# Economics of Multi-Domain Software-Defined EONs: Games among Brokers

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***Abstract*—This paper discusses the network architecture and mechanisms used for advancing the economics of multi-domain software-defined elastic optical networks (SD-EONs) with the considerations of both noncooperative and cooperative games among the incentive-driven brokers. Specifically, in order to architect multi-domain SD-EONs such that the end-to-end lightpath provisioning across multiple domains can be facilitated cost-effectively, we propose to introduce a management plane that contains incentive-driven brokers. As the brokers may compete or cooperate with each other to offer cross-domain lightpath provisioning services due to profits, we design and elaborate on the operation mechanisms for both incentive-driven broker competition (*i.e.*, noncooperative gaming) and market-share based broker bargain (*i.e.*, cooperative gaming). The experimental results that are obtained with an OpenFlow-based control plane SD-EON testbed are also presented to verify the cost-effectiveness of the proposed mechanisms.**

***Index Terms*—Software-defined Elastic optical networks (SD-EONs), Multi-domain, Multi-broker, Game theory.**

## I. INTRODUCTION

The recent advances on the flexible-grid elastic optical networks (EONs) [1, 2] have demonstrated that the management of the optical layer can be more adaptive without being restricted by the fixed wavelength grids or modulation formats [3]. Meanwhile, to fully explore the benefits of EON, service providers need an efficient and powerful network control and management (NC&M) mechanism, as the additional freedom and hence complexity on service provisioning has to be addressed properly. Such a NC&M mechanism can be realized by implementing the idea of software-defined networking (SDN) in EONs (*i.e.*, building software-defined EONs (SD-EONs)) [4]. Previous work has indicated that SD-EONs can potentially achieve adaptive and programmable high-capacity networking with extended service reach [5, 6].

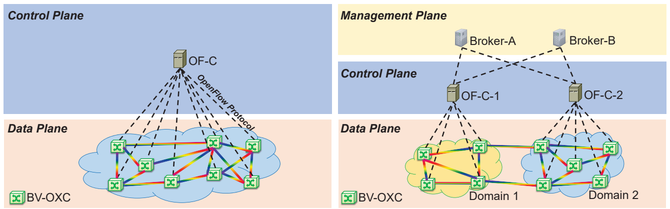
Note that, considering the geographical span of backbone networks and the heterogeneous technologies of multi-vendor network elements, service providers have to address the multi-domain SD-EON scenarios [5, 7]. This can be done by using the hierarchical NC&M architecture that places resource brokers on top of the domain managers in a multi-domain SD-EON [8]. Meanwhile, introducing a management plane with incentive-driven brokers provides a not only practical but also economical mechanism to operate multi-domain SD-EONs [9]. Specifically, the brokers offer cross-domain lightpath provisioning services to domain managers due to profits and they may compete or cooperate with each other to avoid the dictatorship of a single orchestrator. This forms incentive-driven rational games among brokers, which should be investigated carefully to reveal the principle of the networking economics in multi-domain SD-EONs.

This paper discusses the network architecture and mechanisms used for advancing the economics of multi-domain SD-EONs with the considerations of both noncooperative and cooperative games among the incentive-driven brokers. We first briefly describe the motivations and architecture of SD-EONs. Then, we consider the multi-domain scenario and explain the advantages of introducing of a management plane that contains incentive-driven brokers to operate multi-domain SD-EONs. The principle of game theory in multi-broker based multi-domain SD-EONs is discussed afterwards, including the service provisioning procedure and the cost model. We also elaborate on both the noncooperative and cooperative games among incentive-driven brokers and show the corresponding experimental results. Finally, we summarize the paper.

## II. SOFTWARE-DEFINED ELASTIC OPTICAL NETWORKS

By leveraging newly-developed fiber optic technologies, EONs not only facilitate spectrum allocation with the granularity at 12.5 GHz or less but also support supper-channels at 400 GHz and beyond [3]. Lightpaths can adapt their modulation formats to the actual quality-of-transmission (QoT) and achieve improved spectral efficiency [2]. These advantages are realized by assigning optical spectra in the form of spectrally-contiguous frequency slots (FS') and using advanced transmission techniques to optimize spectral efficiency. Meanwhile, the flexible nature of EONs applies more requirements on the NC&M mechanism used in them. Basically, the service provisioning becomes much more complex when being compared with that in fixed-grid wavelength-division multiplexing (WDM) networks, which only manages independent and fix-sized wavelength channels. Moreover, EONs may require centralized NC&M as the spectrum utilization can be optimized better with network-wide information [6]. SD-EONs use programmable and centralized NC&M to undertake sophisticated service provisioning tasks within a domain [4].

As a possible implementation of SDN, OpenFlow was developed as an open standard protocol that leverages flow-based switching and uses a centralized controller to realize software-defined routing. In addition, the latest specification OpenFlow v1.5 has already standardized the extensions for



(a) (b)

Fig. 1. Network architectures of SD-EON for (a) single-domain scenario, and (b) multi-broker based multi-domain scenario.

identifying flexible-grid optical flows. Therefore, in a single-domain SD-EON that is implemented with OpenFlow (as shown in Fig. 1(a)), the domain manager is the centralized OpenFlow-controller (OF-C) [10, 11], which talks with the data plane elements (*i.e.*, bandwidth-variable optical cross-connects (BV-OXCs)) for lightpath management, using the OpenFlow protocol. As the domain manager can dynamically collect, analyze and arrange spectrum usages on the fiber links, programmable and application-aware ultra-high capacity networking with enhanced service support can be realized.

## III. BROKER-BASED SERVICE PROVISIONING IN MULTI-DOMAIN SD-EONS

With the SD-EON scenario in Fig. 1(a), one can provision lightpaths cost-effectively within a domain. Now, what is important is to architect multi-domain SD-EONs such that the end-to-end service provisioning across multiple domains can be facilitated cost-effectively. To achieve this, the simplest scheme is to leverage the flat architecture where the domain managers (*i.e.*, OF-Cs) collaborate in a peer-to-peer manner to provision inter-domain lightpaths [5]. Specifically, an inter-domain request will be forwarded in turn from the domain manager in the source domain to that in the destination domain. After receiving the request, each domain manager will set up the path segment within its own domain and extend the inter-domain lightpath for one domain in sequence. Note that, this peer-to-peer scheme may have scalability issues since each domain manager needs to have full knowledge of the global domain connectivity, which cannot be achieved without a relatively complicated neighbor discovery mechanism.

The unwanted overheads in the flat architecture can be avoided by introducing the hierarchical architecture that allocates an orchestrator to coordinate the domain managers for inter-domain lightpath provisioning [12]. Basically, the orchestrator operates at a higher NC&M level than the domain managers such that it can gather intra-domain information from them and instruct them to set up the necessary path segments of inter-domain lightpaths. The drawbacks of this scheme are mainly two-fold. Firstly, using an orchestrator to control a geographically distributed (geo-distributed) multi-domain network may incur relatively long path setup latency and low reliability. Secondly and more importantly, the way that the orchestrator controls the entire multi-domain network violates the original (and successful) principle of Internet, *i.e.*, the domains are autonomous systems (AS's) and should not be dictated by authoritative management [13].

Therefore, the multi-broker based hierarchical architecture was proposed in [8]. As shown in Fig. 1(b), a management plane that contains incentive-driven brokers is introduced to supply a not only powerful but also practical mechanism to operate the multi-domain SD-EONs that cover geo-distributed areas. Basically, in each domain, the domain manager controls the BV-OXCs for intra-domain service provisioning. Meanwhile, it also subscribes to a few brokers in the management plane for inter-domain service provisioning. Hence, each broker still works as a higher-level orchestrator to coordinate the domain managers for cross-domain network orchestration. However, since each domain manager has options to choose from, its autonomy gets respected, *i.e.*, it would not be dictated by the top-down authoritative management [14, 15].

To this end, we can see that the multi-broker based scheme has the potential to promote higher provisioning performance, better resilience, and more efficient resource utilization in future multi-domain SD-EONs that consists of many AS's. Indeed, our recent study has shown the remarkable effectiveness of this scheme in coordinating multi-domain networks consistent with the original principle of the Internet [16, 17], and the scheme has also been experimentally demonstrated in a small-scale inter-continental multi-domain SD-EON [18]. More importantly, we would expect the management plane with incentive-driven brokers to be effective across heterogeneous AS's, *i.e.*, heterogeneous in terms of physical connections (wireless, wireline, optical, *etc*), in terms of programmability (software-defined *versus* hardware-specified network elements), and in terms of protocols (GMPLS, SONET, *etc*).

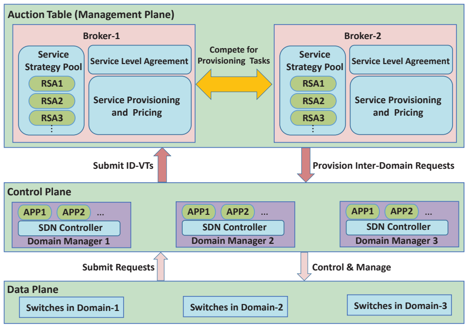


Fig. 2. Interactions for provisioning inter-domain lightpaths in a multi-broker based multi-domain SD-EON.

## IV. GAME THEORY IN MULTI-BROKER BASED MULTI-DOMAIN SD-EONS

Fig. 2 explains the interactions in a multi-broker based multi-domain SD-EON for provisioning inter-domain lightpaths. Basically, according to the policies defined in their service-level agreements (SLAs), the domain managers virtualize their intra-domain topologies for each broker. Note that, a domain manager may not want to disclose all the intra-domain information due to the considerations on privacy and security. Then, to provision an inter-domain lightpath, a broker obtains a global view of the multi-domain network, which essentially contains the status of inter-domain fiber links and the intra-domain virtual topologies (ID-VTs) from the domain managers. More specifically, virtual links (VLs) are abstracted from the related intra-domain path segments. Here, we should point out that depending on their SLAs, a domain manager can submit different ID-VTs to different brokers.

Fig. 3 presents an illustrative example on the procedure of domain managers abstracting ID-VTs for brokers. Here, the physical topology in Fig. 3(a) consists of two domains and hence involves two domain managers. We assume that there are two brokers in the management plane, *i.e.*, *Broker*-1 and *Broker*-2. For *Broker*-1, the domain managers obtain the VLs with the shortest-path routing, while for *Broker*-2, the domain managers get the VLs based on the path that contains the most available spectrum resources (*i.e.*, frequency slots (FS's)). Hence, for an inter-domain lightpath from *Node* 5 to *Node* 15, the domain manager provides 5→4→7→9 to *Broker*-1 as the VL for 5→9, as shown in Fig. 3(a). On the other hand, the VL for 5→9 that is submitted to *Broker*-2 is 5→4→3→7→9, according to the spectrum usages in Fig. 3(b). Finally, the ID-VTs submitted to the brokers are shown in Fig. 3(c). Even though the ID-VTs look the same, the length and available FS's on each individual VL in them can be different. Hence, the brokers would get different provisioning schemes with them, even when they apply the same routing and spectrum assignment (RSA) algorithm on the ID-VTs.

The inter-domain service provisioning in the multi-broker based multi-domain SD-EONs can be modeled as either a noncooperative or cooperative game, depending on whether the brokers in the management plane compete or cooperate with each other. Hence, we model the management plane as an auction table, which operates as a discrete-time system. This means that when each provisioning period begins, the brokers bid for the provisioning tasks of pending inter-domain lightpaths in either a noncooperative or a cooperative manner. When the deals are sealed, the domain managers of the lightpaths' source domains finalize the brokers to rely on for serving their lightpaths. Then, the winning brokers instruct the related domain managers to provision the inter-domain lightpaths accordingly. We need to make sure that the brokers are profitable by offering the inter-domain lightpath provisioning services, and at the same time, the domain managers' interests (*i.e.*, getting their inter-domain lightpath requests served with low costs) should be protected properly as well.

We formulate an economic model to describe how a broker prices its service for provisioning an inter-domain lightpath,

$$C = T \cdot (R_u \cdot c_R + S_u \cdot c_S) \cdot (1 + \delta) = \zeta \cdot (1 + \delta), \qquad (1)$$

where $R_u$ and $S_u$ are the numbers of optical-to-electrical-to-optical (O/E/O) regenerators and FS's that need to be allocated for the lightpath, $c_R$ and $c_S$ are the unit costs for regenerator and FS utilizations, respectively, and $\delta$ ($\delta \geq \delta_{min}$) is the profit ratio with which the broker adjusts its pricing strategy. Note that, the term $\zeta = T \cdot (R_u \cdot c_R + S_u \cdot c_S)$ can be understood as the base cost for serving an inter-domain lightpath, *i.e.*, the amount of money that the broker pays for renting the network resources for the lightpath. Here, we assume that a broker will not provision a lightpath for free (*i.e.*, $\delta = 0$), and it has to secure a minimum profit ratio of $\delta_{min}$ in each lightpath provisioning. This assumption is reasonable because game theory claims that all the players should be intelligent and rational decision makers [19]. Basically, if a broker loses a bid, its profit is 0, which is apparently better off than serving an inter-domain lightpath for free. Since the brokers are incentive-driven, they want to maximize their profits no matter whether they compete or cooperate with each other in the auction table. This means that each broker has to choose the most cost-effective service strategy based on the ID-VT that it obtains from the domain managers, i.e., selecting the best RSA scheme from its service strategy pool in Fig. 2.

## V. NONCOOPERATIVE GAME: INCENTIVE-DRIVEN BROKER COMPETITION

### A. Nash Equilibrium

We first consider the scenario in which the brokers work in a noncooperative way. This means that to serve each inter-domain lightpath, the brokers price their services independently and submit their bids to the auction table simultaneously. Then, the domain manager of the source domain just simply selects the broker with the lowest price to seal the deal and pays the winner broker for provisioning its lightpath.

In order to determine the brokers' pricing strategies in this scenario, we need to find their best responses to each other's strategies, which can be done by leveraging the concept of Nash equilibrium [19]. Specifically, the Nash equilibrium of the game is the strategy profile in which no broker can increase its profit by changing the strategy unilaterally [19]. We consider a simplified version of the problem of broker competition, in which all the brokers receive identical ID-VTs from the domain managers and use the same RSA algorithm to calculate the inter-domain provisioning schemes (denoted as Problem $P_1$). Therefore, they obtain identical inter-domain lightpath provisioning schemes and thus their base costs for serving each inter-domain lightpath are the same.

Then, the problem can be further simplified with assumptions: 1) there are only two brokers in the management plane, and 2) each broker only have two profit ratio to choose from, *i.e.*, $\delta_{min}$ (low bid) and $\delta_{high}$ (high bid). This further simplified problem is denoted as Problem $P_1'$. The noncooperative game in Problem $P_1'$ works as follows. For the batch of pending inter-domain lightpaths, if both brokers submit high bids, each of them wins half of the total lightpaths and obtains a profit of $q_1$. Otherwise, if one broker submits high bids and the other submits low bids, the one submitting low bids wins all the lightpaths and obtains a profit of $q_2$ while the other one gets 0 profit. Finally, if both brokers submit low bids, they still divide the lightpaths equally and each obtains a profit of $q_3$. Apparently, we will have $q_2 > q_1 > q_3$ and can represent the brokers' strategies and the corresponding profits with the bi-matrix [19] in Table I.

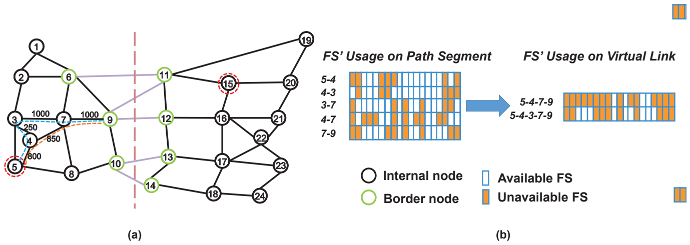


Fig. 3. Example on domain managers abstracting ID-VTs for different brokers, (a) Topology of the multi-domain SD-EON, (b) Spectrum usages on fiber links and procedure to obtain the VLs for 5→9, and (c) ID-VTs submitted to two brokers for serving an inter-domain lightpath from *Node* 5 to *Node* 15.

TABLE I
BI-MATRIX FOR ANALYZING NASH EQUILIBRIUM IN BROKER COMPETITION PROBLEM $P_1'$

| | | Broker-2 | |
|---|---|---|---|
| | | High Bid | Low Bid |
| Broker-1 | High Bid | $q_1$, $q_1$ | 0, $\underline{q_2}$ |
| | Low Bid | $\underline{q_2}$, 0 | $\underline{q_3}$, $\underline{q_3}$ |

In Table I, each cell "($a$, $b$)" denotes the profits of the brokers when their bidding strategies are known, *i.e.*, $a$ and $b$ are for *Broker*-1 and *Broker*-2, respectively. For instance, if *Broker*-1 submits low bids and *Broker*-2 submits high bids, *Broker*-1 wins all the lightpaths and thus the brokers' profits are $a = q_2$ and $b = 0$. Then, the underlined values in the cells are the best responses that the corresponding broker would have if its opponent's strategy had been determined. For instance, if *Broker*-2 submits high bids, the best response of *Broker*-1 should be low bids, which results in higher profit (*i.e.*, $q_2 > q_1$). By repeating this procedure on both brokers, we can get the Nash equilibrium of this game as that both brokers submit low bids and each gets a profit of $q_3$. Apparently, this strategy profile will lead to the situation like the famous prisoners' dilemma [19] and is Pareto inefficient for the brokers. Note that, this is the Nash equilibrium in Problem $P_1'$, but with more sophisticated mathematical derivations, we can also get the prisoners' dilemma like Nash equilibrium in Problem $P_1$. Therefore, we omit the derivations to avoid going into the mathematical details.

### *B. Competition among Incentive-Driven Brokers*

In practice, the problem of broker competition can be more sophisticated and have differences from Problem $P_1$ mainly from two perspectives. First of all, since different brokers can receive different ID-VTs for the same inter-domain lightpath due to the SLAs between them and the domain managers, the base costs of the brokers can be different and unknown to each other. Therefore, the brokers can only compete with incomplete information on their opponents. Secondly, as the inter-domain lightpath requests can arrive dynamically in network provisioning, we need to consider a sequence of repeated games instead of a single one. These differences make it difficult for the brokers to analyze the Nash equilibrium exactly. With these considerations, we design an effective bidding strategy based on the kernel density estimation (KDE) [20], which enables the brokers to forecast their opponents' behaviors and then price their services in the optimal way.

Basically, we first analyze the situation in a single game, *i.e.*, all the brokers bid for the provisioning task of an inter-domain lightpath. Then, the objective of each broker (*e.g.*, *Broker*-$i$) is to maximize the expectation of its profit $\mathbf{E}(q_i)$, which is the product of the profit ($\widehat{q_i}$) that it would get if wins the game and its winning probability ($p_i$), i.e., $\mathbf{E}(q_i) = \widehat{q_i} \cdot p_i$. Meanwhile, the profit $\widehat{q_i}$ is directly determined by the broker's bidding price $\rho_i$, *i.e.*, $\widehat{q_i} = \rho_i - \zeta_i$, where $\zeta_i$ is the base cost calculated by Eq. (1). Note that, the winning probability $p_i$ is related to the bidding price $\rho_i$, since *Broker*-$i$ can only win the game if its bidding price is the lowest among all the brokers.

To this end, we can see that the expectation of the broker's profit $\mathbf{E}(q_i)$ is essentially a function of its bidding price $\rho_i$ as $\mathbf{E}(q_i) = f(\rho_i)$, while $\rho_i$ can be determined if the bidding prices from all of its opponents are known. However, in the noncooperative game, all the brokers submit their bidding prices simultaneously and it would not be possible to know other brokers' bidding price in advance. Fortunately, since the dynamic network provisioning actually address a sequence of repeated games, there is historic information on the brokers to leverage for forecasting the distributions of their bidding prices, *i.e.*, the prices' probability distribution functions (PDF-s). More specifically, the PDFs can be estimated by employing KDE [20]. Then, each broker can calculate its optimal bidding price based on the PDFs of other brokers' bidding prices.

### *C. Experimental Demonstrations*

In order to demonstrate our idea of incentive-driven broker competition for inter-domain lightpath provisioning in multi-domain SD-EONs, we build an OpenFlow-based control plane SD-EON testbed and implement the multi-broker based inter-domain lightpath provisioning framework in it. Here, we use the topology in Fig. 3, which consists of two domains (*i.e.*, two domain managers), and allocate two brokers in the management plane. Each domain manager is realized by modifying an open-source OpenFlow controller (OF-C) platform and the brokers and the auction table are implemented with our own software modules. Meanwhile, since we focus on the NC&M operations in multi-broker based multi-domain SD-

EONs, we program the software-based OpenFlow switch to emulate the BV-OXCs and run each software-emulated BV-OXC on an independent Linux server.

We evaluate the proposed KDE-based bidding strategy against the benchmark in which both brokers operate according to the Nash equilibrium, *i.e.*, the brokers always submit the lowest possible prices to bid for the inter-domain lightpath provisioning tasks. Here, we denote our proposed bidding strategy as KDE-Game, while the benchmark is named as Nash-Game. Based on the SLAs between the domain managers and the brokers, *Broker*-1 always receives ID-VTs that consists of VLs abstracted with the shortest-path routing (*i.e.*, we denote *Broker*-1 as *Broker*-SP), while *Broker*-2 always receives ID-VTs that includes VLs based on the path containing the most available FS's (*i.e.*, we denote *Broker*-2 as *Broker*-LB). We set the minimum profit ratio as $\delta_{min} = 0.1$ and design the KDE scheme to estimate the PDFs of other brokers' bidding prices with a window-size of 300. This means that the KDE scheme estimates the PDFs based on the bidding results in 300 historic games. The inter-domain lightpath requests are randomly generated with the Poisson traffic model.

Fig. 4(a) compares the total profits that are obtained by the two brokers in KDE-Game and Nash-Game. As expected, KDE-Game provides much more total profits than Nash-Game. This is due to the fact that with our proposed bidding strategy, the brokers can predict the behaviors of their opponents and then adjust their bidding prices intelligently for maximizing their profits. The analysis can be confirmed with the results in Fig. 4(b), which plots the evolutions of the bidding prices from the brokers in KDE-Game. Obviously, both brokers adjust their profit ratios adaptively with the KDE scheme. For instance, after losing the fourth game with the profit ratio $\delta = 0.25$, *Broker*-SP reduces its profit ratio to $\delta = 0.2451$ and wins the fifth game. Finally, in order to study the impacts of ID-VTs on brokers' profits, we illustrate the profit of each broker in KDE-Game in Fig. 4(c). We observe that in general, *Broker*-SP is more profitable than *Broker*-LB. This is because *Broker*-SP can obtain lower base costs by calculating the lightpath provisioning schemes with the shorter VLs from the domain managers. Meanwhile, it is also worth to note that when the traffic load increases, the profit gap between *Broker*-SP and *Broker*-LB decreases. This phenomenon can be explained as follows. With the ID-VTs that contains VLs with more available FS's, *Broker*-LB serves lightpaths in a more load-balanced way and hence can potentially serve more lightpaths than *Broker*-SP when the network become more congested.

## VI. COOPERATIVE GAME: MARKET-SHARE BASED BROKER BARGAIN

While the noncooperative game model studies the brokers' strategic decisions on bidding prices due to competition, a cooperative game model can describe the brokers' rational choices when they cooperate. Basically, in service provider networks, the brokers in the management plane can cooperate based on certain agreements to maximize their profits. Then, different from the case in broker competition, we are facing the situation in which the brokers are interested in reaching an agreement over the partition of the market (*i.e.*, the provisioning tasks of all the pending inter-domain lightpaths) but have conflicting interests on the market shares. In this context, we actually need to consider the bargain among the brokers in the auction table in Fig. 2 for market partition [21].

The most interesting and also important thing to look into for studying the market-share based broker bargain is to determine the bargaining outcome, which is the market share of each broker, *i.e.*, how many and which pending inter-domain lightpaths that a broker should serve. The problem can be solved by leveraging the concept of Nash bargaining [21], which is known to be able to get Pareto efficient solutions. Fig. 5(a) shows the our proposed scheme for the Nash bargaining among incentive-driven brokers. Basically, the proposed Nash bargaining scheme takes the expected profit ratio and disagreement point of each broker, and the domain managers' satisfaction factors as the inputs, and then solves the generic optimization [21] defined for Nash bargaining to get the market shares of the brokers.

Here, even though for conciseness, we omit the equations used in the optimization for Nash bargaining, we would like to explain the impacts of the three types of inputs on the bargaining outcome. Firstly, the final market share of *Broker*-$i$ decreases with its expected profit ratio $\delta_i$. This is reasonable in the sense that although the brokers are willing to cooperate, they still have conflicting interests on the market shares, and hence the other brokers will only agree on a bargaining outcome when *Broker*-$i$ trades its market share for the profit ratio. Secondly, the disagreement point of a broker can be understood as the broker's expected profit in the noncooperative game (*i.e.*, broker competition). Basically, this is simply because the foundation of the cooperative game model is that the bargaining outcome should be more profitable for all the brokers when being compared to the case in the noncooperative game. Otherwise, there is no incentive for a broker to cooperate. Thirdly, a domain manager's satisfaction factor is introduced to avoid the situation in which the brokers become greedy and form a coalition to raise their expected profit ratios unrestrictedly. Therefore, the satisfaction ratio can be understood as the possibility that a domain manager would accept the services from the brokers, and it should be a decreasing function of a broker's expected profit ratio $\delta_i$.

In order to verify the effectiveness of the proposed Nash bargaining scheme, we compare its performance with that of the noncooperative broker competition. Fig. 5(b) and 5(c) show the experimental results on the profits of brokers in Nash bargaining and KDE-Game, respectively. By comparing these two figures, we observe that through cooperation with Nash bargaining, the brokers' profits get improved significantly, *i.e.*, the total profit is almost four times of that obtained in KDE-Game at the same traffic load. Moreover, it is interesting to notice that with Nash bargain, the profits are distributed more evenly between the brokers as *Broker*-LB has its share of profit increased significantly related to that in KDE-Game. This

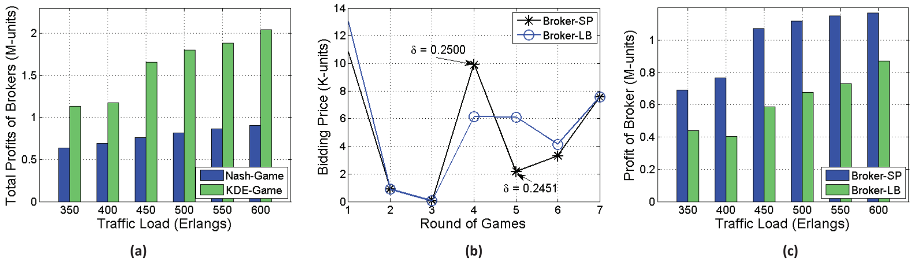


Fig. 4. Experimental results on broker competition for (a) total profits of brokers in Nash-Game and KDE-Game, (b) evolution of each broker's bidding price in KDE-Game, (c) profit of each broker in KDE-Game.

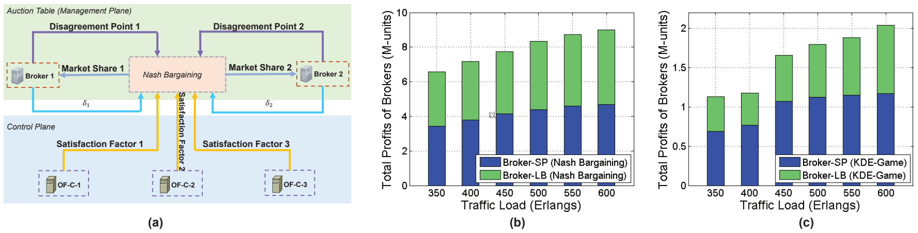


Fig. 5. (a) Nash bargaining principle, (b) total profits of brokers in Nash bargaining, (c) total profits of brokers in KDE-Game.

verifies the effectiveness of the proposed Nash bargaining.

## VII. CONCLUSION

We discussed how to advance the economics of multi-domain SD-EONs with the considerations of both noncooperative and cooperative games among the incentive-driven brokers. Specifically, we proposed to introduce a management plane that contains incentive-driven brokers, which might compete or cooperate with each other to offer cross-domain lightpath provisioning services due to profits. Then, we elaborated on the operation mechanisms for both incentive-driven broker competition (*i.e.*, noncooperative gaming) and market-share based broker bargain (*i.e.*, noncooperative gaming). The experimental results that were obtained with an OpenFlow-based control plane SD-EON testbed were also presented to verify the cost-effectiveness of the proposed mechanisms.

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