Multi-Broker based Service Provisioning in Multi-Domain SD-EONs: Why and How Should the Brokers Cooperate with Each Other?

Lu Sun, Xiaoliang Chen, Zuqing Zhu, *Senior Member, IEEE*

***Abstract*—It is known that software-defined elastic optical networks (SD-EONs) facilitate optical networking that provides better network programmability, more powerful manageability, and more flexible service provisioning capability. Moreover, the hierarchical architecture of multi-broker based multi-domain SD-EONs can not only improve the network scalability but also maintain the autonomy of each administrative domain. In this paper, we study why and how the brokers should cooperate with each other to provision inter-domain lightpaths in multi-broker based multi-domain SD-EONs. We first formulate a cooperative market in which the brokers negotiate about their market shares (*i.e.*, the opportunities to provision inter-domain lightpaths) and seek for a mutual agreement with Nash bargaining [1]. Then, we design a mathematical model to describe the market as well as the brokers' behaviors in it. An effective algorithm is derived from the model to solve the Nash bargaining problem for allocating lightpath requests among the brokers. The proposed algorithm also addresses the resource collision during request provisioning and can achieve collision-free request allocation. Extensive simulations verify the effectiveness of our proposal.**

***Index Terms*—Software-defined elastic optical networks (SD-EONs), Multi-broker, Cooperative game, Nash bargaining.**

I. INTRODUCTION

RECENTLY, with the rapid growth of emerging applications, backbone optical networks would need to undergo dramatic changes to adapt to not only the tremendous traffic increase but also the highly-dynamic traffic fluctuation [2]. For instance, dynamic lightpath establishment with flexible bandwidth allocation and millisecond-scale setup time might be required [3]. Hence, elastic optical networks (EONs), which can be more flexible, adaptive and spectrum-efficient than the traditional fixed-grid wavelength-division multiplexing (WDM) networks, have been considered as a promising future backbone infrastructure [4]. Specifically, with sub-wavelength switching capability, EONs can set up lightpaths by grooming a series of spectrally-contiguous narrow-band (*e.g.*, 12.5 GHz) frequency slots (FS') to provision just-enough bandwidths [5, 6]. Moreover, by leveraging the idea of software-defined networking (SDN), which decouples the control and data planes and provides new networking possibilities with centralized network control and management (NC&M) [7], one can further explore the advantages of EONs to realize the dynamic lightpath establishment for bandwidth-on-demand. Specifically, software-defined EONs (SD-EONs) [8-10] can be built to achieve effective spectrum management and enhanced network programmability.

Meanwhile, we should notice that a practical backbone network usually covers a relatively large geographical area, and equips network elements from multiple vendors. Hence, it is inevitable to extend the research to address multi-domain SD-EONs. Considering the autonomy of each administrative domain, the end-to-end service provisioning that traverses several domains would be more complex to realize than that in a single domain. Therefore, it is essential to design a service provisioning framework that works effectively for multi-domain SD-EONs. Previously, based on the idea that the domain managers (DMs) collaborate in a peer-to-peer manner to provision inter-domain lightpaths, people have designed several flat frameworks [10, 11]. However, later studies in [12, 13] have suggested that the hierarchical framework, which introduces a resource broker to coordinate the DMs, can achieve more cost-effective and scalable inter-domain provisioning. Specifically, the broker is placed at a higher NC&M level than the DMs and works as a centralized orchestrator. Although the practicalness of the hierarchical framework has already been experimentally verified in [14] and the standardization regarding it is in progress [15], the single-broker based scenario still bears a few drawbacks. First of all, high availability can hardly be realized with a single broker, since it is known that in Google's software-defined wide-area network (*i.e.*, B4), management plane failures outweigh those in the data plane [16]. More importantly, the autonomy of each domain would be violated as the broker plays a role of monopoly in such multi-domain SD-EONs [17]. To address these issues, the multi-broker based hierarchical framework was proposed in [18], which assumed a management plane that consists of multiple market-driven brokers that can compete or cooperate to obtain inter-domain lightpath requests to serve. Therefore, each DM can subscribe to several brokers and select the right one to grant the offer of inter-domain lightpath provisioning. Specifically, driven by the incentive of gaining more service offers from the DMs, the brokers try to provide the most cost-effective provisioning schemes to serve the DMs' lightpath requests. Meanwhile, the DM that submits an inter-domain lightpath request can choose the "best" provisioning scheme freely according to its own need, and thus the autonomy of each domain is guaranteed.

Note that, even though multiple brokers are placed in the

L. Sun, and Z. Zhu are with the School of Information Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, P. R. China (email: zqzhu@ieee.org).

X. Chen is with the Department of Electrical and Computer Engineering, University of California, Davis, Davis, CA 95616, USA.

Manuscript received on January 22, 2017; revised on May 4, 2017 and June 23, 2017.

management plane, the inter-domain lightpath provisioning procedure is actually exactly the same as that in the conventional hierarchical framework [12, 13], after each lightpath request has been assigned to a broker. Hence, the practicality of the multi-broker based hierarchical framework would not be an issue. This has already been verified in our previous work [17], where we realized the multi-broker based management plane with existing SDN protocol and software platforms, and conducted experiments to demonstrate multi-broker based inter-domain lightpath provisioning in a non-cooperative market. Specifically, based on the fact that the brokers have conflicting interests in gaining service offers from the DMs, we came up with a simple market to let the brokers compete with each other [17, 19, 20]. And when the DM has collected the provisioning schemes as well as the bidding prices from all the brokers that it subscribes to, it chooses the lowest bidder to grant the service offers. Nevertheless, this non-cooperative scenario bears two drawbacks. Firstly, it only considers the competition among the brokers, which can easily leads to the prisoners' dilemma. This means that to win a service offer, the brokers can only submit the lowest-possible bids [17]. Hence, the non-cooperative market cannot secure the brokers' interests. Secondly, as the lightpath requests are provisioned with the schemes from non-cooperative brokers, joint optimization on resource allocation would not be feasible and thus the DMs' interests cannot be fully secured either.

On the other hand, if the brokers can cooperate with each other based on the consensus that each of them would perform worse otherwise, the market would become a better place for both the brokers and DMs [21]. Hence, in this work, we extend our preliminary study in [21] to investigate why and how the brokers should cooperate when provisioning inter-domain lightpaths. We first formulate a cooperative market in which the brokers negotiate about their market shares (*i.e.*, the opportunities to provision pending inter-domain lightpaths) and seek for a mutual agreement with Nash bargaining [1] based on their performance, *i.e.*, their expected utilities and reputations. Then, we design a mathematical model to describe the cooperative market and the brokers' behaviors in it. An algorithm is derived from the model to solve the Nash bargaining problem for allocating lightpath requests among the brokers. We also consider the resource collision during lightpath provisioning and improve the proposed algorithm to achieve collision-free request allocation. Extensive simulations are used to verify the effectiveness of our proposal. The rest of the paper is organized as follows. Section II surveys the related work. The mathematical model for the cooperative market to facilitate inter-domain service provisioning in multi-domain SD-EONs is discussed in Section III. In Section IV, we propose the algorithm to solve the Nash bargaining problem and improve it to achieve collision-free request allocation. The performance evaluation is presented in Section V. Finally, Section VI summarizes the paper.

II. Related Work

Previously, people have carried out experiments to study the performance of SD-EON on programmability, resiliency, provisioning efficiency, and resource utilization [22-27]. However, these studies only discussed the single-domain scenario. Then, with the awareness on the necessity of multi-domain organization in backbone networks, researchers started to consider multi-domain SD-EONs [9-12, 28]. In [10], Casellas *et al.* proposed to coordinate the operations of an integrated path computation module (PCE) and several OpenFlow controllers (*i.e.*, DMs) to realize service provisioning in multi-domain SD-EONs. Our studies in [9, 11] proposed inter-domain protocols to facilitate DMs to operate in a peer-to-peer way for inter-domain service provisioning. Nevertheless, these investigations on multi-domain SD-EONs relied on the flat NC&M framework, which might not scale well.

To address the scalability issues, the hierarchical framework that places a broker on top of the DMs for cross-domain coordination has been designed in [12]. As a single broker plays the role of monopoly and can violate the autonomy of each domain, the market-driven multi-broker based hierarchical framework has been proposed in [18]. Note that, game theory [1] provides us a powerful mathematical tool to analyze the competition and cooperation among rational players, and hence, it has already been leveraged to solve various problems in optical networks [29, 30]. In [18], the authors discussed how the market-driven brokers should inter-operate to facilitate cost-effective inter-domain service provisioning, while the DMs provide intra-domain status and resources to assist the brokers. Chen *et al.* leveraged game theory to model the brokers' inter-operation as a non-cooperative game to analyze the competitive market behaviors of them [17, 20]. Specifically, the brokers (*i.e.*, the players) bid for lightpath provisioning services while the one that asks for the lowest price would be selected by the DM as the winning bidder. Nevertheless, in this non-cooperative market, the interests of the brokers might not be secured because of the prisoners' dilemma, *i.e.*, the brokers have to decrease their service prices for increasing the possibilities of being chosen by the DM.

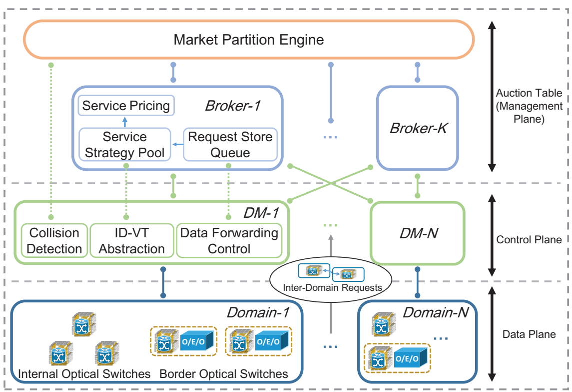


Fig. 1. Network architecture of multi-broker based multi-domain SD-EONs.

To avoid the issues brought by the vicious competition among brokers, we formulated a cooperative market for the brokers in [21]. Specifically, the brokers leverage Nash bargaining to distribute the lightpath requests according to each other's expected profit, *i.e.*, if a broker would expect a higher profit per request, it would get a smaller number of requests, and *vice versa*. Compared with the non-cooperative market, the major advantage of this scenario is that it allocates lightpath requests among the brokers in a fairer way such that the overall profit of all the brokers can be improved. Meanwhile, it ensures that the Nash bargaining among the brokers would not degrade their services to the DMs, *i.e.*, the request blocking probability would not increase. Note that, according to [31], which studied cooperative resource allocation in wireless networks, it is essential to design a time-efficient and sophisticated algorithm to solve the Nash bargaining problem for partitioning the market shares. This, however, has not been fully addressed in [21], and the algorithm for allocating lightpath requests among the brokers can still be improved. Also, the resource collision during lightpath provisioning has not been resolved properly.

III. Cooperative Market for Multi-Broker based Inter-Domain Service Provisioning

A. Network Architecture

Fig. 1 shows the network architecture of a multi-broker based multi-domain SD-EON that uses cooperative market for inter-domain service provisioning. The network employs a hierarchical framework, and on top of the control and data planes, we introduce a management plane to work as the auction table of the brokers. The data plane is divided into multiple administrative domains, each of which has a DM in the control plane to manage the optical switches in the domain for lightpath assembling. As each DM only maintains the information regarding its own domain, the brokers are introduced in the management plane to obtain global network information by integrating the intra-domain status provided by the DMs and coordinate the DMs to build inter-domain lightpaths. Specifically, if a DM is involved in the provisioning of an inter-domain lightpath, it should abstract and submit an intra-domain virtualized topology (ID-VT) to the brokers, according to the service-level agreement (SLA) between them. Here, the DMs are actually telecom operators, while the brokers should be owned and operated by third-party organizations just like the brokers in stock markets. After obtaining all the required ID-VTs, each broker calculates an inter-domain provisioning scheme with the routing and spectrum assignment (RSA) algorithms in the service strategy pool, prices the provisioning scheme, and returns the results to the DM that initiated the inter-domain lightpath request.

Note that, there is no restriction on how many brokers that a DM can subscribe to. Hence, in the extreme case, the DMs and brokers can form a bipartite graph (*i.e.*, one row is the DMs and the other row is the brokers) with full connectivity in between, which means that a DM can broadcast its inter-domain lightpath requests to all the brokers in the management plane. However, in practice, this would not be necessary, and a DM only needs to subscribe to a subset of the brokers.

The multi-broker based architecture makes the inter-domain service provisioning more diversified, which on one hand offers DMs more options but on the other hand leads to conflicting interests among the brokers. Note that, if we only consider the competition among the brokers, the brokers can easily be trapped in the prisoners' dilemma [17]. Therefore, the brokers should cooperate with each other based on the presumption that each of them would perform worse otherwise. This can be realized by introducing a cooperative market in which the brokers negotiate about their market shares and seek for a mutual agreement with Nash bargaining [1]. Basically, with the market partition engine (MPE)[1] in Fig. 1, the Nash bargaining result can be obtained for each broker, *i.e.*, a set of inter-domain lightpath requests is allocated to it. Then, the broker will only handle the requests in its own market share. Note that, the cooperative scenario would not overlook the rationality of each broker since the principle of Nash bargaining ensures that each broker will only agree to be cooperative if its profit would decrease otherwise. Meanwhile, the cooperation among the brokers would not eliminate their competition because the market share of each broker still depends on the relative competitiveness of its service against others', and moreover, we allow the DMs to reject the provisioning schemes that have unreasonably high prices, for avoiding price alliances.

B. Inter-Domain Service Provisioning

1) Overall Procedure: We model an SD-EON with N domains as $G = G_n(V_n, E_n), n \in [1, N]$, where V_n and E_n denote the node and fiber link sets in *Domain-n*, respectively. *Broker-k* represents the k-th broker ($k \in [1, K]$) in the management plane, and an inter-domain lightpath request is denoted as $r_i(s_i, d_i, B_i, T_i)$, where s_i and d_i are the source and destination nodes ($s_i \in V_{n_1}, d_i \in V_{n_2}, n_1 \neq n_2$), B_i is the bandwidth requirement in Gb/s, and T_i is the requested lifetime. Note that, although there are electrical IP routers at the edge of each domain to aggregate traffics, we assume that the traffic in an inter-domain lightpath r_i would not be forwarded to such IP routers before it reaches d_i. This is because there are practical demands to do so [16] and the lightpaths that are terminated by the IP routers in between domains can be treated as intra-domain lightpaths. Each inter-domain lightpath request is submitted to the management plane by the DM that controls the source domain, and the requests from the DMs are stored in the request store queues of the brokers (as shown in Fig. 1) and processed in batches at fixed intervals. The number of requests handled by the brokers each time is denoted as M, which is not a constant, and we use $R = \{r_i, i \in [1, M]\}$ to represent the request set. The provisioning scheme of *Broker-k* for request r_i is $SC(k, i)$. Based on this network model, the procedure of multi-broker based inter-domain service provisioning in the cooperative market is as follows.

- **Step 1**: Each inter-domain request r_i is reported by the DM of its source domain to the brokers, where they are stored in the request store queues.
- **Step 2**: For each $r_i \in R$, every broker
  - collects ID-VTs from the related DMs, which submit ID-VTs according to r_i and their SLAs with the broker;
  - calculates feasible provisioning schemes as well as the corresponding base costs with the global topology

[1]Note that, MPE should be owned and operated by a third-party organization just like the brokers.

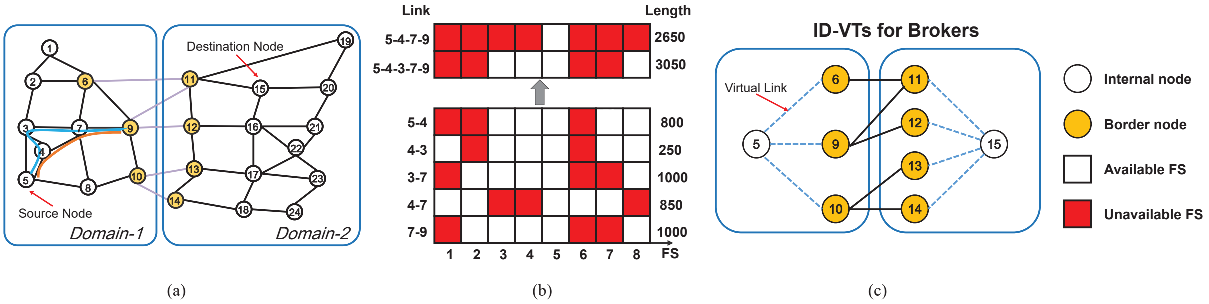


Fig. 2. Example on DMs abstracting ID-VTs for different brokers, (a) Topology of a multi-domain SD-EON, (b) Spectrum usage on fiber links and procedure to obtain VLs for 5→9, and (c) ID-VTs submitted to two brokers for serving an inter-domain lightpath from *Node* 5 to *Node* 15.

aggregated from the ID-VTs, using the RSA algorithms in its service strategy pool;
– chooses the provisioning scheme with the lowest base cost and determines the service price for it.

- **Step 3**: The brokers report their provisioning schemes and expected profits for the requests in R to MPE.
- **Step 4**: MPE requests for the resource collisions among the submitted provisioning schemes from the DMs, which check the provisioning schemes' resource usages in their domains and report conflicts.
- **Step 5**: MPE considers the resource collisions, determines how to distribute the requests in R by solving the Nash bargaining, and returns the results to the brokers.
- **Step 6**: After receiving the Nash bargaining result from MPE, every broker informs the related DMs about its provisioning schemes and corresponding service prices for the requests in its market share. Once a DM agrees with the deal, the broker gets the payment for its provisioning service and then it coordinates the related DMs to build the corresponding inter-domain lightpath.

2) Intra-Domain Virtualized Topology (ID-VT): Similar to our previous work [17], an ID-VT in **Step 2** consists of the virtual links (VLs) that a DM abstracts from related path segments for assisting the establishment of an inter-domain lightpath in its domain. Specifically, a VL represents a path segment that is from the source node to one border node in the source domain, from one border node to the destination node in the destination domain, or in between two border nodes in an intermediate domain. The VL reports the information on the physical length and spectrum usage of the path segment, with which the brokers can calculate RSA schemes for the inter-domain lightpath. Fig. 2 shows an intuitive example on how the ID-VTs are abstracted by the DMs. Here, we have two brokers, *i.e.*, *Broker*-1 and *Broker*-2, and both of them try to provision an inter-domain lightpath from *Node* 5 to *Node* 15. Since both of the domains in the multi-domain SD-EON in Fig. 2(a) will be involved in the inter-domain service provisioning, the brokers ask for ID-VTs from the two DMs.

We assume that the SLAs determine that *DM*-1 needs to abstract ID-VTs for *Broker*-1 based on shortest-path routing, while *Broker*-2 should be offered with ID-VTs that consist of VLs with the most available spectra. Since *DM*-1 controls the source domain of the inter-domain lightpath, it should abstract VLs from the source node (*i.e.*, *Node* 5) to each of the border nodes. Then, with the topology and FS usages in Figs. 2(a) and 2(b), we can see that for the VL from *Node* 5 to *Node* 9, *DM*-1 uses the path segments 5→4→7→9 and 5→4→3→7→9 as the VLs for *Broker*-1 and *Broker*-2, respectively. Hence, in Fig. 2(c), although the two brokers obtain integrated ID-VTs with the same connectivity, the VLs actually have different physical characteristics (*i.e.*, lengths and FS usages).

3) Brokers' Pricing Strategy: In **Step 2**, after calculating feasible provisioning schemes with the RSA algorithms in its service strategy pool, each broker needs to first determine the base costs of the schemes. Note that, although the broker can coordinate multiple DMs to set up an inter-domain lightpath, it still needs to pay the resource cost, which is the base cost of its service. In this work, we calculate the base cost of *Broker*-k provisioning a request r_i as

$$C_i^k = T_i \cdot (SU_i^k \cdot c_S + RE_i^k \cdot c_R), \tag{1}$$

where SU_i^k and RE_i^k refer to the spectrum utilization and number of optical-electrical-optical (O/E/O) regenerators needed for setting up r_i, c_S and c_R are the unit prices of spectrum and regenerator usages, respectively, and T_i is the request's life-time. With Eq. (1), the broker can select the provisioning scheme with the lowest base cost to generate its bid. Next, the broker should determine the profit ratio δ_i^k for serving r_i, and the final service price for its bid would be

$$P_i^k = C_i^k \cdot (1 + \delta_i^k). \tag{2}$$

Apparently, none of the market-driven brokers would admit to provide services for free, and thus we assume that the profit ratio has a minimum value $\delta_{min} > 0$, *i.e.*, we have $\delta_i^k \geq \delta_{min}$. On the other hand, we have to ensure that the brokers cannot inflate their service prices arbitrarily. This can be done by letting the DMs reject the provisioning schemes with unreasonably high prices. Therefore, through the whole process, the DMs have the inter-domain lightpath requests generated in their domains served cost-effectively, which is a must-have feature of telecom operators. Note that, the ultimate undertaker of P_i^k in Eq. (2) is the DM's client who submits the lightpath request, and thus the DM will also have economic gain from the process. However, since this paper mainly focuses on the cooperative market of the brokers, we do not consider the trading between the DMs and their clients.

Definition The **satisfaction ratio** represents the probability that a DM would accept the provisioning service of a broker based on its price, which can be denoted as a function

$$f_{sr}(g_i^k) = f_{sr}(\frac{P_i^k}{B_i \cdot T_i}), \tag{3}$$

where g_i^k is the normalized price. $f_{sr}(\cdot)$ is a decreasing function and would output zero when g_i^k is too high.

Note that, in the cooperative market, each inter-domain lightpath request from a DM is assigned to a broker based on the solution of the Nash Bargaining. Hence, to ensure the autonomy of the DM, we allow it to reject the provisioning service of an assigned broker if the normalized service price g_i^k is too high. For an inter-domain lightpath, the most intuitive metric to measure its requested resources is the amount of spectra occupied during its hold-time. Hence, the normalized service price should be calculated as $\frac{P_i^k}{B_i \cdot T_i}$. Since the DMs can reject the provisioning services with unreasonably high prices, the broker has to optimize its service price carefully instead of raising or lowering it excessively [32]. Therefore, the broker's pricing strategy should be maximizing the mathematical expectation of its profit. Specifically, with the lowest base cost C_i^k, the broker needs to determine the profit ratio δ_i^k by solving the following optimization

$$\underset{\delta_i^k}{Maximize} \quad (C_i^k \cdot \delta_i^k) \cdot \hat{f_{sr}}\left(\frac{(1+\delta_i^k) \cdot C_i^k}{B_i \cdot T_i}\right), \tag{4}$$

where $\hat{f_{sr}}(\cdot)$ represents the estimated satisfaction ratio by the broker. This is because in a practical scenario, the DMs' satisfaction ratio function should not be disclosed to the brokers explicitly. On the contrary, the brokers should estimate $f_{sr}(\cdot)$ by submitting prices with different profit ratios to the DMs and recording the acceptance ratio each time. Specifically, the first several bids from each broker are used as the training sequence, and the broker uses the normalized prices of the bids as sampling points. The sampling points provide the estimated satisfaction ratios for various normalized prices, and then we perform curve-fitting to obtain $\hat{f_{sr}}(\cdot)$. Then, with $\hat{f_{sr}}(\cdot)$, the broker solves Eq. (4) to get its service price for each bid.

4) Resource Collision: In **Step 3**, the brokers submit their provisioning schemes as well as expected profits of each request to MPE, where the Nash bargaining is solved for allocating the requests in R to the brokers. We will discuss the algorithm for solving the Nash bargaining in the next section. But before that, we should note that there might be resource collisions among the provisioning schemes submitted by the brokers. This is because when the brokers calculate the provisioning schemes, the network status in which none of the pending requests are served is used. Hence, different brokers may use the same network resources (*i.e.*, the same FS' and/or O/E/O regenerators) to provision different requests.

In order to avoid resource collisions, MPE needs to collect conflicting resource usages in the provisioning schemes from the DMs, as shown in **Step 4**. Basically, each DM needs to check the provisioning schemes that use its domain and construct a collision graph as shown in Fig. 3. There are three brokers to use a domain for provisioning four inter-domain lightpath requests. Each node in Fig. 3 represents the provisioning scheme from a broker for a specific request. We

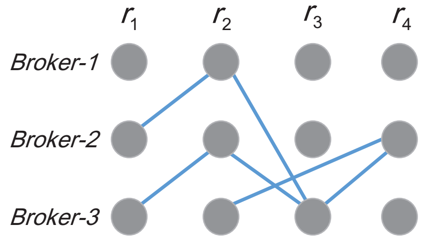


Fig. 3. Example on the collision graph of provisioning schemes.

connect two nodes in the collision graph to indicate that the two corresponding provisioning schemes have conflicts. For instance, in Fig. 3, it can be seen that the provisioning scheme from *Broker*-3 for r_3 (*i.e.*, *SC*$(3,3)$) has resource collisions with *SC*$(1,2)$, *SC*$(2,2)$ and *SC*$(2,4)$. To gain a collision-free request allocation result, there should exists no edge among the nodes selected. For example, *SC*$(1,1)$, *SC*$(2,2)$, *SC*$(2,3)$and *SC*$(3,4)$ can constitute a collision-free allocation solution, which means r_1 and r_4 are distributed to *Broker*-1 and *Broker*-3, respectively, while r_2 and r_3 are distributed to *Broker*-2. *SC*$(1,1)$, *SC*$(3,3)$, and *SC*$(2,4)$ can also make up a collision-free solution, however, r_2 cannot be allocated to any broker since all the schemes to provision r_2 have collisions with the nodes selected. Hence, when distributing the requests in the Nash bargaining, MPE should try to avoid selecting the nodes with a relatively high degree, *e.g.*, the one representing *SC*$(3,3)$ in Fig. 3.

IV. Collision-Free Request Allocation based on Nash Bargaining

In this section, we briefly introduce the working principle of Nash bargaining, based on which we propose an algorithm to distribute the pending inter-domain lightpath requests to the brokers. The algorithm also considers the resource collisions to achieve collision-free request allocation.

A. Nash Bargaining

Nash bargaining is for the bargaining scenario in which K players try to achieve a profit-based mutual agreement. We use $\mathbf{S} = \{(u_1, \cdots, u_k, \cdots, u_K) | u_k \geq d_k, \ k \in [1, K]\}$ to denote the profits that the players can obtain if they agree to be cooperative for reaching an agreement, where d_k is the profit of *Player*-k if it decides not to be cooperative (*i.e.*, the outcome of a non-cooperative game). Hence, the disagreement point of the Nash bargaining is $\mathbf{D} = \{(d_1, \cdots, d_k, \cdots, d_K)\}$. According to Nash's theory [33], the solution of the Nash bargaining $(\mathbf{S}, \mathbf{D})$ should satisfy Pareto-efficiency, which means that it is impossible for a player to increase its profit without sacrificing any other player's profit. Moreover, Nash proved that there exists a unique Nash bargaining solution, which can be obtained by solving the following optimization.

$$\begin{aligned} &\underset{(u_1,\cdots,u_K)\in\mathbf{S}}{Maximize} \quad \prod_{k=1}^{K}(u_k - d_k), \\ &s.t. \quad u_k \geq d_k, \quad \forall k \in [1, K]. \end{aligned} \tag{5}$$

B. Nash Bargaining based Request Allocation

As Nash bargaining can precisely model the players' behaviors in a cooperative market, we leverage it to distribute the requests in R to the brokers, *i.e.*, determining each broker's market share. Based on the optimization in Eq. (5), we formulate the problem of request allocation as follows.

Input Parameters:

- δ_i^k: the profit ratio of provisioning scheme $SC(k,i)$.
- D_k: the profit that *Broker*-k can obtain in the non-cooperative market.
- S_i^k: the expected profit that *Broker*-k can get in the cooperative market by provisioning request r_i with $SC(k,i)$.
- C_i^k: the base cost of $SC(k,i)$.
- F_k: the reputation of *Broker*-k, which represents the ratio that the DMs accepted the service deals from *Broker*-k in previous provisioning periods.

Variables:

- $\mathbf{R}$: a feasible collision-free request allocation among the brokers, *i.e.*, $\mathbf{R} = (R_1, \cdots, R_K),\ R_1 \cup \cdots \cup R_K \subseteq R$, $R_{k_1} \bigcap R_{k_2} = \emptyset,\ \{k_1, k_2 : k_1 \neq k_2\}$, where R_k is the set of pending requests that are allocated to *Broker*-k.

Outputs:

- $\hat{\mathbf{R}}$: the collision-free request allocation result from Nash bargaining.
- S_k: the total expected profit of *Broker*-k.

Objective:

The objective is to maximize the following equation.

$$\begin{aligned} &\underset{(R_1,\cdots,R_K)}{Maximize} \quad \prod_{k=1}^{K}(S_k - D_k), \\ &s.t. \quad \bigcup_{k=1}^{K} R_k \subseteq R, \\ &\qquad R_{k_1} \bigcap R_{k_2} = \emptyset,\ \{k_1, k_2 : k_1 \neq k_2\}, \end{aligned} \tag{6}$$

where S_k is the total expected profit of *Broker*-k according to $\mathbf{R} = (R_1, \cdots, R_K)$, which is calculated as

$$S_k = \sum_{\{i:\ SC(k,i) \in R_k\}} S_i^k = \sum_{\{i:\ SC(k,i) \in R_k\}} C_i^k \cdot \delta_i^k \cdot F_k. \tag{7}$$

Here, F_k denotes the reputation of *Broker*-k, which reflects the satisfaction of the DMs regarding its service prices. Note that, since we allow the DMs to reject provisioning schemes with unreasonably high prices, a broker might not always get the full payment for all the requests allocated to it. Hence, F_k is introduced here to model the profit gap. In Eq. (6), we calculate D_k based on the fact that in the non-cooperative market, the Nash equilibrium suggests that only the lowest bid from the brokers can be chosen [17], *i.e.*,

$$D_k = \sum_{\{i:\ C_i^k = \min(C_i^1, \cdots, C_i^K)\}} C_i^k \cdot \delta_{min}, \tag{8}$$

where δ_{min} is the minimum profit ratio that a broker can use.

The Nash bargaining in Eq. (6) is a nonlinear combinatorial optimization problem, which is a relatively complex problem. Since its output should be collision-free and each request can be allocated to any of the K brokers or be blocked to avoid the collision with other requests, the size of the overall solution space would be $(K+1)^M$ if there are M pending inter-domain lightpath requests. In reality, since the multi-domain SD-EON is a backbone network, the requests would not come in as frequently as those in access networks [34]. Moreover, when provisioning dynamic lightpath requests, the DMs might demand for very short setup latency [3], and thus, the provisioning period of the brokers should be relatively short. Even though the lightpath requests could come in more frequently, we can always reduce the provisioning interval to maintain the value of M. These practical issues suggest that it would be reasonable to assume that the number of pending inter-domain lightpath requests M in our problem is a relatively small and upper-bounded number (*e.g.*, $M \leq 20$). Therefore, when the number of brokers is also small (*e.g.*, $K = 2$), MPE can solve the optimization in Eq. (6) by simply enumerating all the feasible solutions, and a time-efficient heuristic is only needed when K is so large such that the exhaustive search is impractical.

C. Collision-Free Request Allocation Algorithm

In this subsection, we develop a broker grouping mechanism and propose a time-efficient algorithm (*i.e.*, the collision-free request allocation (CFRA) algorithm) based on it to solve the optimization in Eq. (6) when $K > 2$. CFRA leverages an iterative approach to obtain a near-optimal request allocation solution without resource collision. Specifically, it divides the brokers into two-member groups to reduce the complexity to the maximum extent, and solves the Nash bargaining for each group according to Eq. (6). However, the grouping mechanism cannot protect the allocation result from resource collisions, even though the request allocation is collision-free in each two-member group. Therefore, CFRA takes collision-avoidance into consideration and makes sure that the allocation result is collision-free eventually. Here, the collision-avoidance follows the intuitive observation that in the collision graph, the nodes with relatively high degrees should not be put into $\mathbf{R}$, as explained in Section III-B. To achieve this, we add some variables and modify the optimization objective as follows.

Variables:

- H_i^k: the number of selected provisioning schemes in $\mathbf{R}$, which have conflicts with $SC(k,i)$ (*i.e.*, $SC(k,i) \in R_k$ according to $\mathbf{R}$) in the collision graph.
- W_i^k: the collision-weighted profit of $SC(k,i)$.
- W_k: the total collision-weighted profit of *Broker*-k according to $\mathbf{R}$.

Objective:

$$\begin{aligned} &\underset{(R_1,\cdots,R_K)}{Maximize} \quad \prod_{k=1}^{K}(W_k - D_k), \\ &s.t. \quad \bigcup_{k=1}^{K} R_k = R, \\ &\qquad R_{k_1} \bigcap R_{k_2} = \emptyset,\ \{k_1, k_2 : k_1 \neq k_2\}, \end{aligned} \tag{9}$$

where W_k is the total collision-weighted profit of *Broker*-k according to $\mathbf{R} = (R_1, \cdots, R_K)$.

Definition The **collision-weighted profit** of provisioning scheme $SC(k,i)$ is calculated as

$$W_i^k = \frac{S_i^k}{H_i^k + 1}, \tag{10}$$

where H_i^k denotes the number of selected provisioning schemes that have conflicts with $SC(k,i)$. With W_i^k, we can get the **total collision-weighted profit** of *Broker*-k as

$$W_k = \sum_{\{i:\ SC(k,i)\in R_k\}} W_i^k. \tag{11}$$

With Eqs. (9)-(11), we can ensure that when solving the Nash bargaining, the provisioning schemes that have more conflicts with others would be less likely selected by MPE. Note that, we introduce the collision-weighted profit W_i^k to reduce the resource collision among the service provisioning schemes. Hence, the definition can be empirical as long as it can achieve this target and its value can be calculated time-efficiently. We have tried a few definitions and found that the one in Eq. (10) provides the best performance on reducing the resource collisions, which is the reason why it is used here.

Algorithm 1 shows the detailed procedure of CFRA. It first divides the brokers into a few two-member groups and obtains the Nash bargaining solutions for all the groups. Then, it re-groups the brokers and solves the Nash bargaining in each group again, and this procedure is repeated until the output of Eq. (9) cannot be increased anymore. *Lines* 1-6 get an initial resource allocation result with the Nash bargaining benchmark (NB-benchmark) that we developed in [21], and the variables for collision-weighted profits are initialized. Note that, since the brokers in each group will exchange their requests according to the Nash bargaining in the following steps, each broker should be assigned a set of requests initially. This is why NB-Benchmark is leveraged here. Here, we use σ to record the increment of Eq. (9) in each iteration, and thus it should be initialized as an arbitrary positive number. The while-loop that covers *Lines* 7-16 shows how to solve the Nash bargaining among the brokers in iterations. Specifically, brokers are divided into two-member groups with a scheme that is modified from the Hungarian method based algorithm in [31]. Note that, if K is an odd number, there would be a group that only contains one broker whose request allocation will not change in the upcoming iteration. After grouping the brokers, MPE solves the Nash bargaining between the brokers in each group exactly by checking all the feasible solutions, as shown in *Lines* 9-12. Then, Eq. (9) is updated in *Lines* 13-15.

Finally, if the request allocation result $\hat{\mathbf{R}}$ still induces resource collisions, *Line* 19 applies the procedure in *Algorithm* 2 to remove the collisions, which leverages the maximum-weighted independent set [35] in a collision graph to guarantee that the final request allocation is collision-free. Specifically, we build a collision graph based on the schemes in $\hat{\mathbf{R}}$, set S_i^k (*i.e.*, the profit that *Broker*-k can obtain by provisioning request r_i with $SC(k,i)$) as the weight of $SC(k,i) \in \hat{\mathbf{R}}$, and then get the final allocation result by finding the independent set of $\hat{\mathbf{R}}$ with the maximum total weight. Therefore, the allocation result would be collision-free while ensuring that the brokers can obtain the maximum total profit.

Algorithm 1: Collision-Free Request Allocation

input : $\{S_i^k\}$, $\{D_k\}$, R, and the collision graph.
output : $\hat{\mathbf{R}} = (R_1, \cdots, R_K)$.

```
1  initialize R̂ with NB-Benchmark in [21];
2  for k = 1 to K do
3  |  calculate {W_i^k} and W_k;
4  end
5  calculate x = ∏_{k=1}^{K} (W_k − D_k) based on R̂;
6  assign an arbitrary positive value to σ;
7  while σ > 0 do
8  |  divide brokers into two-member groups with a
   |  Hungarian method based scheme [31];
9  |  for each broker group do
10 |  |  solve the optimization in Eq. (9) for two
   |  |  brokers in the group;
11 |  |  readjust the brokers' request allocation
   |  |  according to the optimization result;
12 |  end
13 |  store allocation result in R̂ and get x' based on R̂;
14 |  update H_i^k, W_i^k and W_k for the brokers;
15 |  σ = x' − x, x = x';
16 end
17 if R̂ still induces collisions then
18 |  apply Algorithm 2 to remove the collisions;
19 end
```

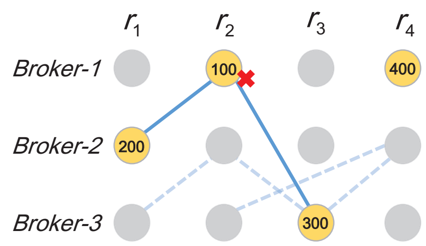


Fig. 4. Example on removing resource collisions of provisioning schemes.

Fig. 4 provides an intuitive example on realizing collision removal with *Algorithm* 2. In the collision graph, the yellow nodes with numbers represent the provisioning schemes in $\hat{\mathbf{R}}$ and the numbers are their weights. According to the collision relations denoted by the solid lines, we can find two maximal independent sets, which are $\{SC(1,2), SC(1,4)\}$ and $\{SC(2,1), SC(3,3), SC(1,4)\}$. After comparing the total weights of these two independent sets, we can see that $SC(1,2)$ should be removed to resolve collisions and the other three schemes can be kept in $\hat{\mathbf{R}}$, since the second independent set has a larger total weight. Note that, finding the maximum-weighted independent set in an arbitrary graph is $\mathcal{NP}$-hard [35], and thus *Algorithm* 2 leverages the time-efficient greedy algorithm developed in [35] to realize collision removal. In *Line* 1, we build the collision graph based on the request allocation result $\hat{\mathbf{R}}$. The while-loop that covers *Lines* 2-5 removes one provisioning scheme from $\hat{\mathbf{R}}$ each time, until there is no edge in the collision graph (*i.e.*, the modified request allocation result is collision-free). Specifically, in each iteration, *Lines* 3-4 find the scheme $SC(k^*, i^*)$ that can minimize the objective function $\frac{S_i^k}{H_i^k \cdot (H_i^k+1)}$, and remove it from $\hat{\mathbf{R}}$ to resolve collisions.

Algorithm 2: Collision Removal

input : $\hat{\mathbf{R}} = (R_1, \cdots, R_K)$ that induces resource collisions.
output : $\hat{\mathbf{R}} = (R_1, \cdots, R_K)$ that is collision-free.

```
1 build a collision graph based on R̂;
2 while edge(s) exist in collision graph do
3     [k*, i*] = argmin_{SC(k,i)∈R̂} [ S_i^k / (H_i^k·(H_i^k+1)) ];
4     remove SC(k*, i*) from R_{k*} and delete its node
      in the collision graph;
5 end
```

D. Complexity Analysis

As the while-loop in *Algorithm* 2 will run $(M-1)$ times at most, the time complexity of collision removal is $O(M)$. For *Algorithm* 1, the complexity is mainly from grouping the brokers in *Line* 8. Specifically, we need to obtain the Nash bargaining results for all the feasible two-member groups, which has a complexity of $O(K^2 \cdot 2^M)$, and then, we need to determine the optimal grouping scenario with the Hungarian method, whose complexity is $O(K^4)$. Hence, for each iteration, the time complexity of the while-loop covering *Lines* 7-16 in *Algorithm* 1 is $O(K^2 \cdot 2^M + K^4)$. Note that, the operation principle of the while-loop determines that it would not enter endless loops and will stop before constant iterations in the worst case. We denote the maximum iteration number as Q and use extensive simulations to confirm that we can set $Q = 50$ for all the reasonable combinations of M and K that concern us. Therefore, the complexity of *Algorithm* 1 is finally obtained as $O(Q \cdot (K^2 \cdot 2^M + K^4) + M)$. As we have explained in Section IV-B, M would be a relatively small and upper-bounded number in reality, and thus 2^M is upper-bounded too. Hence, according to [36], we can claim that *Algorithm* 1 is a pseudo-polynomial time algorithm.

Note that, the motivation of CFRA is that when K is so large such that the exhaustive search with a complexity of $O((K+1)^M)$ is impractical. For instance, if we assume that $Q = 50$, $K = 6$ and $M = 10$, CFRA would be much more time-efficient than the exhaustive search since $(K+1)^M \gg Q \cdot (K^2 \cdot 2^M + K^4) + M$. However, this might not always be the case. Hence, MPE should determine which algorithm to use by checking the values of Q, K and M. Specifically, if it has $K = 2$ or $Q \cdot (K^2 \cdot 2^M + K^4) + M > (K+1)^M$, the exhaustive search that solves Eq. (6) directly should be used. Otherwise, CFRA should be incorporated.

V. Performance Evaluation

In this section, we perform numerical simulations to evaluate the performance of our proposed algorithm. Note that, since the algorithm design that uses exhaustive search is trivial, the simulations do not consider the cases in which MPE uses the exhaustive search that solves Eq. (6) directly.

A. Simulation Setup

The multi-domain SD-EON uses the two-domain topology in Fig. 2(a), and we assume that there are 4 brokers in the management plane. Each fiber link accommodates 358 FS', each of which has a bandwidth of 12.5 GHz. We assume that O/E/O regenerators are only equipped on the border nodes between the two domains, and each border node contains 50 regenerators. With the O/E/O regenerators, each inter-domain lightpath can change its spectrum allocation and modulation format in between the domains to adapt to the spectrum incontinuity and transmission reach, respectively [19]. We normalize the unit costs of FS usage and O/E/O regenerator, and assume that they are $c_S = 1$ and $c_R = 5$, respectively.

The inter-domain lightpath requests are dynamically generated according to the Poisson traffic model. Note that, the requests arrive with an average rate of 10 per provisioning period, and their life-time follows the negative exponential distribution with an average that increases evenly from 40 to 100 to emulate different traffic loads. The source and destination nodes are selected randomly, while the bandwidth requirements are distributed uniformly within $[25, 500]$ Gb/s. For each broker, its service strategy pool contains three RSA algorithms, *i.e.*, the fragmentation-aware (FA) scheme [37], the shortest-path and first-fit (SP-FF) and the K-shortest path and load-balancing (KSP-LB) schemes [6].

Regarding the SLAs between the brokers and the DMs for ID-VT abstraction, each DM can provide ID-VTs consisting of VLs based on shortest-path routing (-SP) or load-balanced routing (-LB). Moreover, we consider two types of brokers in terms of pricing strategy, which means that the brokers can either decide service prices by solving the optimization in Eq. (4) with rational estimation (-E) or just determine their profit ratio randomly (-R). Hence, in order to analyze the impacts of the SLA and pricing strategy, we assume that the four brokers use different combinations of them, *i.e.*, BR-SP-E, BR-LB-E, BR-SP-R, and BR-LB-R. To compare the performance of brokers in a fairer way, we assume that each DM can subscribe to any broker for inter-domain services. The simulations consider three benchmarks, the non-cooperative benchmark (NC-Benchmark) in [17], the Nash bargaining benchmark (NB-Benchmark) in [21], and the Nash bargaining leveraging coalition (NB-LC), which is realized by modifying the algorithm for the Nash bargaining to allocate carriers in wireless networks [31]. To ensure sufficient statistical accuracy, we run 10 independent simulations and average the results to get each data point.

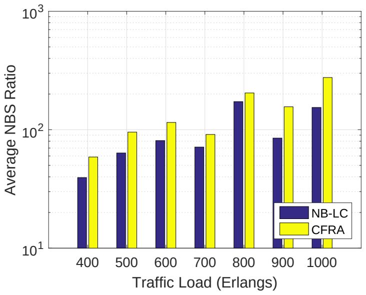
B. Performance of Cooperative Market Algorithms

Definition The **Nash bargaining solution (NBS) ratio** is defined to evaluate the performance of a request allocation algorithm against NB-Benchmark [21], which is calculated as

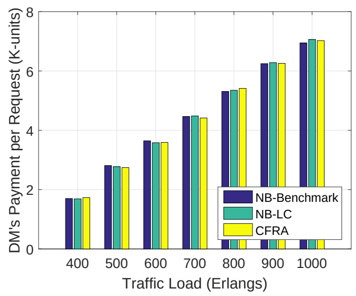
$$\textbf{NBS ratio} = \prod_{k=1}^{K} \frac{(S_k - D_k)}{(S'_k - D'_k)}, \tag{12}$$

TABLE II
AVERAGE RUNNING TIME PER REQUEST AT TRAFFIC LOAD AS 600 ERLANGS (MSEC)

# of Brokers (K)	# of Requests ($M = 10$)			# of Requests ($M = 15$)			# of Requests ($M = 20$)		
	NB-Benchmark	NB-LC	CFRA	NB-Benchmark	NB-LC	CFRA	NB-Benchmark	NB-LC	CFRA
4	0.9840	1.6446	2.5332	1.0646	2.4528	3.5711	1.1007	6.7943	9.3576
6	2.0288	2.9858	4.9730	2.1188	3.3956	5.630	2.4098	4.6462	7.5803
8	3.3177	4.5730	7.8509	3.6556	5.1649	9.0382	4.4275	6.4108	11.4723



(a) NBS ratios from CFRA and NB-LC



(b) Average payment per request from DMs

Fig. 5. Performance comparison of algorithms for cooperative market.

TABLE I
RELATIVE GAPS ON NBS RATIOS FROM THE HEURISTIC ALGORITHMS AND THOSE FROM AN EXACT ONE USING EXHAUSTIVE SEARCH (TRAFFIC LOAD AS 600 ERLANGS)

Algorithm	# of Requests (M)		
	$M = 6$	$M = 8$	$M = 10$
NB-Benchmark	47.19%	49.59%	54.75%
NB-LC	11.94%	15.13%	16.76%
CFRA	7.23%	8.85%	9.37%

where S_k and D_k are calculated based on the output of the algorithm, while S'_k and D'_k are from NB-Benchmark. The reason why we use NBS ratio in the performance evaluation is that the objective of Nash bargaining is to maximize $\prod_{k=1}^{K}(S_k - D_k)$. Note that, for a fair comparison, all the algorithms' outputs should be collision-free.

We first compare the performance of the algorithms designed for the cooperative market, *i.e.*, CFRA, NB-Benchmark, and NB-LC, and the NBS ratio is defined for this purpose. Fig. 5(a) shows the results on NBS ratio. Here, we modify NB-Benchmark and NB-LC by adding *Algorithm* 2 to ensure that they output collision-free request allocation. We observe that both CFRA and NB-LC outperform NB-Benchmark significantly in terms of Nash bargaining performance since their results on NBS ratio are much larger than 1. Meanwhile, the NBS ratio from CFRA is also much larger than that from NB-LC, since the y-axis of Fig. 5(a) is in logarithmic scale. Here, the advantage of CFRA over NB-LC can be understood as follows. As CFRA considers resource collisions in Nash bargaining, it can significantly reduce the number of requests that would be blocked due to them. This increases the brokers' profits effectively and improve the performance of Nash bargaining.

To further evaluate the algorithms' performance, we also compare the NBS ratios from them with the optimal ones that are obtained by exhaustive searches. Specifically, we calculate the relative gaps on the NBS ratios from the three heuristics and those from an exact algorithm using exhaustive search. Note that, to achieve an apple-to-apple comparison, we make sure that the results from all the algorithms are collision-free. Meanwhile, to guarantee that the optimal solutions from exhaustive searches can be obtained within a reasonable time duration, we only simulate the problems with relatively small scales, *i.e.*, the value of M is chosen within $\{6, 8, 10\}$, K is set as $K = 4$, and the traffic load is set as 600 Erlangs. The results on the relative gap are shown in Table I. It can be seen that NB-LC and CFRA both provide much smaller relative gaps than NB-Benchmark. Moreover, the relative gaps from CFRA are always less than 10% and smaller than those from NB-LC, which are consistent with the results shown in Fig. 5(a). These results confirm that CFRA can achieve a reasonably good approximation of the optimal solution.

Fig. 5(b) compares the results on the average payments from the DMs for an inter-domain lightpath request. It can be seen that when we run the cooperative market with the three algorithms, the DMs' payments for each request are almost the same. This suggests that the highest NBS ratio from CFRA is actually attributed to its best performance on request allocation, rather than exploiting the DMs with the highest service prices. To compare the complexity of the algorithms, we conduct simulations with several combinations of M and K while fixing the traffic load as 600 Erlangs. The results are shown in Table II, which indicate that NB-Benchmark always consumes the shortest running time. This is because CFRA and NB-LC both use the iterative approach to solve the Nash bargaining. Meanwhile, the running time of CFRA is longer than that of NB-LC. This is because we introduce the collision-weighted profits in it, which makes CFRA converge slower than NB-LC. In general, the running time of these algorithms increases with M and K. It is interesting to notice that the running time of NB-LC and CFRA for $K = 6$ and $M = 20$ is shorter than that for $K = 4$ and $M = 20$. This is because even though a larger K leads to more feasible broker groups, the complexity of the Nash bargaining in each group actually decreases since it is assigned with less requests. As the second effect is more dominate in this particular case, the overall running time decreases. Finally, we hope to point out that even though the running time of CFRA is the longest, the actual value is still relatively short (*i.e.*, in milli-seconds), and thus it can fit into the requirement of dynamic provisioning.

C. Cooperative Market versus Non-Cooperative Market

Then, we compare the performance of non-cooperative and cooperative markets. For the non-cooperative market, we use NC-Benchmark to determine the request allocation, while the cooperative market is addressed with CFRA. Table III summarizes the proportion of requests provisioned by each broker in the simulations. It is interesting to notice that in the non-cooperative market, NC-Benchmark favors BR-SP-E too much and makes the request allocation very unbalanced. This is because BR-SP-E calculates provisioning schemes based on ID-VTs that consist of VLs based on shortest-path routing, which helps reduce the resource consumption and thus provides BR-SP-E the highest winning probability in the non-cooperative market. However, this makes the market unfair to the remaining brokers since the SLAs between a broker and the DMs can affect its market share too much. The request allocation becomes much more balanced with CFRA in the cooperative market, which verifies that the brokers have the incentive to cooperate with each other. Specifically, in the cooperative market, CFRA tries to maximize the output of Eq. (9), which can only be done when the market share is distributed relatively evenly among the brokers.

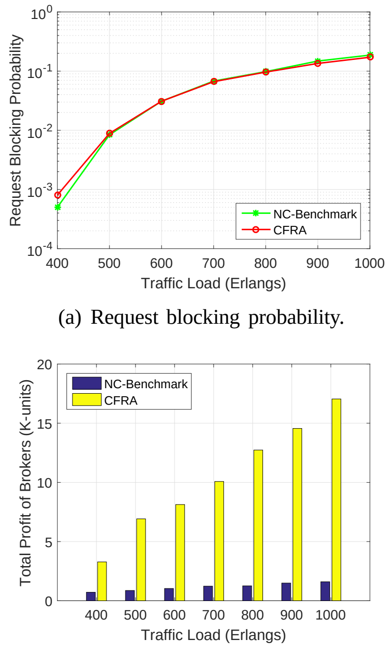
Furthermore, Fig. 6(a) compares the results on request blocking probability from NC-Benchmark and CFRA, which indicates that their blocking performance is almost the same. These results verify that cooperative games ensure the interests of brokers without sacrificing their QoS to the DMs. Note that, in CFRA, we make each broker provision the requests in its market share independently, which is similar to the scheme used in NC-Benchmark from the perspective of request provisioning. This is the reason why CFRA cannot obtain lower blocking probability than NC-Benchmark. However, since the cooperation among brokers makes it possible to realize joint optimization of request provisioning, the blocking performance of CFRA can actually be further improved, which will be addressed in our future work. For instance, if a broker knows that certain requests assigned to it would be blocked, it can trade with other brokers to exchange requests. The results on the total profit of the brokers are shown in Fig. 6(b). As expected, in the cooperative market, CFRA brings much more profits to the brokers with Nash bargaining. Again, this verifies that the brokers should cooperate with each other and have the incentive to do so. To this end, we can conclude that compared with the non-cooperative market, the cooperative one brings noticeable benefits to the brokers, which makes it a more appropriate place for serving inter-domain lightpaths in multi-broker based multi-domain SD-EONs.

D. Brokers' Performance in Cooperative Market

Finally, we compare the brokers' performance in the cooperative market with CFRA. The profit of each broker is shown in Fig. 7. We observe that the brokers that determine their service prices intelligently, *i.e.*, BR-SP-E and BR-LB-E, gain much more profits than those that choose random profit ratios. Meanwhile, by using the ID-VTs that consist of VLs based on shortest-path routing, BR-SP-E and BR-SP-R can achieve slightly higher profits than their counterparts, *i.e.*, BR-LB-E and BR-LB-R, respectively. Hence, we can conclude that BR-SP-E performs the best in terms of profit in the cooperative market. The results also suggest that in the cooperative market, the pricing scheme of a broker has a much larger impact on its profit than its SLAs with the DMs. This is because the pricing scheme of a broker can affect its profit ratios and reputation significantly. Therefore, it would be necessary for the brokers to adopt the rational estimation scheme explained in Section III-B-3. Note that, in order to verify that our proposal is scalable and can work well with the multi-domain SD-EONs that have more than two domains, we also divide the topology into three domains and conduct similar simulations. With the simulations, we find that there is no fundamental difference between the results from two- and three-domain scenarios. Therefore, due to the page limit, we omit those results. In [17], we have already implemented the multi-broker based management plane and conducted experiments to demonstrate the multi-broker based

TABLE III
PROPORTION OF REQUESTS PROVISIONED BY BROKERS IN NON-COOPERATIVE AND COOPERATIVE MARKETS

Algorithms	Proportion of Requests Provisioned by Brokers			
	BR-SP-E	BR-LB-E	BR-SP-R	BR-LB-R
NC-Benchmark	0.5314	0.4585	0.0093	0.0008
CFRA	0.4076	0.3999	0.1054	0.0871



(a) Request blocking probability.

(b) Brokers' total profits in non-cooperative and cooperative games.

Fig. 6. Performance comparison of non-cooperative and cooperative markets.

inter-domain service provisioning in a non-cooperative market. The system can be leveraged to realize the cooperative market based management plane discussed in this work, and we will need to upgrade the software implementation of the brokers and develop the software system for MPE. These tasks will be addressed in the future work.

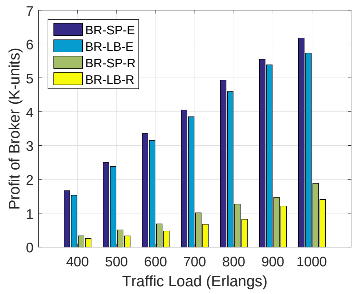


Fig. 7. Brokers' profits in the cooperative market.

VI. Conclusion

In this paper, we studied why and how the brokers should cooperate with each other to provision inter-domain lightpaths in multi-broker based multi-domain SD-EONs. We first formulated the cooperative market in which the brokers negotiate about their market shares through Nash bargaining, and designed a mathematical model to describe the market as well as the brokers' behaviors in it. Then, with the model, we proposed the CFRA algorithm that solves the Nash bargaining problem for allocating lightpath requests among the brokers. CFRA also addressed the resource collision during lightpath provisioning and could achieve collision-free request allocation. Simulation results confirmed the effectiveness of our proposal and answered the questions on why and how the brokers should cooperate with each other well.

Acknowledgments

This work was supported in part by the NSFC Project 61371117, Natural Science Research Project for Universities in Anhui (KJ2014ZD38), and the SPR Program of CAS (XDA06011202).

References

[1] Z. Han *et al.*, *Game Theory in Wireless and Communication Networks*. Cambridge University Press, 2012.

[2] M. Zhang, C. You, H. Jiang, and Z. Zhu, "Dynamic and adaptive bandwidth defragmentation in spectrum-sliced elastic optical networks with time-varying traffic," *J. Lightw. Technol.*, vol. 32, pp. 1014–1023, Mar. 2014.

[3] A. Malis, B. Wilson, G. Clapp, and V. Shukla, "Requirements for very fast setup of GMPLS label switched paths (LSPs)," *RFC 7709*, Nov. 2015. [Online]. Available: https://tools.ietf.org/html/rfc7709

[4] P. Lu *et al.*, "Highly-efficient data migration and backup for Big Data applications in elastic optical inter-datacenter networks," *IEEE Netw.*, vol. 29, pp. 36–42, Sept./Oct. 2015.

[5] L. Gong, X. Zhou, W. Lu, and Z. Zhu, "A two-population based evolutionary approach for optimizing routing, modulation and spectrum assignments (RMSA) in O-OFDM networks," *IEEE Commun. Lett.*, vol. 16, pp. 1520–1523, Sept. 2012.

[6] Z. Zhu, W. Lu, L. Zhang, and N. Ansari, "Dynamic service provisioning in elastic optical networks with hybrid single-/multi-path routing," *J. Lightw. Technol.*, vol. 31, pp. 15–22, Jan. 2013.

[7] S. Li *et al.*, "Protocol oblivious forwarding (POF): Software-defined networking with enhanced programmability," *IEEE Netw.*, vol. 31, pp. 12–20, Mar./Apr. 2017.

[8] L. Liu *et al.*, "OpenSlice: an OpenFlow-based control plane for spectrum sliced elastic optical path networks," *Opt. Express*, vol. 21, pp. 4194–4204, Feb. 2013.

[9] Z. Zhu *et al.*, "OpenFlow-assisted online defragmentation in single-/multi-domain software-defined elastic optical networks," *J. Opt. Commun. Netw.*, vol. 7, pp. A7–A15, Jan. 2015.

[10] R. Casellas *et al.*, "Control and management of flexi-grid optical networks with an integrated stateful path computation element and OpenFlow controller," *J. Opt. Commun. Netw.*, vol. 5, pp. A57–A65, Oct. 2013.

[11] Z. Zhu *et al.*, "Demonstration of cooperative resource allocation in an OpenFlow-controlled multidomain and multinational SD-EON testbed," *J. Lightw. Technol.*, vol. 33, pp. 1508–1514, Apr. 2015.

[12] D. Marconett, L. Liu, and B. Yoo, "Optical FlowBroker: load-balancing in software-defined multi-domain optical networks," in *Proc. of OFC 2014*, pp. 1–3, Mar. 2014.

[13] R. Munoz *et al.*, "Transport network orchestration for end-to-end multilayer provisioning across heterogeneous SDN/OpenFlow and GMPLS/PCE control domains," *J. Lightw. Technol.*, vol. 33, pp. 1540–1548, Apr. 2015.

[14] M. Fabrega *et al.*, "Demonstration of adaptive SDN orchestration: A real-time congestion-aware services provisioning over OFDM-based 400G OPS and flexi-WDM OCS," *J. Lightw. Technol.*, vol. 35, pp. 506–512, Jan. 2017.

[15] L. Ong, "ONF SDN architecture and standards for transport networks," in *Proc. of OFC 2017*, pp. 1–3, Mar. 2017.

[16] R. Govindan *et al.*, "Evolve or die: High-availability design principles drawn from Google's network infrastructure," in *Proc. of SIGCOMM 2016*, pp. 58–72, Aug. 2016.

[17] X. Chen *et al.*, "Incentive-driven bidding strategy for brokers to compete for service provisioning tasks in multi-domain SD-EONs," *J. Lightw. Technol.*, vol. 34, pp. 3867–3876, Aug. 2016.

[18] D. Marconett and B. Yoo, "FlowBroker: Market-driven multi-domain SDN with heterogeneous brokers," in *Proc. of OFC 2015*, pp. 1–3, Mar. 2015.

[19] L. Sun *et al.*, "Broker-based multi-task gaming to facilitate profit-driven network orchestration in multi-domain SD-EONs," in *Proc. of OFC 2016*, pp. 1–3, Mar. 2016.

[20] X. Chen *et al.*, "Multi-broker based market-driven service provisioning in multi-domain SD-EONs in noncooperative game scenarios," in *Proc. of ECOC 2015*, pp. 1–3, Sept. 2015.

[21] L. Sun *et al.*, "Broker-based cooperative game in multi-domain SD-EONs: Nash bargaining for agreement on market-share partition," in *Proc. of ECOC 2016*, pp. 1–3, Sept. 2016.

[22] W. Lu *et al.*, "Implementation and demonstration of revenue-driven provisioning for advance reservation requests in OpenFlow-controlled SD-EONs." *IEEE Commun. Lett.*, vol. 18, pp. 1727–1730, Oct. 2014.

[23] X. Chen *et al.*, "Availability-aware service provisioning in SD-EON based inter-datacenter networks," *Photon. Netw. Commun.*, vol. 31, pp. 543–549, Jun. 2016.

[24] S. Li, W. Lu, X. Liu, and Z. Zhu, "Fragmentation-aware service provisioning for advance reservation multicast in SD-EONs," *Opt. Express*, vol. 23, pp. 25 804–25 813, Oct. 2015.

[25] X. Chen *et al.*, "Flexible availability-aware differentiated protection in software-defined elastic optical networks," *J. Lightw. Technol.*, vol. 33, pp. 3872–3882, Sept. 2015.

[26] B. Zhao, X. Chen, J. Zhu, and Z. Zhu, "Survivable control plane establishment with live control service backup and migration in SD-EONs," *J. Opt. Commun. Netw.*, vol. 8, pp. A57–A65, Oct. 2016.

[27] X. Chen *et al.*, "Leveraging master-slave openflow controller arrangement to improve control plane resiliency in SD-EONs," *Opt. Express*, vol. 23, pp. 7550–7558, Mar. 2015.

[28] C. Chen *et al.*, "Demonstration of OpenFlow-controlled cooperative resource allocation in a multi-domain SD-EON testbed across multiple nations," in *Proc. of ECOC 2014*, pp. 1–3, Sept. 2014.

[29] J. Zhu, B. Zhao, and Z. Zhu, "Leveraging game theory to achieve efficient attack-aware service provisioning in EONs," *J. Lightw. Technol.*, vol. 35, pp. 1785–1796, May 2017.

[30] L. Liang, W. Lu, M. Tornatore, and Z. Zhu, "Game-assisted distributed decision-making to build virtual TDM-PONs in C-RANs adaptively," *J. Opt. Commun. Netw.*, vol. 9, pp. 546–554, Jul. 2017.

[31] Z. Han, Z. Ji, and K. Liu, "Fair multiuser channel allocation for OFDMA networks using Nash bargaining solutions and coalitions," *IEEE Trans. Comm.*, vol. 53, pp. 1366–1376, Aug. 2005.

[32] A. Zellner, J. Kmenta, and J. Dreze, “Specification and estimation of Cobb-Douglas production function models,” *Econometrica*, vol. 34, pp. 784–795, Oct. 1966.

[33] J. Nash, “The bargaining problem,” *Econometrica*, vol. 18, pp. 155–162, 1950.

[34] Z. Zhu, P. Lu, J. Rodrigues, and Y. Wen, “Energy-efficient wideband cable access networks in future smart cities,” *IEEE Commun. Mag.*, vol. 51, pp. 94–100, Jun. 2013.

[35] S. Sakai, M. Togasaki, and K. Yamazaki, “A note on greedy algorithms for the maximum weighted independent set problem,” *Discrete Applied Mathematics*, vol. 126, pp. 313–322, Mar. 2003.

[36] M. Garey and D. Johnson, *Computers and Intractability: a Guide to the Theory of NP-Completeness*. W. H. Freeman & Co. New York, 1979.

[37] Y. Yin *et al.*, “Spectral and spatial 2D fragmentation-aware routing and spectrum assignment algorithms in elastic optical networks,” *J. Opt. Commun. Netw.*, vol. 5, pp. A100–A106, Oct. 2013.