Cloud-Carrier Cooperation for Efficient and Reliable Optical Networks

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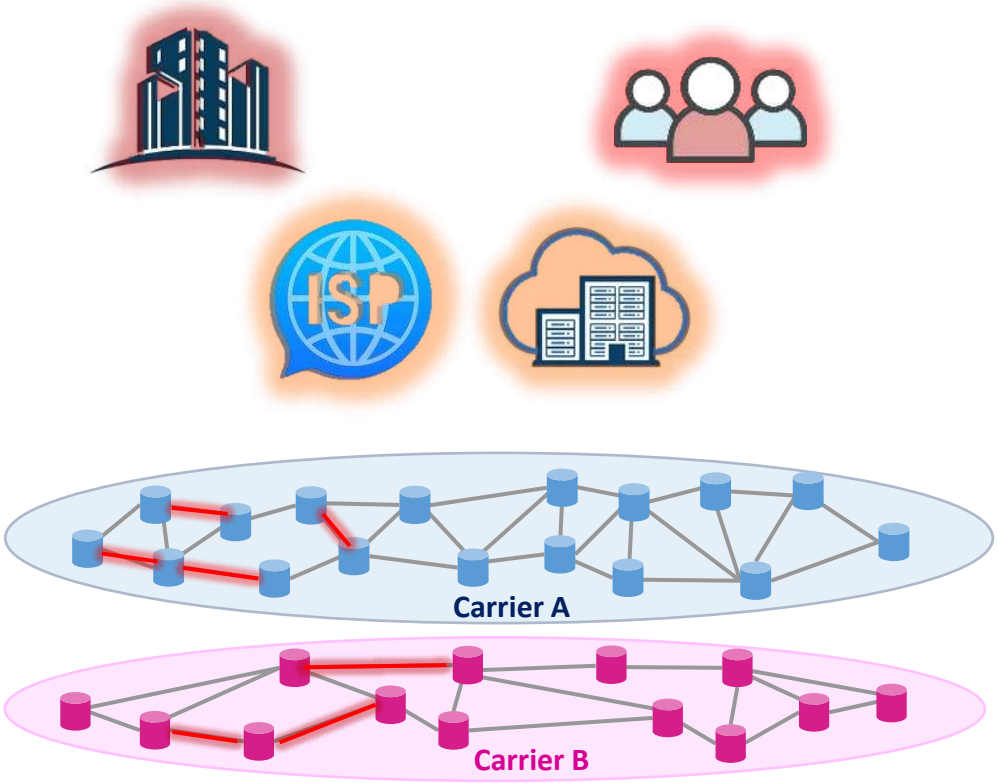
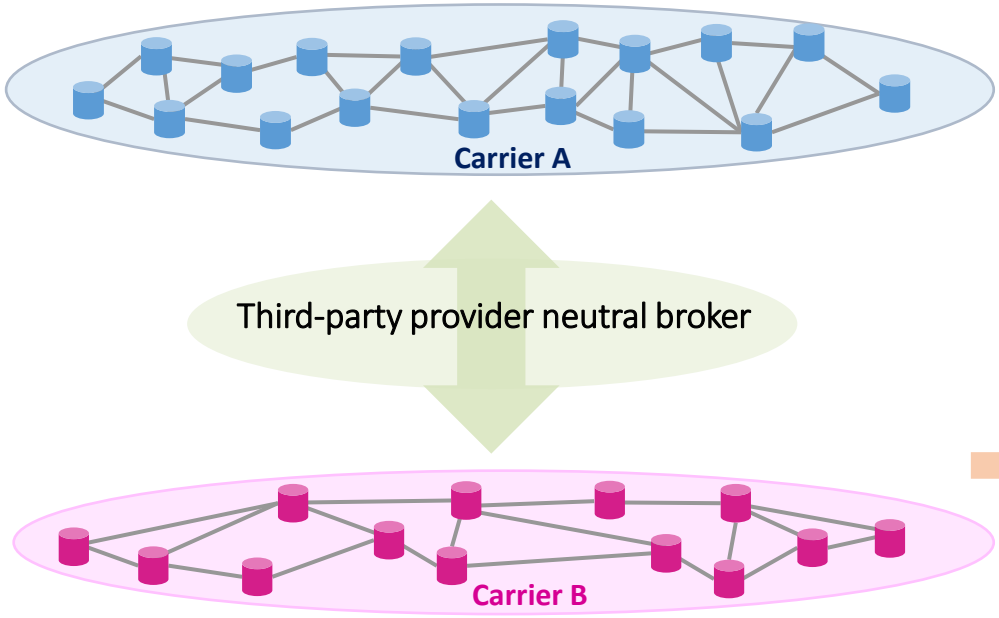
https://arstechnica.com/information-technology/2014/07/how-comcast-became-a-powerful-and-controversial-part-of-the-internet-backbone/



https://arstechnica.com/information-technology/2014/07/how-comcast-became-a-powerful-and-controversial-part-of-the-internet-backbone/

Provider Neutral Exchange (PNE)



!POLICY!

Confidential Information

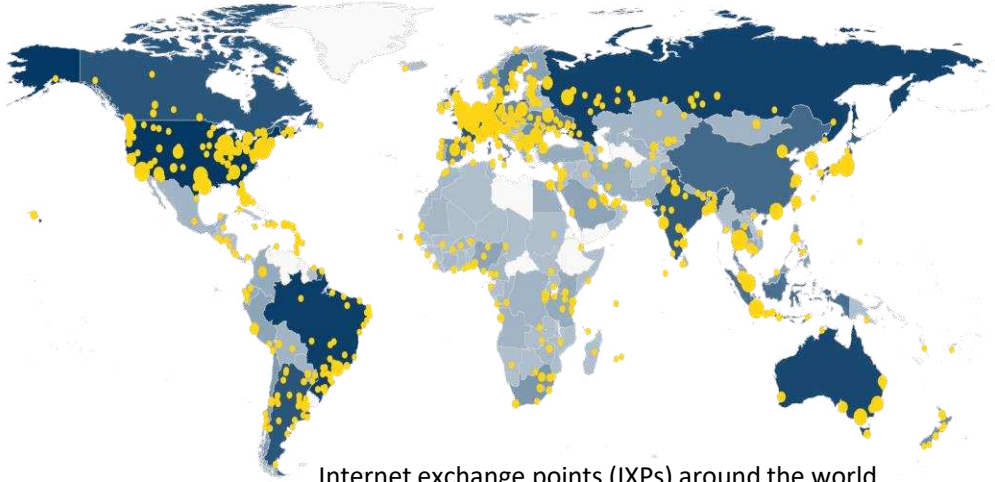
Cooperation possible?

Uncoordinated planning

Delayed service restoration

Inefficient resource utilization

Resource sharing possible?



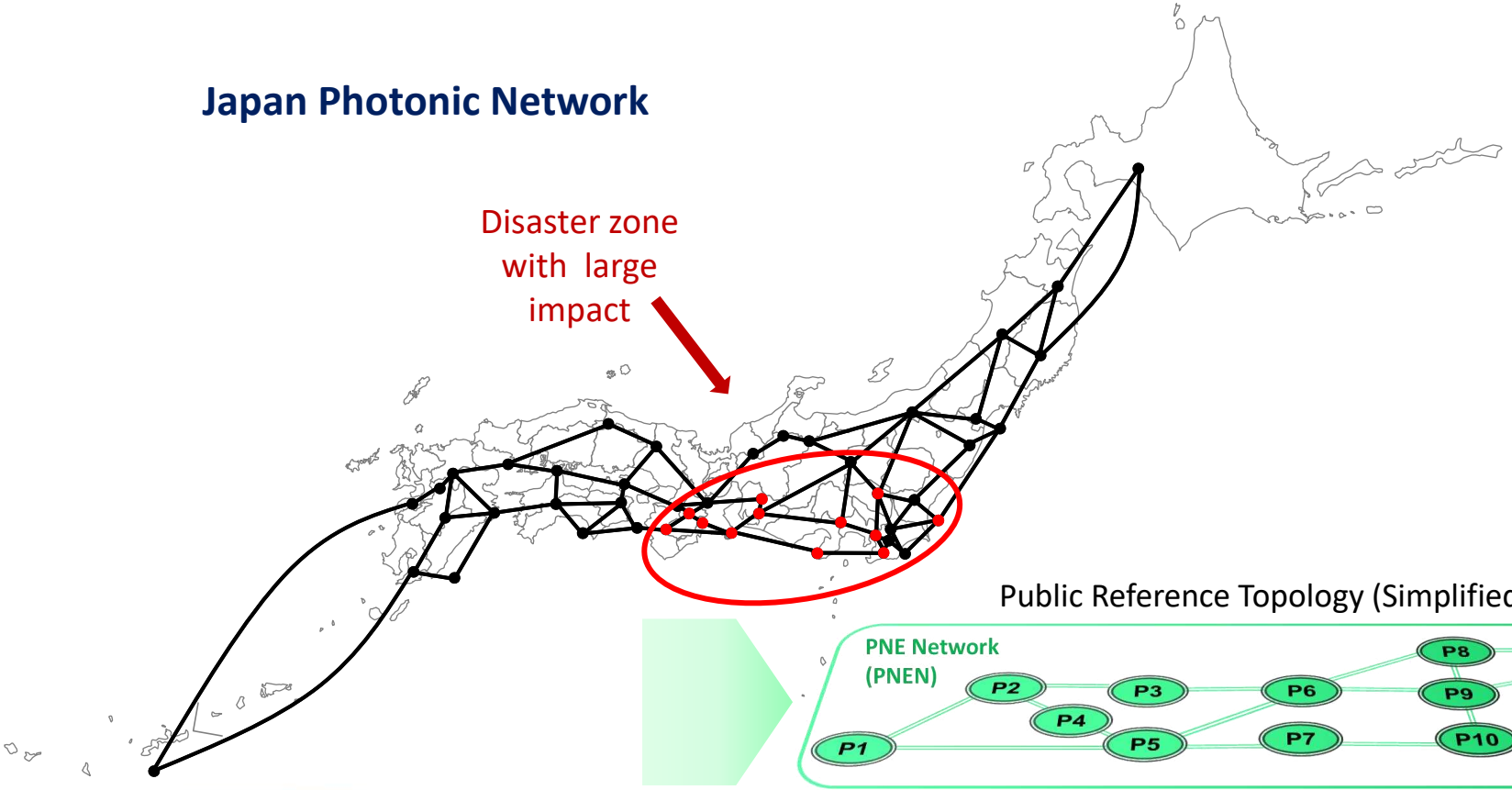
Internet exchange points (IXPs) around the world

New 125 carrier-neutral IXPs across the US to have regional hub cities (middle mile program)

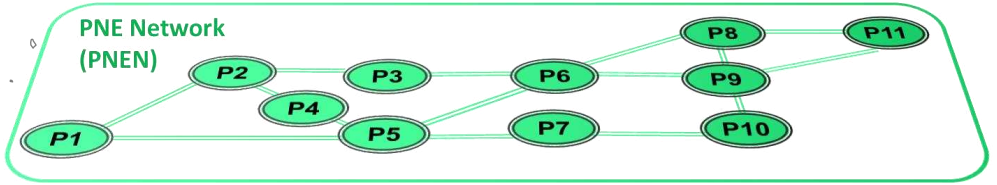
These IXPs can be good candidates to play the role of PNE by offering traffic exchange capabilities and enabling cooperation among carriers and other entities

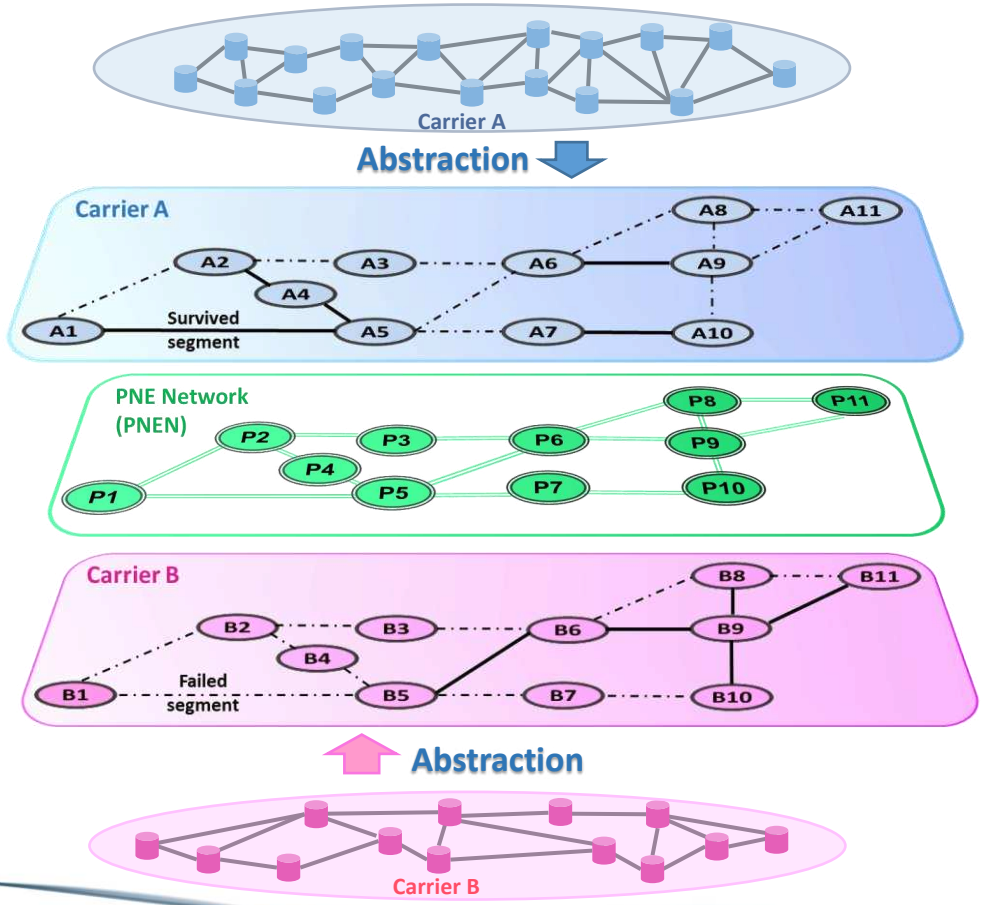
https://en.wikipedia.org/wiki/List_of_Internet_exchange_points
https://www.pch.net/ixp/dir
https://www.internetexchangemap.com/#/
https://connectednation.org/programs/internet-exchange-points

Japan Photonic Network



Public Reference Topology (Simplified)

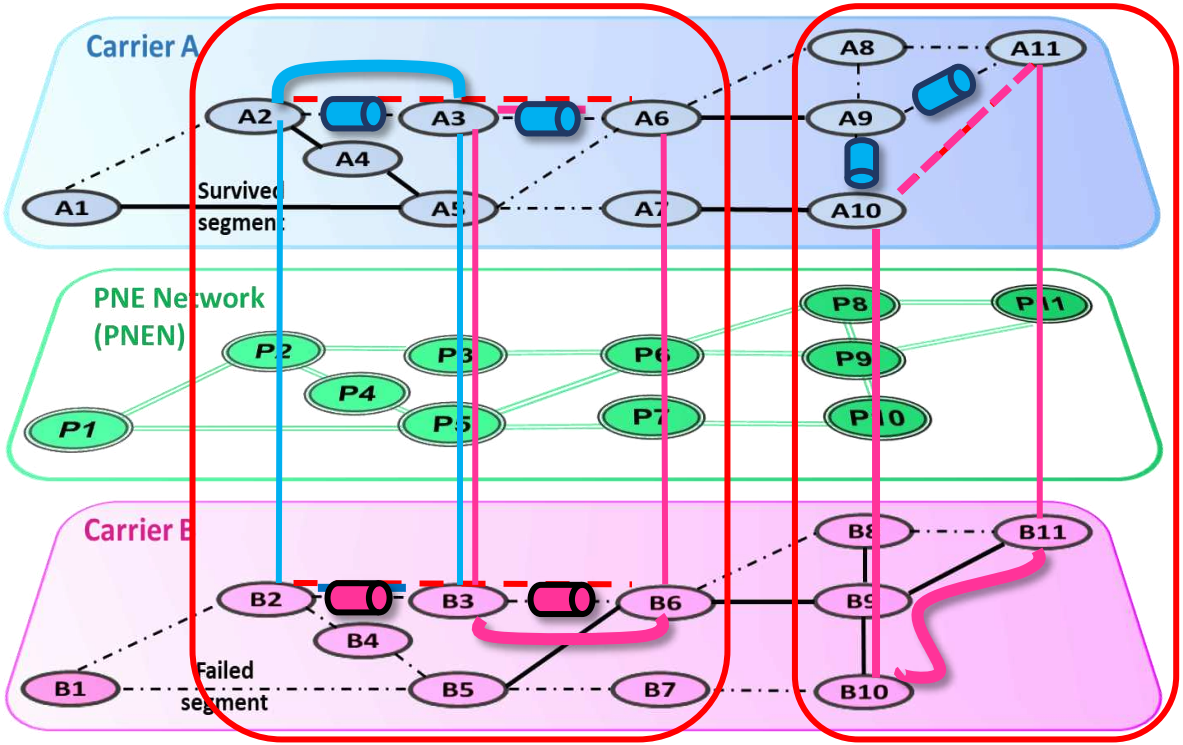


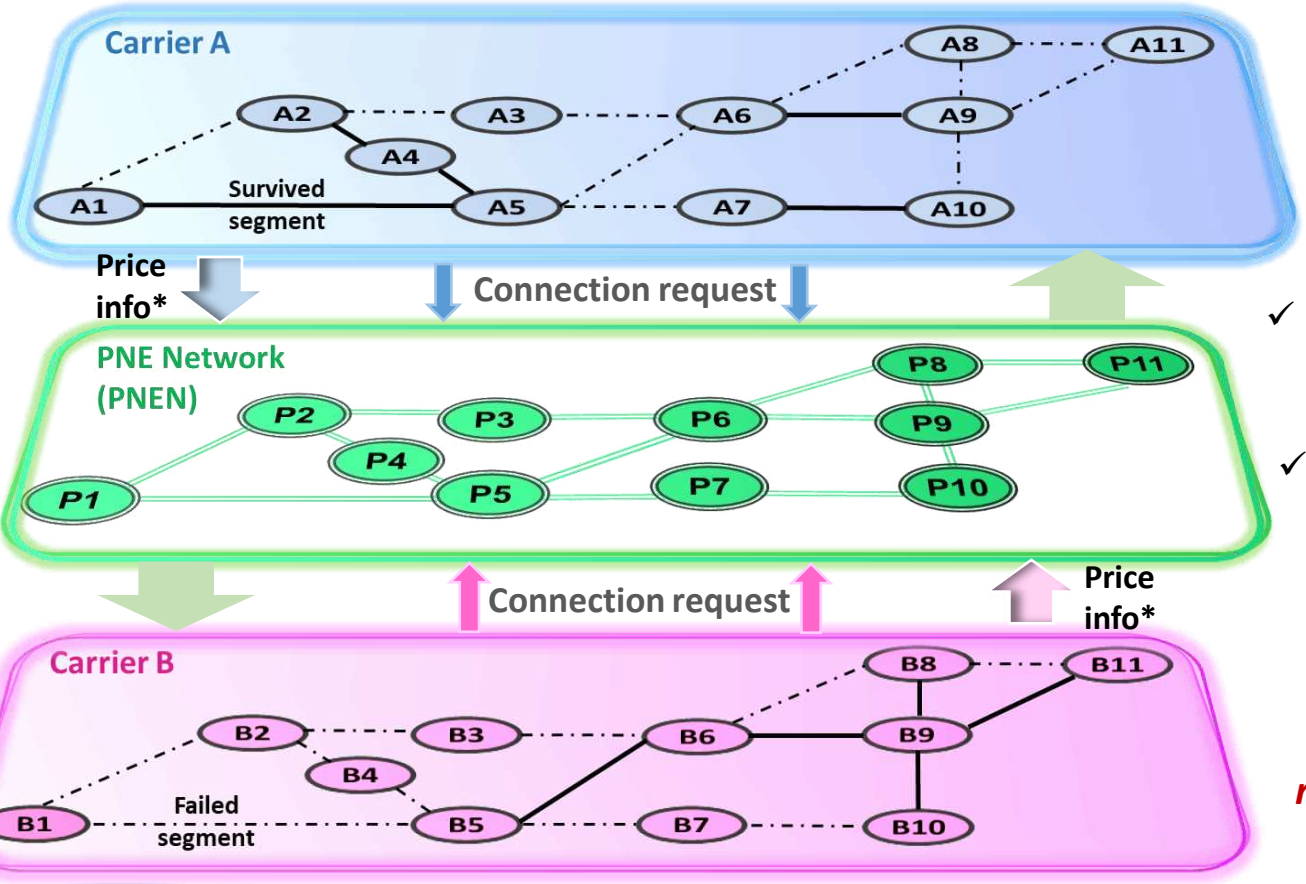


No need to share confidential information such as topology details, failure/damage info, resource availability, bandwidth/capacity, etc.

**a segment can represent single or multiple node(s)/link(s) in the actual physical carrier topology*

Multi-Carrier Cooperation





- ✓ Standalone recovery time *vs* service restoration time
- ✓ Recovery cost *vs* paying for connection service

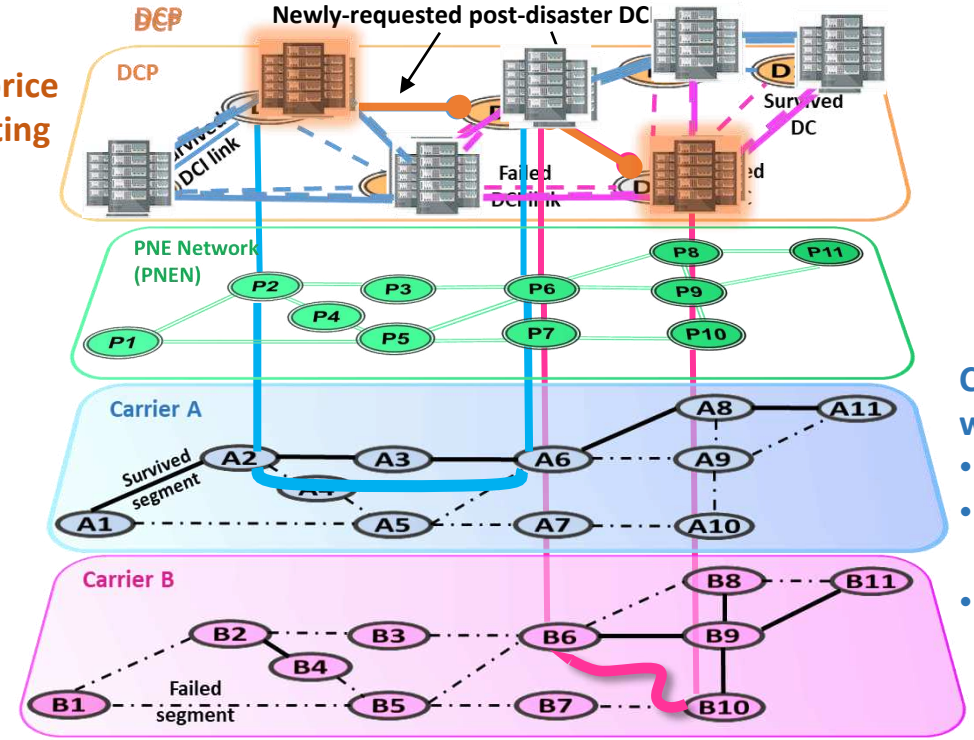
Incentive and need based resource sharing

**connection price for each PNE node pair*
**Carriers add extra price for failed links which need to be repaired*

Single DCP

Cloud-Carrier Cooperation

DCPs consider connection price from carriers while generating connection requests



Carriers provide feedback - whether a request is:

- immediately acceptable,
- acceptable with *k* unit restoration time, or
- rejected

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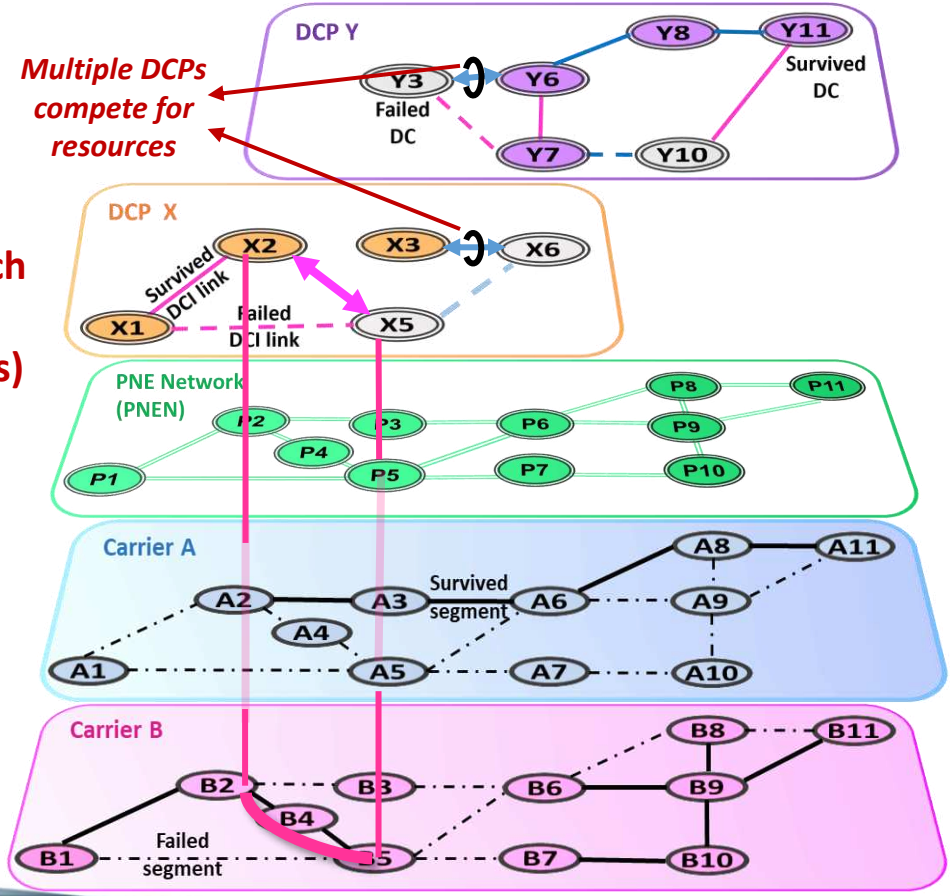
Multi DCP

How to best fit/match DCP *demands* (connection requests) to carrier *supplies* (available network resources)?

Multiple DCPs compete for resources



Each DCP generates multiple sets of candidate DCI connection requests to offer flexibility to carriers

PNE performs balanced resource-driven demand matching

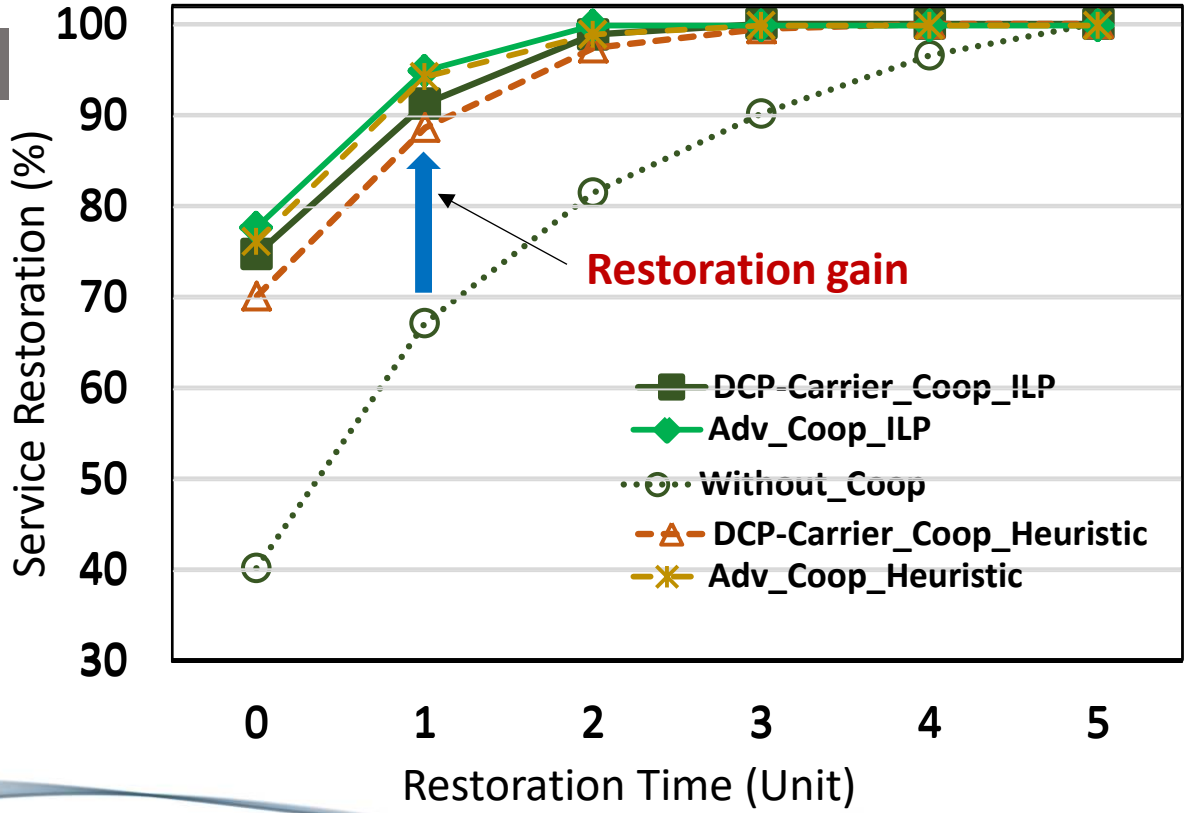
Carriers generate a score for each request based on priority, resource availability, and recovery planning

Cloud-Carrier Cooperation

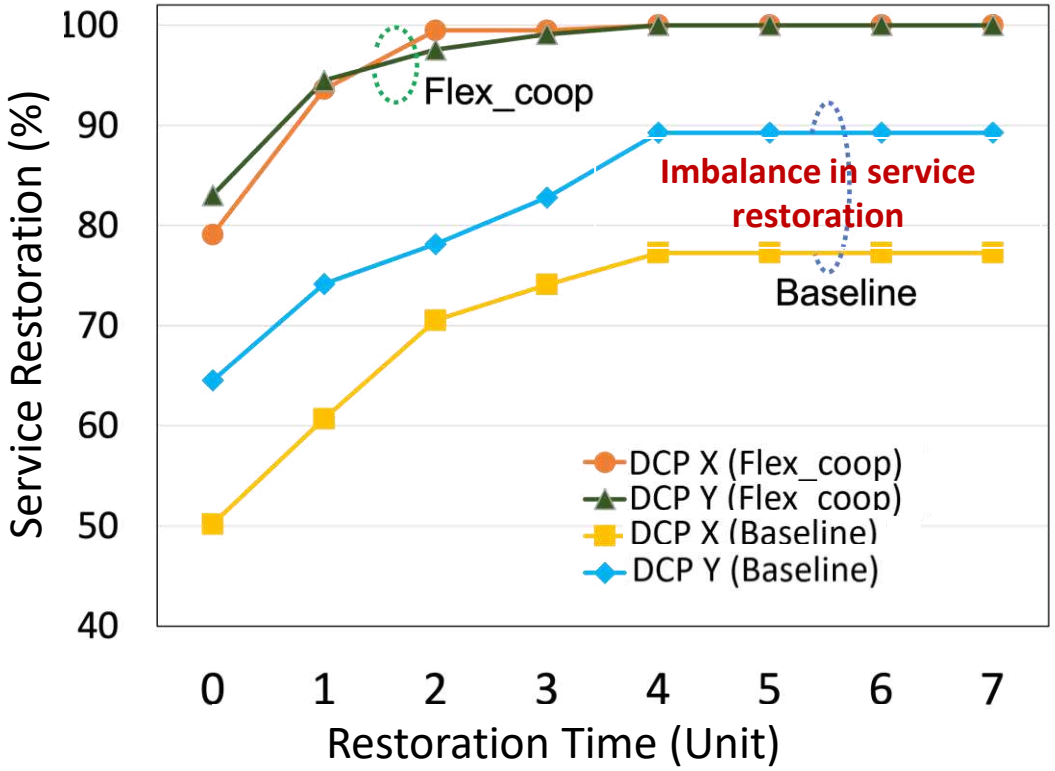
Compared schemes

- Service restoration *without* cloud-carrier cooperation (DCP generates connection requests without any carrier info)
- Service restoration *with* cloud-carrier cooperation (DCP generates connection requests based on price info from carriers)
- Service restoration *with* Advanced cloud-carrier cooperation (carriers engage in further cooperation if needed)
- Service restoration *with* flexible cloud-carrier cooperation (DCPs generate multiple sets of connection requests for carriers)

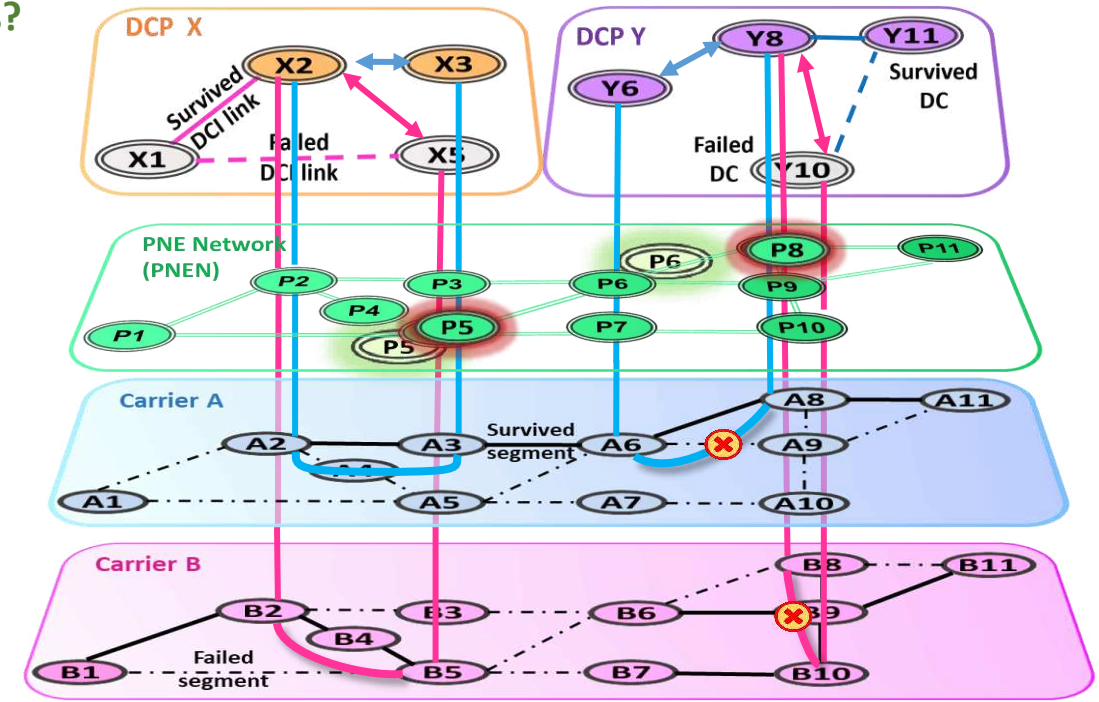
Single DCP

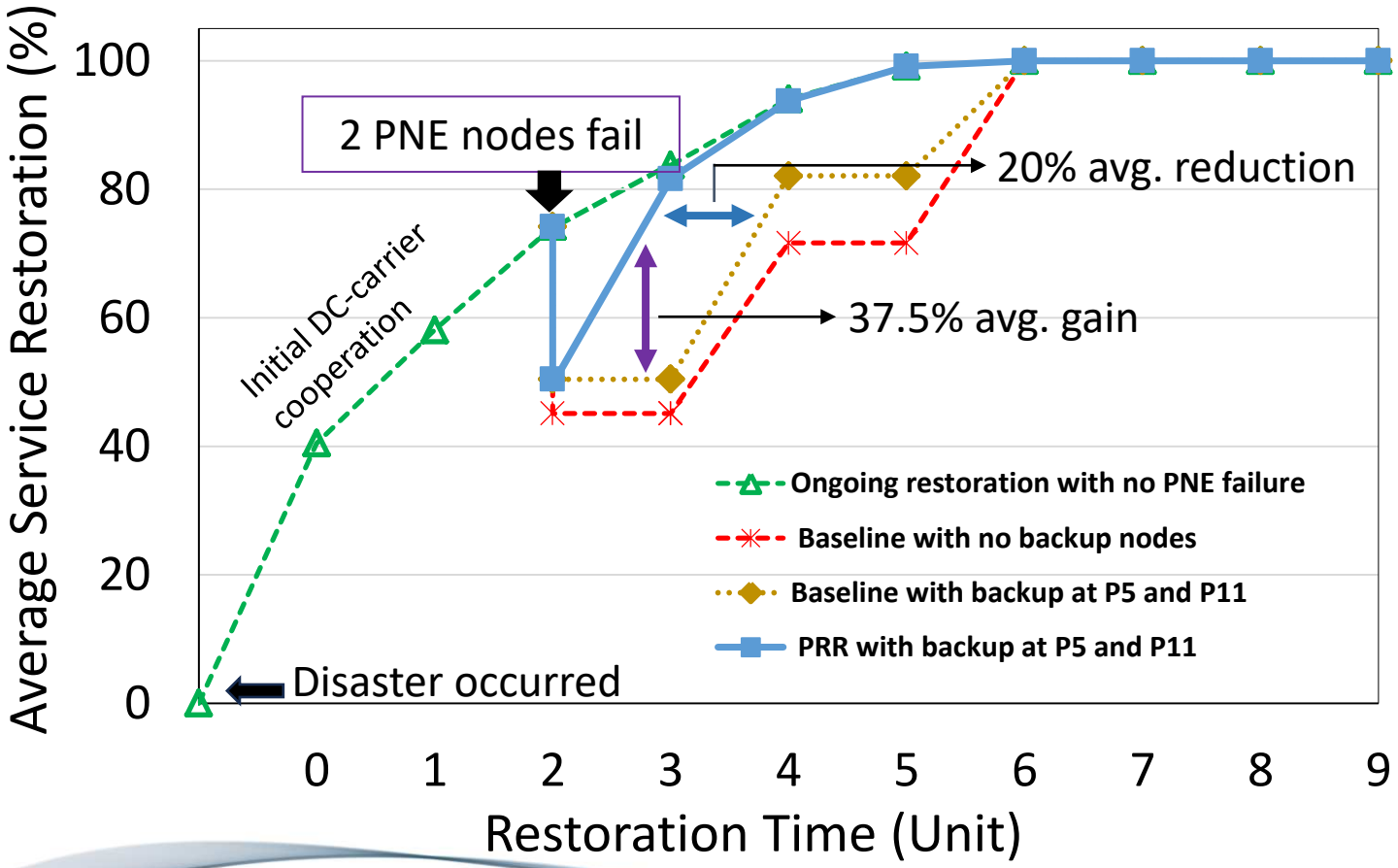

Service Restoration (%)
100
90
80
70
60
50
40
30
0
1
2
3
4
5
Restoration Time (Unit)
Restoration gain
DCP-Carrier_Coop_ILP
Adv_Coop_ILP
Without_Coop
DCP-Carrier_Coop_Heuristic
Adv_Coop_Heuristic

Multi DCP

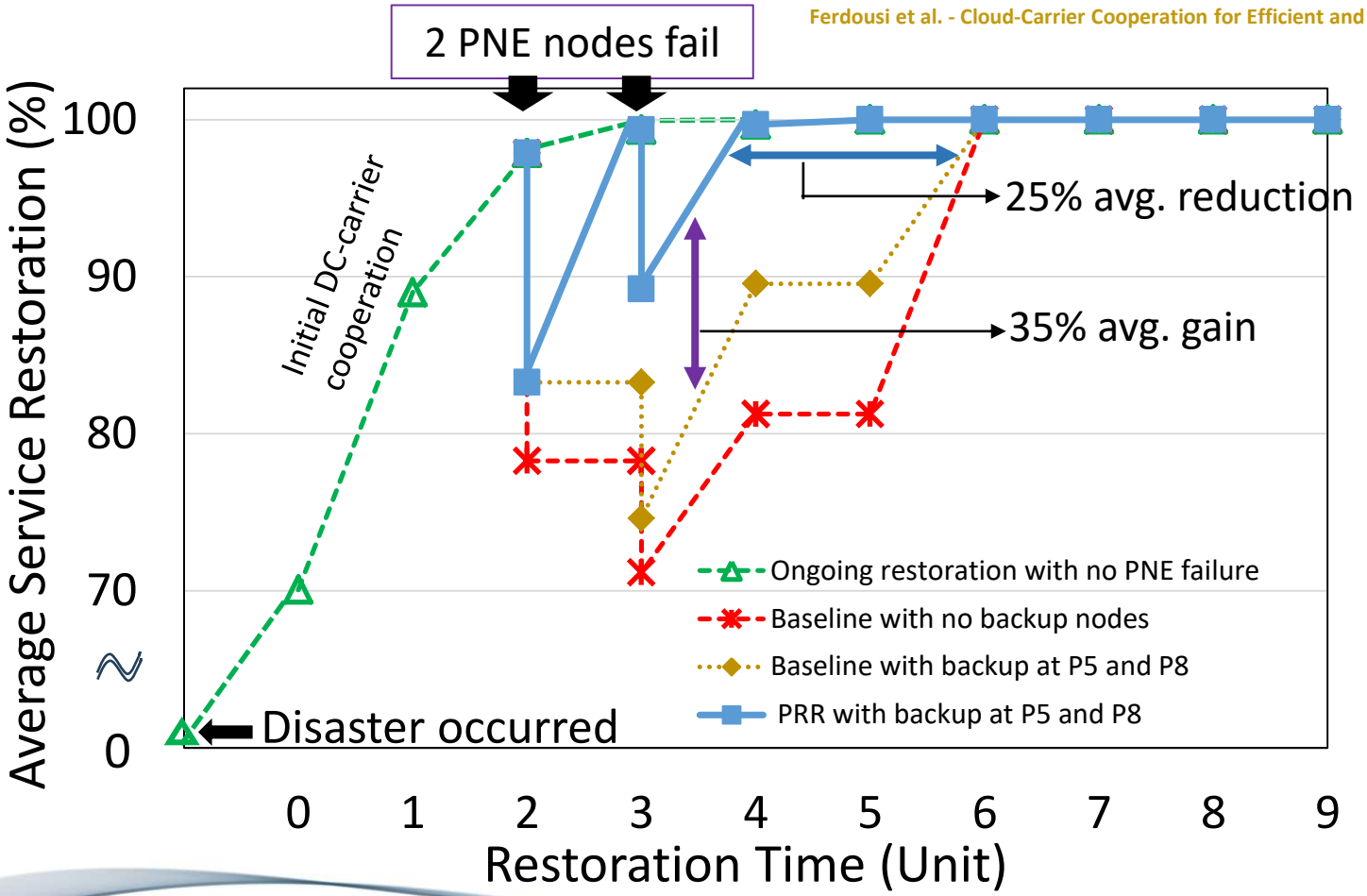

Service Restoration (%)
100
90
80
70
60
50
40
Flex_coop
Imbalance in service restoration
Baseline
DCP X (Flex_coop)
DCP Y (Flex_coop)
DCP X (Baseline)
DCP Y (Baseline)
0
1
2
3
4
5
6
7
Restoration Time (Unit)

What if PNE site fails?





Concurrent PNE-Node Failure



Sequential PNE-Node failure

Network-Cloud Ecosystem

FL model for privacy preserving

Monitoring and Assessment

Decentralized End-to-End C/M-Plane

Decentralized End-to-End C/M Plane

DLT, smart contracts

DCP Y C/M Plane

Cloud-Carrier Cooperation

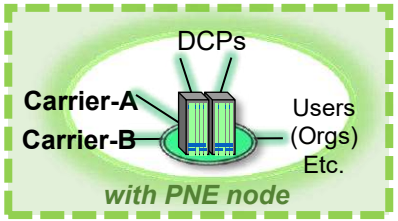
DCP Y

DCP X C/M Plane

DCP X

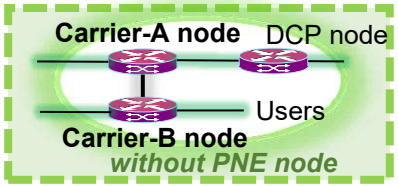
Connection supported by Carrier A
Connection supported by Carrier B

Indirect interconnection



PNE site

Direct interconnection



PNE site

PNE C/M Plane

PNE Network (PNEN)

P1 P2 P3 P4 P5 P6 P7 P8 P9 P10 P11

PNE Business Model

Carrier A C/M Plane

Carrier A

Carrier Cooperation

Carrier B C/M Plane

Carrier B

Failure Detection and Management

ML/AI based solutions with Testbed data

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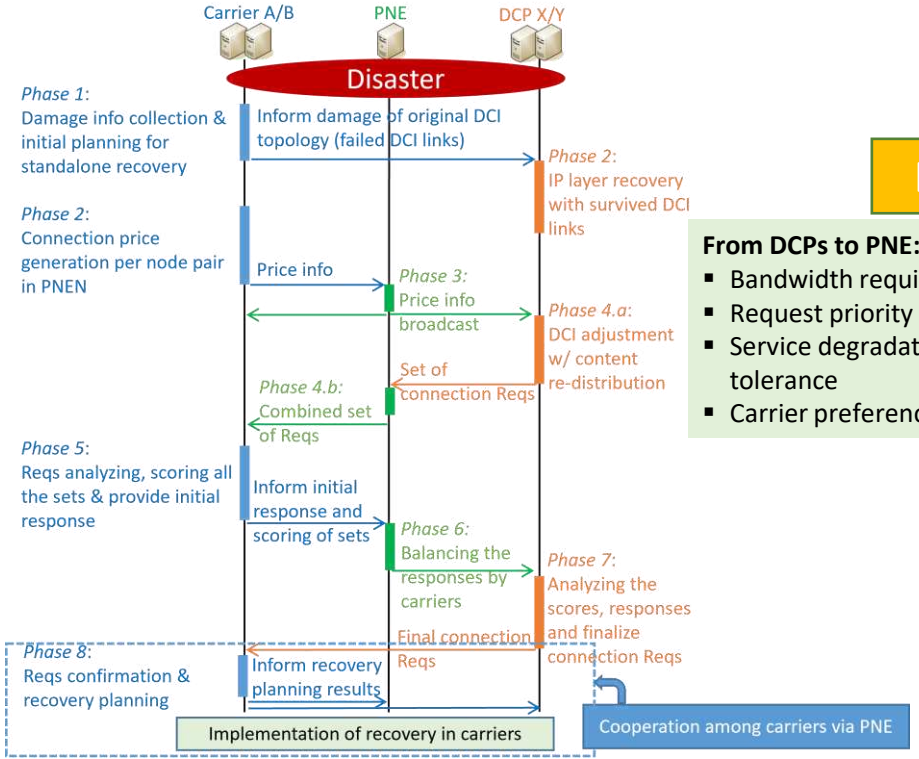
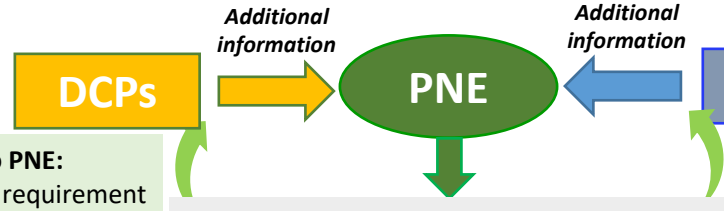




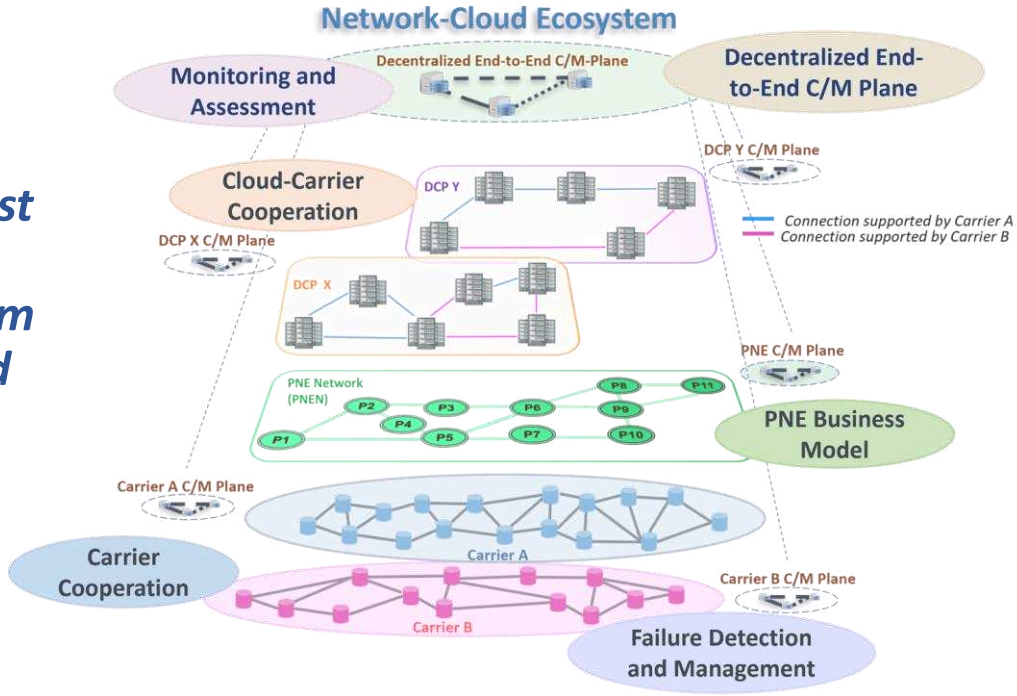
From DCPs to PNE:
- Bandwidth requirement
- Request priority level
- Service degradation tolerance
- Carrier preference

From PNE to Carriers and DCP:
- Optimized logical topology for each DCP
- Approved bandwidth allocation per request
- Assigned restoration schedule
- Fairness adjustment to balance competing requests

From Carriers to PNE:
- Abstracted topology
- Available bandwidth on each link
- Connection price

- S. Xu, N. Yoshikane, M. Shiraiwa, T. Tsuritani, X. Zhang, Y. Awaji, and N. Wada, “A novel carrier-cooperation scheme with an incentive to offer emergency lightpath support during disaster recovery,” Photonic Network Communications, vol. 40, no. 3, July 2020.
- S. Sahoo, S. Xu, S. Ferdousi, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “Datacenter-Carrier Cooperation over Optical Networks during Disaster Recovery,” Optical Fiber Communication Conference (OFC), San Diego, California, USA, Mar. 2022.
- S. Xu, K. Ishii, N. Yoshikane, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, M. Tornatore, Y. Awaji, S. Namiki, and B. Mukherjee, “Enhancement of Network-Cloud Ecosystem Resilience with Openness Disaggregation and Cooperation [Invited],” Optical Fiber Communication Conference (OFC), San Diego, California, USA, Mar. 2023.
- S. Xu, K. Ishii, N. Yoshikane, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, M. Tornatore, Y. Awaji, S. Namiki, and B. Mukherjee, “Investigation of Disaster-Resilient Network-Cloud Ecosystem with Open Disaggregation and Cooperation Technologies [Invited],” Cyber Physical Systems enabled by Sensing/Network/AI and Photonics Conference (CPS-SNAP), April 2023.
- S. Xu, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “A Novel Strategy of Carrier Cooperation with Coordinated Scheduling for Swift Failure/Disaster Recovery,” Optical Network Design and Modelling (ONDM), Coimbra, Portugal, May 2023.
- S. Sahoo, S. Xu, S. Ferdousi, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “Strategic Cooperation among Datacenter Providers and Optical-Network Carriers for Disaster Recovery,” *IEEE Global Communications Conference (Globecom)*, Rio de Janeiro, Brazil, Dec. 2022.
- S. Xu, K Ishii, N. Yoshikane, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, M. Tornatore, Y. Awaji, S. Namiki, and B. Mukherjee, “Resilience enhancement in open network–cloud ecosystems through disaggregation and cooperation [Invited],” IEEE/ OSA Journal of Optical Communications and Networking (JOCN), vol. 16, no. 2, pp. A105−A117, Jan. 2024.
- S. Xu, S. Sahoo, S. Ferdousi, N. Yoshikane, M. Shiraiwa, Y. Hirota, M. Tornatore, T. Tsuritani, Y. Awaji, and B. Mukherjee, “Scheme of carrier cooperation with coordinated scheduling for faster and lower-cost failure/disaster recovery,” IEEE/ OSA Journal of Optical Communications and Networking (JOCN), vol. 16, no. 5, pp. B45−B59, May 2024.
- S. Sahoo, S. Ferdousi, S. Xu, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “DC-Carrier Cooperation for Rapid Restoration against PNE-Node Failure in Optical Networks,” Optical Fiber Communication Conference (OFC), San Diego, California, USA, Mar. 2024.

- Z. Li, M. Ibrahimi, Y. Zhao; B. Mukherjee, J. Zhang, and M. Tornatore , “Content Evacuation in Inter-DC Optical Networks Under Post-Disaster Cascading Failures ,” Optical Network Design and Modelling (ONDM), Madrid, Spain, May 2024.
- S. Sahoo, S. Xu, S. Ferdousi, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “Service Restoration in Multi-Entity Networking Ecosystem: How to Cooperate?” IEEE Communications Magazine, vol. 63, no. 3, Dec. 2024.
- Y. Hirota, Y. Goto, H. Furukawa, “Machine Learning-based Spectrum Resource Assignment and End-to-End Path Reconfiguration for Flexible Optical Networks,” 24th International Conference on Transparent Optical Networks (ICTON), Bari, Italy, July 2024. (Invited).
- S. Xu, S. Sahoo, N. Yoshikane, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, M. Tornatore, Y. Awaji, and B. Mukherjee, “A Distributed-Ledger-based Multi-Entity Cooperation Platform for Network-Cloud Recovery,” Optical Network Design and Modelling (ONDM), Madrid, Spain, May 2024.
- G. Le, V. T. Hoang, S. Ferdousi, A. Marotta, S. Xu, Y. Hirota, Y. Awaji, M. Tornatore, and B. Mukherjee, "Reliable Provisioning of Low-Latency and High-Bandwidth Extended Reality Live Streams," in IEEE Journal on Selected Areas in Communications (JSAC), vol. 43, no. 5, pp. 1755-1766, May 2025.
- S. Sahoo, S. Xu, S. Ferdousi, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “Post-disaster cloud-service restoration through datacenter-carrier cooperation,” IEEE/ OSA Journal of Optical Communications and Networking (JOCN), vol. 17, no. 8, pp. 700−712, Aug. 2025.
- S. Xu, A. Mitrovska, S. Sahoo, Y. Hirota, B. Shariati, Y. Yoshida, P. Safari, J. K. Fischer, R. Freund, H. Furukawa, K. Akahane, S. Ferdousi, M. Tornatore, Y. Awaji and B. Mukherjee, “Resilience enhancement of optical network-cloud ecosystems with dataspace framework and multi-entity cooperation (invited),” in Proc. IEEE Summer Topicals2025, WA3.3, July 2025.
- F. S. Abkenar, R. Kalkunte, V. V. Garbhapu, S. Ferdousi, Y. Hirota, S. Xu, M. Shiraiwa, A. Attarpour, M. Tornatore, Y. Awaji, and B. Mukherjee, “Federated Privacy-Preserving Strategy for Generalizing Soft-Failure Localization in Multi-Carrier Optical Networks,” Optical Network Design and Modelling (ONDM), Pisa, Italy, May 2025.
- S. Xu, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, M. Tornatore, Y. Awaji, and B. Mukherjee, “Multi-entity cooperation platform facilitating network-cloud recovery,” IEEE/ OSA Journal of Optical Communications and Networking (JOCN), vol. 17, no. 9, pp. D53−D72, Sept. 2025.
- S. Xu, N. Yoshikane, X. Zhang, S. Sahoo, S. Ferdousi, M. Shiraiwa, Y. Hirota, T. Tsuritani, S. Suzuki, M. Tornatore, Y. Awaji and B. Mukherjee, “A novel use case of future multi-carrier interconnection—swift and low-cost disaster recovery via carrier cooperation,” In Proc. PIERS2025, Chiba, Japan, Nov. 2025.

Conclusion

Cloud-carrier cooperation is not just a networking solution – it is a promising network-cloud ecosystem framework for future reliable and secure communication