Game Theoretical Flexible Service Provisioning in IP over Elastic Optical Networks

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***Abstract*—In this work, aiming to enhance network automation and service fairness, we formulate a stackelberg game for flexible service provisioning in an IP over elastic optical network (IP-over-EON). In the proposed game, the service provider is the leader and maximizes its revenue by pricing the lightpaths in the EON layer and changing their capacities adaptively, while the incoming requests are the followers and determine their routing schemes and capacity requirements individually to make the maximum profit for themselves. To study the existence of Stackelberg Equilibriums (SEs) in the game, we consider both the single-logic-link and multiple-logic-links scenarios.**

***Index Terms*—Stackelberg Game, Stackelberg Equilibrium, Flexible Service Provisioning, IP over Elastic Optical Networks**

I. Introduction

Since Internet Protocol (IP) is widely used among emerging networks services and applications, IP layer has become a necessity of today's communication networks. Meanwhile, to transport the ever-growing IP traffic timely, having an advance optical network as the underlying physical layer is a timeless pursuit in the telecommunication industry [1]. Recently, elastic optical networks (EONs) are proposed to overcome the bottlenecks of traditional wavelength-division-multiplexing (WDM) optical networks [2]. With a finer bandwidth allocation granularity, EONs can largely enhance network capacity and flexibility by customizing any-size of transmission channels [3, 4]. For this reason, the architecture of IP-over-EONs is envisioned as a promising solution to the next-generation backbone networks, and therefore it is crucial to study the concerned problems in an IP-over-EON [5].

Fig. 1 shows the architecture of an IP-over-EON. Basically, the IP routers in the IP layer are interconnected with the bandwidth-variable optical switches (BV-OXCs) in the EON layer by short-reach fibers, and the logic link between two IP routers is supported by the underlying lightpaths. To forward the incoming IP packets to their destinations, an intermediate IP router first modulates and transforms them into optical signals via the plugged bandwidth-variable transponders (BV-Ts), and then transmits the optical signals to the associated BV-OXC for long-haul transmission with quality-of-transmission (QoT) guarantee [6]; when the destination IP routers have received the optical signals, they demodulate and transform them into electrical packets via the plugged BV-Ts, and drop all the arrival packets. Wherein, how to provide flexible service provisioning for diverse requests is one of the fundamental problems. Previously, researchers have investigated the service provisioning schemes for different types of requests in IP-over-EONs [7–11]. Most of the existing studies assumed that the service provisioning is managed by the service provider in a entirely centralized manner, *i.e.*, all the decisions are made on the service provider's side. This unilateral optimization would, on one hand, bring heavy workload to the service operator, on the other hand, cause service unfairness since the operator is free to degrade the QoS of those cheaper requests for serving more expensive requests.

In this work, to enhance network automation and service fairness, we propose a game theoretical flexible service provisioning model in an IP-over-EON, in which both the service operator and the incoming requests can make decisions for their own benefit. More specifically, we formulate a stackelberg game in which the service operator is the leader and maximizes its revenue by pricing the lightpaths in the EON layer and changing their capacities adaptively, while the incoming requests are the followers and determine their routing schemes and capacity requirements individually. To study the existence of SEs in the game, we consider both the single-logic-link and multiple-logic-links scenarios.

The rest of the paper is constructed as follows. Section II presents the stackelberg game formulation for flexible service provisioning in an IP-over-EON. Section III studies the existence of SEs in the single-logic-link scenario. As an extension, the multiple-logic-links scenario is considered in Section IV. Finally, Section V gives a brief conclusion.

II. Stackelberg Game Formulation for Flexible Service Provisioning

A directed graph $G(V_i, E_i, L_o)$ is used to model an IP-over-EON, where V_i and E_i are the IP router and logic link sets, respectively, in the IP layer, and L_o is the lightpath set in the EON layer. For each logic link $e \in E_i$, its associated lightpath set $L_{o,e} \subseteq L_o$ is $\{lp_{e,k} : k = 1, 2, ..., |L_{o,e}|\}$, where $lp_{e,k}$ is the k-th lightpath in $L_{o,e}$ and operation $|\cdot|$ returns the element number of a set, and therefore its capacity equals to the total capacities of lightpaths in $L_{o,e}$. Owning such a network, the service operator aims to maximize its revenue in service provisioning for diverse requests by pricing the lightpaths in L_o and changing their capacities adaptively. For each lightpath $lp_{e,k} \in L_o$, we define its price function as $P_{e,k}$, its capacity as $C_{e,k}$, its hop counts as $H_{e,k}$, and its modulation level as $M_{e,k}$. On the other hand, the cost of a frequency slot

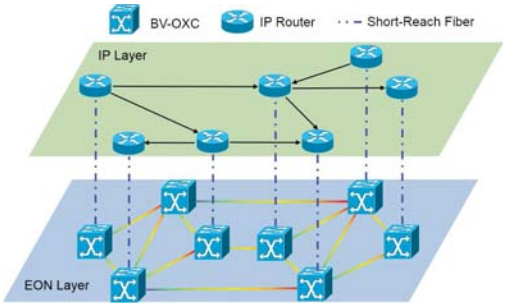


Fig. 1. Architecture of an IP-over-EON.

(FS) in the EON layer is U_{slot}, having a capacity of C_{slot} when the modulation level is 1, *i.e.*, BPSK. Then, the revenue of the service provider is calculated as:

$$R^{SP} = \sum_{lp_{e,k} \in L_o} P_{e,k}(c) - U_{slot} \cdot H_{e,k} \cdot \lceil \frac{C_{e,k}}{M_{e,k} \cdot C_{slot}} \rceil, \quad (1)$$

where c is a strategy profile of the incoming requests about their capacity requirements. Meanwhile, the following constraints should be satisfied:

$$\sum_{r_i \in D: lp_{e,k} \in L_{o,r_i}} c_i \leq C_{e,k}, \quad \forall lp_{e,k} \in L_o, \quad (2)$$

where D is the incoming request set, r_i is the i-th request, c_i is the capacity requirement of r_i, and L_{o,r_i} is the lightpath set of r_i. Note that, for an incoming request whose source and destination IP routers are not direct connected in the IP layer, its routing scheme has to go through intermediate IP routers, thus including a set of lightpaths. Hence, we formulate *Problem 1* for the service operator as:

$$\begin{aligned} &\max_{\mathbf{P^{SP}} \succeq \mathbf{0}, \mathbf{C^{SP}} \succeq \mathbf{0}} R^{SP}(\mathbf{P^{SP}}, \mathbf{C^{SP}}, \mathbf{L}, \mathbf{C}), \\ &s.t. \sum_{r_i \in D: lp_{e,k} \in L_{o,r_i}} c_i \leq C_{e,k}, \quad \forall lp_{e,k} \in L_o, \end{aligned} \quad (3)$$

where $\mathbf{P^{SP}} \triangleq \{P_{e,k} : lp_{e,k} \in L_o\}$, $\mathbf{C^{SP}} \triangleq \{C_{e,k} : lp_{e,k} \in L_o\}$, $\mathbf{L} \triangleq \{L_{o,r_i} : r_i \in D\}$, and $\mathbf{C} \triangleq \{c_i : r_i \in D\}$.

On the other hand, a tuple $(s_i, d_i, C_i^{min}, C_i^{max}, G_i)$ is used to denote request r_i, where s_i and d_i are the source and destination IP routers, respectively, C_i^{min} is the minimum capacity requirement, C_i^{max} is the maximum capacity requirement, and G_i is the utility function. given $\mathbf{P^{SP}}$ and $\mathbf{C^{SP}}$, r_i determines its lightpath set L_{o,r_i} and capacity requirement c_i to maximize its own profit, which is calculated as:

$$R_i = G_i(c_i) - \sum_{lp_{e,k} \in L_{o,r_i}} P_{e,k,i}(c_i, c_{-i}), \quad (4)$$

where c_{-i} is a strategy profile of all the incoming requests except r_i, and $P_{e,k,i}$ is the price function of $lp_{e,k}$ with respect to r_i, satisfying $P_{e,k}(c) = \sum_{r_i \in D} P_{e,k,i}(c_i, c_{-i})$. Therefore, we formulate *Problem 2* for request r_i as:

$$\max_{L_{o,r_i} \subseteq L_o, C_i^{min} \leq c_i \leq C_i^{max}} R_i(\mathbf{P^{SP}}, \mathbf{C^{SP}}, L_{o,r_i}, c_i). \quad (5)$$

Problem 1 and *Problem 2* together form a stackelberg game, in which the service provider is the leader while the incoming requests are the followers. The SE points are the ones from which neither the leader nor the followers have incentives to deviate. The mathematical definition is given as follows:
Definition 1: Let $(\mathbf{P^{SP^*}}, \mathbf{C^{SP^*}})$ be a solution to *Problem 1* and (L^*_{o,r_i}, c^*_i) be a solution to *Problem 2*. $\mathbf{L}^* \triangleq \{L^*_{o,r_i}\}$ and $\mathbf{C}^* \triangleq \{c^*_i\}$. To be an SE, the point $(\mathbf{P^{SP^*}}, \mathbf{C^{SP^*}}, \mathbf{L}^*, \mathbf{C}^*)$ satisfies:

$$\begin{aligned} R^{SP}(\mathbf{P^{SP^*}}, \mathbf{C^{SP^*}}, \mathbf{L}^*, \mathbf{C}^*) &\geq R^{SP}(\mathbf{P^{SP}}, \mathbf{C^{SP}}, \mathbf{L}^*, \mathbf{C}^*), \\ R_i(\mathbf{P^{SP^*}}, \mathbf{C^{SP^*}}, L^*_{o,r_i}, c^*_i) &\geq R_i(\mathbf{P^{SP^*}}, \mathbf{C^{SP^*}}, L_{o,r_i}, c_i), \forall r_i. \end{aligned} \quad (6)$$

for any feasible points $(\mathbf{P^{SP}}, \mathbf{C^{SP}}, \mathbf{L}, \mathbf{C})$.

To find an SE, we should study the best response of each player. Specifically, on the leader's side, since there is only one player, the best response of the service operator is to solve *Problem 1*. To do it, the best response functions of the followers should be studied first. On the followers' side, a non-cooperative game on competing for the lightpath capacities is formed due to the constraints in Eq. (2), in which all the players tend to reach the Nash Equilibrium (NE) points at which no players can improve profit by changing its strategy unilaterally. Therefore, we can first solve *Problem 2* given $\mathbf{P^{SP}}$ and $\mathbf{C^{SP}}$. Then, with the obtained $\mathbf{L}^*$ and $\mathbf{C}^*$, we solve *Problem 1* for the optimal $\mathbf{P^{SP^*}}$ and $\mathbf{C^{SP^*}}$.

III. Single-Logic-Link Scenario

For simplicity, we first study the stackelberg game in the single-logic-link scenario and analyze the existence of SEs in it. As illustrated in Fig. 2, on the service provider's side, we define the price of unit capacity $p_{1,1}$ as:

$$p_{1,1}(c) = \frac{1}{\sum_{r_i \in D} c_i} + B_{1,1}, \quad (7)$$

which decreases with the total amount of capacity requirement on it to encourage traffic aggregation but also has a basic price of $B_{1,1}$ to guarantee a non-negative revenue. Then, the service provider's revenue is calculated as:

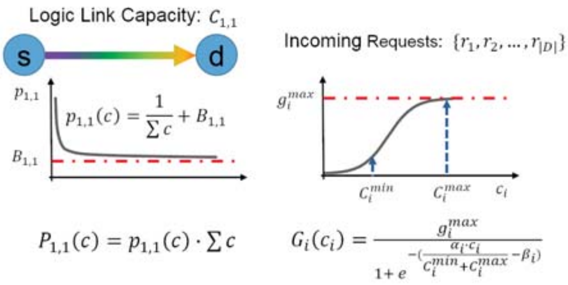
$$R^{SP}(c) = p_{1,1}(c) \cdot \sum_{r_i \in D} c_i - U^{1,1}_{capacity} \cdot C_{1,1}, \quad (8)$$

where $U^{1,1}_{capacity}$ is the cost of unit capacity on $lp_{1,1}$ which can be calculated according to the second part in Eq. (1). We can find that: 1) $C_{1,1}$ tends to be equal to $\sum_{r_i \in D} c_i$ to maximize R^{SP}, and 2) when $B_{1,1} \geq U^{1,1}_{capacity}$, R^{SP} increases with the total amount of capacity requirement. Therefore, to maximize R^{sp}, the service provider needs to set a proper value for $B_{1,1}$ to attract the most traffic on $lp_{1,1}$.

On the incoming requests' side, by referring to the sigmoid functions, we design the utility function G_i as:

$$G_i(c_i) = \frac{g_i^{max}}{1 + e^{-(\frac{\alpha_i \cdot c_i}{C_i^{min} + C_i^{max}} - \beta_i)}}, \quad (9)$$

where g_i^{max} is the maximum utility value that request r_i can create, and α_i and β_i are two parameters to control the shape



(a) Service Provider's Side (b) Incoming Requests' Side

Fig. 2. Stackelberg game in the single-logic-link scenario.

of G_i. Then, the profit of request r_i is calculated as:

$$\begin{aligned} R_i(c_i, c_{-i}) &= G_i(c_i) - p_{1,1}(c_i, c_{-i}) \cdot c_i \\ &= \frac{g_i^{max}}{1 + e^{-(\frac{\alpha_i \cdot c_i}{C_i^{min}+C_i^{max}} - \beta_i)}} - (\frac{1}{c_i + \sum c_{-i}} + B_{1,1}) \cdot c_i. \end{aligned} \tag{10}$$

Given c_{-i}, the best response function B_i of request r_i is:

$$B_i(c_{-i}) = \frac{g_i^{max} - log(\frac{g_i^{max} \cdot \Delta}{2\Theta} \cdot (1 + \sqrt{1 - \frac{4\Theta}{g_i^{max} \cdot \Delta}}) - 1)}{\Delta}, \tag{11}$$

where $\Delta = \frac{\alpha_i}{C_i^{min}+C_i^{max}}$ and $\Theta = \frac{1}{C_{1,1}} + B_{1,1}$. The existence of SE points depends on whether there are feasible solutions in the following equation set:

$$\begin{cases} B_i(c_{-i}) = c_i, \quad \forall r_i \in D, \\ \sum\limits_{r_i \in D} c_i = C_{1,1}, \end{cases} \tag{12}$$

since each SE point should be a solution in Eq. (12).

IV. Multiple-Logic-Links Scenario

As an extension, we further analyze the existence of SEs in the multiple-logic-links scenario. In this case, the situation becomes much more complicated. First, there are parallel stackelberg games between the service provider and the incoming requests on multiple logic links. Second, an incoming request may involve in multiple stackelberg games on different logic links. For example, as shown in Fig. 3, there are two logic links: the incoming request set on link 1 is $D_{1,1} = \{r_1, r_3, r_5\}$ while that on link 2 is $D_{2,1} = \{r_2, r_4, r_5\}$, on each of which there is an ongoing stackelberg game and their SE points are interdependent since request r_5 involves in both games.

In the multiple-logic-links scenario, the SE point on each lightpath $lp_{e,k}$, denoted as $\{c_{i,e,k}^*, B_{e,k}^*, C_{e,k}^* : r_i \in D_{e,k}\}$, should satisfy:

$$\begin{cases} B_i(c_{-i,e,k}) = c_{i,e,k}, \quad \forall r_i \in D_{e,k}, \\ \sum\limits_{r_i \in D_{e,k}} c_{i,e,k} = C_{e,k}, \end{cases} \tag{13}$$

where $D_{e,k}$ is the incoming request set on $lp_{e,k}$, $c_{i,e,k}$ is the capacity requirement of request r_i on $lp_{e,k}$, and $c_{-i,e,k}$ is a strategy profile of all the incoming request except r_i in $D_{e,k}$.

Moreover, for two lightpaths $lp_{e,k}$ and $lp_{e',k'}$, if they have common incoming requests, *i.e.*, $D_{e,k} \cup D_{e',k'} \neq \emptyset$, denoted

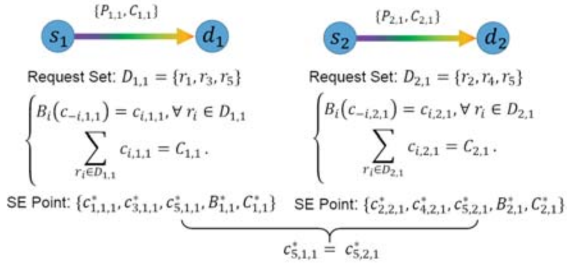


Fig. 3. Stackelberg game in the multiple-logic-links scenario.

as set $D_{e,k,e',k'}$, their SE points are interdependent that the request in $D_{e,k,e',k'}$ should also satisfy:

$$c_{i,e,k}^* = c_{i,e',k'}^*, \quad \forall r_i \in D_{e,k,e',k'}. \tag{14}$$

V. Conclusions

In this work, we studied game theoretical flexible service provisioning in an IP-over-EON. We formulated a stackelberg game in which the service operator is the leader and the incoming requests are the followers, and analyzed the existence of SEs in the single-logic-link and multiple-logic-links scenarios.

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