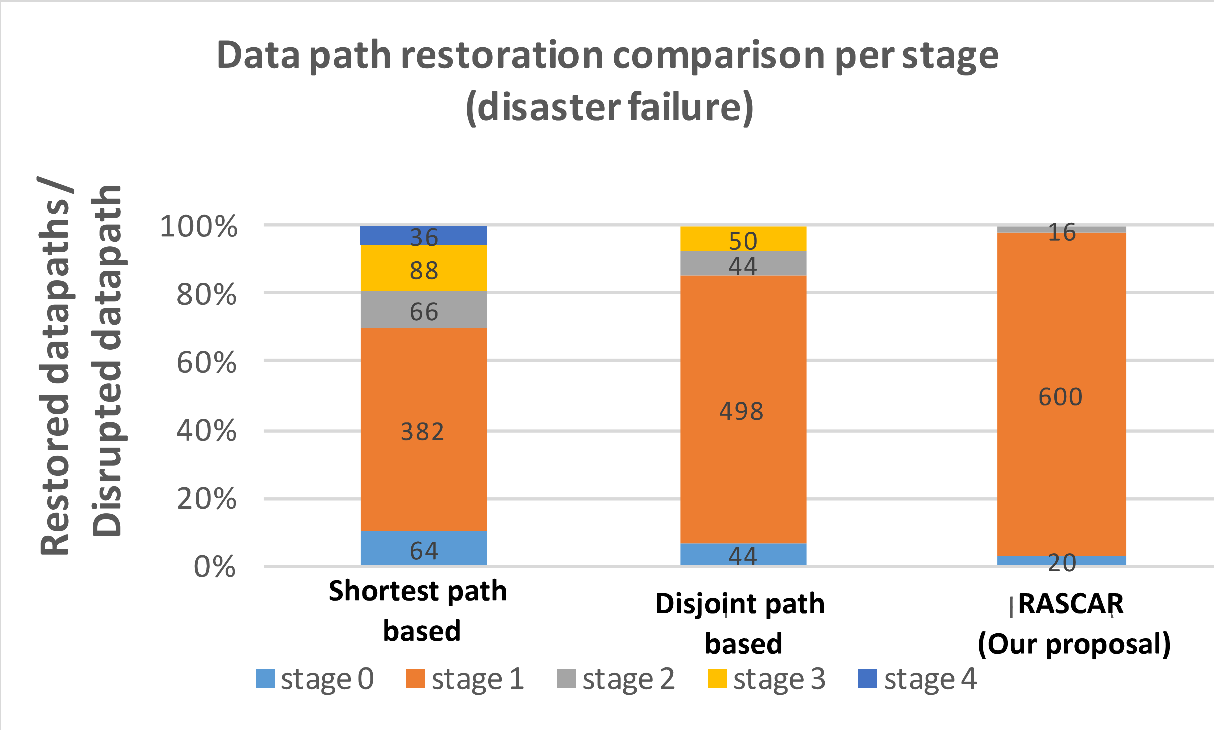
- Even a single failure affects multiple switch-to-controller **control paths**
- When switches lose control paths, they become “**uncontrolled**”:
  - route traffic using old flow entries
  - cannot exchange control messages (e.g., flow setup request, flow installation)
  - cannot be used for data path restoration



Results: recovery speed vs. cost

- **GEANT Network**
- **All possible disasters with radius = 100km**

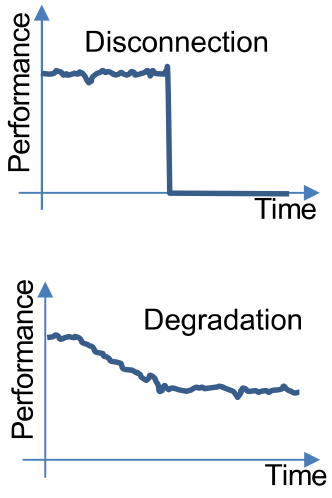




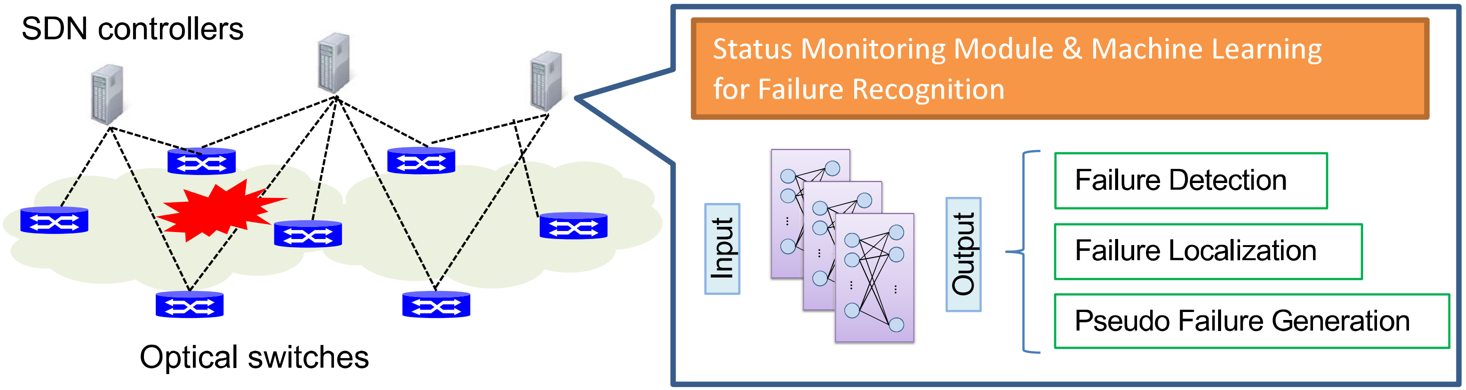
<u>Note: what about additional cost?</u>

Less than 1% additional resource consumption.
Only control paths become longer!

Task 2: SDN Modules for Network Slicing and Data Analytics



SDN to support advanced network functionalities



- ***SDN-Based monitoring for Detecting Failures***: Failure detection mechanisms that make use of the global network view provided by SDN to promptly correlate disaster failures.
    - Detection mechanism for disconnected links and failed nodes
    - Machine Learning based failure recognition mechanisms for incomplete network connectivity

- Purpose:
    - With the distributed SDN controllers, perform the resilient slice management, and, failure detection and analytics ➡ Support advanced network functionalities, quick response to failures suppressing performance degradation

UCDAVIS

NICT

Outline of 1st year's research in Task 2

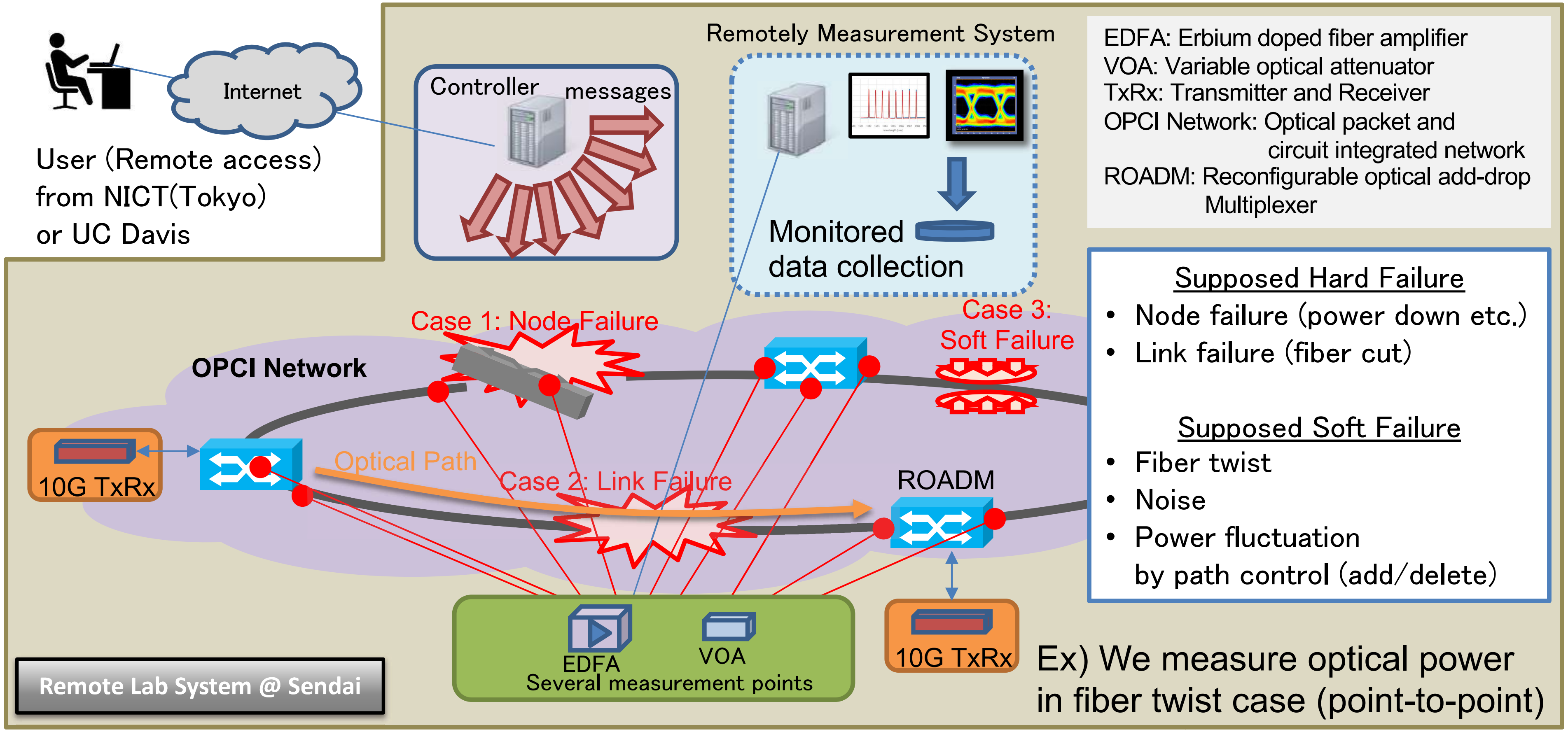
- Issues (3 years)
  - Create dataset for learning including failure cases
  - Develop machine learning algorithms
  - Establish failure recognition scheme in SDN control
  - Cooperative operation between multiple SDN controllers

- 1st years achievements
  - Preliminary experiments to obtain dataset.
    - Only optical power
    - Limited failure events
    - Manually setup for every events
  - In addition, we discussed a closer collaboration research.

UCDAVIS

NICT

Development of Sendai Testbed for Advanced Network Functionality

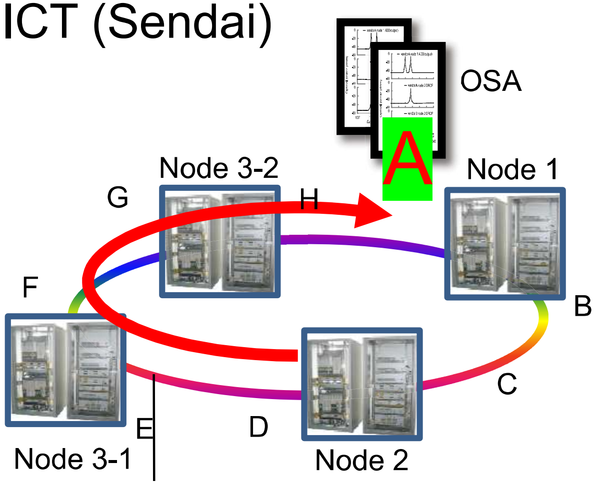


- In Task 2, we obtained several data of optical power (1 sec interval).
  - Not enough data to learning and recognize failures.
- Next step: We develop CLI-based multipoint measurement system for collecting large dataset and utilize the dataset.

Collaborative Research

- Real data acquisition at Sendai testbed.
  - Locally setup experiments at NICT side
  - Data acquisition in local (NICT side)
  - Remote control of several equipment and data acquisition (UC Davis side)
  - Evaluation and discussion

NICT (Sendai)

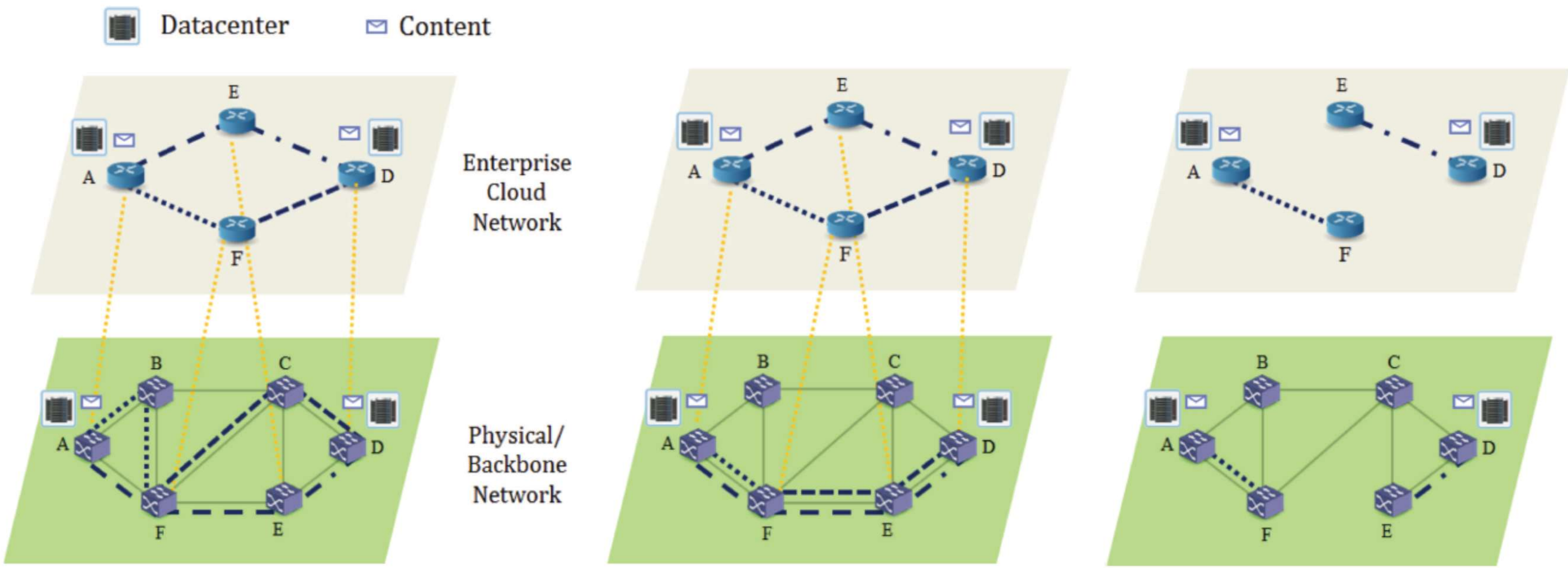


Develop failure recognition algorithm
in both side and discuss in detail
for better algorithm.

Task 3: "Content Connectivity" for Disaster Resiliency

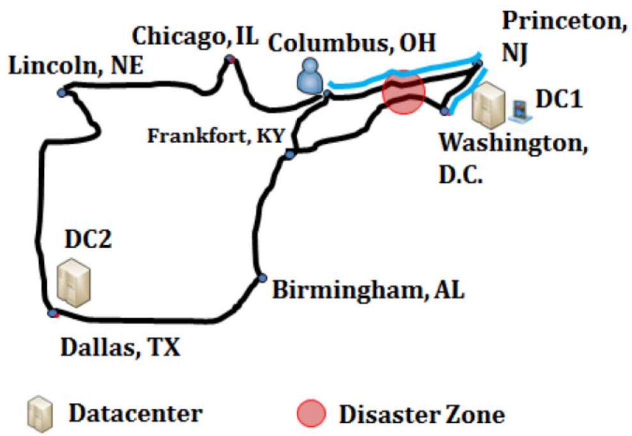
Network Connectivity - ensure reachability of any pair of nodes in the network (end-to-end) in case of failure

Content Connectivity - ensure reachability of content from any point of a network (end-to-content) in case of failure

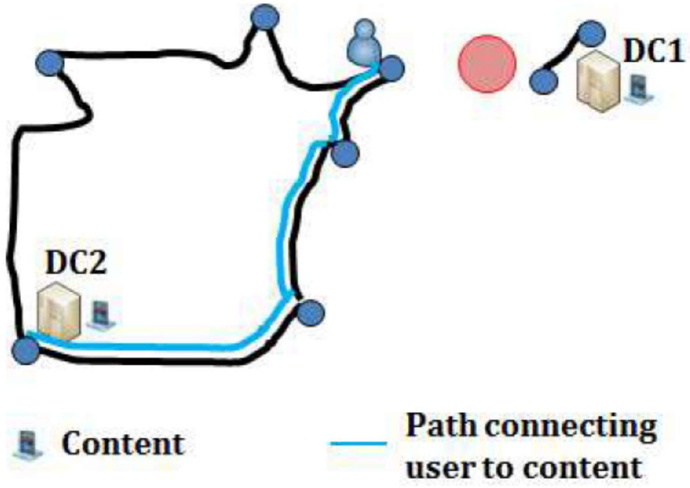


Content Connectivity: Why it is important?

- Content connectivity:
  - **costs less** than network connectivity
  - might be **feasible** when network connectivity is not



Network connectivity not possible



Content connectivity possible

[3] M. Farhan Habib, M. Tornatore and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," in *Proc. IEEE/OSA Opt. Fiber Comm. Conf. (OFC'13)*, Mar. 2013.

Current activity: generalization of content connectivity modeling against n link failures

We developed an Integer Linear Program

DONE

Given:

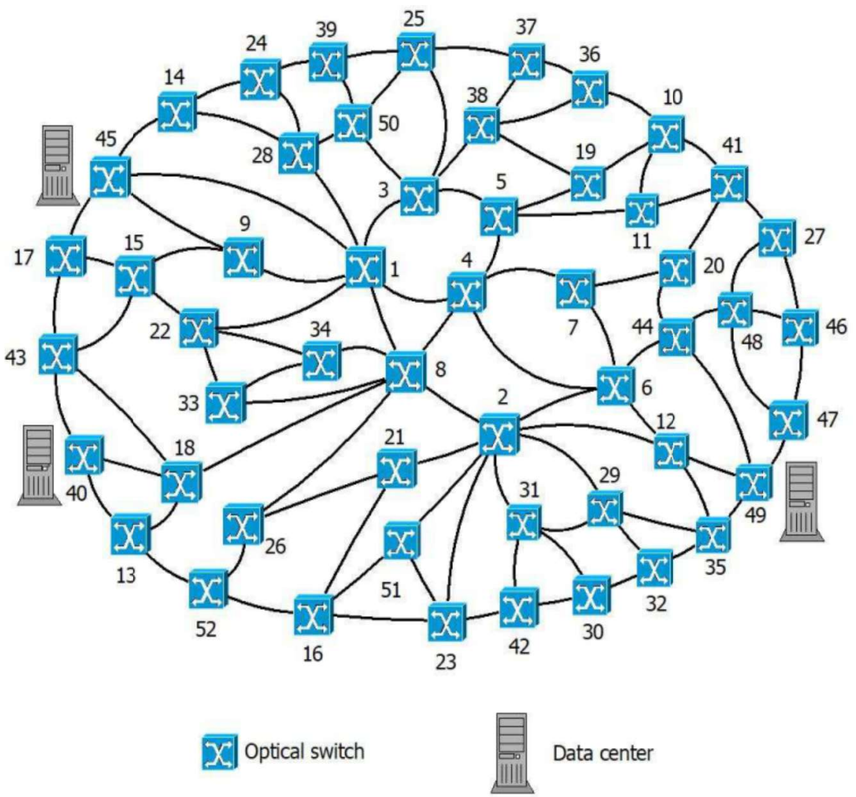
- ✓ Physical topology: $G_P(V_P,\ E_P)$
- ✓ Logical topology: $G_L(V_L,\ E_L)$
- ✓ Set of data center locations: D
- ✓ Number of wavelengths per fiber: W

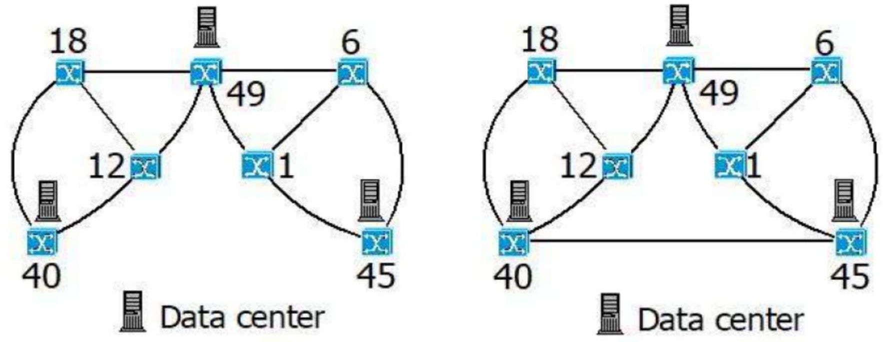
Outputs:

- ✓ Content-connected mapping of a virtual network over physical network against n−physical-link failures (previous work only up to n=2)
- ✓ Minimize total wavelength channel number

G. Le, A Marotta, S. Xu, Y. Hirota, Y. Awaji, M. Tornatore, B. Mukherjee, "Logical Network Mapping With Content Connectivity Against Multiple Link Failures in Optical Metro Networks", IEEE ANTS 2019

Illustrative Numerical Examples



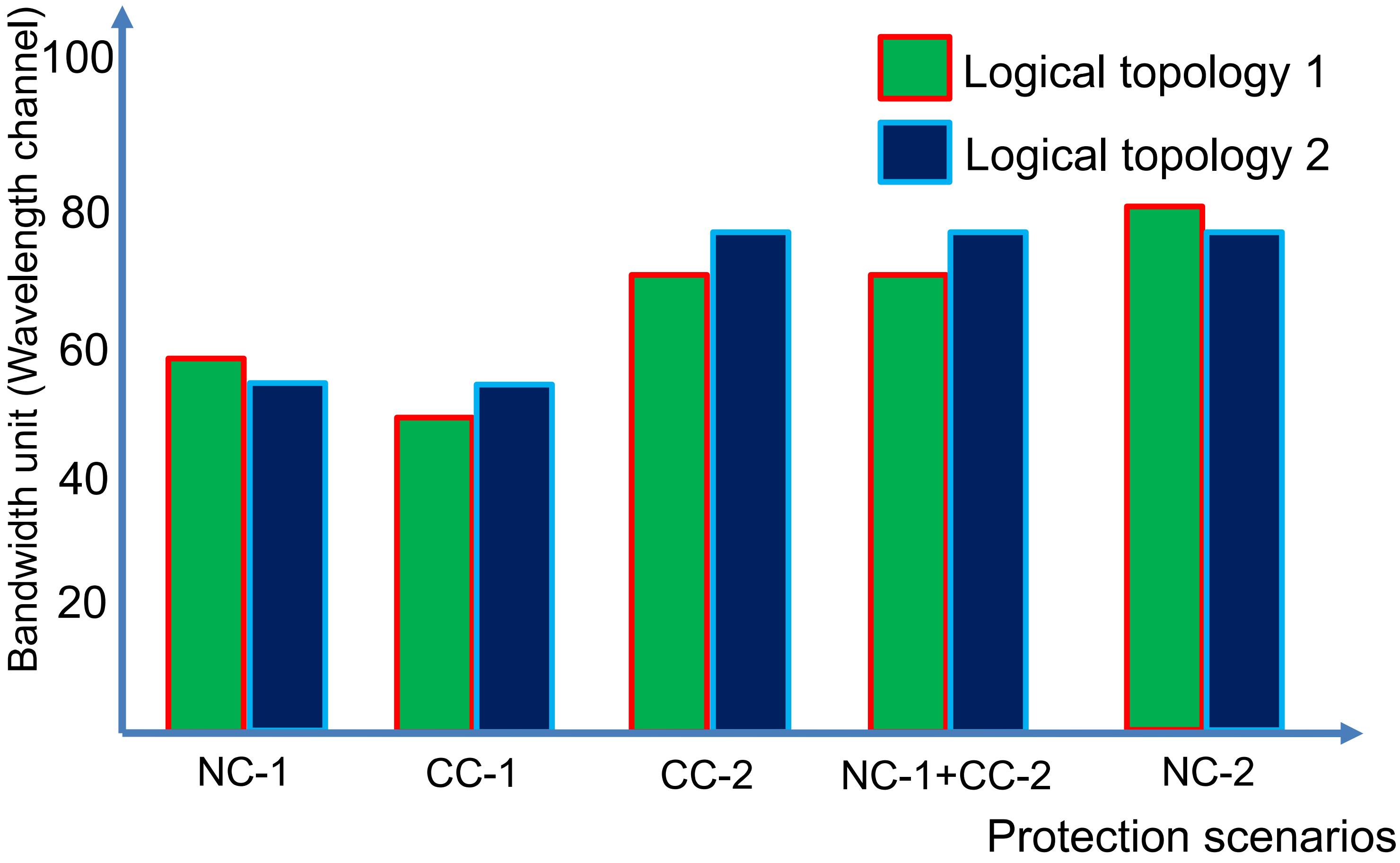


a) Logical topology 1 b) Logical topology 2

Virtual Networks
(7 nodes, 10 links (a), and 11 links (b)

Physical Network:
Modified Telecom Italia Network
(52 nodes, 98 links)

Illustrative Numerical Examples



Our new approach is more generic (arbitrary n) and more scalable than those in [10], [11]

[10] M. F. Habib, M. Tornatore, and B. Mukherjee, "Fault-tolerant virtual network mapping to provide Content Connectivity in optical networks," *Proceedings of OFC*, Mar. 2013.

[11] A. Hmaity, F. Musumeci, and M. Tornatore, "Survivable virtual network mapping to provide content connectivity against double-link failures," *Proceedings of DRCN*, Mar. 2016.

Content Connectivity [CC]: In-Progress Research

- ✓ Generalize conclusions:
  - ✓ When NC > CC and when NC = CC?
  - ✓ When NC not possible but CC possible?

- ✓ Main question: to ensure a given survivability level to a 5G service using a slice, shall I add more data centers or more logical connections?

Task 4: Optical Multicast for Effective Content Transfer among Edge DCs

"Content connectivity" can be realized only if relevant data is replicated in several edge DCs

- *Constant and intensive synchronization and backup procedures among edge DCs via optical multicasting (Verification on OPCI network testbed)*

- ***Selection of multicast tree leaves for disaster resiliency*** - How do we determine which nodes receive the synchronization data of the multicast tree?
- ***Slicing and multicasting*** - How to slice network resources for multicast transmissions?
- ***Verification of optical multicasting with SDN control in Sendai testbed*** - SDN controllers need to monitor transmitted data and to construct multicasting slices considering the locations of edge DCs.

OPCI network testbed @Sendai NICT branch

Outline of 1st year's research in Task 4

- In Task 4, we study how to deliver large size data for enhancing content connectivity.
- 3 types of transmissions for data transfer to multiple receivers.

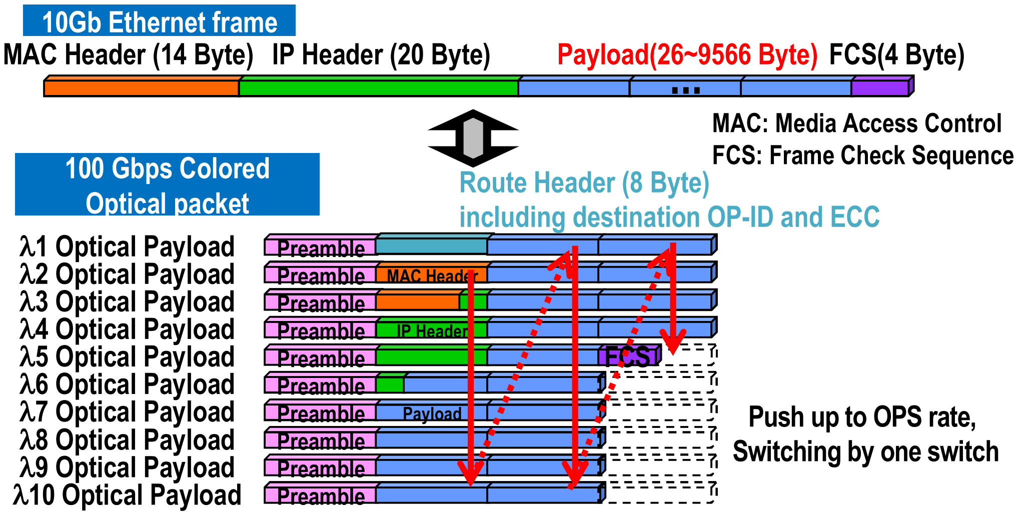
	Required bandwidth	Elapsed time	Switching load
Serial unicast	Low	Very long	Not heavy
Parallel unicast	Very large	Short	Moderate
Optical multicast	Low	Short	Not heavy

* To duplicate packets electrically is not suitable for Large data transfer.

- Optical path multicast is difficult because …
  - Wavelength continuity constraint is difficult in case of multicast against unicast.
  - One 10G Tx cannot execute handshake to multiple 10G Rxs simultaneously.

- Proposal: Optical level multicast packet transmission
  – We firstly developed OPCI node and demonstrate its functionality.

Experimental Setup



- Demonstration on optical level multicast
  - Multicast 1: Background traffic
  - Multicast 2: Video Streaming
  - Multicast 3: Large File Transfer

Optical Multicast 1: Background Traffic

Demo movie

Optical Multicast 2: Video Streaming

Demo movie

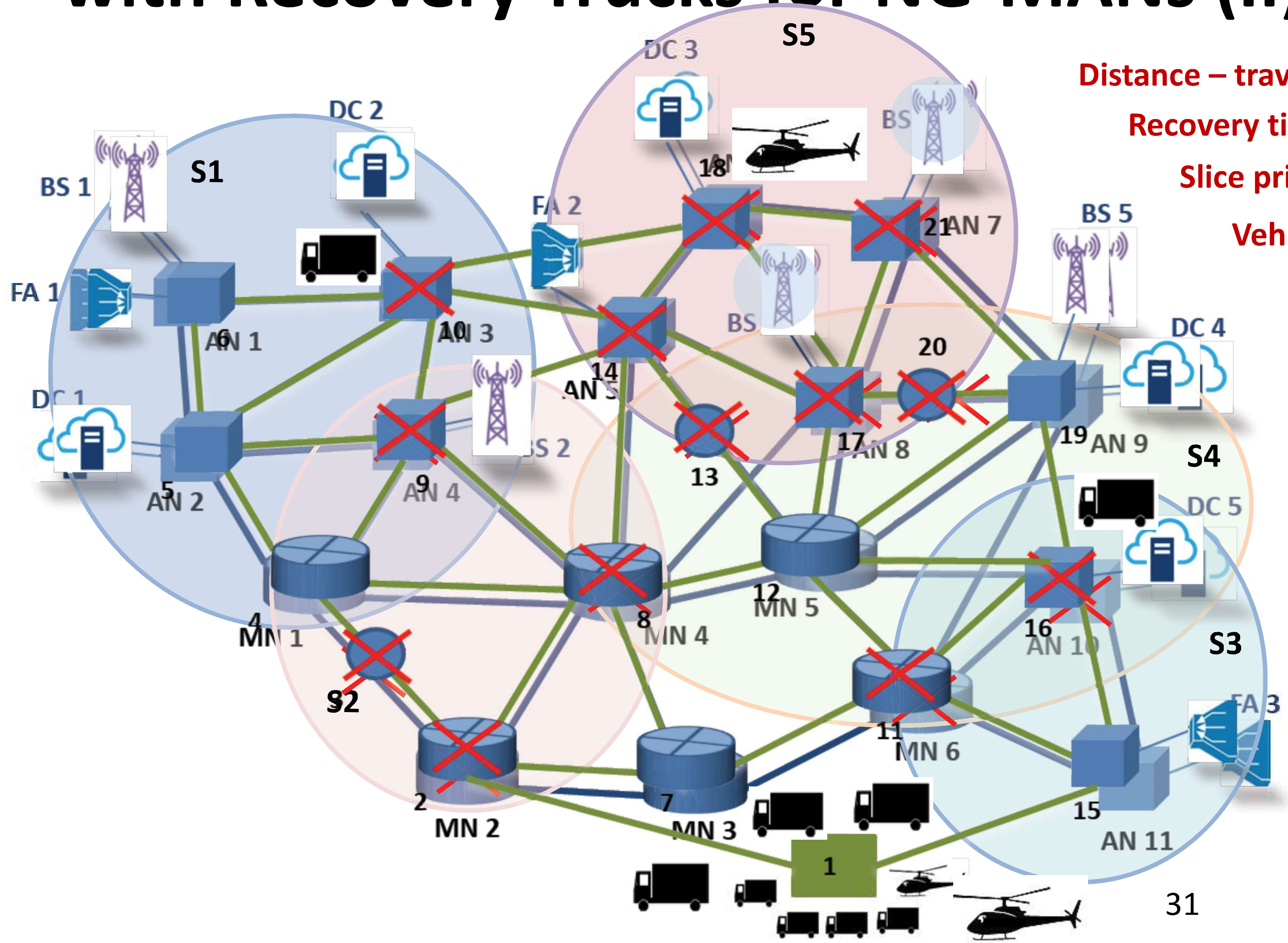
Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs (I)

Some examples of deployable recovery units (e.g., recovery trucks, FAUs)?

- In t e, recovery both rep */service* whi ng on (un overy)
  - *How*
  - *Wh*
  - *Wh*

“Slice-aware” routing and deployment strategy to minimize downtime penalty and ensure fast restoration of important slices

Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs (II)



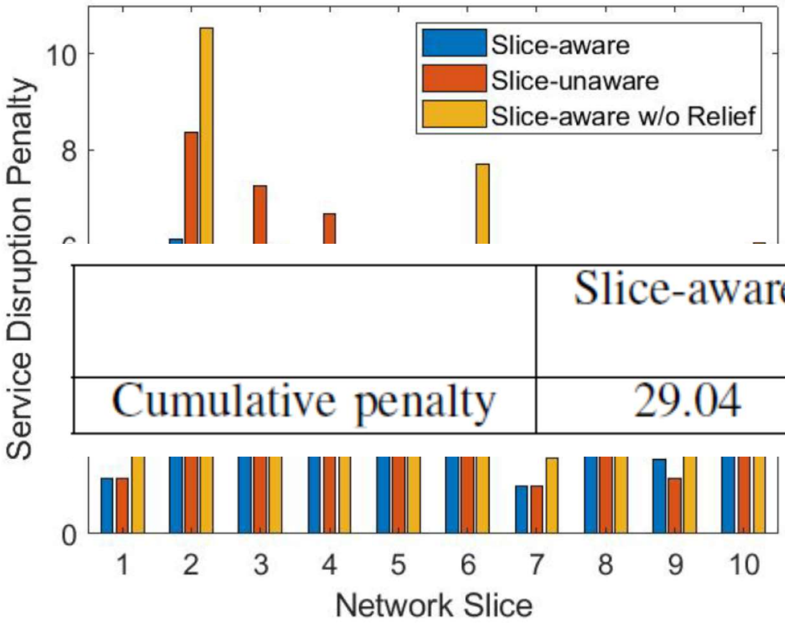
Distance – travel time

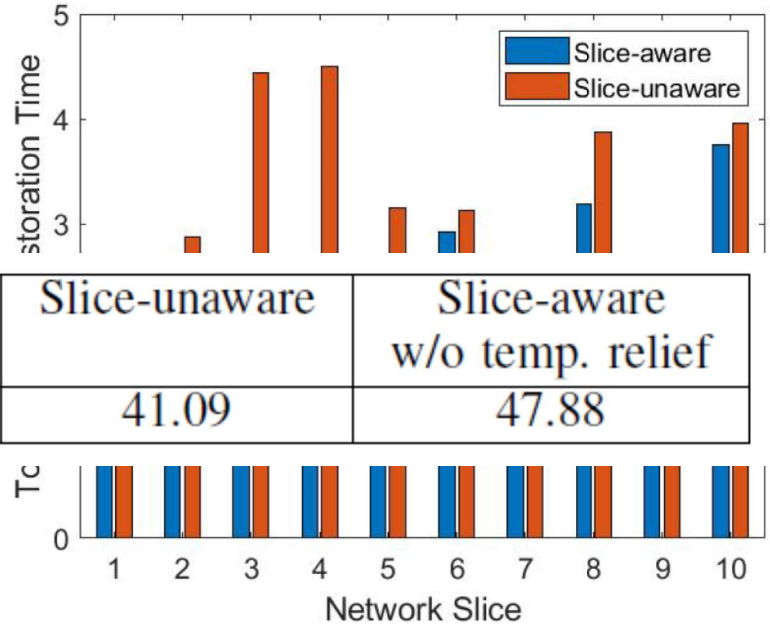
Recovery time

Slice priority

Vehicle type

Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs (II)





	Slice-aware	Slice-unaware	Slice-aware w/o temp. relief
Cumulative penalty	29.04	41.09	47.88

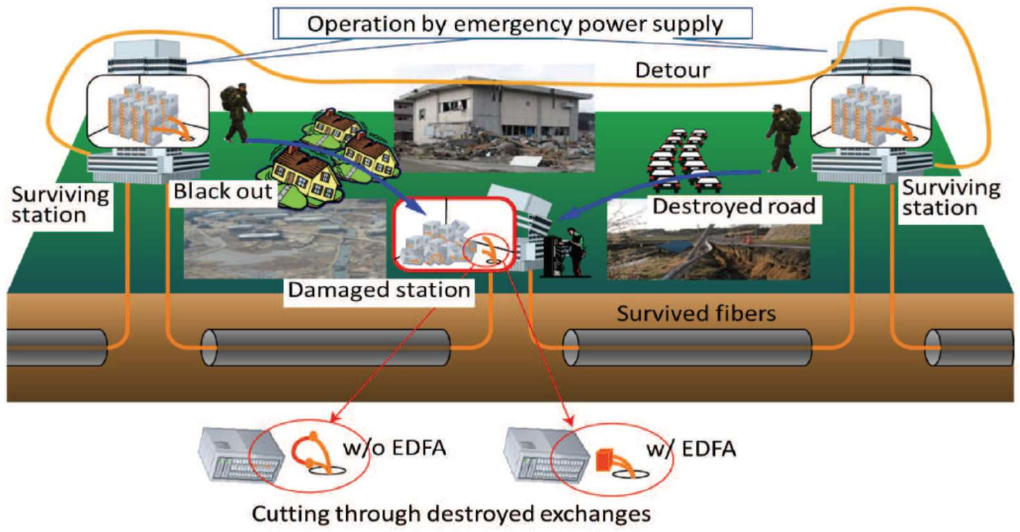
60% reduction in service disruption penalty

46% service-restoration time savings

S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, "Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," accepted to IEEE GlobeCom conference 2019

Task 6: Develop and exploit First Aid Unit (FAU)

Interconnection of surviving facilities and FAU to restore network connectivity



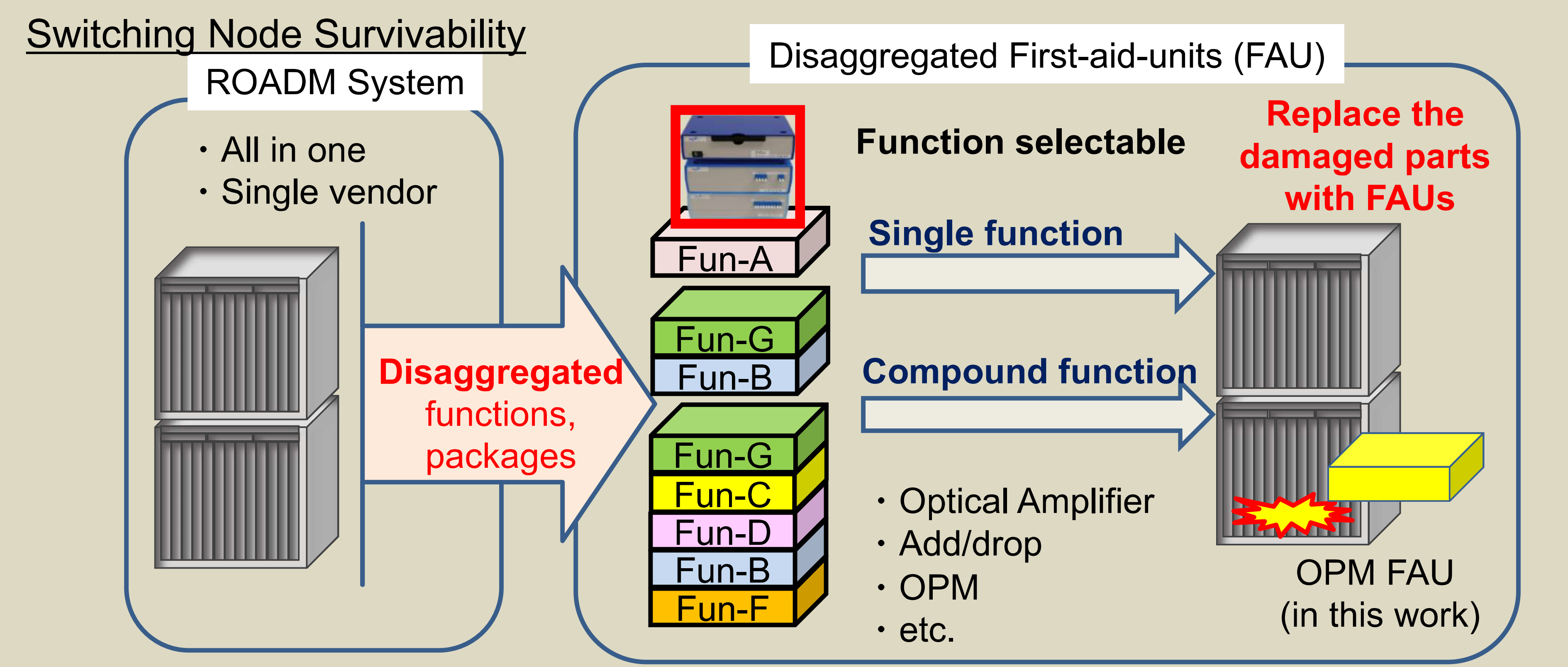
- *Impairment information collection utilizing monitoring systems*
- *Impairment-aware emergency optical network planning*
- *Development of supportive hardware and control system*

- *Impairment information collection*
  - Employ emergency optical performance monitoring (OPM) subsystem in FAU
  - Create emergency telemetry platform using outside surviving network resources (e.g., wireless/Internet)
- *Impairment-aware emergency optical network planning*
- *FAU upgrade*

UCDAVIS

NICT

Emergency First-aid-Unit (FAU)-based OPM Quick Recreation and Robust Telemetry in Disaster Recovery



Control Plane Survivability

- When disaster occurs, capacity in control plane also decreases or control plane may be heavily congested.

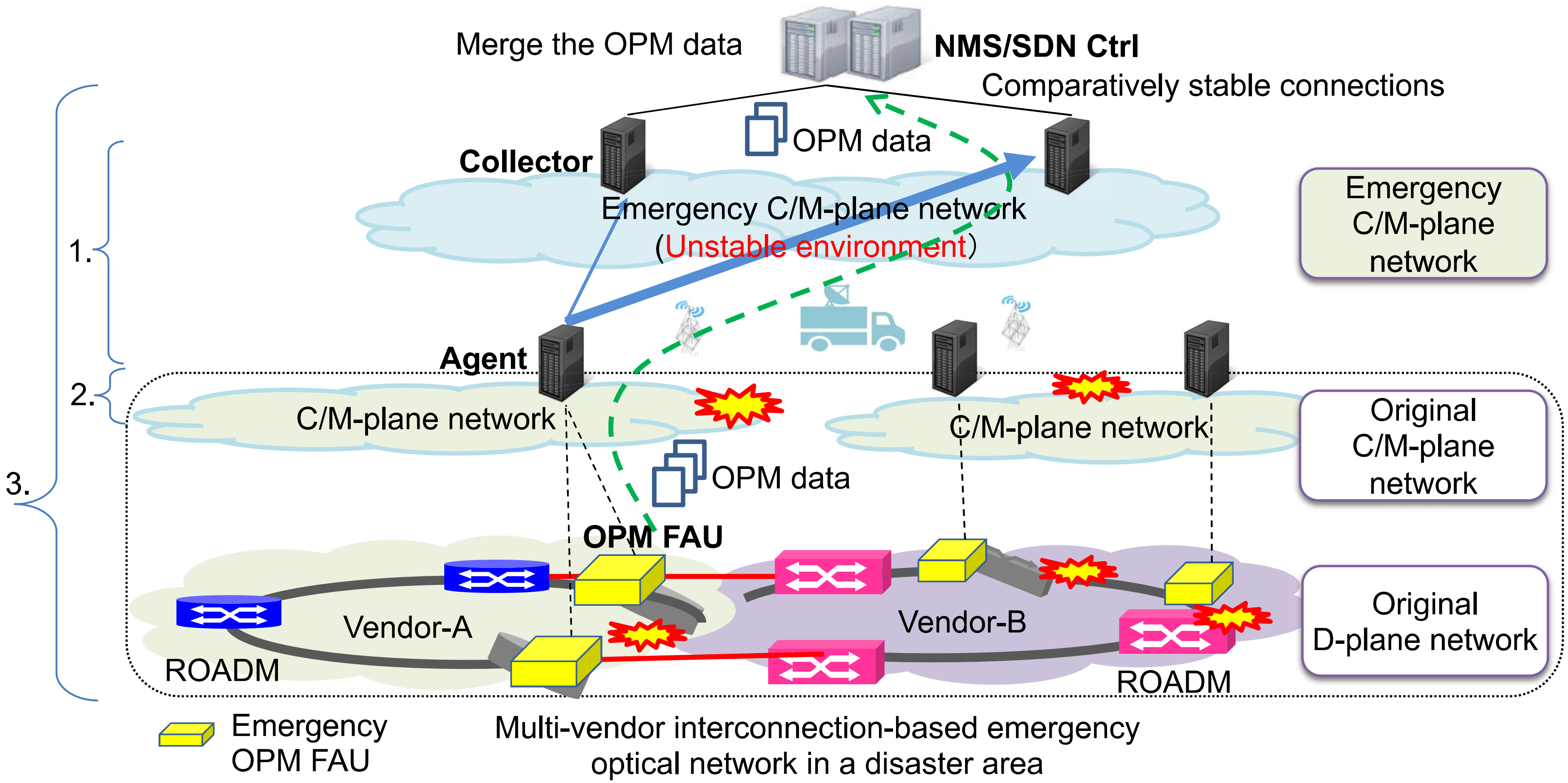
Target in this work

- Recreation of the lost capabilities after disasters as early as possible
  - Optical performance monitoring (OPM)
  - Telemetry

Proposal for OPM Recreation and Open and Robust Telemetry

Main Issues and Proposal (including the following three new capabilities)

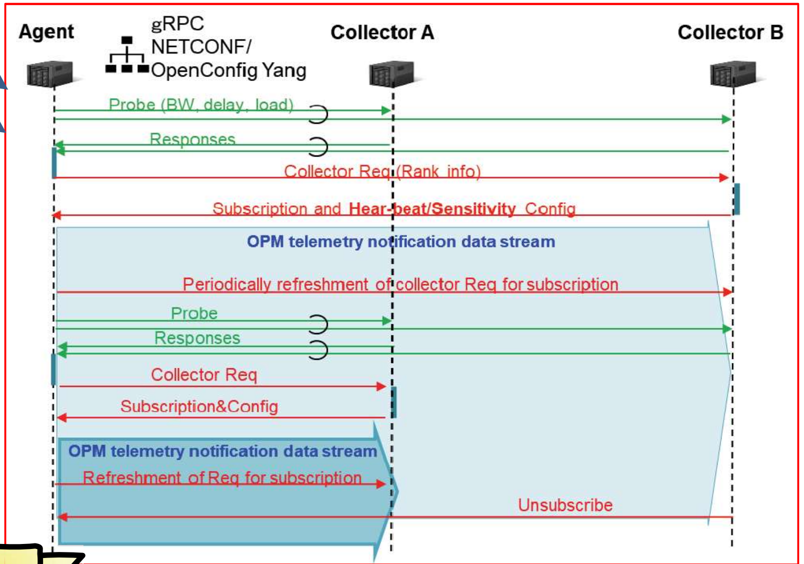
1. Robust Telemetry Protocol between agents and collectors
2. OPM Data Analysis and Triage in Agent
3. Multi-vendor OPM FAUs integration via OpenConfig

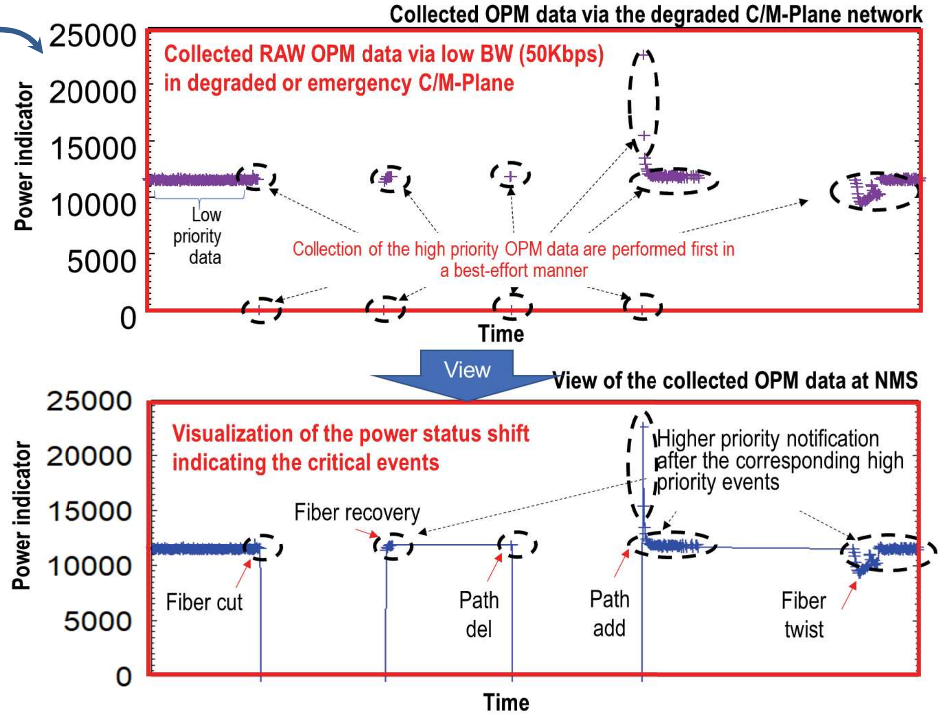


Results and Future Works

Main Issues and Proposal (including the following three new capabilities)

1. Robust Telemetry Protocol between agents and collectors
2. OPM Data Analysis and Triage in Agent
3. Multi-vendor OPM FAUs integration via OpenConfig





This study is presented in ECOC2019 as HIGHLY SCORED paper.

S. Xu et al., "**Quick OPM recreation and robust telemetry in emergency optical networks for early disaster recovery**", ECOC, M.1.E.2, Sep. 2019.

Next Step:

- R&D of the Robust-telemetry in Open OPM telemetry systems introducing the active OPM telemetry capability to quickly grasp the status of network in disaster recovery
- Modeling study for the optimal placement of the emergency FAU resources.

Recapping

- 2 in-person visits
- 6 publications (3 journals, 3 conferences)
  - S. Savas, M. Tornatore, F. Dikbiyik, A. Yayimli, C. Martel, and Biswanath Mukherjee, "RASCAR: Recovery-Aware Switch-Controller Assignment and Routing in SDN," in IEEE Transactions on Systems and Network Management, vol. 15, no. 4, pp. 1222-1234, Dec. 2018.
  - R. Lourenco, S. Savas, M. Tornatore, B. Mukherjee, "Robust Hierarchical Control Plane for Transport Software-Defined Networks", in Optical Switching and Networking, Vol. 30, pp. 10-22, Nov. 2018
  - F. Musumeci, C. Rottondi, G. Corani, S. Shahkarami, F. Cugini, and M. Tornatore, "A Tutorial on Machine Learning for Failure Management in Optical Networks," in IEEE/OSA Journal of Lighwave Technology, vol. 37, no. 16, pp. 4125-4139, 15 Aug.15, 2019
  - S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, "Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," accepted to IEEE GlobeCom conference 2019
  - S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, Y. Awaji, N. Wada, B. Mukherjee, "Quick OPM Recreation And Robust Telemetry In Emergency Optical Networks For Early Disaster Recovery", accepted to European Conference on Optical Communication (ECOC) 2019
    - Highly scored, invited for a full extension in JLT
  - G. Le, A Marotta, S. Xu, Y. Hirota, Y. Awaji, M. Tornatore, B. Mukherjee, "Logical Network Mapping With Content Connectivity Against Multiple Link Failures in Optical Metro Networks", accepted for publication, IEEE ANTS 2019
- + 3 in preparation
- 1 keynote (DRCN 2019) / 1 tutorial (OECC) /1 survey (JLT)

Thanks for your attention!

Disaster-Resiliency Strategies
for Next-Generation Metro Optical Networks
ATN: 1818972

National Science Foundation
WHERE DISCOVERIES BEGIN

On-going activities

- **Task 2**
  - Published a survey on failure management in optical networks (JLT)
  - Experimenting ML-based failure management using data from Sendai testbed
- **Task 3**
  - Evolution of work on content connectivity (joint paper @ ANTS19)
  - Reliable network slicing (to be submitted to OFC 2020, not covered)
- **Task 4**
  - Alert-based data evacuation algs. (to be submitted to a journal, not covered)
  - Experimental activities on optical multicast trees
- **Task 5**
  - Slice-aware restoration with recovery trucks (joint paper @ GB19)
- **Task 6**
  - OPM recreation and robust telemetry (joint paper @ ECOC19)

2021 Japan-US Network Opportunity 2 (JUNO2)

Project Title: *Disaster-Resiliency Strategies for Next-Generation Metro Optical Networks*

ATN: 1818972

Speakers:
Dr. Yoshinari Awaji (NICT)
Dr. Massimo Tornatore (UCDavis)

August 18, 2021
Principal Investigator Meeting

Project Team

- **PIs**
  - Massimo Tornatore; University of California, Davis; PI
  - Biswanath Mukherjee; University of California, Davis; Co-PI
  - Yoshinari Awaji; NICT (Japan); Team leader (PI Japan side)

- **@NICT**
  - Sugang Xu; NICT (Japan); Collaborator
  - Yusuke Hirota; NICT (Japan); Collaborator
  - Masaki Shiraiwa; NICT (Japan); Collaborator

- **@UCD**
  - Sifat Ferdousi; University of California, Davis; PDF
  - Giap Le; University of California, Davis; GSR
  - Subhadeep Sahoo, University of California, Davis; GSR
  - Ramanuja Kalkunte, University of California, Davis; GSR
  - Andrea Marotta; University of L'Aquila, Italy; Visiting Student

- **International Collaborators**
  - Prof. Francesco Musumeci; Politecnico di Milano, Italy
  - Prof. Gustavo Bittencourt; University of Bahia, Brasil
  - Virajit Garbhapu, M.Sc. Student, Politecnico di Milano, Italy
  - Giacomo Marchionni, M.Sc. Student, Politecnico di Milano, Italy

UCDAVIS

NICT

2019: 3 in-person meetings

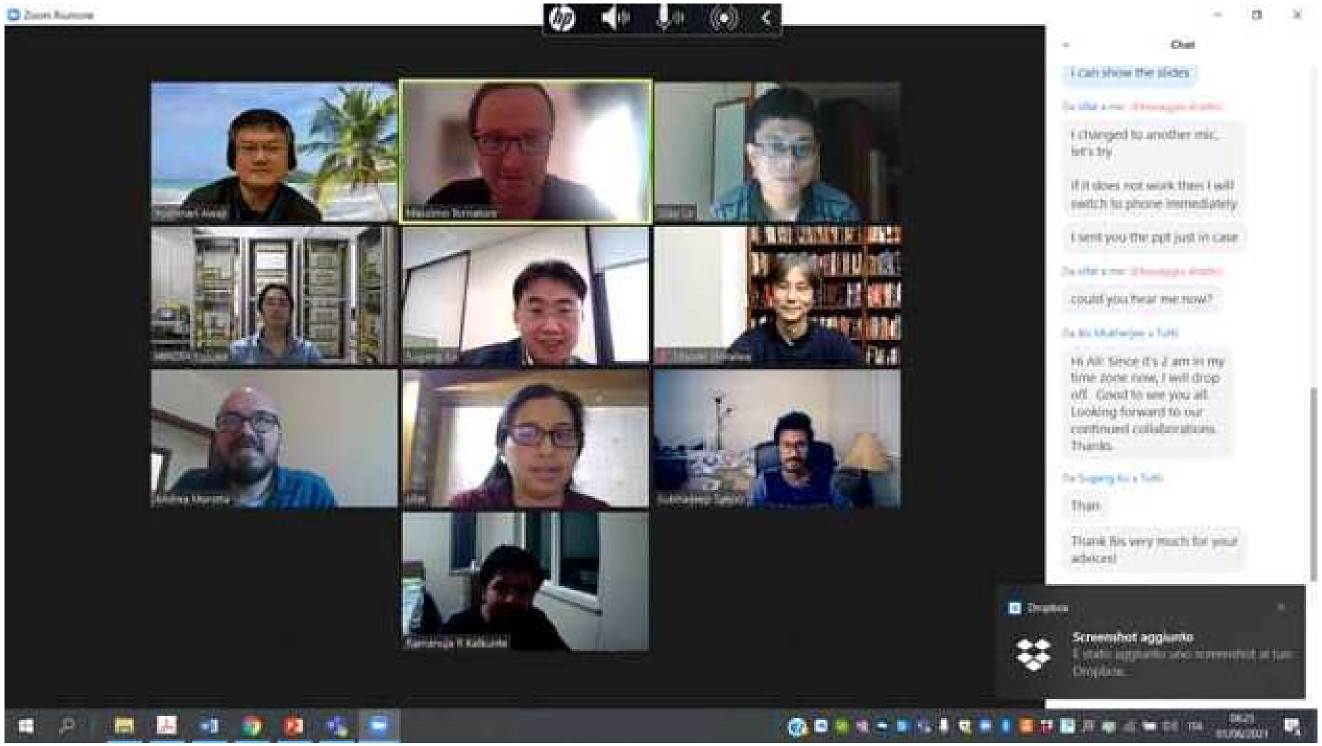
- Davis, Feb 27th to Mar. 1st 2019
  – Pre-OFC visit by Dr. Awaji and Dr. Hirota
- Sendai, July 4th and 5th, 2019
  – Pre-OECC visit by Dr. Tornatore
- Chicago, Oct 11°, 2019 (PI meeting)

2020: 1 in-person + 1 online general meeting

- San Diego, OFC, March 9, 2020
  – Dr. Hirota and Prof Tornatore
- Online, Sept 9, 2020

2021: 1 online meeting

- General online meeting, May 31/June 1
- Several other interactions via email and smaller telco



Motivation

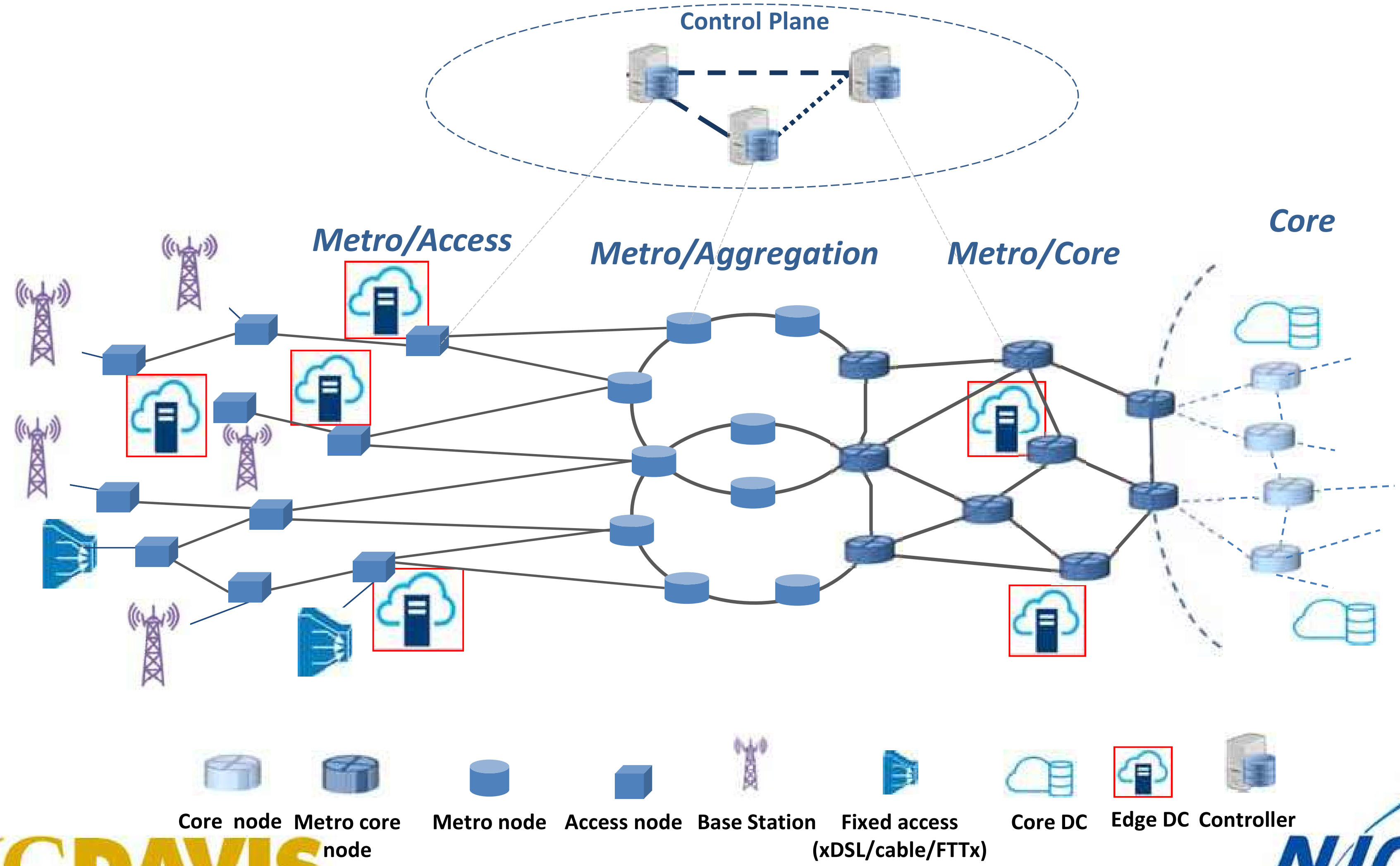
A new generation of optical metro networks is needed to turn the vision of "Smart Cities" into reality

- From a **rigid ring-based aggregation infrastructure** to a **composite network-and-computing ecosystem** to support critical 5G services (e.g., autonomous driving)

- Several technical enablers:
  - Increased reconfigurability enabled by **SDN**
  - **Integration of optical and wireless** access networks
  - Metro nodes becoming edge data centers (**edge computing**)
  - **Network slicing** to logically partition network, computing, and storage resources
  - …

Evolution of Metro Access Networks (I)

Edge computing and SDN



Evolution of Metro Access Networks (II)

Network Slicing

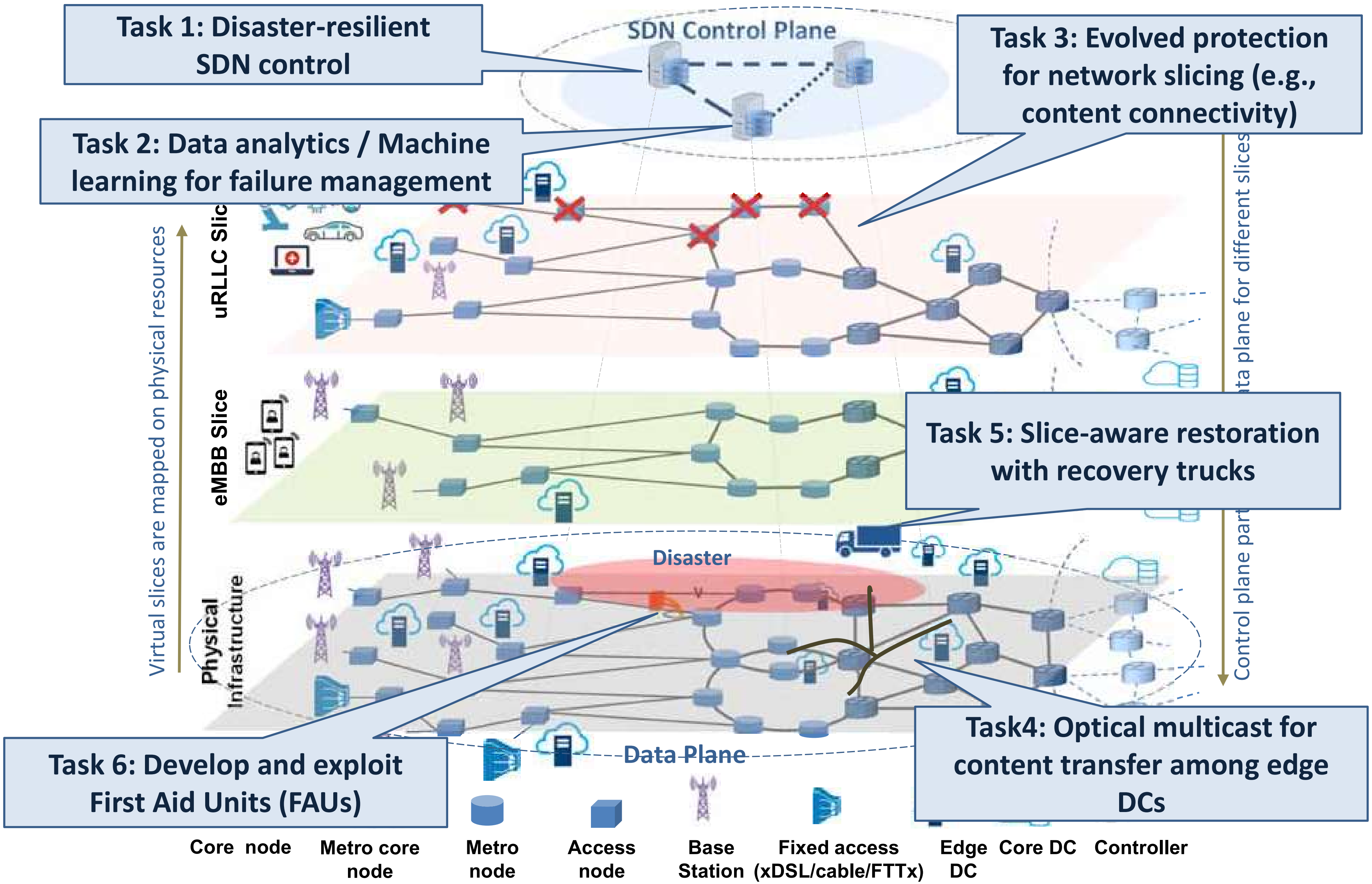
This transformation calls for new solutions for resilient and sliceable next-generation metro-area networks (NG-MANs)

Disaster affecting underlying NG-MAN

UCDAVIS

NICT

Project Overview



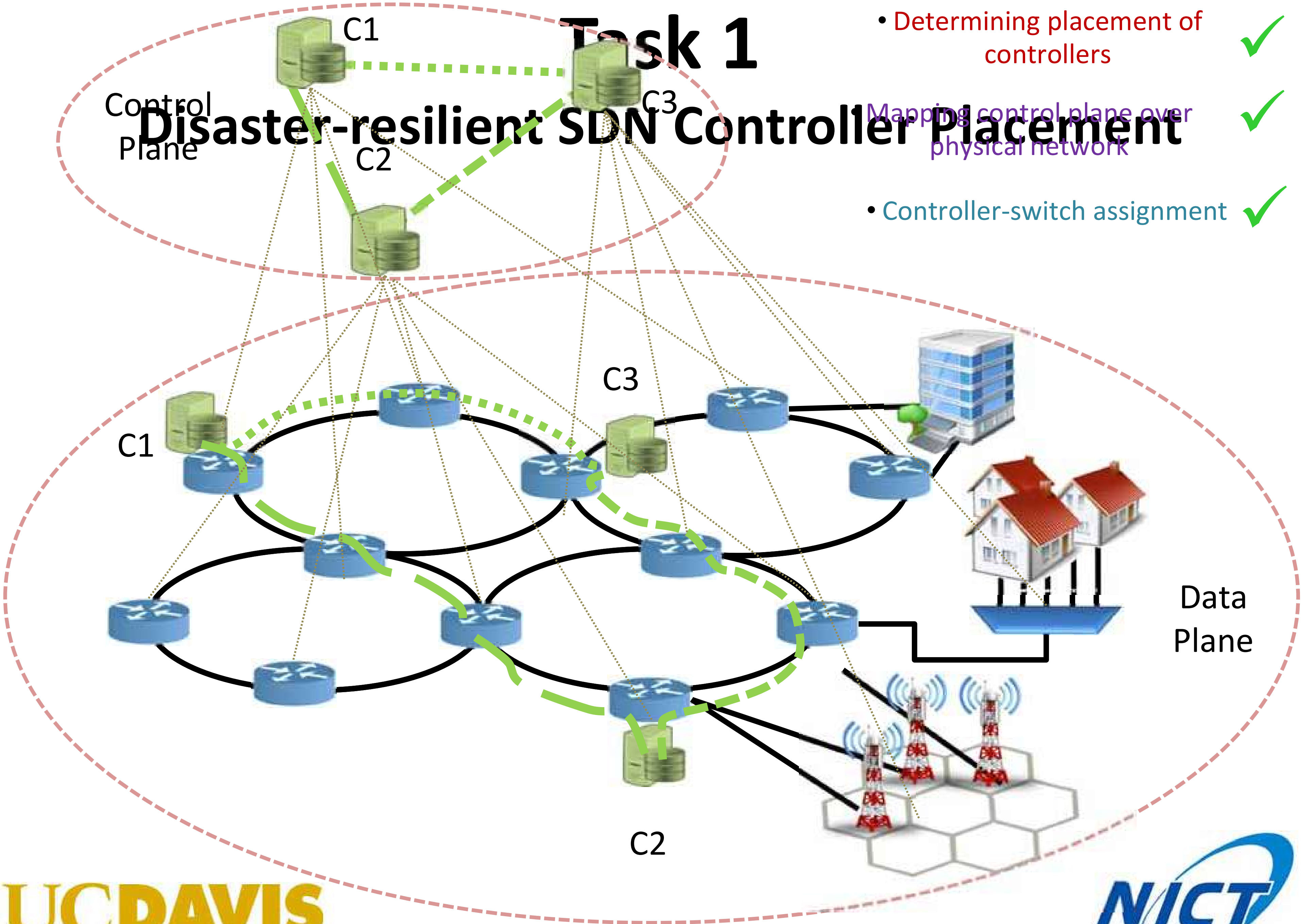
Overall Topics

	Disaster-resilient NG-MANs		
Phase	Pre-disaster phase		Post-disaster phase
Theme	Theme 1: Prevention Disaster-resilient design of the SDN control plane	Theme 2: Preparedness Protection strategies for sliceable NG-MANs	Theme 3: Fast recovery Recovery strategies with portable devices in NG-MANs
UC Davis	Task 1 Disaster-resilient SDN controller placement	Task 3 Disaster-resilient content-connected slice mapping	Task 5 Slice-aware restoration with recovery trucks for NG-MAN
NICT	Task 2 SDN modules for network slicing and data analytics	Task 4 Optical multicast for effective content transfer among edge DCs	Task 6 Develop and exploit First Aid Unit (FAU)
Key technologies	SDN/NFV, Machine learning	Edge computing, flexi grid & multicast	Novel portable/movable disaster recovery systems

Task 1

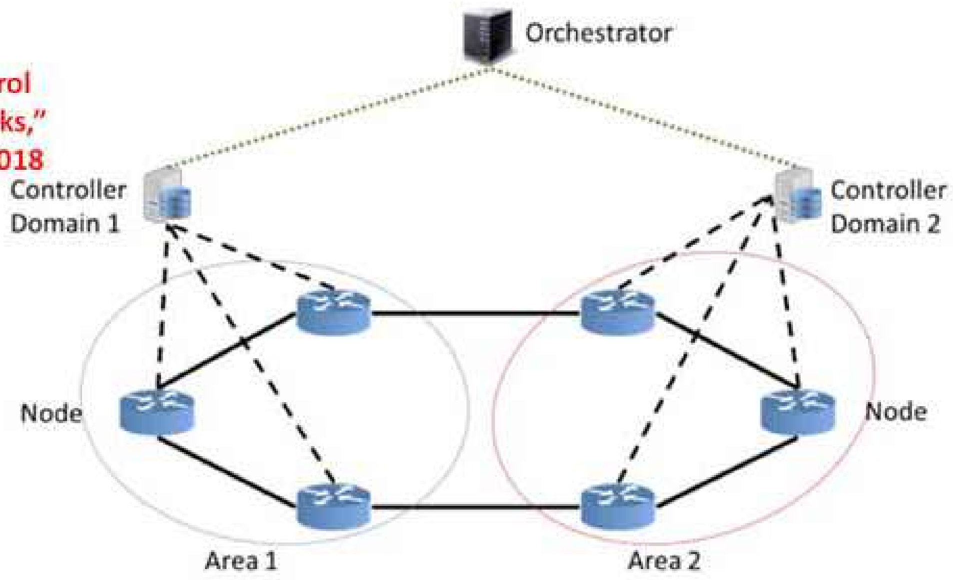
Disaster-resilient SDN Controller Placement

- Determining placement of controllers
- Mapping control plane over physical network
- Controller-switch assignment



Task 1: Our Contribution on Fault-Tolerant Controller Placement (CP)

- **[Pre-planned controller replicas]** F.J. Ros, P.M. Ruiz, Five nines of southbound reliability in software-defined networks, in: Proc. of the ACM HotSDN, New York, NY, USA, 2014 & (B. Killi, et al., Capacitated next controller placement in software defined networks, IEEE Trans. Netw. Service Manage. 14 (3) (2017) 514–527)
- **[Path diversity]** F. Müller, et al., Survivor: an enhanced controller placement strategy for improving SDN survivability, in: Proc. of the IEEE GLOBECOM, 2014
- **[Disaster awareness]** S. Savas, et al., "Disaster-resilient control plane design and mapping in Software-Defined Networks," *In Proc. of HPSR,* Budapest, Hungary, July 2015
- **[Malicious Attacks]** D. Santos, A. de Sousa, C.M. Machuca, Robust SDN controller placement to malicious node attacks, in: Proc. of IEEE DRCN, 2018.
- **[Several types of failures]** D. Hock, et al., Pareto-optimal resilient controller placement in SDN-based core networks, in: Proc. of the 25th International Teletraffic Congress (ITC), 2013.
- **[T-SDN (Orchestrator+Controllers)]**
  - **R. Lourenço, et. al, "Robust hierarchical control plane for transport software-defined networks," Optical Switching and Networking, vol. 30, 2018**



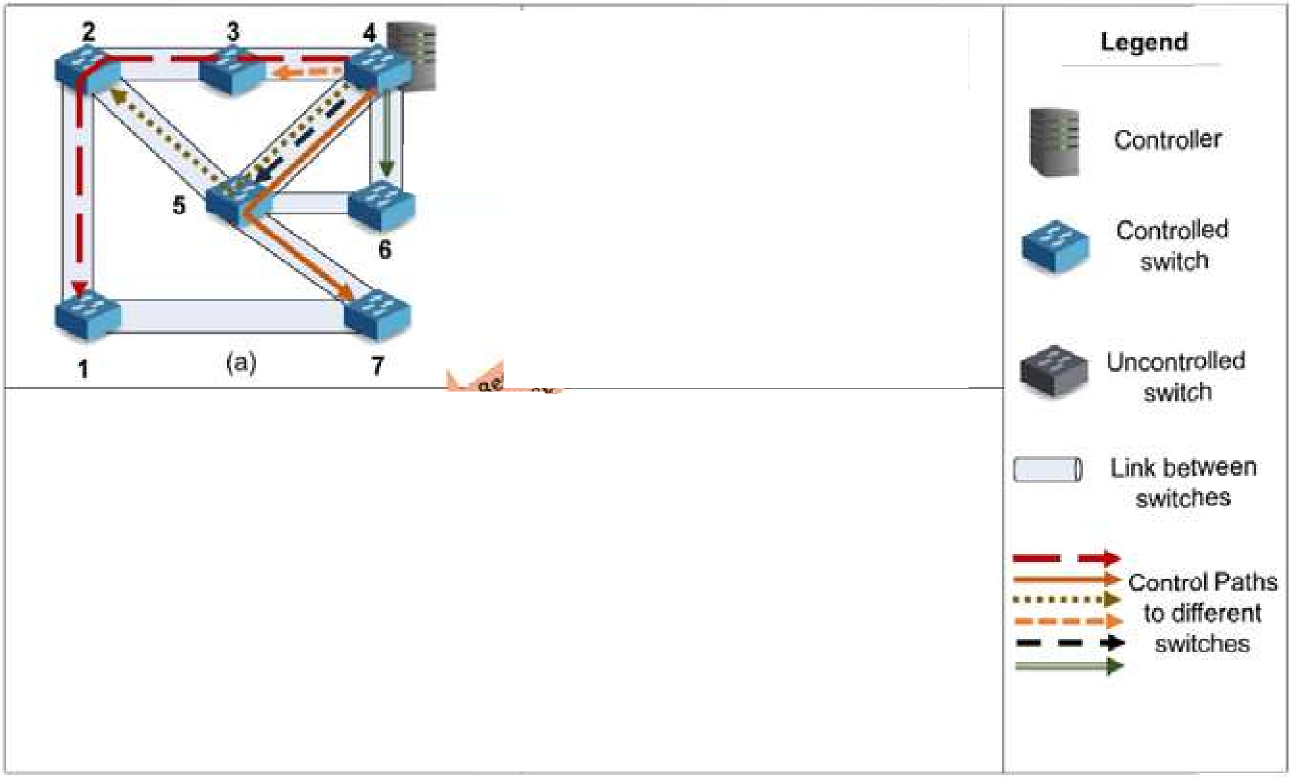
Ok controller has been properly placed…

.. still *<u>how we interconnect controllers to switches</u>* is crucial to minimize recovery time!

Task 1: Looking at "Controller to Switch" Paths!

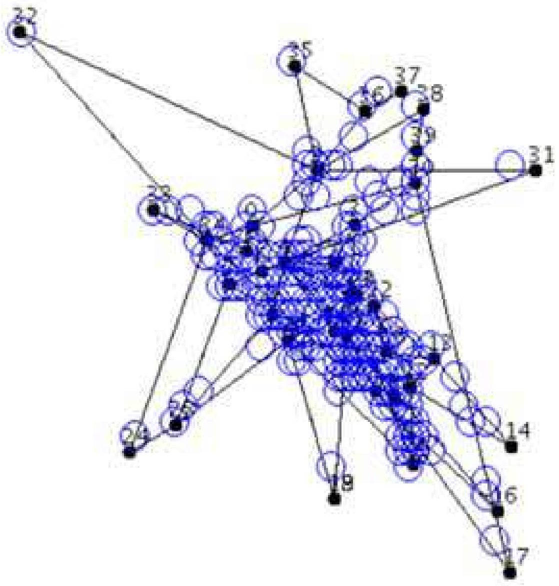
Multi-Stage Recovery

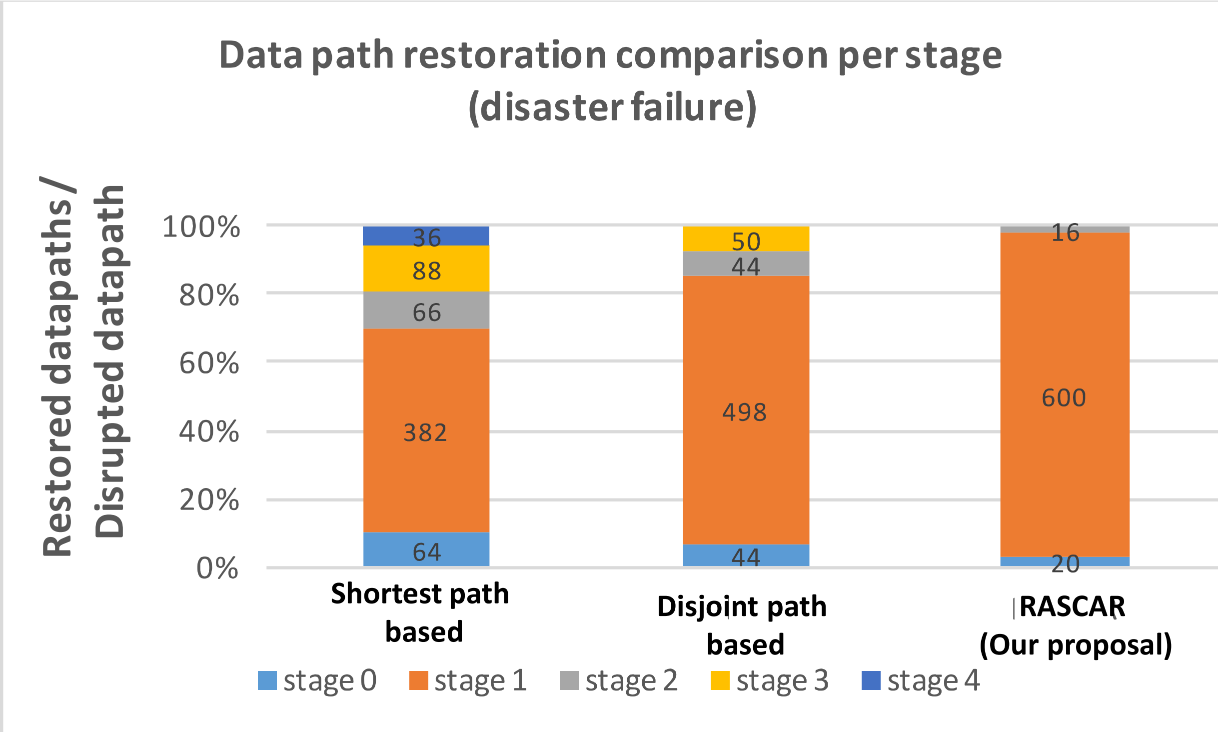
- Even a single failure affects multiple switch-to-controller **control paths**
- When switches lose control paths, they become "**uncontrolled**":
  - route traffic using old flow entries
  - cannot exchange control messages (e.g., flow setup request, flow installation)
  - cannot be used for data path restoration



Results: Recovery Speed vs. Cost

- **GEANT Network**
- **All possible disasters with radius = 100km**





<u>Note: what about additional cost?</u>

Less than 1% additional resource consumption.
Only control paths become longer!

S. Savas, M. Tornatore, F. Dikbiyik, A. Yayimli, C. Martel, and Biswanath Mukherjee, "RASCAR: Recovery-Aware Switch-Controller Assignment and Routing in SDN," in IEEE Transactions on Systems and Network Management, vol. 15, no. 4, pp. 1222-1234, Dec. 2018.

Task 2: Two major topics using NICT testbed

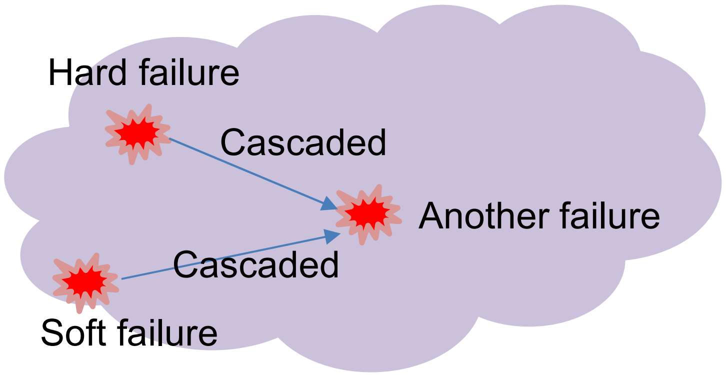
Development of Sendai Testbed

Remote testbed @Sendai NICT branch

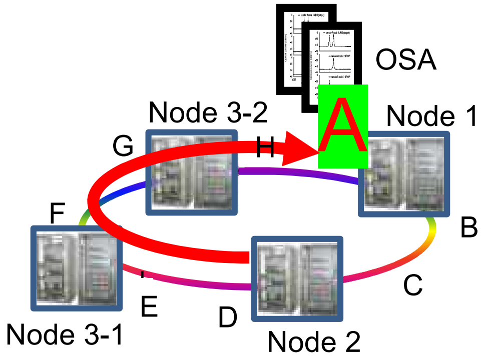
Collaborative Research

Cascade Failure in Optical Networks

ML-based Failure Recognition



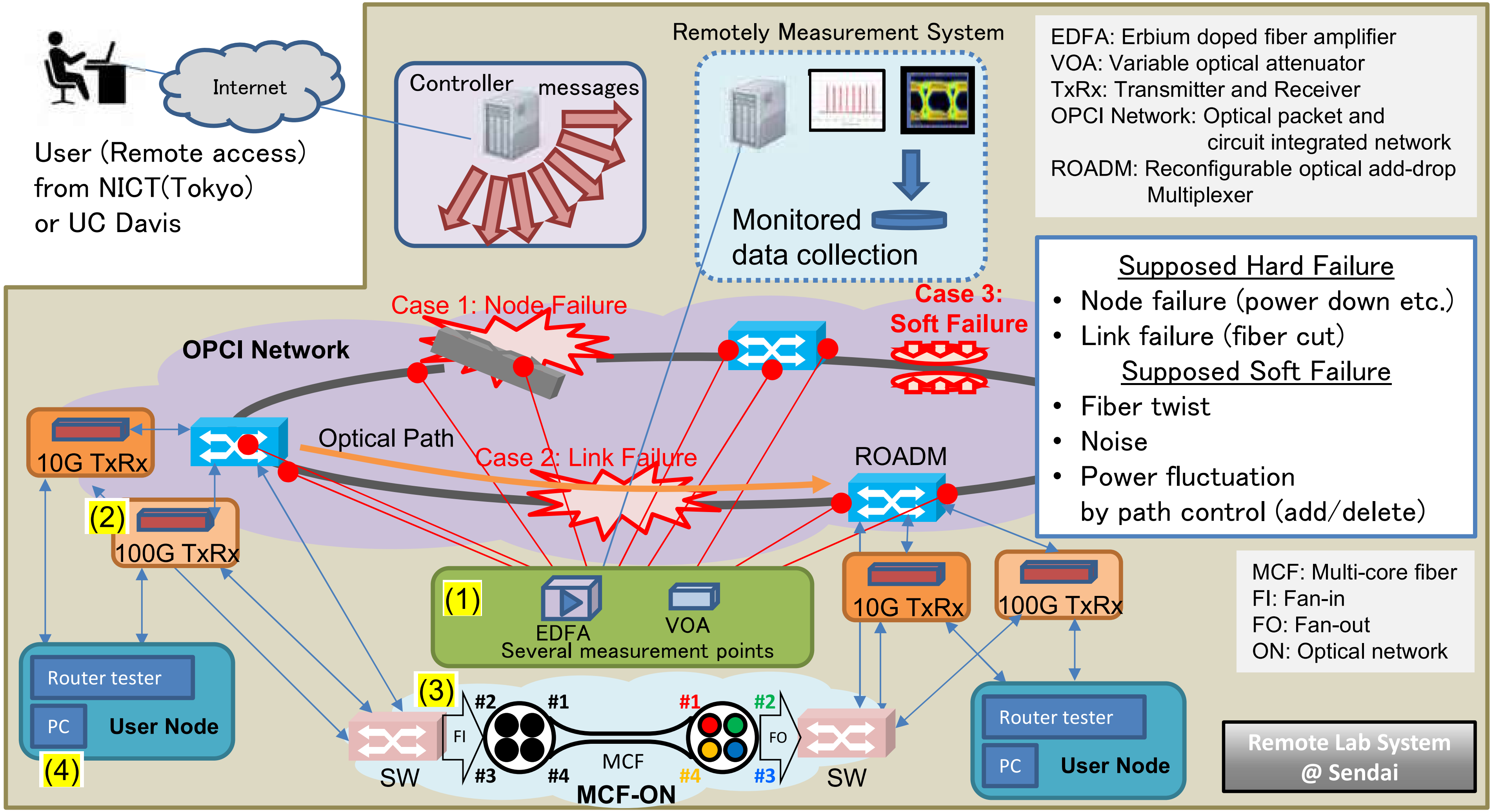
NICT (Sendai) + UC Davis



Data acquisition

Improvement of ML algorithms

Development of Sendai Testbed for Advanced Network Functionality



(1) Multipoint measurement system developed for remote data acquisition

(2) Coherent optical signals generated by 100G transponders

(3) Multi-core fiber optical network

(4) End-to-end network performance evaluation using application/IP traffic

Task 2: Cascade Failure

- Cascade failure: A failure causes another failure of different part of interconnected system. It may degrade quality of transmission (QoT) as soft failure/silent failure.
- Two possible approaches:
  - (1) Hardware implementation for mitigating the cascaded impact of hard failure which causes soft failures
  - (2) Early detection of failures and quick response to restore failures (ML based approach)

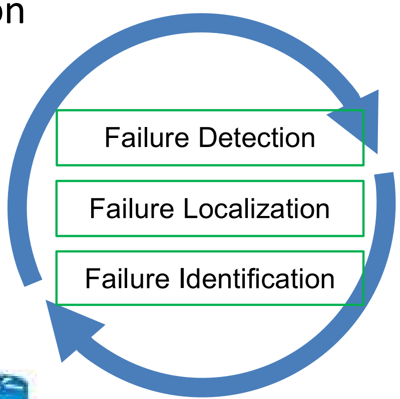
Details are undisclosed

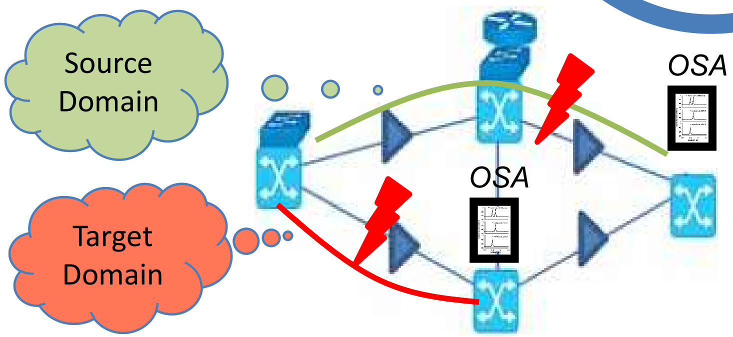
Collaborative Research

- Failures in optical networks
  - Hard Failure
  - Soft Failure
- Quick recognition of failures is important for failure management
  - Machine Learning (ML) technique is a promising solution
- Real data acquisition at Sendai testbed.
  - Experimental setup for several types of failure
  - Data acquisition by remote/local control of several equipment
  - Improvement of ML algorithm
  - Evaluation and discussion

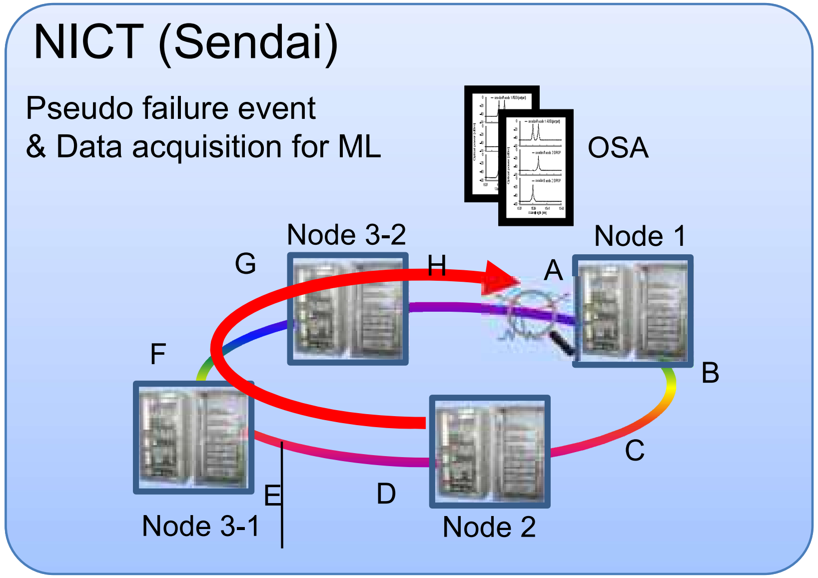
UC Davis

Improvement of ML algorithms
- Neural Network
- Transfer Learning etc.





Transfer Learning: Re-use data form source domain in a target domain



Develop failure recognition algorithm in both side and discuss in detail for better algorithm.

F. Musumeci, V. G. Venkata, Y. Hirota, Y. Awaji, S. Xu, M. Shiraiwa, B. Mukherjee, M. Tornatore, "Transfer Learning across Different Lightpaths for Failure-Cause Identification in Optical Networks," ECOC, Mo2K-1, 2020.

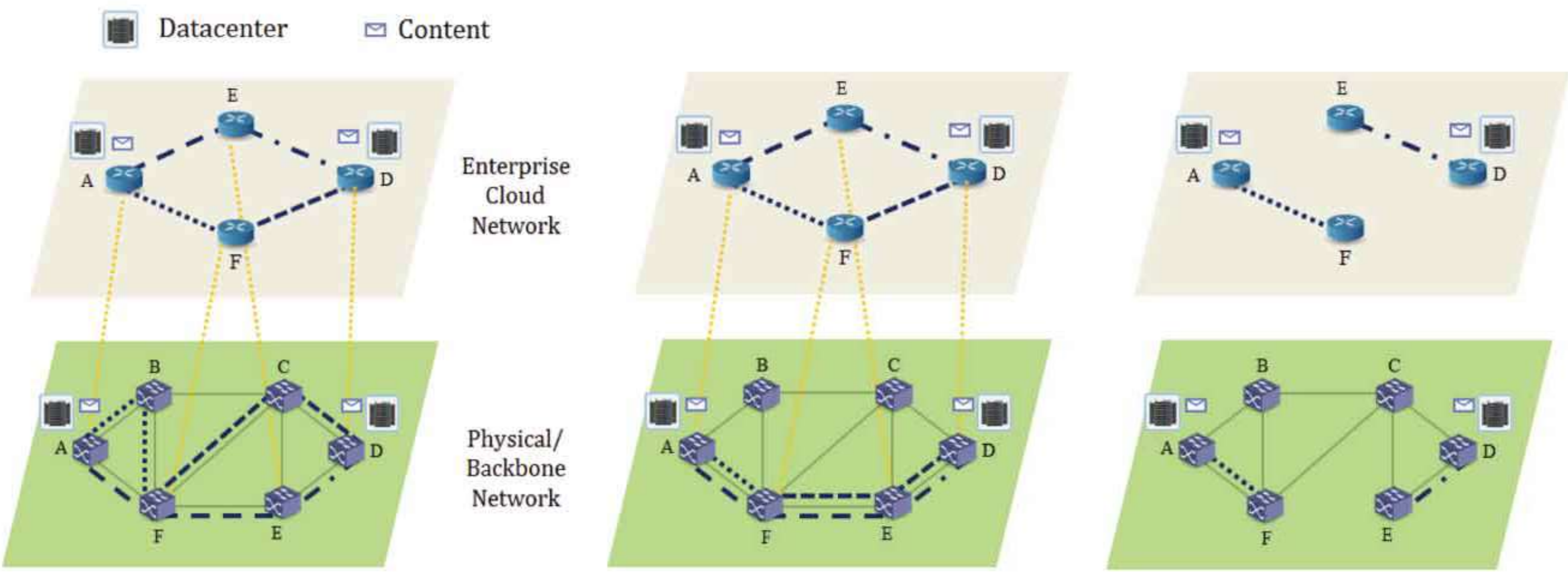
Task 3: "Content Connectivity" for Disaster Resiliency

Network Connectivity - ensure reachability of any pair of nodes in the network (end-to-end) in case of failure

Content Connectivity - ensure reachability of content from any point of a network (end-to-content) in case of failure

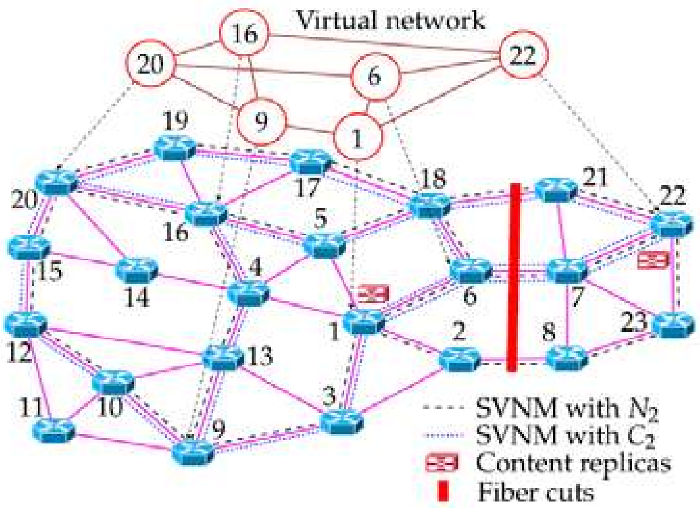
***Costs less** than network connectivity*

*Might be **feasible** when network connectivity is not*

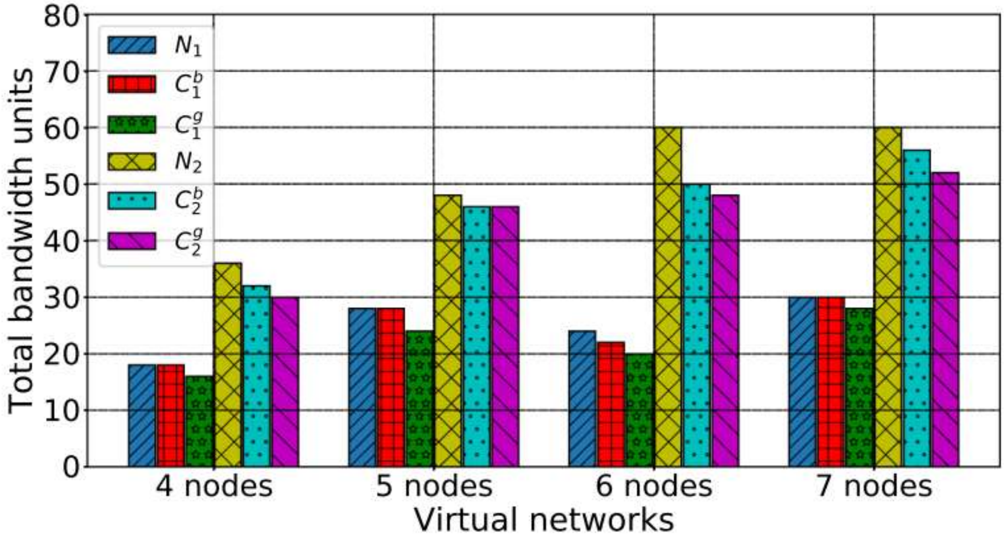


Task 3: ① Generalization of content connectivity modeling against k-link failures (C_k)

Survivable virtual network mapping (SVNM) with content connectivity against multiple link failures



Tokyo23 network provided by NICT

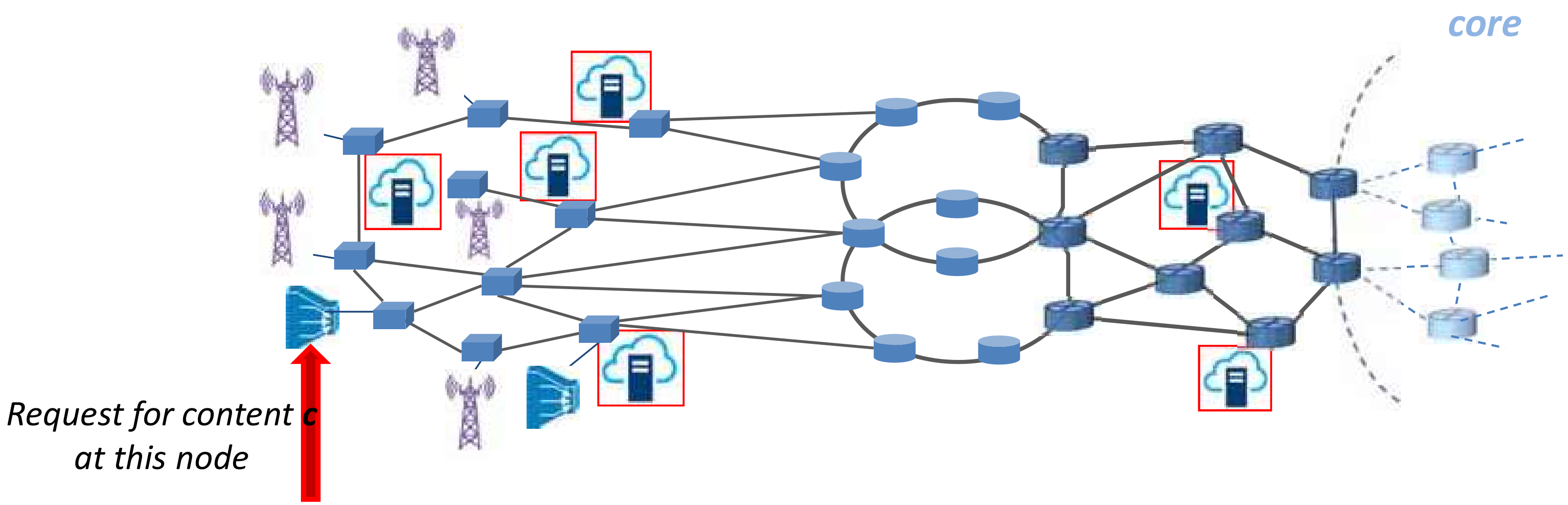


- **N_1 / N_2** - cost of **Network Connectivity** against single-link and double-link failures
- **C_1 / C_2** - cost of **Content Connectivity** against single-link and double-link failures

Main conclusion: Content Connectivity **decreases cost** and **increases availability** wrt Network Connectivity

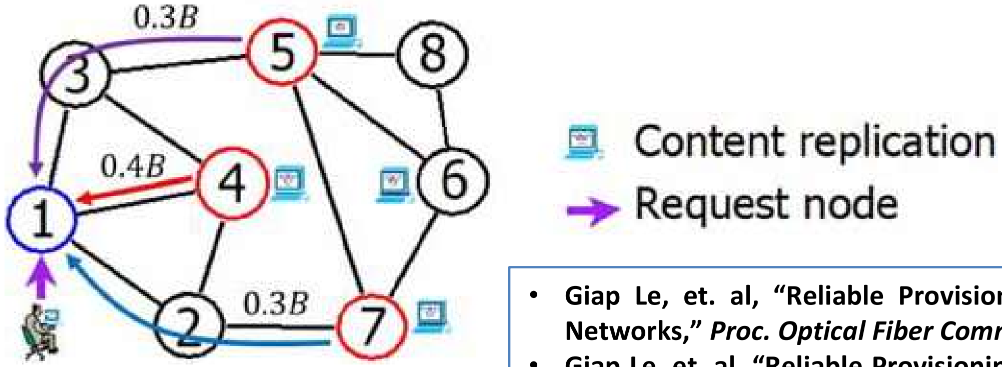
G. Le, et. al, "Survivable Virtual Network Mapping with Content Connectivity Against Multiple Link Failures in Optical Metro Networks," IEEE/OSA Journal of Optical Communication and Networking, 2020

Task 3: ② Reliable Provisioning Using Multipath Routing from Multiple DCs (MPMD)



Content *c* is widely replicated at multiple DCs --> opportunity for MPMD

Example of MPMD

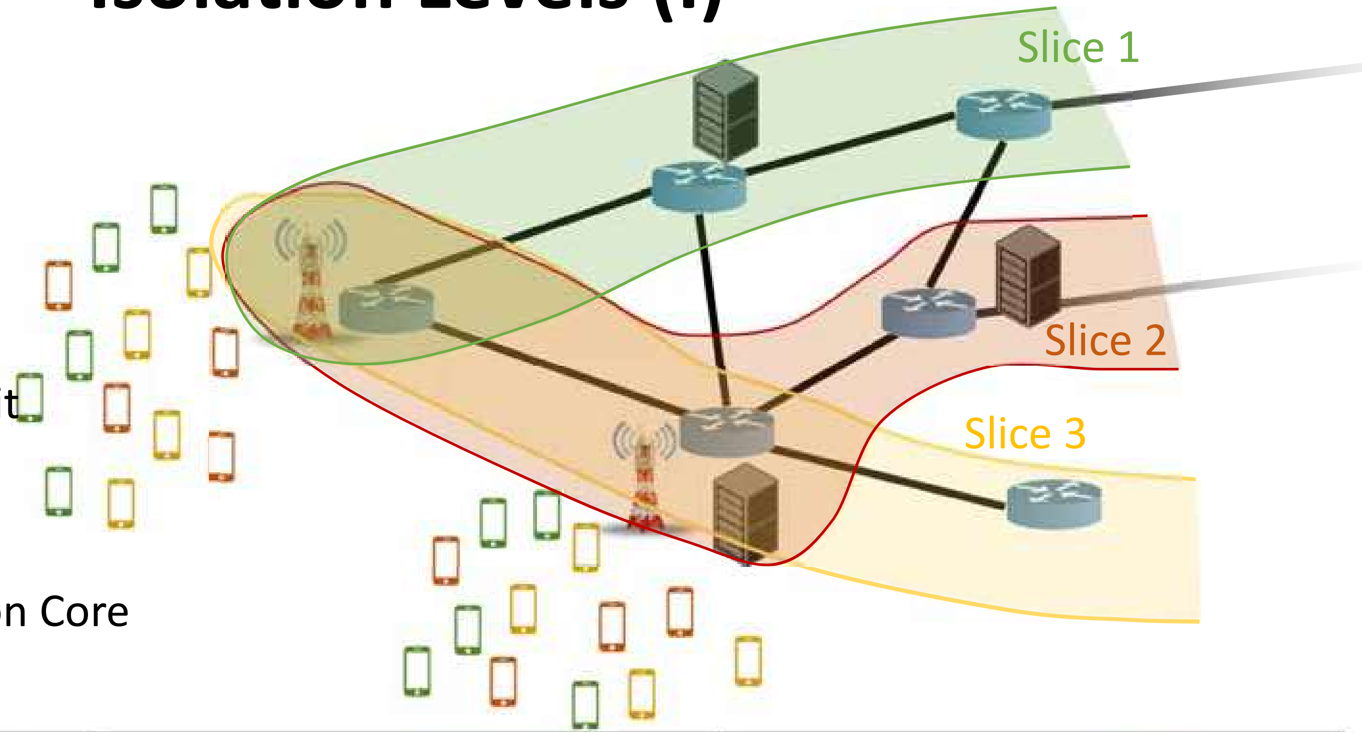


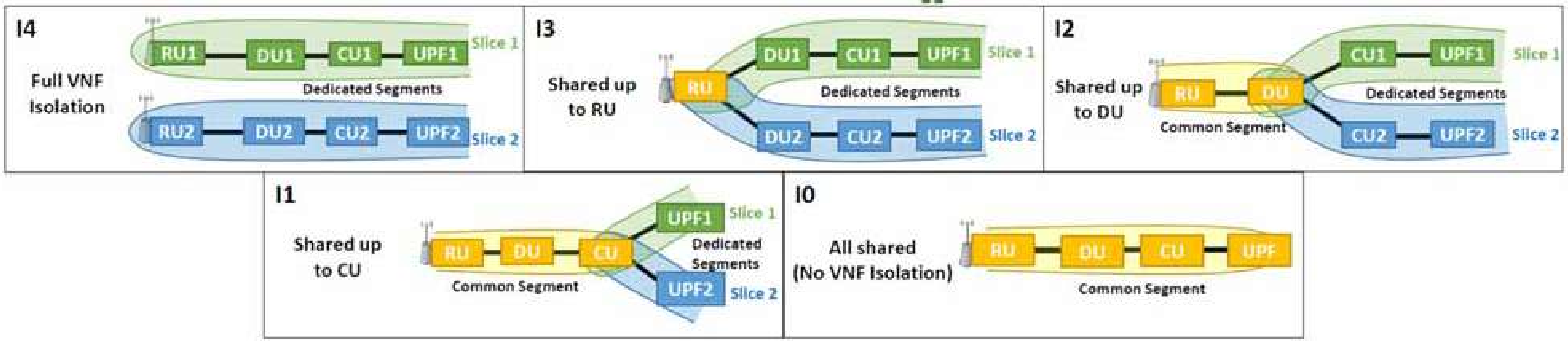
- *We formulated the MPMD problem as an ILP and developed heuristics*
- *Compared with MPSD (Multipath Routing from a Single DC) and DPP (Dedicated-Path Protection)*

- Giap Le, et. al, "Reliable Provisioning for Dynamic Content Requests in Optical Metro Networks," *Proc. Optical Fiber Communications Conference (OFC)*, June 2021.
- Giap Le, et. al, "Reliable Provisioning with Degraded Service using Multipath Routing from Multiple Datacenters for Dynamic Content Requests in Optical Metro Networks," *IEEE/OSA Journal of Optical Communications and Networking* (to submit)

Task 3: ③ Reliable Slicing with Different Isolation Levels (I)

- **RU** Radio Unit
- **DU** Distributed Unit
- **CU** Central Unit
- **NGC** New Generation Core





- A. Marotta, D. Cassioli, M. Tornatore, Y. Hirota, Y. Awaji, and B. Mukherjee, "Reliable Slicing with Isolation in Optical Metro-Aggregation Networks," Proc., Optical Fiber Communications Conference OFC, 2020.

Task 4: Optical Multicast for Effective Content Transfer among Edge DCs

"Content connectivity" can be realized only if relevant data is replicated in several edge DCs

- *Constant and intensive synchronization and backup procedures among edge DCs via optical multicasting (Verification on OPCI network testbed)*

- ***Selection of multicast tree leaves for disaster resiliency*** - How do we determine which nodes receive the synchronization data of the multicast tree?
- ***Slicing and multicasting*** - How to slice network resources for multicast transmissions?
- ***Verification of optical multicasting with SDN control in Sendai testbed*** - SDN controllers need to monitor transmitted data and to construct multicasting slices considering the locations of edge DCs.

OPCI network testbed @Sendai NICT branch

UCDAVIS NICT

Task 4: Multicast/multipath in SDN-controlled ON

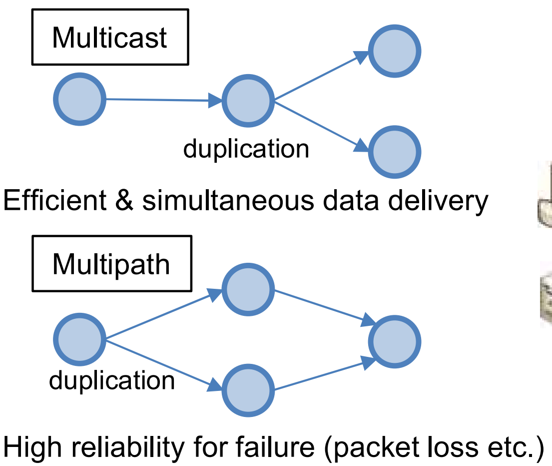
- We study how to deliver large size data for enhancing content connectivity
- 3 types of transmissions for data transfer to multiple receivers

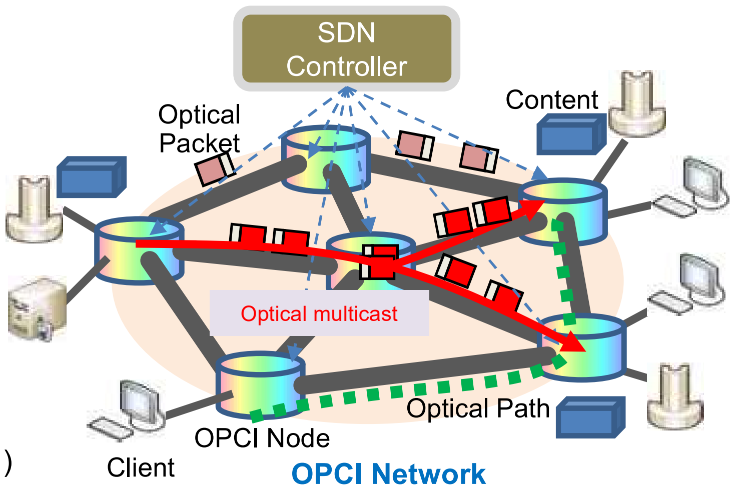
	Required bandwidth	Elapsed time	Switching load
Serial unicast	Low	Very long	Not heavy
Parallel unicast	Very large	Short	Moderate
Optical multicast	Low	Short	Not heavy

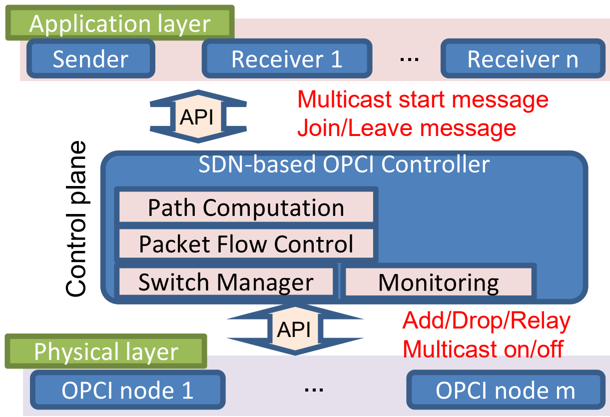
* To duplicate packets electrically is not suitable for large data transfer.

- Optical path multicast is difficult because …
  - Wavelength continuity constraint is difficult in case of multicast against unicast
  - One 10G transceiver cannot execute handshake to multiple 10G receivers simultaneously

- Proposal: Optical level multicast/multipath packet transmission
  - We developed OPCI node and demonstrate its functionality with end-to-end transmissions.
    - Optical multicast transmissions
    - Optical multipath transmissions





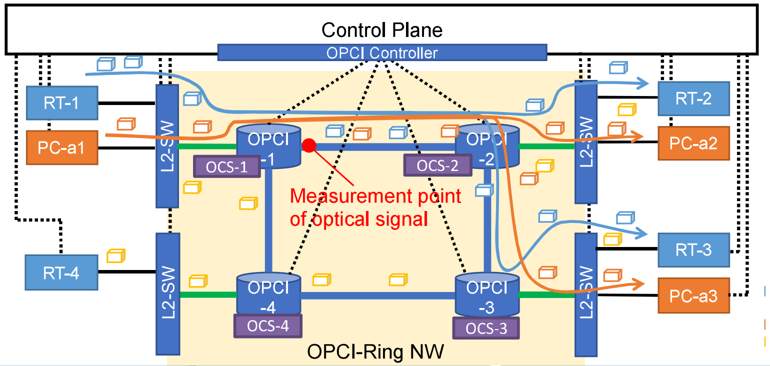


Overview of Optical Multicast Control in OPCI Network

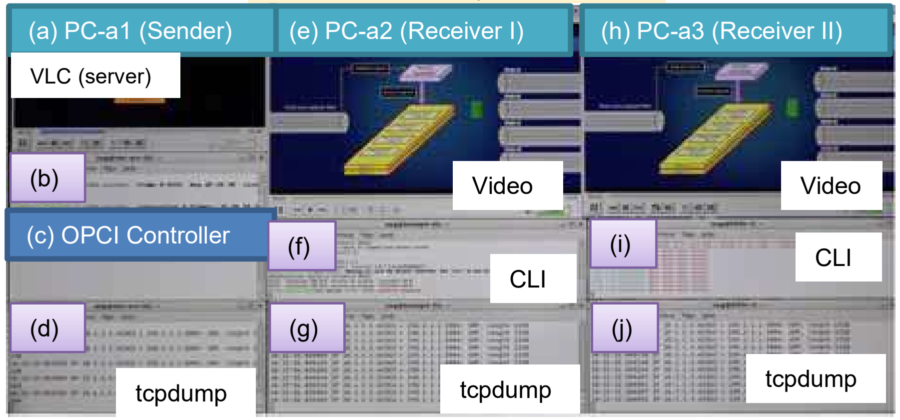
Task 4: Multiple transmissions for CC in ON

Optical Multicast for High Content Connectivity

We develop an SDN-based control for optical-multicast packet transmission and experimentally demonstrate multicast functionality by validating it using an application-layer network service for efficient content duplication in Optical Packet/Circuit Integrated (OPCI) network.



PoC



Video streaming using optical multicast

Efficient Content Delivery to multiple DCs simultaneously

Y. Hirota, S. Xu, M. Shiraiwa, Y. Awaji, M. Tornatore, B. Mukherjee, H. Furukawa, N. Wada, "Experimental Demonstration of Optical Multicast Packet Transmissions in Optical Packet/Circuit Integrated Networks," OFC, Th2A.27, Mar. 2020.

Optical Multipath for High Reliability

We develop a highly reliable optical packet transmissions using multipath and continuous repetition transmission (CRT) techniques, and experimentally demonstrate their functionalities in an Optical Packet/Circuit Integrated (OPCI) network testbed. The combination of both techniques reduces the packet loss rate as one hundredth.

Details are undisclosed

Task 5: Slice-Aware Service Restoration with Recovery Trucks for NG-MANs

Some examples of deployable recovery units (e.g., recovery trucks, FAUs)?

- Rec e *both* repa *porary relie* s going on *twork reco*

repair uni , i.e., t

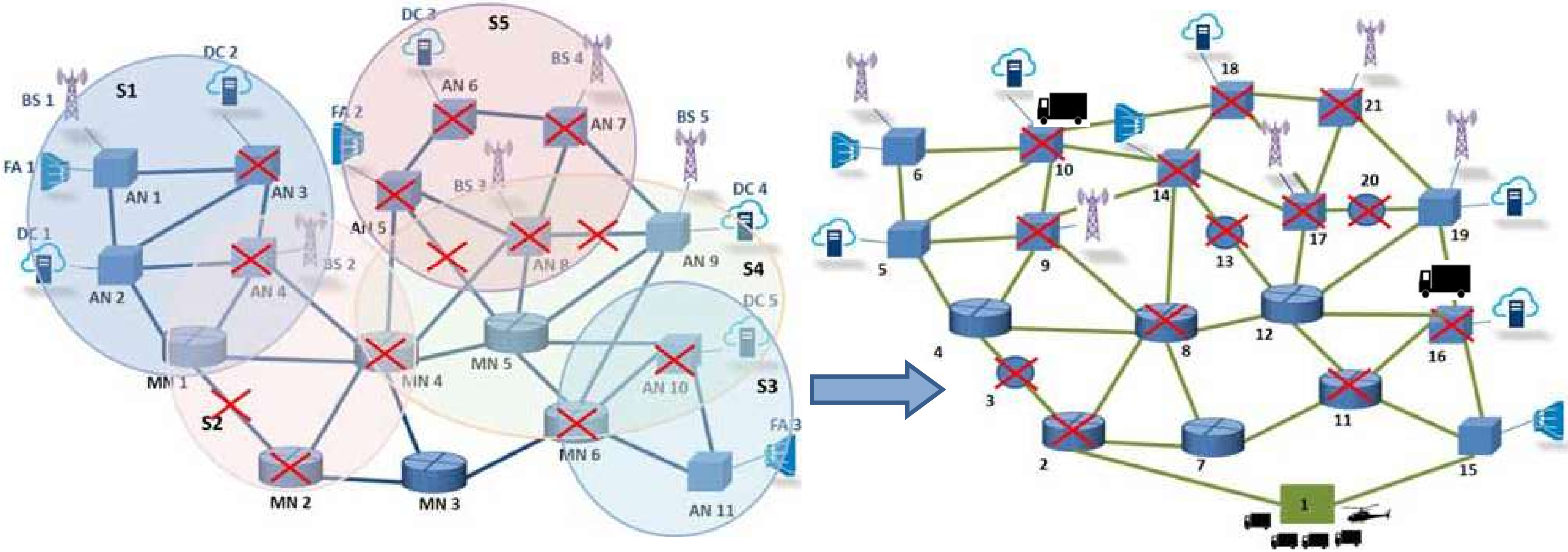
–

–

–

"Slice-aware" routing and deployment strategy to minimize downtime penalty and ensure fast restoration of important slices

Task 5: Slice-Aware Service Restoration with Recovery Trucks



Slice-aware routing and deployment strategy considerations:

	Slice-aware	Slice-unaware	Slice-aware w/o temp. relief
Cumulative penalty	29.04	41.09	47.88

Objective: Minimize service downtime penalty

➢ ***Vehicle type***

S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee,, "Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," IEEE GlobeCom 2019 (Best Paper Award)

Task 5: Dynamic Slice-Aware Service Restoration – work in progress

Focus shifting from red area to blue area

Increase in user demands - require more service units (e.g., radio resources)

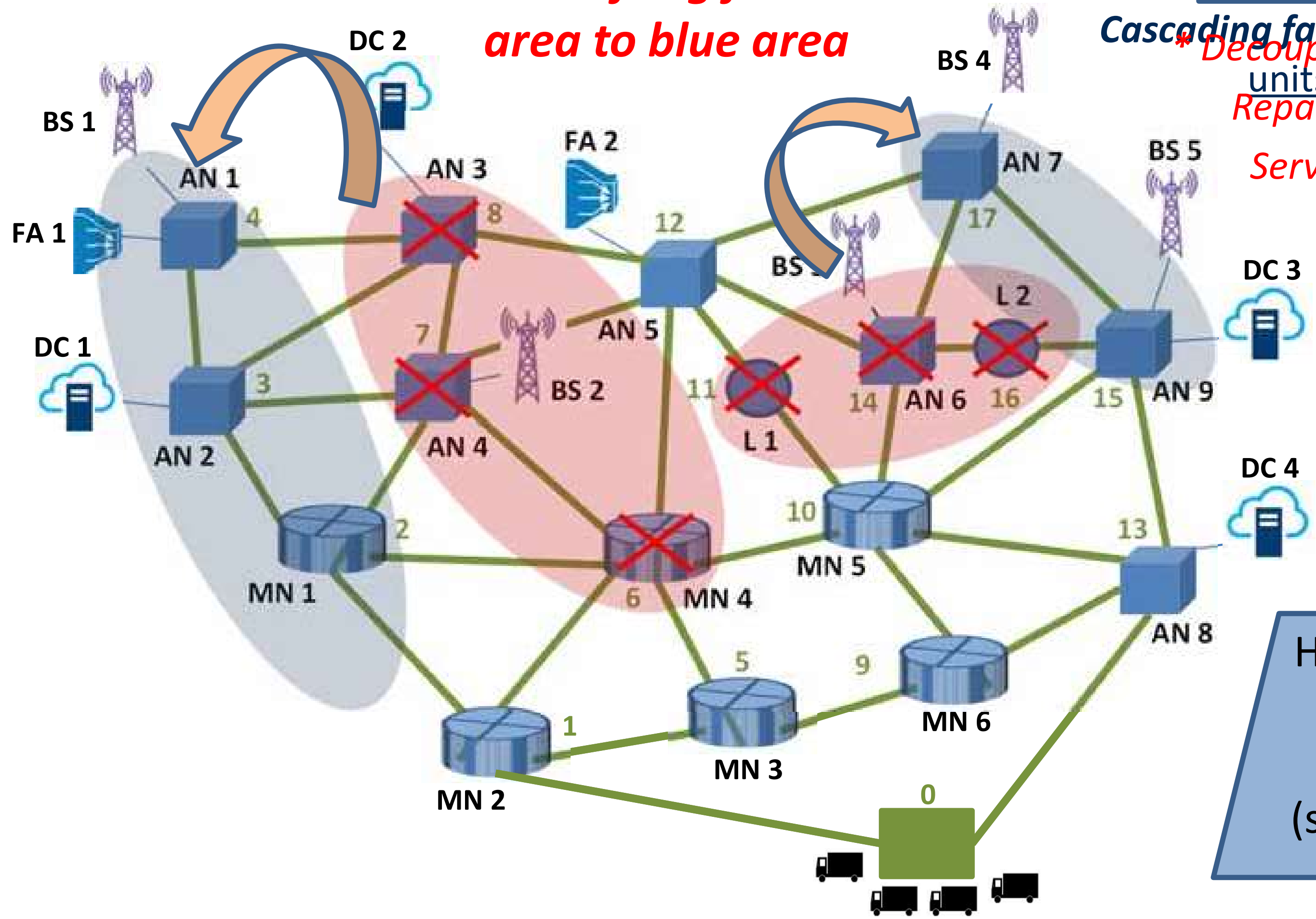
Cascading failures - require more repair units and service units

Disjoint Resource Allocation

** Decouple repair and service units **

Repair units remain deployed

Service units can be mobile



Highly applicable for disaggregated subsystems – FAU (synergy with Task 6)

S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, paper in preparation for TNSM

Task 6: Develop and exploit First Aid Unit (FAU)

Interconnection of surviving facilities and FAU to restore network connectivity

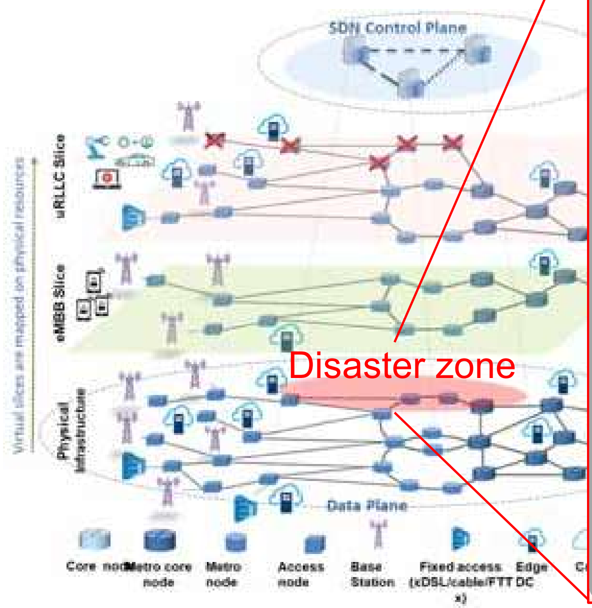
- *Impairment information collection utilizing monitoring systems*
- *Impairment-aware emergency optical network planning*
- *Development of supportive hardware and control system*

- *Impairment information collection*
  - Employ emergency optical performance monitoring (OPM) subsystem in FAU
  - Create emergency telemetry platform using outside surviving network resources (e.g., wireless/Internet)
- *Impairment-aware emergency optical network planning*
- *FAU upgrade*

Task 6 Goal: Offer Robust OPM/Telemetry in Post-disaster Recovery

- A. Emergence integration of multi-vendor OPM resource (FAU)
  - Integration of multi-vendor monitor devices FAU via open API and OpenConfig YANG model
- B. Robust OPM/Telemetry
  - Swift creation of robust OPM/Telemetry which is functionable in the degraded and unstable C/M-Plane, or an emergency C/M-plane with limited BW

Details are undisclosed



Details are undisclosed

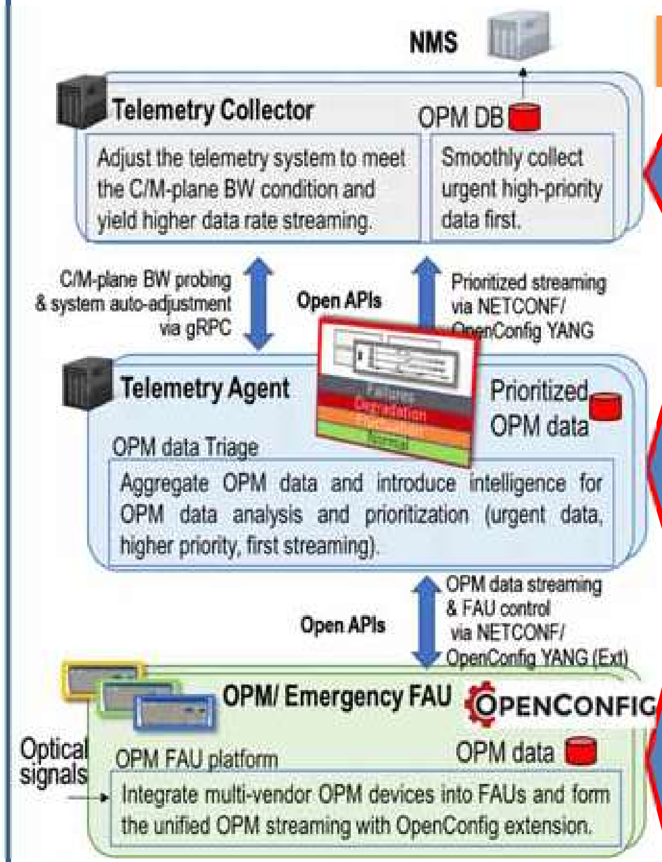
A

Various first aid units (FAUs) OPM monitors

Integration of multi-vendor monitor devices FAU via open API and OpenConfig YANG model

Task 6 (A, B): Achieve Emergency FAU integration and Robust OPM/Telemetry under C/M-plane Constraint

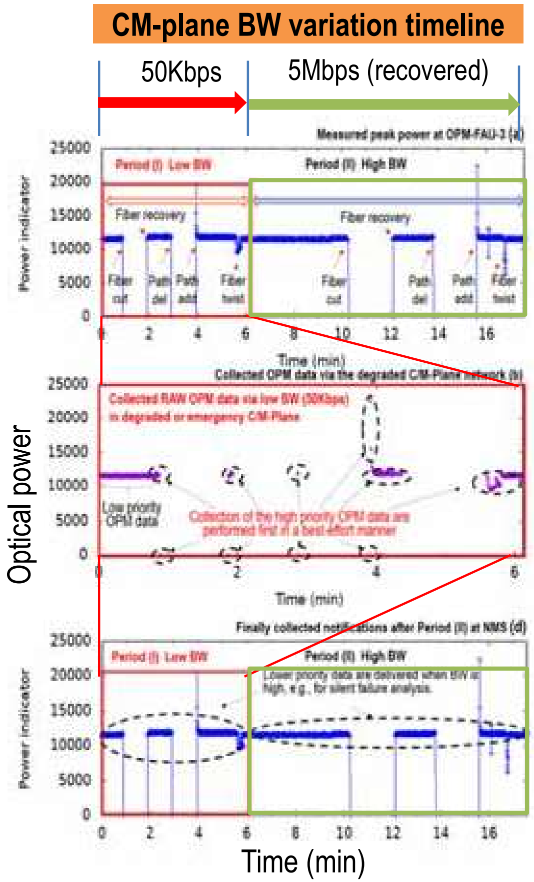
Hierarchical Open and Robust OPM/Telemetry functionable under C/M-plane BW constraint



Features

- Telemetry system self-adjustment
- OPM data Triage in degraded C/M-plane network
- FAU platform for multivendor OPM devices integration

POC experiments: validation of Robust OPM/Telemetry in degraded C/M-plane network



Self-adaptive to C/M-plane BW condition

1. Original OPM data monitored @**FAU** (as reference)
2. First correctly collected high-priority OPM data @**NMS** with limited C/M-plane BW
3. Collected all OPM data @**NMS** after CM-plane BW recovery

S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, Y. Awaji, N. Wada, and B. Mukherjee, "Quick OPM recreation and robust telemetry in emergency optical networks for early disaster recovery," European Conference on Optical Communication (ECOC) 2019.
S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, S. Ferdousi, Y. Awaji, N. Wada, and B. Mukherjee, "Emergency OPM recreation and telemetry for disaster recovery in optical networks," IEEE/OSA Journal of Lightwave Technology, vol. 38, no. 9, pp. 2656-2668, Jan. 2020.

Task 6 (C): Achieve Tight Interaction between Decentralized Telemetry and SDN Control

Details are undisclosed

Publications (Year 1)

TASK 1

- S. Savas, M. Tornatore, F. Dikbiyik, A. Yayimli, C. Martel, and Biswanath Mukherjee, "RASCAR: Recovery-Aware Switch-Controller Assignment and Routing in SDN," in **IEEE Transactions on Systems and Network Management,** vol. 15, no. 4, pp. 1222-1234, Dec. **2018**.
- R. Lourenco, S. Savas, M. Tornatore, B. Mukherjee, "Robust Hierarchical Control Plane for Transport Software-Defined Networks", in **Optical Switching and Networking**, Vol. 30, pp. 10-22, Nov. **2018** .

TASK 2

- F. Musumeci, C. Rottondi, G. Corani, S. Shahkarami, F. Cugini, and M. Tornatore, “A Tutorial on Machine Learning for Failure Management in Optical Networks,” in **IEEE/OSA Journal of Lighwave Technology,** vol. 37, no. 16, pp. 4125-4139, 15 Aug.15, **2019** (Task 2).

TASK 5

- S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, "Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," **IEEE GlobeCom 2019** (BPA).

TASK 6

- S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, Y. Awaji, N. Wada, ans B. Mukherjee, "Quick OPM Recreation And Robust Telemetry In Emergency Optical Networks For Early Disaster Recovery", European Conference on Optical Communication **(ECOC) 2019.**

Publications (Year 2)

TASK 2

- F. Musumeci, V. Venkata, Y. Hirota, Y. Awaji, S. Xu, M. Shiraiwa, B. Mukherjee, and M. Tornatore, "Transfer Learning across Different Lightpaths for Failure-Cause Identification," submitted to **ECOC, 2020**.

TASK 3

- G. Le, A. Marotta, S. Ferdousi, S. Xu, Y. Hirota, Y. Awaji, M. Tornatore, and B. Mukherjee, "Survivable Virtual Network Mapping with Content Connectivity Against Multiple Link Failures in Optical Metro Networks," **IEEE/OSA Journal of Optical Communication and Networking 2020**.
- O. Ayoub, A. Bovio, F. Musumeci, and M. Tornatore, "Survivable Virtual Network Mapping in Filterless Optical Networks," Proc., 24th International Conference on Optical Network Design and Modeling (**ONDM**), May. **2020**.
- A. Marotta, D. Cassioli, M. Tornatore, Y. Hirota, Y. Awaji, and B. Mukherjee, "Reliable Slicing with Isolation in Optical Metro-Aggregation Networks," Proc., Optical Fiber Communications Conference **OFC, 2020**.

TASK 4

- Y. Hirota, S. Xu, M. Shiraiwa, Y. Awaji, M. Tornatore, B. Mukherjee, H. Furukawa, and N. Wada, "Experimental Demonstration of Optical Multicast Packet Transmissions in Optical Packet/Circuit Integrated Networks," Proc,. Optical Fiber Communication Conference, **OFC 2020.**

TASK 5

- S. Ferdousi, M. Tornatore, F. Dikbiyik, C. U. Martel, S. Xu, Y. Hirota, Y. Awaji, and B. Mukherjee, "Joint progressive network and datacenter recovery after large-scale disasters**," IEEE Transactions on Network and Service Management, 2020.**

TASK 6

- S. Xu, N. Yoshikane, M. Shiraiwa, Y. Hirota, T. Tsuritani, S. Ferdousi, Y. Awaji, N. Wada, and B. Mukherjee, "Toward Disaster-Resilient Optical Networks with Open and Disaggregated Subsystems, " 16th International Conference on the Design of Reliable Communication Networks **(DRCN), 2020**.
- S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, S. Ferdousi, Y. Awaji, N. Wada, and B. Mukherjee, "Emergency OPM recreation and telemetry for disaster recovery in optical networks," **IEEE/OSA Journal of Lightwave Technology,** vol. 38, no. 9, pp. 2656-2668, Jan. **2020**.

Publications (Year 3)

TASK 2

- Y. Hirota, M. Shiraiwa, S. Xu, M. Tornatore, B. Mukherjee, and Y. Awaji, "Experimental Demonstration of Potential Performance Degradation by Gain Changes in Multi-core Fiber Networks and Suppression of Soft Failure using Burst-mode EDFA," **Photonics in Switching and Computing (PSC) 2021** (under review).

TASK 3

- G. Le, S. Ferdousi, A. Marotta, S. Xu, Y. Hirota, Y. Awaji, M. Tornatore, B. Mukherjee, "Reliable Provisioning for Dynamic Content Requests in Optical Metro Networks", in Proc. **OFC 2021**.
- O. Ayoub, A. de Sousa, S. Mendieta, F. Musumeci and M. Tornatore, "Online Virtual Machine Evacuation for Disaster Resilience in Inter-Data Center Networks," in **IEEE Transactions on Network and Service Management** (accepted, early access).
- L. Askari, M. Tamizi, O. Ayoub, M. Tornatore, "Protection Strategies for Dynamic VNF Placement and Service Chaining ," Proc. of **ICCCN 2021** [Invited].
- A. Marotta, D. Cassioli, M. Tornatore, Y. Hirota, Y. Awaji, and B. Mukherjee, "Reliable Slicing with Isolation in Optical Metro-Aggregation Networks", submitted to **JOCN**.
- O. Ayoub, A. Bovio, F. Musumeci and M. Tornatore, "New Technique for Survivable Virtual Network Mapping Based on Capacity Sharing against Double-Link Failures", In Proc. **CNSM 2021.**

TASK 5

- J. Rak, R. Girão-Silva, T. Gomes, G. Ellinas, B. Kantarci, M. Tornatore, "Disaster Resilience of Optical Networks: State of the Art, Challenges, and Opportunities," **Optical Switching and Networking**, **2021**.
- O. Ayoub, A. Bovio, F. Musumeci and M. Tornatore, "Survivable Virtual Network Mapping with Fiber Tree Establishment in Filterless Optical Networks," in **IEEE Transactions on Network and Service Management** (submitted, second round of review).

TASK 6

- S. Xu, K. Ishii, N. Yoshikane, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, M. Tornatore, Y. Awaji, N. Wada, S. Namiki, and B. Mukherjee, "An Approach to Large-scale Disaster-Resilient Optical Networks with Openness and Disaggregation," in Proc. **IEICE Communication System Tech. Rpt.**, Sept. **2021**.
- S. Xu, K. Ishii, N. Yoshikane, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, Y. Awaji, N. Wada, S. Namiki, and B. Mukherjee, "Towards large-scale disaster-resilient open and integrated disaggregate/legacy optical networks," in Proc. Asia Communications and Photonics Conference (**ACP2021**) , Shanghai, China, Oct. 2021. [Invited].

Submitted or planned (Year 4)

- S. Ferdousi, M. Tornatore, S. Xu, Y. Awaji, and B. Mukherjee, “Dynamic Slice-Aware Service Restoration with Recovery Trucks for Optical Metro-Access Networks," to be submitted to **IEEE Transactions on Network and Service Management**.
- G. Le, S. Ferdousi, A. Marotta, S. Xu, Y. Hirota, Y. Awaji, S. S. Savas, M. Tornatore, B. Mukherjee, “Reliable Provisioning with Degraded Service using Multipath Routing from Multiple Datacenters for Dynamic Content Requests in Optical Metro Networks,” to be submitted to **IEEE/OSA Journal of Optical Communications and Networking**.
- S. Xu, Y. Hirota, M. Shiraiwa, M. Tornatore, Y. Awaji, and B. Mukherjee, “Achieve instinctive local reaction and chained network-wide SDN control to failures in multi-vendor multi-domain post-disaster recovery,” to be submitted to **OFC 2022**.
- Q. Zhang, O. Ayoub, J. Wu, F. Musumeci, G. Li and M. Tornatore, "Progressive Slice Recovery with Guaranteed Slice Connectivity after Massive Failures," submitted to **IEEE/ACM Transaction on Networking**, first round of review, minor revision.

Summary of dissemination

- 23 publications to date [11 journals, 12 in conference]
  - 14 publications [5 journals, 9 conferences] (*joint*)
  - 9 [6 journals, 3 conferences] (*single partner*)

  +4 in preparation (3 *joint collaboration*)
- Invited talks:
  - DRCN 2020, ECOC 2020, OECC 2019, OFC 2019, OMTA 2021, ACP 2021, ECOC 2021 (tutorial) …
- *Other activities*: PI Tornatore is lead Guest Editor of a new yearly special issue of IEEE Transaction on Network and Service Management on "Design of Reliable Communication Networks"

END

Thanks for your attention!!