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A Novel Strategy of Carrier Cooperation with Coordinated Scheduling for Swift Failure/Disaster Recovery

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Abstract—**Large-scale network-cloud ecosystems are fundamental infrastructures to support future 5G/6G services, and their resilience is a primary societal concern for the years to come. Differently from a single-entity ecosystem (in which one entity owns the whole infrastructure), in multi-entity ecosystems (in which the networks and datacenters are owned by different entities) cooperation among such different entities is crucial to achieve resilience against large-scale failures. Such cooperation is challenging since diffident entities may not disclose confidential information, e.g., detailed resource availability. To enhance the resilience of multi-entity ecosystems, carriers are important as all the entities rely on carriers' communication services. Thus, in this study we investigate how to perform carrier cooperative recovery in case of large-scale failures/disasters. We propose a two-stage cooperative recovery planning by incorporating a coordinated scheduling for swift recovery. Through preliminary numerical evaluation, we confirm the potential benefit of carrier cooperation in terms of both recovery time and recovery cost/burden reduction.**

Keywords—ecosystems, carrier cooperation, recovery, coordinated scheduling, lightpath support

I. INTRODUCTION

To accommodate the growing demand for 5G/6G services the underlying telecom networks, the Internet, and datacenters (DCs) form large-scale network-cloud ecosystems (ecosystems for short) hosting these services. These ecosystems must be resilient to provide safe support to critical services. In networks, telecom carriers (carriers for short) have already investigated sophisticated protection, restoration and post-disaster recovery schemes [1]–[9], etc. More recently, to cope with scenarios of large-scale failures (e.g., due to disasters), joint network and DC recovery including scheduling [10][11] have been investigated, showing the benefit of coordinated network-DC repair in terms of service restoration and resource utilization. These schemes are based on complete knowledge of network and DC infrastructures, assuming that they are owned by a single entity. Meanwhile, for the (quite common) cases in which the ecosystems are owned by different entities [e.g., carriers, DC providers, and Internet Service Providers (ISPs)], cooperation among entities is crucial. However, such cooperation becomes more challenging, as these entities may not be willing to disclose confidential information, e.g., detailed resource availability. For large-scale disaster recovery, we have conducted some preliminary studies on carrier cooperation [12] and DC-carrier cooperation [13] aided by a third-party entity, *provider neutral exchange* (*PNE*), to show the benefits and viability of multi-entity cooperation without violating confidentiality.

In multi-entity ecosystems, the resilience of carriers is crucial as all the entities rely on carriers' communication services. In the COMBO European project, benefit of carrier cooperation for failure protection and power saving in mobile networks was observed in [14][15], assuming a full visibility of carriers' networks. For disaster recovery, with limited visibility among carriers, we have illustrated that carrier cooperation is beneficial for reducing the recovery cost/burden [12]. However, the *recovery time* is also a crucial factor and needs to be considered to enhance the resiliency performance. In this study, we investigate the scheduling problem in carrier cooperation for swift recovery. We propose a two-stage cooperative recovery planning by incorporating a coordinated scheduling scheme and devise corresponding Integer Linear Programming (ILP) models. Through numerical evaluation, we show the potential benefit of carrier cooperation which can significantly accelerate recovery while reducing the recovery cost/burden.

The remainder of this paper is organized as follows. Section II introduces carrier cooperative recovery use cases and the new coordinated scheduling problem. Section III presents the proposed PNE-based coordinated scheduling scheme. Section IV presents evaluation results. Section V concludes the paper.

II. USE CASES OF COOPERATIVE RECOVERY AND PROBLEM STATEMENT OF CARRIERS COORDINATED SCHEDULING

A. Network Model and Use Cases of Cooperative Recovery

Fig. 1(a) illustrates a scenario of carriers' cooperative disaster recovery in a disaster area. A third-party entity, *PNE* [e.g., a distributed internet exchange point (IXP) or a co-location center] interconnects different carriers' optical packet transport networks (with overlapped coverage and nodes in the same proximity) at packet layer. To enable cooperation without violating confidentiality, carriers abstract their network topologies to a common public reference PNE topology for concealing their detailed network topology and damage information [12][13]. Carriers declare the price of a connection service between PNE nodes (e.g., in the form of a lightpath or an IP-over-WDM connection). It is assumed that a regular price is charged for services that are still available over surviving resources, while a higher dummy price is additionally declared for those that need recovery, trying to avoid utilization in emergency recovery first. To achieve efficient recovery carriers

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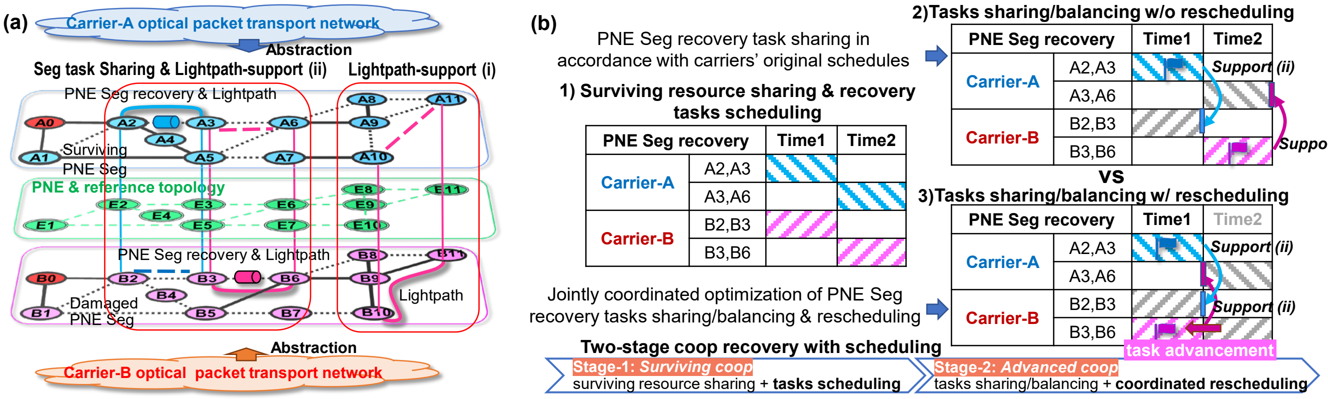

Fig. 1. Network model: (a) carrier cooperative recovery facilitated by PNE, (b) advanced recovery via two-stage cooperative recovery and scheduling.

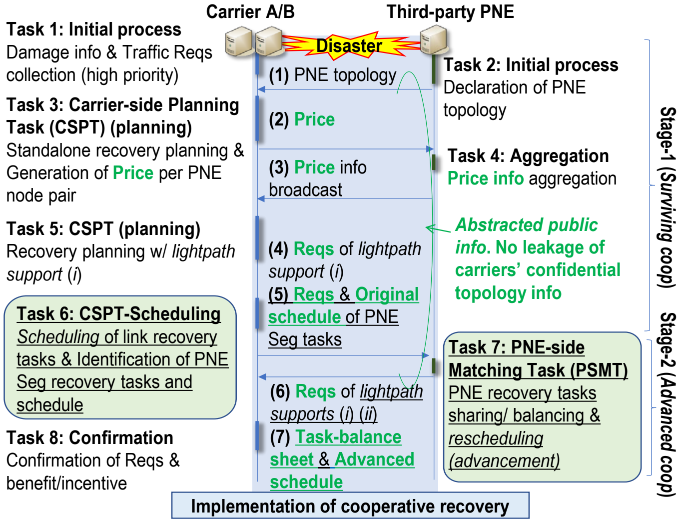

Fig. 2. Decomposed optimization tasks for the planning of carrier cooperation.

can offer each other *lightpath supports* (*i*) with their surviving resources through PNE nodes. For instance, Carrier B offers a *lightpath support* (*i*) between (B10, B11) to Carrier A via PNE nodes E10/E11. Moreover, carriers can further share the recovery tasks of the mutually desired PNE segments (Segs) (i.e., the edges in PNE topology) and offer each other the *lightpath supports* (*ii*) with the recovered resources [12]. For instance, in the same PNE topology Carrier A and Carrier B require the same damaged PNE Segs <A2, A3>, <A3, A6>, and <B2, B3>, <B3, B6>, respectively. They can undertake the recovery tasks of <A2, A3> and < B3, B6>, respectively, and offer each other *lightpath supports* (*ii*) via PNE nodes E2/E3/E6.

B. *Swift Recovery with Carrier Coordinated Scheduling*

In this study we consider a new problem: *how to enable carrier cooperative recovery with minimum recovery time, considering a coordinated scheduling in a multi-entity scenario without violating confidentiality during cooperation?* We propose a PNE-based two-stage cooperative recovery planning to solve this problem gradually, which integrates a coordinated scheduling, as shown in Fig. 1(b).

Stage-1 Surviving resource sharing & Scheduling (*Surviving coop* for short): Carriers optimize (1) the demands for counterpart carriers' *lightpath supports* (*i*) with surviving resources sharing (in cooperation aided by PNE [12]) and (2) a *preliminary scheduling* of the necessary recovery tasks to shorten recovery time. In case 1), Carrier A and Carrier B schedule their recovery tasks of the desired PNE Segs <A2, A3> and <B2, B3> at Time1, <A3, A6> and <B3, B6> at Time2, respectively. Both carriers need two units of recovery time.

Stage-2 Task sharing/balancing & Rescheduling (*Advanced coop* for short): To further improve the recovery planning and scheduling PNE performs a jointly coordinated optimization of (1) PNE Seg recovery tasks sharing/balancing [12] (i.e., assign and balance the PNE Seg recovery tasks among carriers) and (2) *rescheduling* of the carriers' originally scheduled PNE Seg recovery tasks (i.e., that solved in stage-1). If only the recovery tasks sharing/balancing are optimized, although the recovery cost is reduced, the recovery time cannot be shortened. In case 2), Carrier A and Carrier B restore Segs <A2, A3> and <B3, B6> at Time1 and 2, respectively, two units of recovery time are still needed. However, if tasks sharing/balancing are jointly optimized with rescheduling, e.g., in case 3), by further advancing Carrier B recovery task <B3, B6> from Time2 to Time1, the recovery time can reduce by 50%.

III. PNE-BASED CARRIER COOPERATIVE RECOVERY

A. *Framework Extention of Cooperative Recovery Planning*

Fig. 2 illustrates a detailed breakdown of the decomposed optimization tasks for the planning of cooperative recovery based on that in [12][13], including the planning tasks on both the carrier side and PNE side. Tasks 1/3/5/6/8 are performed by carriers, including the carrier-side planning task (CSPT) for both the standalone and cooperative recovery planning. Tasks 2/4/7 are performed by PNE, including the PNE topology publication and price broadcasting. Tasks from 1 to 6 correspond to the aforementioned stage-1, and Task 7 corresponds to stage-2. In particular, we propose the new Task 6 CSPT-Scheduling and Task 7 PNE-side matching task (PSMT) (highlighted) for enabling the coordinated scheduling in the two stages, on the carrier side and on the PNE side, respectively. Initially, carriers perform the standalone recovery planning. Under cooperation, carriers can improve their original standalone recovery plans. These distributed optimization tasks are performed based on the exchanged abstracted public information (facilitated by the PNE) and the private information of the stakeholders themselves without violating confidentiality. Finally, individual carriers implement the assigned PNE Seg recovery tasks and sell the *lightpath supports* (*i*) and (*ii*) to counterpart carriers accordingly. The payment received from the counterpart carriers is treated as an income partially compensating the recovery cost. We propose new ILP models for CSPT-Scheduling and PSMT to investigate the problems and observe the potential of recovery acceleration and recovery cost/burden reduction through carrier cooperation. These models and the process are described as follows.

B. Modeling of Carrier-side Planning Task (CSPT)

For Tasks 3/5 of carriers, we have proposed a generalized ILP model CSPT for each carrier as a reference model [12]. For reference purpose, CSPT is briefly described as below.

Given Info:

$G = (V, E)$	Graph of the carrier network topology in the failure/disaster area.
V	Set of nodes consisting of optical node, e.g., a reconfigurable optical add/drop multiplexer (ROADM) and switch/router.
E	Set of long-haul fibre links.
Δ	Set of all the carriers and customers identifications.
S	Set of abstracted outside source nodes, $S \subset V$.
B	Set of candidate border nodes connecting to the undamaged nodes outside the failure/disaster area, $B \subset V$.
Ω	Set of PNE nodes (e.g., one per major city), $\Omega \subset V\text{-}S$.
$G^* = (\Omega, E^*)$	Reference PNE network topology. where E^* is the set of PNE Segs.
Ψ	Set of counterpart carrier's declared *lightpath supports* (*i*).
R	Set of node pairs with traffic demands in the packet layer.
$\Gamma_{s,d}^{a}$	High priority packet traffic volume of customer a ($a \epsilon \Delta$) between node pair $(s, d) \epsilon R$.
$A_{s,d}^{a}$	Priority of packet traffic of customer a ($a \epsilon \Delta$) between node pair $(s, d) \epsilon R$. A large value indicates a high priority.
$O_{i,j}^{a}$	Request for lightpaths between node pair (i, j) by customer a ($a \epsilon \Delta$), or between PNE node pair (i, j) by the counterpart carrier.
$I_{i,j}^{a}$	Priority of the lightpaths requests $O_{i,j}^{a}$.
W	Set of wavelengths.
$U_{m,n}^{w}$	Indicator of the existing wavelength utilization of w ($w \epsilon W$) in the long-haul fibre link from node m to n, $(m, n) \epsilon E$. 0 indicates free and 1 indicates occupied.
$T_{m,n}$	Restoration cost of a damaged fibre link $(m, n) \epsilon E$. Links with $T_{m,n} \neq \inf$ are the candidates for restoration.
$p_{i,j}$	Price when selling a lightpath between node pair (i, j) including the *lightpath supports* (*i*) and (*ii*).
$p'_{i,j}$	Price when buying the counterpart carrier's lightpath between node pair (i, j), including the *lightpath supports* (*i*) and (*ii*).
a_{opt}	Weight for suppressing wavelength consumption.
a_{IP}	Weight for suppressing bandwidth consumption (IP layer).

Binary variables:

$\alpha_{s,d}^{a}$	1 indicates satisfied packet traffic demand of customer a ($a \epsilon \Delta$) between a node pair $(s, d) \epsilon R$; 0 indicates otherwise.
$o_{i,j}^{a}$	1 indicates the requested $O_{i,j}^{a}$ numbers of lightpaths of carrier or customer a ($a \epsilon \Delta$) between node pair (i, j) are satisfied; 0 indicates otherwise.
μ_b	1 indicates a border node at $b \epsilon B$; 0 indicates otherwise.
$\beta_{m,n}$	1 indicates the selected long-haul fibre link (m, n) for repair; 0 indicates otherwise.
σ_{ij}	1 indicates a request for a *lightpath support* (*i*) of the counterpart carrier between PNE nodes (i, j); 0 indicates otherwise.
$P_{m,n}^{(i,j),w}$	1 indicates the routing and wavelength assignment (RWA) for the lightpath between node pair (i, j) traversing long-haul fibre link (m, n) with wavelength w; 0 indicates otherwise.
$\lambda_{i,j}^{s,d,a}$	1 indicates packet traffic routing of customer a ($a \epsilon \Delta$) between node pair $(s, d) \epsilon R$ passing through the lightpath between node pair (i, j); 0 indicates otherwise.

Objective:

The five terms in the objective function (1) are as follows: (i) maximize the satisfied traffic demands and lightpath requests, (ii) minimize the number of border nodes (to reduce management costs), (iii) minimize necessary (a) long-haul fibre links to restore and (b) purchases of emergency *lightpath supports* (*i*) between the PNE nodes from the counterpart carrier, (iv) minimize the wavelength consumption in the optical network layer, and (v) minimize the total logical link bandwidth consumption in the upper packet layer. The coefficients B_1, B_2, B_3, a_{opt}, and a_{IP} separate the different portions into non-overlapping value ranges. The readers are referred to [12] for details of CSPT.

$$\begin{aligned} \min \Bigg[& -B_1 \left(\sum_{a\,\epsilon\Delta} \sum_{(s,d)\in R} \Gamma_{s,d}^{a} A_{s,d}^{a} \alpha_{s,d}^{a} + \sum_{a\,\epsilon\Delta} \sum_{i,j\in V} O_{i,j}^{a} I_{i,j}^{a} o_{i,j}^{a} \right) + B_2 \sum_{b\in B} \mu_b \\ & + B_3 \left(\sum_{(m,n)\in E} T_{m,n} \beta_{m,n} + \sum_{(i,j)\in\Psi} p'_{i,j} \sigma_{i,j} \right) + a_{\text{opt}} \sum_{i,j\in V} \sum_{w\in W} \sum_{(m,n)\in E} P_{m,n}^{(i,j),w} \\ & + a_{\text{IP}} \sum_{a\,\epsilon\Delta} \sum_{(s,d)\in R} \sum_{i,j\in V} \lambda_{i,j}^{s,d,a} \Bigg] \end{aligned} \tag{1}$$

C. Modeling of CSPT-Scheduling

In stage-1, we propose a CSPT-Scheduling ILP model to yield a *preliminary schedule* for the coordinated scheduling. Given the fibre links to be recovered (those identified by $\beta_{m,n} = 1$ in the CSPT solution), CSPT-Scheduling optimizes the schedule of fibre link recovery tasks in such a way that the highest priority traffic demands are recovered as early as possible. The CSPT-Scheduling ILP model is described below.

Given info:

F	Set of damaged fibre links, yielded by CSPT ($\beta_{m,n} = 1$).
$Y_{m,n}^{s,d}$	1 indicates the request between $(s, d) \epsilon R$ needs to wait for the restoration of the damaged long-haul fibre link $(m, n) \epsilon F$. 0 indicates otherwise.
$K_{s,d}$	Total number of long-haul fibre links that need restoration to satisfy the request between $(s, d) \epsilon R$.

Binary variables:

$q_{m,n}^{g}$	1 indicates a damaged long-haul fibre link $(m, n) \epsilon F$ is scheduled for restoration at the gth unit time slot.

Objective:

$$\min \left[\sum_{(s,d)\in R} \frac{\sum_{0\leq g<|F|} \sum_{(m,n)\epsilon F} \left[(g+1) Y_{m,n}^{s,d} \right] q_{m,n}^{g}}{\sum_{t=0}^{K_{s,d}-1} (t+1)} \right] \tag{2}$$

It is assumed that, for simplicity, only one damaged long-haul fibre link can be recovered per unit time slot owing to the man-power limit. The objective function (2) minimizes the recovery time of all the requests. Namely, among the total $|F|$ number of recovery time slots, CSPT-Scheduling arranges the recovery tasks of the damaged long-haul fibre links those are required by a larger number of requests as early as possible. The constraints are detailed in Appendix A.

D. Modeling of PNE-side Matching Task (PSMT)

For the PNE Segs which are mutually desired by carriers, in [12] we have proposed a PNE coordination scheme for sharing/balancing the PNE Seg recovery tasks among carriers to reduce the recovery cost/burden. To investigate the potential of recovery acceleration coordinated by PNE, in stage-2, we propose a new PSMT ILP model. Based on the preliminary solutions solved in stage-1, PSMT performs a jointly coordinated optimization of PNE Seg recovery tasks sharing/balancing and rescheduling, which is described below.

Given info:

X^{a}	Set of damaged PNE Segs that need to be recovered by carrier a to satisfy its highest-priority traffic ($a \epsilon \Delta$).

X_{com}	Set of common PNE Segs that need to be recovered to satisfy the highest-priority traffic by both carriers in Δ.
$p_{i,j}^{a}$	Selling price for *lightpath supports* (*ii*) between PNE Seg $<i,j>$ declared by carrier a ($a \in \Delta$).
$Q_{i,j}^{a,g}$	Original PNE Seg recovery schedule analyzed by carrier a with the solution of CSPT-Scheduling. 1 indicates the recovery of PNE Seg between PNE node pair $<i,j> \in X^a$ is scheduled at the gth time slot.
J^a	Set of originally scheduled recovery time of carrier a.
Z^a	Max number in J^a ($a \in \Delta$), slot of the last Seg recovery.

Continuous variable:

$\lambda_{\max}$	Greatest sum paid by individual carriers.

Binary variable:

$\gamma_{i,j}^{a,t}$	Indicator of recovery task assignment and scheduling. 1 indicates that the recovery task for the PNE Seg $<i,j>$ is assigned to carrier a, and is scheduled at the time slot t ($t \in J^a$); 0 indicates otherwise ($a \in \Delta$, $<i,j> \in X_{\text{com}}$).

Objective:

$$\min\left[B_4\lambda_{\max} + B_5\sum_{a\in\Delta}\sum_{<i,j>\in X_{\text{com}}}\sum_{t\in J^a}(t+1)\gamma_{i,j}^{a,t} - B_6\sum_{a\in\Delta}\sum_{<i,j>\in X_{\text{com}}}\sum_{t\in J^a}\frac{(Z^a-t)\gamma_{i,j}^{a,t}}{\sum_{g\in J^a}(g+1)Q_{i,j}^{a,g}}\right] \tag{3}$$

The terms in the objective function (3) are as follows: (i) minimize the largest payment of carriers for balancing the tasks undertaken by carriers, (ii) minimize the total recovery time by rescheduling and accordingly assigning the PNE Seg recovery tasks to the carriers that can recover early. To further drive the recovery of each PNE Seg earlier than carriers' original schedules we add an auxiliary term mathematically in rescheduling. Namely, (iii) maximize the advancement of individual PNE Seg recovery compared to the carriers' original schedules. The coefficients B_4, B_5, and B_6 separate the different terms into non-overlapping value ranges. The constraints are detailed in Appendix B.

E. Process of the Distributed Optimization Tasks

In this subsection, we present an implementation process of the PNE-based carrier cooperative recovery (see Fig. 2), including the aforementioned CSPT, CSPT-Scheduling, and PSMT performed by carriers and PNE, respectively. In Task 1, carriers collect the damage information and traffic demands of the highest priority. In Task 2, PNE declares the reference PNE topology covering the disaster area. The implementation of Tasks from 3 to 8 are described as follows.

(1) **Task 3:** Standalone recovery planning of carrier network and price generation of connection/*lightpath supports* per node pair in PNE topology (by carrier).

Step-1: Solve **CSPT** for standalone recovery without the counterpart carrier's *lightpath support* (*i*) (i.e., $\Psi = \{\}$).

Step-2: Evaluate the fibre links recovery cost ($\beta_{m,n} = 1$).

Step-3: Generate and declare the price $p_{i,j}$ of lightpath or connection services between PNE nodes (i,j).

(2) **Task 4:** Price info aggregation (by PNE).

Step-1: Collect and aggregate the carriers' price information.

Step-2: Broadcast the aggregated price information to carriers.

(3) **Task 5:** Recovery planning with *lightpath supports* (*i*) (by carrier)

Step-1: Solve **CSPT** for cooperative recovery with the counterpart carrier's *lightpath support* (*i*) (i.e., $\Psi = \{(i,j) \mid$ the *lightpath supports* (*i*) between PNE nodes (i,j) of the counterpart carrier is available, i.e., with a regular price$\}$.

Step-2: Evaluate the recovery costs including the fibre link recovery cost ($\beta_{m,n} = 1$) and the payment of *lightpath support* (*i*) ($\sigma_{ij} = 1$).

(4) **Task 6:** Scheduling of the necessary fibre links recovery tasks and identification/abstraction of the necessary PNE Seg recovery tasks & schedule (by carrier)

Step-1: Solve **CSPT-Scheduling** with the solutions of **CSPT** in Task 5 as the input, e.g., identification of fibre links for recovery, RWA and packet flow routing. Record the solution of fibre link recovery tasks schedule ($q_{m,n}^{g} = 1$).

Step-2: Transform the requirement of network recovery from the detailed fibre link recovery tasks (private info) to the abstracted PNE Seg recovery tasks (public info) by setting X. $X = \{<x,y> \mid$ there exists traffic request (s,d) traversing a PNE Seg $<x,y>$, and need to wait for the recovery of fibre links in the underlying optical network$\}$.

Step-3: From the fibre link recovery scheduling solution ($q_{m,n}^{g} = 1$) set the schedule of PNE Seg $<x,y>$ recovery task stored in X at the zth slot ($Q_{x,y}^{a,z} = 1$). The value of z is the recovery time slot of the last fibre link recovery task which will recover the reachability of PNE Seg $<x,y>$.

Step-4: Aggregate and deliver (a) the *lightpath support* (*i*) requests ($\sigma_{ij} = 1$) solved in **CSPT** of Task 5, (b) the set of desired PNE Seg recovery tasks X^a and the *lightpath support* (*ii*) requests in desired PNE Segs, and (c) the corresponding PNE Seg recovery schedule $Q_{x,y}^{a,z}$ to PNE.

(5) **Task 7:** Joint optimization of PNE Seg recovery tasks sharing/balancing and rescheduling (advancement) (by PNE)

Step-1: Solve **PSMT** with the mutually desired PNE Seg recovery tasks among carriers and the corresponding carriers' original schedules as the input. Record the solution of PNE Seg recovery task assignment and rescheduling ($\gamma_{i,j}^{a,t} = 1$), and generate the task-balance sheet and corresponding schedule information accordingly.

Step-2: Broadcast the task-balance sheet/advanced schedule and the *lightpath supports* (*i*) and (*ii*) requests to carriers.

(6) **Task 8:** Confirmation of carriers' *lightpath supports* requests, the task-balance sheet and advanced schedule of PNE Seg recovery tasks (by carrier).

Step-1: Confirm the *lightpath support* (*i*) requests, the PNE Seg recovery task assignment and advanced schedule including the corresponding *lightpath support* (*ii*) requests. Evaluate the *net cost* which is the sum of costs [including the fibre link recovery cost and the payment for purchasing the *lightpath supports* (*i*) and (*ii*)] minus the sum of incomes for offering *lightpath supports* (*i*) and (*ii*).

Step-2: Since some PNE Seg recovery tasks are assigned to the counterpart carrier, the carrier can hang on these recovery tasks and further advance the later necessary fibre link recovery tasks (i.e., those are not shared in carrier cooperation) to accelerate the recovery process.

Step-3: Confirm the effects of cost reduction and the recovery acceleration. If it is beneficial, cooperation is adopted.

Carriers may employ a part of wavelengths in the optical networks for cooperatively recovering the highest priority requests first. For those unsatisfied and other requests, multiple rounds of cooperation can be performed via left resources.

IV. ILLUSTRATIVE NUMERICAL RESULTS

A. Evaluation Model

Evaluations were conducted to observe the effect of the aforementioned two-stage cooperative recovery with a coordinated scheduling among two carriers (Carrier A and Carrier B), and a PNE, as presented in Fig. 1(a). A subset of the Japan photonic network topology [16] was employed as the PNE reference topology. To preliminarily observe the performance trend, for simplicity, the topologies of the original optical packet transport networks of Carrier-A and Carrier-B were identical to this PNE topology as shown in Fig. 1(a). That is, the PNE Segs were identical to the fibre links of the original carrier networks. Note that, theoretically, an identical topology is not required. The carrier's network consisted of 12 nodes, with one abstracted outside node, two border node candidates, nine inside nodes (e.g., one node per city), and 17 bidirectional fibre links. For each carrier node, it was assumed that 7 wavelength-tunable transponders were equipped in a colorless, directionless and contentionless ROADM, and connected to the upper layer packet switch/router. PNE nodes (packet switches/routers) from 1 to 11 were interconnected with the co-located carrier nodes.

We observed three *damage situations* in carrier networks. (i) Heavy damage (10:10): in both carrier networks, 10 fibre links were damaged; (ii) Mixed damage (10:5): in Carrier A network, 10 fibre links were damaged, whereas in Carrier B network, 5 fibre links were damaged; (iii) Light damage (5:5): in both carrier networks 5 fibre links were damaged. For carrier networks, the damaged fibre links were randomly selected such that they had a strong correlation [12]. That is, if a fibre link failed in Carrier A network, the co-located fibre link of Carrier B failed simultaneously with a high probability, e.g., 0.8. To further detail the degree of damage, for each damaged fibre link, three *levels of the recovery cost* were generated. (i) Low cost level: the recovery cost of a fibre link was set to a random value which was uniformly selected in [1, 4], noted as cost = 4; (ii) Medium cost level: the recovery cost was randomly selected in [1, 7], noted as cost = 7; (iii) High cost level: the recovery cost was randomly selected in [1, 10], noted as cost = 10.

To simulate the emergency recovery of the highest priority traffic of customers we randomly generated packet traffic demands among nodes (e.g., around 12 highest priority IP-over-WDM connection requests each on average 130 Gbps) for both carriers. We preliminarily observed the proposed cooperative recovery with 4 wavelengths available in the optical networks, which were sufficient to satisfy almost all of the generated traffic demands (except in rare cases one request was not satisfied). For *lightpath supports* (*i*) and (*ii*), the capacity of the lightpath was set to 100 Gbps. The price of *lightpath support* (*i*) with the surviving resources was set as 1 unit (e.g., regular price), and an extra dummy price of 100 units was declared if a carrier needed to recover the fibre link first (i.e., for abstracting the damage information and avoiding the utilization of the damaged resource). When the PNE Seg recovery task sharing/balancing was performed, the price of *lightpath support* (*ii*) during payment was set as 4 units (e.g., to present certain incentive for sharing the recovered resource). For the coefficients in objective (1), $B_1 = 10^{10}$, $B_2 = 10^8$, $B_3 = 10^5$, $a_{\text{opt}} = 10^3$, and $a_{\text{IP}} = 1$. The coefficients in objective (3) were set as $B_4 = 10^8$, $B_5 = 10^7$, $B_6 = 10^4$. The optimization instances (for CSPT, CSPT-Scheduling and PSMT) were solved by IBM CPLEX, on a PC (Xeon Gold 5115 2.4-GHz 20-core CPU, 128 GB memory). By combining three *damage situations* and three *recovery cost levels*, nine disaster conditions were observed. For each disaster condition, we randomly generated 50 instances. The average computational time for one instance was less than 15 min.

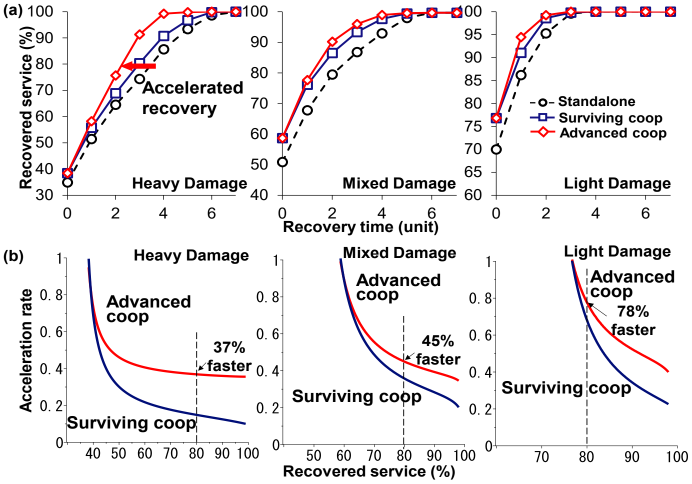

Fig. 3. Accelerated recovery via cooperation (*Surviving coop* and *Advanced coop*): (a) reduced recovery time, (b) trend of the acceleration rate performance.

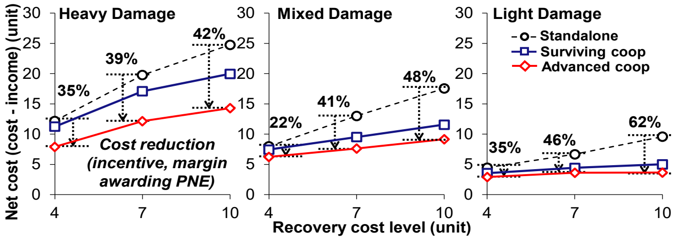

Fig. 4. Significant reduction of recovery net cost via cooperative recovery.

B. Numerical Analysis

The performance of three recovery strategies were observed. (i) *Standalone* (the benchmark): carriers only performed Tasks 1/3/6, i.e., implemented the standalone recovery planning (with CSPT) and the scheduling (with CSPT-Scheduling) without cooperation; (ii) *Surviving coop* (stage-1): carriers additionally performed Tasks 5/8, i.e., implemented the cooperative recovery planning with CSPT and CSPT-Scheduling. PNE performed Tasks 2/4 to facilitate carrier cooperation. (iii) *Advanced coop* (both stages 1 and 2): PNE further performed Task 7, a jointly coordinated optimization of PNE Seg recovery tasks sharing/balancing and rescheduling (with PSMT).

Fig. 3(a) plots the average performance in terms of the recovery time for services recovery under three *damage situations* and with the *recovery cost level* cost = 10. By analyzing the approximated polynomial trend lines of individual strategies shown in Fig. 3(a), we further visualize the trends of the acceleration rate of recovery of the cooperative recovery strategies compared to that of *Standalone*, as shown in Fig. 3(b). Under all of the *damage situations*, the cooperative recovery strategies outperformed the standalone recovery significantly. Especially, with the *Advanced coop* strategy the recovery of the majority of customer services, e.g., 80% of traffic requests, was accelerated by 37%, 45% and 78%, faster than *Standalone*, in heavy, mixed and light *damage situations*, respectively. We can clearly see a trend that in the light damage situation, recovery acceleration effect brought by the *Advanced coop* was even larger. In fact, this was mostly contributed by *Surviving coop* that efficiently employed the redundant surviving resources distributed in different carriers' networks. In heavy damage, owing to the limited surviving resource, the acceleration effect of *Surviving coop* was lower than *Advanced coop*. This reveals that *Advanced coop* including the joint optimization of PNE Seg recovery task sharing/balancing and coordinated rescheduling is efficient and applicable for different *damage situations*, and it can enhance resilience of both carriers. A similar trend was confirmed in the cases with other *recovery cost levels* (not shown due to space limitation).

Fig. 4 further plots the improvement in terms of *net cost* (total cost/payment minus total income, see Sect. III.E Task 8) under all the *damage situations* and *recovery cost levels*. For instance, in the cases of a larger *recovery cost level*, cost = 10, compared to the *Standalone* strategy, with the *Advanced coop* strategy the *net cost* was reduced by 42%, 48% and 62%, in heavy, mixed and light *damage situations*, respectively. When the *recovery cost level* decreased, this effect decreased accordingly. The reduction on both the recovery time and cost presents a strong incentive to carriers to cooperate. In addition, as highlighted in Fig. 4, the range of cost reduction can be considered as a margin for carriers, which can be partially employed as an incentive to award PNE who facilitates cooperation via both the interconnection service in data-plane and the mediation service in cooperative recovery planning.

V. CONCLUSIONS

We investigate a carrier-cooperative recovery scheduling problem and propose a PNE-based two-stage cooperative recovery planning by incorporating a coordinated scheduling scheme for swift failure/disaster recovery. Evaluation results clearly show the potential benefit of carrier cooperation which can significantly accelerate recovery while reducing the recovery cost/burden. For instance, the recovery of the majority of customer services, e.g., 80% of traffic requests, was accelerated by more than 1/3 in heavy damage and even around 4/5 in light damage situations. Improvement on the proposal and detailed evaluations are envisioned as future work.

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Appendix A: Constraints in CSPT-Scheduling

Constraint on the total number of damaged long-haul fibre links which need restoration for individual requests is presented in (a.1). Constraint on the total number of damaged long-haul fibre links which can be recovered per time slot is presented in (a.2). Constraint (a.3) indicates that every damaged long-haul fibre link can be recovered at most one time.

$$\sum_{0\le g<|F|}\sum_{(m,n)\,\epsilon F} Y^{s,d}_{m,n} q^{g}_{m,n} = K_{s,d}, \forall (s,d) \in R \qquad (\text{a}.1)$$

$$\sum_{(m,n)\,\epsilon F} q^{g}_{m,n} \le 1, \forall g \in [0,|F|) \qquad (\text{a}.2)$$

$$\sum_{0\le g<|F|} q^{g}_{m,n} \le 1, \forall (m,n)\,\epsilon F \qquad (\text{a}.3)$$

Appendix B: Constraints in PSMT

The constraint on the maximum cost/payment experienced by each carrier during PNE Seg recovery tasks sharing/balancing is shown in (b.1). Using the first term in the objective function (3) the recovery burden among carriers can be balanced. Constraint (b.2) assures that at least one carrier will recover a PNE Seg in X_{com}. The constraints on recovery task rescheduling are presented in (b.3)–(b.6). Constraint (b.3) shows that for any PNE Seg which both carriers need to recover, at most one carrier can recover one time. Constraint (b.4) shows that in any recovery time slot t which is planned for recovery, any carrier can at most recover one PNE Seg. Constraints (b.5) and (b.6) show that the rescheduling of the PNE Seg recovery tasks in carrier cooperation should improve or no worse (i.e., should not be later) than the original schedule for individual PNE Seg recovery. More specifically, (b.5) shows the cases if the recovery tasks are assigned to a carrier a. (b.6) shows the cases if the recovery tasks are assigned to a counterpart carrier $b \in \Delta - \{a\}$.

$$\sum_{<i,j>\in X_{\text{com}}}\sum_{t\in J^a} p^{a}_{i,j}\gamma^{a,t}_{i,j} \le \lambda_{\max}, \forall a \in \Delta \qquad (\text{b}.1)$$

$$\sum_{a\in\Delta}\sum_{t\in J^a} \gamma^{a,t}_{i,j} \ge 1, \forall <i,j> \in X_{\text{com}} \qquad (\text{b}.2)$$

$$\sum_{t\in J^a} \gamma^{a,t}_{i,j} \le 1, \forall <i,j> \in X_{\text{com}}, \forall a \in \Delta \qquad (\text{b}.3)$$

$$\sum_{<i,j>\in X_{\text{com}}} \gamma^{a,t}_{i,j} \le 1, \forall a \in \Delta, t \in J^a \qquad (\text{b}.4)$$

$$\sum_{t\in J^a} (t+1)\gamma^{a,t}_{i,j} \le (g+1)Q^{a,g}_{i,j}, \forall <i,j> \in X_{\text{com}}, \forall a \in \Delta \qquad (\text{b}.5)$$

$$\sum_{b\in\Delta-\{a\}}\sum_{t\in J^b} (t+1)\gamma^{b,t}_{i,j} \le (g+1)Q^{a,g}_{i,j}, \forall <i,j> \in X_{\text{com}}, \forall a \in \Delta \qquad (\text{b}.6)$$