# A Novel Carrier-Cooperation Scheme with an Incentive for Offering Emergency Lightpath Support in Disaster Recovery

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**Abstract.** To achieve the fast recovery of optical transport networks following a disaster, we investigate a novel scheme to enable cooperation between carriers. Carriers can take advantage of their surviving or recovered optical resources to aid one another with emergency lightpath support to reduce efficiently the burden of recovery, which is heavy immediately after disasters. These lightpaths can be employed exclusively by the counterpart carriers to satisfy their highest priority traffic demands, such as safety confirmation and victim relief. In addition, we introduce an incentive to carriers to prompt cooperation. The carrier cooperation-planning problem is decomposed into eight tasks, and distributed to individual carriers and a third-party organization. During cooperation, the carriers' confidential information can be strictly protected by employing a carrier optical network abstraction mechanism. The evaluation results reveal that our proposal can significantly reduce the burden on recovery and the corresponding cost for carriers, resulting in fast and efficient disaster recovery.

**Keywords:** Carrier cooperation, Disaster recovery, Emergency lightpath support, Incentive.

## 1 Introduction

In modern transport networks, sophisticated protection and restoration schemes are taken into account in both the network design phase and operation phase to enhance the resiliency of networks and to protect services from failures [1]–[5]. In addition to schemes based on a proactive approach, the fast and efficient restoration of damaged networks following disasters, such as megaquakes or tsunamis, is critical for network carriers (hereinafter called carriers). Major disasters have demonstrated that it is costly and time-consuming to independently recover individual original optical transport networks, as this process takes several days to weeks to complete [6].

To achieve fast and efficient disaster recovery, sparsely located surviving network resources should first be used. In a single-carrier recovery scenario, interconnection mechanisms between the surviving resources in multi-vendor networks have been investigated [7], [8]. To further take advantage of surviving resources in the networks of various carriers, and to perform well-balanced recovery tasks among carriers, in [9] and [10], we have investigated a carrier-cooperation scheme. In this scheme, carriers collaborate to construct an emergency common packet transport network in the disaster area with their surviving optical resources; this emergency common transport network is shareable among carriers.

In this paper, we propose an alternative cooperation approach and a corresponding scheme (to provide more options to meet different situations in disaster recovery) in which carriers offer one another emergency lightpath support employed exclusively by the counterpart carriers. In addition, we introduce an incentive to carriers that supply emergency lightpaths. In this scheme, the planning problem for carrier cooperation-based recovery is decomposed and distributed to carriers and a third-party organization, and the carriers' confidential topology information is strictly protected during cooperation. Simulation results reveal that our proposal can significantly reduce the number of recovery tasks undertaken by each carrier, and the corresponding cost.

The remainder of this paper is organized as follows. Section II introduces the carrier-cooperation network model and an incentive mechanism for prompting emergency lightpath support between carriers. Section III presents the distributed planning for disaster recovery based on carrier cooperation. Section IV presents simulations and results, and Section V summarizes the paper.

## 2 Model of Recovery based on Carrier Cooperation

### 2.1 Network Model

Fig. 1 illustrates the optical transport networks of two carriers, Carrier-A and Carrier-B, which overlap in a disaster area. To hide the confidential topology information during cooperation, carriers perform an abstraction of their topologies to a common reference topology. It should be noted that the reference topology in a disaster area is assumed available prior to disasters. The details of the preparation of the reference topology are beyond the scope of this paper.

The numbered circles in the reference topology in Fig. 1 represent nodes in major cities. Each node contains an underlying optical node (e.g., reconfigurable optical add/drop multiplexer [ROADM]) and an upper-layer packet switch/router. Nodes in different carriers' abstracted networks with the same number are located in the same city. Nodes A0 and B0 (for Carrier-A and Carrier-B, respectively) are abstracted nodes that represent nodes outside of the disaster area. Nodes A1–A11 and B1–B11

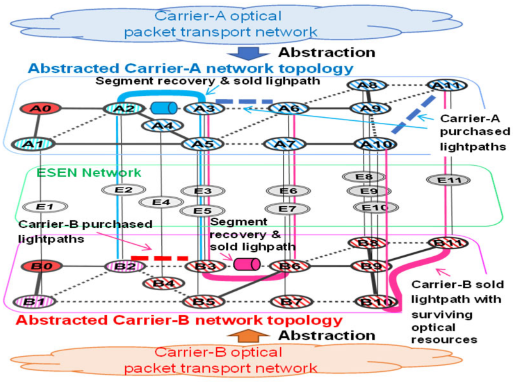


**Fig. 1.** Network model of disaster recovery based on carrier cooperation.

are in the disaster area; of these, A1–A2 and B1–B2 are candidate borders for relaying packet traffic between the disaster area and outside network. The lines between adjacent nodes in this reference topology represent the segments that traverse the underlying individual carriers' optical networks. Solid lines between nodes represent the surviving segments, dotted lines are damaged ones that are candidates for restoration.

In Fig. 1, between the two carriers' abstracted topologies, the third-party nodes, E1–E11, are selected points in an emergency shareable exchange network (ESEN) that are employed to connect the nodes of different carriers within a city, e.g., performing optical-electrical-optical (OEO) conversion. Details of the ESEN nodes are omitted herein due to space limitations. The thin vertical lines between the ESEN nodes and carrier nodes represent short-distance fibres for carrier interconnection. Because these fibres are short, the cost of the interconnection of closely located nodes of different carriers in a city is lower than the cost of a long-distance optical network restoration. For simplicity, short-distance fibre costs are omitted from this paper.

### 2.2 Emergency Lightpath Support with an Incentive

To achieve fast and efficient recovery, carriers can cooperate and offer emergency lightpath support to their counterpart carriers. In this paper, an emergency ligthpath is a wavelength path. Besides the lightpaths which are employed by carriers themselves, the emergency lightpaths are offered to and employed exclusively by the counterpart carriers through the ESEN nodes (e.g., via OEO conversion), creating the temporary connectivity between the packet switches/routers in the packet layer. To offer an incentive to carriers that supply the emergency lightpaths, we assume that emergency lightpath support is offered at a fee. Emergency lightpath support is performed in two scenarios: (i) carriers can establish lightpaths with their surviving optical network resources and sell the lightpaths to their counterpart carrier; (ii) carriers can initially recover some of the damaged segments and establish/sell the lightpaths over the recovered segments for the counterpart carrier. Due to the high cost of segment recovery, the fee of the emergency lightpath support (ii) is high. For instance, in Fig. 1, Carrier-B sells a scenario (i) lightpath between B10–B11 to Carrier-A with its surviving resources. Additionally, two carriers recover damaged segments A2–A3 and B3–B6, respectively, and sell the scenario (ii) lightpaths to one other.

Fig. 2 presents a negotiation model in carrier cooperation. In addition to carriers, a third-party entity is introduced (hereinafter referred to as ESEN). First, the ESEN collects and exchanges the price information of the candidate emergency lightpaths (scenario [i]) among carriers; these lightpaths are based on surviving optical network resources. Based on the price information, each carrier evaluates the minimum requests necessary for its counterpart carrier's emergency lightpath support, which can reduce its recovery tasks and the cost of satisfying its highest priority traffic demands

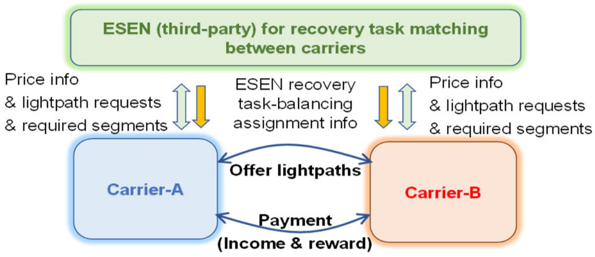


**Fig. 2.** Negotiation model in carrier cooperation-based disaster recovery.

(e.g., safety confirmation and victim relief). Second, when there is a set of damaged segments that both carriers wish to recover, the ESEN acquires information pertaining to these shared segments from the carriers, including the price for emergency lightpath support (scenario [ii]). Based on this information, the ESEN performs segment recovery task matching between carriers to balance the segment recovery and reduce the recovery tasks and costs for individual carriers. For instance, as illustrated in Fig. 1, there are shared damaged segments, A2–A3/B2–B3 and A3–A6/B3–B6, which must be recovered. After the ESEN performs recovery task matching, Carrier-A and Carrier-B perform the recovery of segments A2–A3 and B3–B6, respectively, which is simply a part of the original recovery task. Both carriers aid one another with the emergency lightpath support scenario (ii), and both receive corresponding income and rewards to compensate for their expenses. Thus, the segment recovery task and costs are significantly reduced, resulting in fast and efficient recovery.

## 3 Planning of Carrier Cooperation

To enable carrier cooperation and prompt the emergency lightpath support among carriers during disaster recovery, the recovery planning problem is decomposed into eight tasks, as displayed in Fig. 3. These tasks are distributed to carriers and a third-party organization; the latter does not require the confidential information (e.g., topology) of any carrier. For simplicity, only segment recovery costs are taken into account here; the problem of nodal recovery cost is left for future work.

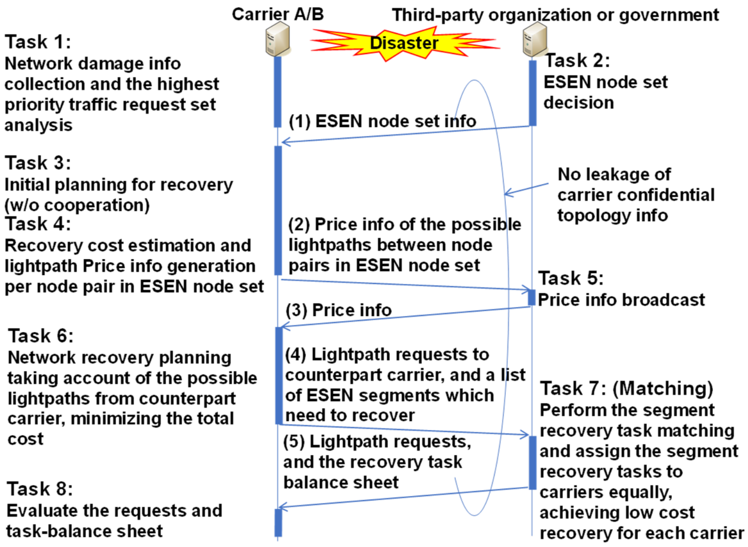


**Fig. 3.** Planning process in disaster recovery based on carrier cooperation.

### 3.1 Modeling of Carrier-side Planning Tasks (CSPTs)

For Tasks 3, 4, and 6 performed by carriers and shown in Fig. 3, we propose a generalized integer linear programming (ILP) model CSPT to carriers as a reference model. For each task, the values of the given information are adjusted; the information is summarized as follows. The constraints are presented in Appendix A.

$G = (V, E)$ Graph of carrier network.

| | |
|---|---|
| $V$ | Set of nodes. Each node consists of a ROADM and an electrical switch/router. |
| $E$ | Set of long-haul fibre links, i.e., the set of all edges in graph $G$. |
| $\Delta$ | Set of all carrier identifications, e.g., integer 0, 1, 2, etc. |
| $S$ | Set of abstracted outside source nodes. $S \subset V$. |
| $B$ | Set of candidate border nodes. $B \subset$ V. |
| $\Omega$ | Set of ESEN nodes. $\Omega \subset V\text{-}S$. |
| $G^*=(\Omega,E^*)$ | Common reference ESEN network topology abstracted from graph $G$. $E^*$ is the set of optical network segments between nodes (each in a major city). |
| $\Psi$ | Set of possible emergency lightpaths (scenario [i]) between ESEN nodes declared by counterpart carrier. |
| $\Pi$ | Set of emergency lightpaths (scenario [i]) between ESEN nodes required by counterpart carrier. |
| $R$ | Set of node pairs with traffic demands in the upper-layer packet network. |
| $\Gamma_{s,d}$ | Packet traffic volume (e.g., 10 Gbps) between node pair ($s$, $d$) $\in R$. |
| $A_{s,d}$ | Profit of traffic between node pair ($s$, $d$). A large value indicates a high priority. |
| $W$ | Set of wavelengths. |
| $U^w_{m,n}$ | Indicator of the existing wavelength utilization of $w$ ($w \in W$) in the long-haul fibre link from nodes $m$ to $n$. 0: free, 1: occupied. ($m$, $n \in V$). |
| $L_{m,n}$ | Indicator of the long-haul fibre link between nodes $m$ and $n$; 0: does not exist, 1: exists. ($m$, $n \in V$). |
| $T_{m,n}$ | Restoration cost of damaged long-haul fibre link between nodes $m$ and $n$. The cost can be defined with a positive value or inf (infinite). $T_{m,n} \neq$ inf is considered the candidates for restoration. ($m$, $n \in V$). |
| $C_{i,j}$ | Recovery cost of ESEN segments in the abstracted ESEN topology, which is estimated by the carrier itself. (($i$, $j$) $\in E^*$, $i, j \in \Omega$). |
| $p_{ij}$ | Price when selling emergency lightpath between ESEN node pair ($i$, $j$), estimated by the carrier itself, e.g., by employing surviving optical network resources (scenario [i]) or recovered ESEN segments (scenario [ii]). (($i$, $j$) $\in E^*$, $i, j \in \Omega$). |
| $p'_{ij}$ | Price when purchasing the emergency lightpath between ESEN node pair ($i$, $j$) estimated by the counterpart carrier, e.g., by employing surviving optical network resources (scenario [i]) or recovered ESEN segments (scenario [ii]). (($i$, $j$) $\in E^*$, $i, j \in \Omega$). |
| $O_{ij}$ | Request for emergency lightpath (scenario [i]) between ESEN node pair ($i$, $j$), which is required by the counterpart carrier after evaluation. 0: not required, 1: required. (($i$, $j$) $\in E^*$, $i, j \in \Omega$). |
| $F_i^w$ | Number of free transponders at node $i$ ($i \in V$) with wavelength $w$ ($w \in W$). |
| $G_m$ | Number of free transponders at node $m$ ($m \in V$). |
| $D_m$ | Degree limitation imposed on node $m$ ($m \in V$). |
| $C$ | Data rate of each lightpath (e.g., 100 Gbps). |
| $a_{\text{opt}}$ | Weight for suppressing wavelength consumption in underlying optical networks. |
| $a_{\text{IP}}$ | Weight for suppressing bandwidth consumption in upper-layer packet networks. |

**Binary variables:**

| | |
|---|---|
| $\alpha^{s,d}$ | 1: indicates the satisfied traffic demands between node pair ($s$, $d$) $\in R$; 0: otherwise. |
| $u_b$ | 1: indicates the border node at $b \in B$; 0: otherwise. |
| $\beta_{m,n}$ | 1: indicates the selected long-haul fibre link ($m$, $n$) for repair; 0: otherwise. ($m$, $n \in V$). |
| $P^{(i,j),w}_{m,n}$ | 1: routing and wavelength assignment (RWA) for the lightpath between nodes $i$ and $j$ passing through long-haul fibre link ($m$, $n$) with wavelength $w$; 0: otherwise. ($w \in W$; $i, j \in V$; $m$, $n \in V$). |
| $v^w_{i,j}$ | 1: indicates lightpath between nodes $i$ and $j$ using wavelength $w$; 0: otherwise. ($w \in W$; $i, j \in V$). |
| $\lambda^{s,d}_{i,j}$ | 1: indicates packet traffic routing. Traffic between source $s$ and destination $d$ passing through the lightpath between nodes $i$ and $j$; 0: otherwise. ($i, j \in V$, [$s$, $d$] $\in R$). |
| $\sigma_{ij}$ | 1: indicates request for purchasing counterpart carrier's lightpath between ESEN node pair ($i$, $j$); 0: otherwise. [($i$, $j$) $\in \Psi$, $i, j \in \Omega$]. Note that $\sigma_{ij}$ = 1 indicates that $O_{ij}$ = 1 for the counterpart carrier. |

**Objective:**

The concern in (1) are summarized as follows. (Portion 1) Satisfy the highest priority traffic demands as many as possible; (Portion 2) Select the minimum necessary border nodes to reduce management cost; (Portion 3) Select the minimum necessary (a) long-haul fibre links for restoration in the carrier's underlying optical network and

(b) the purchase of the emergency lightpaths (scenario [i]) between the ESEN node pairs from the counterpart carrier; (Portion 4) Minimize the wavelength consumption in the carrier's optical layer network for all necessary lightpaths; (Portion 5) Solve the packet routing in the upper layer, minimizing the total logical link bandwidth consumption. We converted the profits in the first portion, the border creation cost in the second portion, the recovery cost in the third portion, the wavelength consumption (e.g., energy consumption) in the fourth portion, and the logical link bandwidth consumption in the fifth portion to currency, using a specified unit in order to unify the dimensions. The detailed conversion method, however, is outside the scope of this paper. Coefficients $B_1$, $B_2$, $B_3$, $a_{\mathrm{opt}}$, and $a_{\mathrm{IP}}$ separate different portions into non-overlapping value ranges.

$$\min\left[-B_1\sum_{(s,d)\in R}\Gamma_{s,d}A_{s,d}\alpha^{s,d}+B_2\sum_{b\in B}\mu_b+B_3\left(\sum_{m,n\in V|T_{m,n}\neq inf}T_{m,n}\beta_{m,n}+\sum_{(i,j)\in\Psi}p'_{i,j}\sigma_{i,j}\right)\right.$$
$$\left.+\,a_{opt}\sum_{i,j\in V}\sum_{w\in W}\sum_{m,n\in V|U^{w}_{m,n}=0,orT_{m,n}\neq inf}P^{(i,j),w}_{m,n}+a_{IP}\sum_{(s,d)\in R}\sum_{i,j\in V}\lambda^{s,d}_{i,j}\right] \quad (1)$$

### 3.2 Modeling of Third-party-side Matching Task (TSMT)

For the matching task, Task 7 (see Fig. 3), performed by a third-party organization (ESEN), we propose an ILP model. The given information is summarized in Table II. The TSMT is described as follows. The constraints are shown in Appendix B.

| | |
|---|---|
| $X^a$ | Set of damaged ESEN segments that must be recovered by Carrier $a$ to satisfy Carrier $a$'s highest priority traffic. ($a \in \Delta$). |
| $X_{\mathrm{common}}$ | Set of common ESEN segments that must be recovered to satisfy the highest priority traffic by both carriers in $\Delta$. |
| $p_{ij}^{a}$ | Price for selling an emergency lightpath (scenarios [i] and [ii]) between an ESEN node pair $(i, j)$, which is estimated and declared by Carrier $a$. ($a \in \Delta$, $i, j \in \Omega$). |

**Linear variable:**

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

**Binary variables:**

$\gamma^{a}_{i,j}$ 1: indicates that the task for ESEN segment $(i, j)$ recovery and lightpath (scenario [ii]) creation is assigned to Carrier $a$; 0: otherwise. ($a \in \Delta$, $i, j \in E^*$).

**Objective:**

$$\min(\lambda_{\max}) \quad (2)$$

When carriers have damaged ESEN segments need to recovery ($X^a$), the third-party organization identifies the jointly desired ESEN segments for both carriers ($X_{\mathrm{common}}$). For $X_{\mathrm{common}}$, the third-party organization performs the matching of the ESEN segment recovery task to individual carriers. To achieve well-balanced task matching, the objective in (2) is to minimize the greatest sum paid by any carrier. Upon receiving a recovery task assignment, individual carriers perform ESEN segment recovery and sell the lightpaths over the recovered ESEN segment to their counterpart carriers. The corresponding payment received from the counterpart carrier is treated as a reward in compensation for performing the ESEN segment recovery task, as part of the cooperation between carriers.

### 3.3 Distributed Task Implementations

In Task 1, the carriers collect the damage information and traffic demands which are of the highest priority for safety confirmation and victim relief [8]. In Task 2, the third-party ESEN identifies the disaster area and selects the major cities and ESEN nodes. The implementations of Tasks 3, 4, 6, 7, and 8 (see Fig. 3) are described as follows and considered to be a reference guideline. Task 3, 4, 6, and 8 are performed by carriers. Task 7 is performed by a third-party organization. Details of the simple Task 5 are omitted due to space limitations.

(1) Task 3: Initial planning for standalone recovery (by carrier)

**Step-1:** Assign highest priority traffic requests $R$ and $\Gamma_{s,d}$;

**Step-2:** Set $\Psi = \{\}$, $\Pi = \{\}$;

**Step-3:** Solve **CSPT**; Record the fibre links that must necessarily be recovered ($\beta_{m,n} = 1$);

(2) Task 4: Recovery cost and price estimation (by carrier)

**Step-1:** Assume that there is dummy traffic between nodes 0 and 1;

**Step-2:** For each node pair $(i, j)$, where $i, j \in \Omega$ estimate cost,

Assign $\Pi = \{(i, j)\}$, and solve **CSPT** (with surviving fibre links and the damaged fibre links recorded in Task 3);

Record recovery cost $C_{i,j} = \sum_{m,n \in V | T_{m,n} \neq \inf} T_{m,n} \beta_{m,n}$ ;

**Step-3:** For the damaged ESEN segments $(i, j) \in E^*$, where $C_{i,j} > 0$, the carrier generates price $p_{i,j}^a$ for offering the scenario (ii) emergency lightpath. For example, $p_{i,j}^a = b * C_{i,j}$, ($b > 1$), or a flat price, $p_{i,j}^a = H$, ($H > C_{i,j}$) for all of the damaged ESEN segments to conceal the detailed damage information; For the scenario (i) lightpaths, where $C_{i,j} = 0$, generate price $p_{i,j}^a$. For example, $p_{i,j}^a = b *$ normal_price$_{i,j}$, ($b > 1$), or a flat price, $p_{i,j}^a = r * H$, ($r > 0$) to conceal the detailed information;

**Step-4:** Send the price of the emergency lightpaths for both scenarios (i) and (ii) to the third-party ESEN.

(3) Task 6: Evaluation of the candidate emergency lightpaths support (scenario [i]) of the counterpart carrier (by carrier)

**Step-1:** Assign highest priority traffic requests $R$ and $\Gamma_{s,d}$;

**Step-2:** Set $\Psi = \{(i, j) | \, p_{i,j}^a$ is disclosed by counterpart Carrier $a\}$ $(i, j \in \Omega)$, $\Pi = \{\}$;

**Step-3:** Solve **CSPT**;

**Step-4:** Send the emergency lightpath $(i, j)$ request solution, where $\sigma_{ij} = 1$, and $X^a$, including the ESEN segment $(i, j)$, with recovery cost $C_{i,j} = \sum_{m,n \in V | T_{m,n} \neq \inf} T_{m,n} \beta_{m,n}$ , where $C_{i,j} > 0$, to the third-party organization.

(4) Task 7: The third-party organization performs ESEN segment recovery matching (by the ESEN)

**Step-1:** Based on $X^a$ received from the carriers, identify the maximum even number of jointly desired ESEN segments for both carriers, $X_{\text{common}}$;

**Step-2:** Based on the carriers' price information for offering the scenario (ii) emergency lightpaths received after Task 4, solve **TSMT** for recovery task matching;

**Step-3:** Collect all solutions where $\gamma_{i,j}^a = 1$, namely, the segment recovery and lightpath (scenario [ii]) creation task-balance result and the emergency lightpath request list (after Task 6); send to individual carriers.

(5) Task 8: Evaluation of the required emergency lightpaths and ESEN segment recovery task matching (by carrier)

**Step-1:** Carrier calculates its costs;

$C_1$: Total payment amount for counterpart's emergency lightpath support (scenario [i]);
$C_2$: Total payment amount for counterpart's emergency lightpath support (scenario [ii]);
$C_3$: Total segment recovery cost, which is assigned by the third-party organization in recovery task matching;
$C_4$: Total remaining cost for segment recovery that is not involved in carrier cooperation; namely, those that cannot be balanced and must be performed by this carrier;

**Step-2:** Carrier calculates its incomes and rewards;
$I_1$: Total income amount received from counterpart carrier for offering emergency lightpath support with surviving optical resources (scenario [i]);
$I_2$: Total income amount received from counterpart carrier for offering the emergency lightpath support with recovered ESEN segments (scenario [ii]);

**Step-3:** Carrier calculates its profit as the sum of the income and reward minus the sum of the costs. If the profit in cooperation is larger than that of standalone recovery, carrier cooperation is deemed beneficial and will be adopted.

In the cases where some required emergency lightpaths cannot be satisfied, e.g., due to the changes in resource availability according to after-shock etc., the failed lighpath(s) can be marked and repeat the aforementioned process for refinement.

# 4 Simulations and Numerical Results

## 4.1 Evaluation Model

Evaluations were conducted to observe the effects of the aforementioned carrier-cooperation scheme. With respect to the shared ESEN abstracted network topology in the disaster area, a network topology that is a subset of the Japan photonic network model [11] was employed, as shown in Fig. 1. For simplicity, the topologies of the original networks of Carrier-A and Carrier-B were identical to this reference topology. Namely, the ESEN segments were identical to the fibre links of the carriers' original networks. Note that theoretically, an identical topology is not required. Each carrier's network consisted of 12 nodes, including one outside node, two border node candidates, and another nine inside nodes (i.e., one node per city, and 17 bidirectional fibre links). At each node $i$, $F_i^w$ was set to 7 for each wavelength $w$, and $G_i = 7$. Eleven ESEN nodes from nodes 1 to 11 were co-located with the carriers' nodes in the cities, and the data rate of the lightpath was set to $C = 100$ Gbps. The number of surviving long-haul fibre links in each carrier's original network was changed as 5 and 10 (these surviving links were assigned as $L_{m,n} = 1$). For both carriers' networks, the distribution pattern of the surviving fibre links was selected such that they had a strong correlation [8]. For example, the fibre links of both the Carrier-A/B networks between two cities had a high probability to have survived or have been damaged together. In this study, this probability was set to 0.8 to represent the strong correlation between link (segment) failures in different carriers' networks. The cases with a probability 0.4 had similar performance, which is omitted due to space limitations.

For simplicity, for all damage situations, the value of $T_{m,n}$ was set to 10 for restoring the damaged long-haul fibre links; therefore, the ESEN segment restoration cost $C_{i,j} = 10$. A flat price for emergency lightpaths was adopted; that is, for the scenario (ii) lightpath, $p_{i,j}^a = H$, and $H$ was fixed at 10 for all cases. For the scenario (i) lightpath, $p_{i,j}^{a} = r * H$ to conceal the detailed information. The coefficient $r$ was set to 0.3, 0.5, 0.7, and 1.1 to observe the effect on the pricing of the scenario (i) lightpath. A non-flat pricing scheme is beyond the scope of this paper and left for future work.

For the Carrier-A and Carrier-B networks, it is assumed that each of the nine inside nodes, $d$, has the highest priority packet traffic demand to/from the outside node (node 0) for safety confirmation and victim relief (with the same value, $A_{0,d} = 10$, $\Gamma_{0,d} = 10$ Gbps). For each carrier's network, the number of wavelengths $|W| = 4$ was adequate for all high-priority traffic requests in the evaluation. $U_{m,n}^{w}$ is set to 0 for all of the surviving links. For the coefficients in (1), $B_1 = 1000000$, $B_2 = 10000$, $B_3 = 100$, $a_{\text{opt}} = 10$, and $a_{\text{IP}} = 1$. The optimization of the aforementioned network planning models (CSPT, TSMT) is solved by CPLEX [12], on a PC (Xeon Gold 5115 2.4-GHz 20-core CPU, 128 GB memory).

### 4.2 Numerical Results

We simulated three damage situations, namely, with surviving fibre links 5:5, 10:10, and 5:10 between the networks of Carrier-A and Carrier-B. The first two ones reflect an identical damage level, whereas the last situation reflects unequal damage among carriers. For each situation, we generated 50 cases of damage patterns. For all cases, the traffic demands of carriers were satisfied. Major results are selected and plotted in Figs. 4–7. The average computational time for each case is less than 15 minutes.

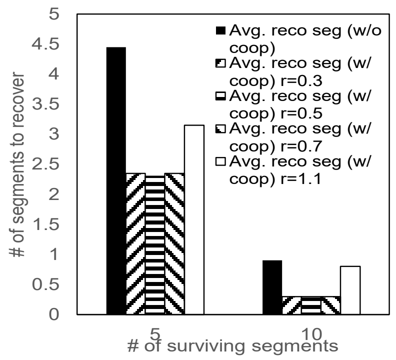


**Fig. 4.** Recovery burden reduction effect with identical damage level.

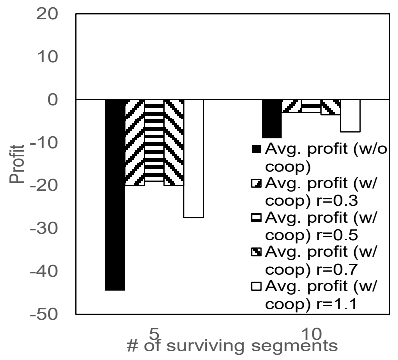


**Fig. 5.** Improved profit via cooperation with identical damage level.

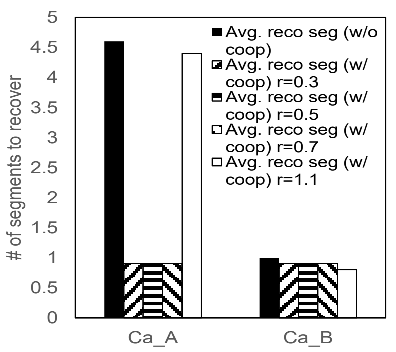


**Fig. 6.** Recovery burden reduction effect in unequal damage situation.

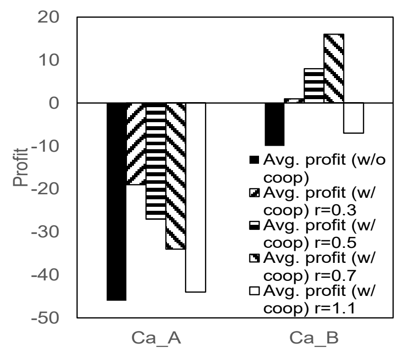


**Fig. 7.** Improved profit via cooperation in unequal damage situation.

For the identical damage situations, we first observed the effect of our proposal on the recovery burden reduction. Fig. 4 plots the average number of ESEN segments recovered per carrier, which was yielded by standalone single-carrier recovery (w/o coop) and our proposal of carrier cooperation (w/ coop). With price coefficient $r$ = 0.3, 0.5, and 0.7, in comparison to standalone recovery, a nearly 50% reduction of the recovery burden can be achieved via carrier cooperation due to the surviving resource utilization and recovery task balancing among carriers. With a significantly reduced burden on recovery, a fast recovery of communication can be expected. However, when we increased the price of the scenario (i) emergency lightpath (e.g., $r$ = 1.1), which exceeds the cost of segment recovery, the carrier does not purchase the scenario (i) lightpath support from the counterpart carrier because it is even more costly than the segment recovery performed by carrier itself. The corresponding burden reduction effect is decreased.

Fig. 5 plots the profits calculated in Task 8 (see Section III-C). The results clearly indicate that with carrier cooperation and an appropriate price of the scenario (i) lightpath, income and reward can be achieved in cooperation, and carriers can significantly improve their profits compared to single-carrier standalone recovery. This demonstrates the strong incentive for carriers to offer emergency lightpath support to one another in both heavy and lightweight disasters. However, when we increased the price of the scenario (i) emergency lightpath (e.g., $r$ = 1.1), the profit decreases, especially in lightweight disaster cases. Many surviving resources cannot be efficiently utilized due to the high price.

For an unequal damage situation with a differing amount of surviving fibre links (e.g., 5:10) between the Carrier-A (Ca_A) and Carrier-B (Ca_B) networks, Fig. 6 plots the average number of ESEN segments recovered per carrier, and Fig. 7 plots the corresponding profits. For Carrier-A, which was heavily damaged, given an appropriate price of the lightpath (scenario [i]), the recovery task performed by Carrier-A was dramatically reduced, owing to emergency lightpath support from Carrier-B (in particular, scenario [i]). Accordingly, with the income and reward received from each other, Carrier-A and Carrier-B experienced larger profits than that of single-carrier standalone recovery. Because Carrier-B was the supplier of the emergency lightpath, its profit was much higher than that of Carrier-A. When the price was increased (e.g., from $r$ = 0.3 to 0.7), the profit of Carrier-B increased accordingly. Meanwhile, when we further increased the price, namely with $r$ = 1.1, because Carrier-A would not purchase the lightpath support (scenario [i]), the income and reward from Carrier-A were not acquired. Thus, Carrier-B's profit was low. This indicates that an appropriate price also plays an important role in this system. For further investigation, a non-fixed recovery cost and non-flat pricing scheme, and the observations with wide parameter ranges and more situations, e.g., where there is less co-location of nodes between carriers, should be considered and left as future work.

## 5 Conclusions

In this paper, we propose a novel planning scheme for disaster recovery based on carrier cooperation, in which carriers aid one another by offering emergency lightpath support. The lightpaths are employed exclusively by the counterpart carriers to satisfy the highest priority traffic demand, such as safety confirmation and victim relief with a significantly reduced recovery burden. In addition, we introduce an incentive in the planning scheme to stimulate carrier cooperation. Importantly, during cooperation, the confidential information of the carriers can be protected by introducing a carrier optical network abstraction mechanism. The evaluation results reveal that our proposal can significantly reduce the number of recovery tasks undertaken by each carrier and the corresponding costs, resulting in a fast and efficient recovery.

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## Appendix A: Constraints in CSPT

The constraints on the number of available transponders are shown from (a.1) to (a.4). RWA constraints in the underlying optical network are from (a.5) to (a.7). The constraint on wavelength utilization that each lightpath can utilize at most is one wavelength on a surviving long-haul fibre link as shown in (a.8), including the constraints for using the co-route and the same wavelength for both directions. Expression (a.9) implies that wavelength utilization can also be possible if there is a restored fibre link. The degree-limitation constraint at each node is given in (a.10). In case of emergency interconnection between ROADMs, there will be a limitation on the degree of ROADM. Constraints on upper-layer packet routing are shown from (a.11) to (a.13). The constraint on bandwidth consumption of aggregated packet traffic in lightpaths that are not for sale or purchase in carrier cooperation is shown in (a.14). The aggregated traffic constraints on the emergency lightpaths that are to be sold to the counterpart carrier and are the candidates for purchase from the counterpart carrier in carrier cooperation are shown in (a.15) and (a.16), respectively. Constraint (a.17) indicates that the lightpaths $(i, j) \in \Pi$ should be created and sold to the counterpart carrier. The constraints on border specification are shown in (a.18) and (a.19).

$$\sum_{j\in V}\sum_{n\in V|(U^{w}_{i,n}=0,\text{or}T_{i,n}\neq\inf)} P^{(i,j),w}_{i,n} \le F^{w}_{i}, \forall i\in V; \forall w\in W \tag{a.1}$$

$$\sum_{i\in V}\sum_{m\in V|(U^{w}_{m,j}=0,\text{or}T_{m,j}\neq\inf)} P^{(i,j),w}_{m,j} \le F^{w}_{j}, \forall j\in V; \forall w\in W \tag{a.2}$$

$$\sum_{j\in V}\sum_{w\in W}\sum_{n\in V|(U^{w}_{i,n}=0,\text{or}T_{i,n}\neq\inf)} P^{(i,j),w}_{i,n} \le G_{i}, \forall i\in V \tag{a.3}$$

$$\sum_{i\in V}\sum_{w\in W}\sum_{m\in V|(U^{w}_{m,j}=0,\text{or}T_{m,j}\neq\inf)} P^{(i,j),w}_{m,j} \le G_{j}, \forall j\in V \tag{a.4}$$

$$\sum_{m\in V|(U^{w}_{m,k}=0,\text{or}T_{m,k}\neq\inf)} P^{(i,j),w}_{m,k} = \sum_{n\in V|(U^{w}_{k,n}=0,\text{or}T_{k,n}\neq\inf)} P^{(i,j),w}_{k,n}, \tag{a.5}$$

$$\forall i,j,k\in V \mid (i\neq j\neq k); \forall w\in W$$

$$\sum_{n\in V|(U^{w}_{i,n}=0,\text{or}T_{i,n}\neq\inf)} P^{(i,j),w}_{i,n} = v^{w}_{i,j}, \forall i,j\in V \mid (i\neq j); \forall w\in W \tag{a.6}$$

$$\sum_{m\in V|(U^{w}_{m,j}=0,\text{or}T_{m,j}\neq\inf)} P^{(i,j),w}_{m,j} = v^{w}_{i,j}, \forall i,j\in V \mid (i\neq j); \forall w\in W \tag{a.7}$$

$$\sum_{i,j\in V}[P^{(i,j),w}_{m,n} + P^{(i,j),w}_{n,m}] \le 1, \forall w\in W; \forall m,n\in V \mid U^{w}_{m,n}=0 \tag{a.8}$$

$$\sum_{i,j\in V}[P^{(i,j),w}_{m,n} + P^{(i,j),w}_{n,m}] \le \beta_{m,n}, \forall w\in W; \forall m,n\in V \mid T_{m,n}\neq\inf \tag{a.9}$$

$$\sum_{n\in V|T_{m,n}\neq\inf} \beta_{m,n} + \sum_{n\in V|L_{m,n}=1} L_{m,n} \le D_{m}, \forall m\in V \mid (\exists n\in V, T_{m,n}\neq\inf) \tag{a.10}$$

$$\sum_{i\in V|i\neq k\neq s\neq d} \lambda^{s,d}_{i,k} = \sum_{j\in V|j\neq k\neq s\neq d} \lambda^{s,d}_{k,j}, \forall (s,d)\in R, \forall k\in V \tag{a.11}$$

$$\sum_{j\in V|(j\neq s\neq d)} \lambda^{s,d}_{s,j} = \alpha^{s,d}, \forall (s,d)\in R \tag{a.12}$$

$$\sum_{i\in V|(i\neq s\neq d)} \lambda^{s,d}_{i,d} = \alpha^{s,d}, \forall (s,d)\in R \tag{a.13}$$

$$\sum_{(s,d)\in R} \Gamma_{s,d}\lambda^{s,d}_{i,j} \le C\sum_{w\in W} v^{w}_{i,j}, \forall i,j\in V|(i\neq j) and\ (i,j)\notin(\Psi\cup\Pi) \tag{a.14}$$

$$\sum_{(s,d)\in R} \Gamma_{s,d}\lambda^{s,d}_{i,j} \le C[\left(\sum_{w\in W} v^{w}_{i,j}\right) - O_{i,j}], \forall (i,j)\in\Pi \tag{a.15}$$

$$\sum_{(s,d)\in R} \Gamma_{s,d}\lambda^{s,d}_{i,j} \le C[\left(\sum_{w\in W} v^{w}_{i,j}\right) + \sigma_{i,j}], \forall (i,j)\in\Psi-\Pi \tag{a.16}$$

$$\sum_{w\in W} v^{w}_{i,j} \ge O_{i,j}, \forall (i,j)\in\Pi \tag{a.17}$$

$$\lambda^{s*,d}_{s*,b} \le u_{b}, \forall s*\in S, \forall d\in(V-S) \mid (s*,d)\in R; \forall b\in B \tag{a.18}$$

$$\lambda^{s*,d}_{b,k} \le u_{b}, \forall s*\in S, \forall d\in(V-S) \mid (s*,d)\in R; \forall b\in B; \forall k\in V-S-B \tag{a.19}$$

# Appendix B: Constraints in TSMT

The constraint on the maximum cost experienced by individual carriers is shown in (b.1). The constraint assuring task assignment in $X_{\text{common}}$ among carriers is in (b.2).

$$\sum_{(i,j)\in X_{\text{common}}} p^{a}_{i,j}\gamma^{a}_{i,j} \le \lambda_{\max}, \forall a\in\Delta \tag{b.1}$$

$$\sum_{a\in\Delta} \gamma^{a}_{i,j} = 1, \forall (i,j)\in X_{\text{common}} \tag{b.2}$$