Implementation and Demonstration of Revenue-Driven Provisioning for Advance Reservation Requests in OpenFlow-Controlled SD-EONs

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***Abstract*—This paper aims to realize OpenFlow-controlled revenue-driven advance reservation (AR) provisioning in software-defined elastic optical networks (SD-EONs). We design control plane framework, propose two algorithms for the OpenFlow controller, implement the whole system in a semi-practical SD-EON testbed, and conduct experiments with two payment models. Experimental results indicate the proposed system performs well and can increase total revenue-gain effectively.**

***Index Terms*—Software-defined elastic optical networks (SD-EONs), Advance reservation (AR), revenue-driven provisioning.**

I. INTRODUCTION

NOWADAYS, elastic optical networks (EONs) have been considered as a promising physical infrastructure for the next-generation Internet, due to the agile optical spectrum management brought by the flexible-grid. EONs leverage bandwidth-variable transponders (BV-Ts) to realize flexible spectrum allocation by grooming a few narrow-band frequency slots (FS') for each lightpath. Therefore, compared with the traditional wavelength-division multiplexing (WDM) networks, EONs require more sophisticated bandwidth allocation mechanisms, which perform better if incorporating with centralized network control and management (NC&M). Meanwhile, it is known that software-defined networking (SDN) with OpenFlow (OF) can enhance the programmability of optical networks by leveraging flow-switching and using a centralized controller [1]. Hence, we expect the combination of SDN and EON (i.e., SD-EON) to provide new opportunities for making optical networks adapt to the highly-dynamic traffic from emerging applications easily [2].

Previously, service provisioning for normal lightpath requests in SD-EONs have been experimentally demonstrated in [2], [3]. Note that in addition to these requests that need to be served immediately upon arrivals, there are also advance reservation (AR) requests in optical networks, which allow certain setup delay as long as the resources are allocated before a deadline [4]. Moreover, AR provisioning is essential to carry delay-tolerant services, such as video-on-demand and grid computing. Previous studies on AR provisioning usually tried to reduce request blocking probability [4], [5], but in reality, a network operator would concern more about the revenue-gain from service provisioning [6]. In this work, we investigate how to realize OF-controlled revenue-driven AR provisioning in SD-EONs. We design control plane architecture, propose two efficient algorithms to be programmed in the OF controller, implement the whole system in a semi-practical SD-EON testbed, and conduct AR provisioning experiments with two payment models to evaluate the proposed system and algorithms. To the best of our knowledge, this is the first system implementation that facilitates revenue-driven AR provisioning in SD-EONs. The rest of the paper is organized as follows. Section II explains the architecture of SD-EONs and the control plane framework for revenue-driven AR provisioning. We design two revenue-driven AR provisioning algorithms in Section III. Experimental demonstrations are shown in Section IV. Finally, Section V summarizes the paper.

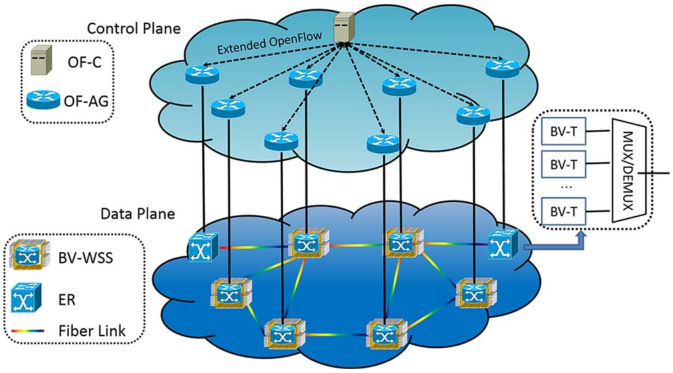

Fig. 1. Network architecture of an SD-EON.

II. SOFTWARE-DEFINED ELASTIC OPTICAL NETWORKS

Fig. 1 shows the overall network architecture of an SD-EON. The data plane is in charge of transmitting high-speed data through lightpaths, and it interconnects bandwidth-variable wavelength selective switches (BV-WSS') and edge routers (ERs) with fiber links. An ER includes several bandwidth-variable transponders (BV-Ts) and a spectrum multiplexer/demultiplexer (MUX/DEMUX). Operating on the flexible-grid wavelength plan defined in ITU-T G.694.1 [7], the BV-Ts establish each lightpath for client traffic by allocating just enough number of FS', while BV-WSS' switch the variable-size spectra correctly. It is worth noting that, BV-Ts accommodate various quality of transmission (QoT) by adjusting the optical signals' modulation-levels adaptively [8].

The control plane is built based on the OF protocol, where we have a centralized OF controller (OF-C) and a few OF agents (OF-AGs) that each attaches to a data plane equipment (i.e., ER or BV-WSS'). Note that this approach is different from those that are based on the distributed NC&M with GMPLS [9], which are less efficient on spectrum management but

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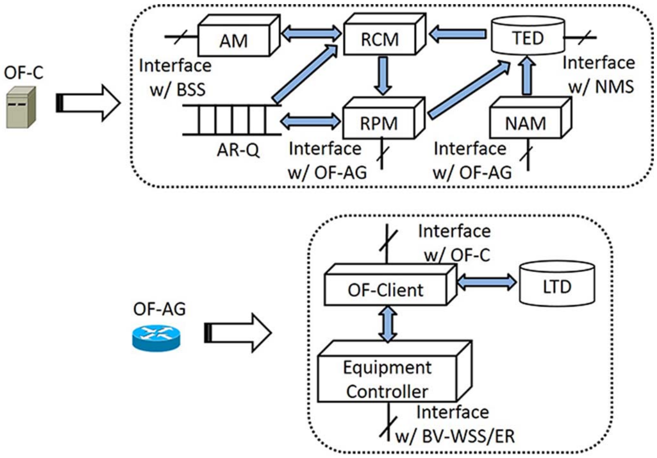
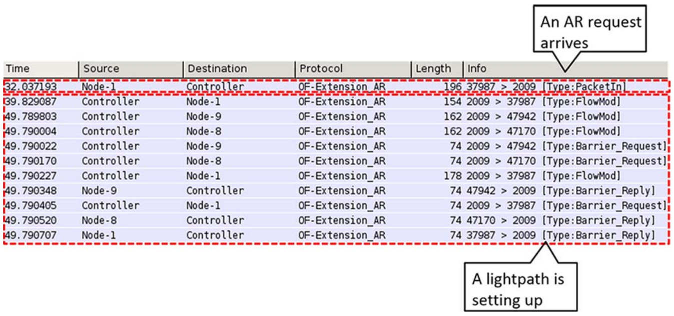


Fig. 2. Functional designs for OF-C and OF-AG to realize revenue-driven AR provisioning in SD-EONs.


An AR request arrives

```
Time        Source      Destination  Protocol         Length Info
32.037193   Node-1      Controller   OF-Extension_AR     196 37987 > 2009 [Type:PacketIn]
39.829087   Controller  Node-1       OF-Extension_AR     154 2009 > 37987 [Type:FlowMod]
49.789803   Controller  Node-9       OF-Extension_AR     162 2009 > 47942 [Type:FlowMod]
49.790004   Controller  Node-8       OF-Extension_AR     162 2009 > 47170 [Type:FlowMod]
49.790022   Controller  Node-9       OF-Extension_AR      74 2009 > 47942 [Type:Barrier_Request]
49.790170   Controller  Node-8       OF-Extension_AR      74 2009 > 47170 [Type:Barrier_Request]
49.790227   Controller  Node-1       OF-Extension_AR     178 2009 > 37987 [Type:FlowMod]
49.790348   Node-9      Controller   OF-Extension_AR      74 47942 > 2009 [Type:Barrier_Reply]
49.790405   Controller  Node-1       OF-Extension_AR      74 2009 > 37987 [Type:Barrier_Request]
49.790520   Node-8      Controller   OF-Extension_AR      74 47170 > 2009 [Type:Barrier_Reply]
49.790707   Node-1      Controller   OF-Extension_AR      74 37987 > 2009 [Type:Barrier_Reply]
```

A lightpath is setting up

Fig. 3. Wireshark capture for provisioning an AR request.

could have better scalability. OF-C works as the "brain" of the SD-EON, and it provisions lightpaths intelligently according to the network status. The provisioning instructions are sent to OF-AGs with an extended OF protocol, which encodes the information of each lightpath, e.g., the routing and spectrum assignment (RSA), the modulation-level, the service window, the input and output ports etc, in OF messages. Each OF-AG works as a bridge for the control and data planes. Specifically, it configures the data plane equipments according to the OF messages from OF-C, and reports the data plane status back.

To facilitate revenue-driven AR provisioning, we design the functional blocks for OF-C and OF-AG as shown in Fig. 2. When the OF-AG on an ER receives an AR request for client traffic, the OF-client in it will encode the request's information in a *Packet-In* message and forward it to OF-C. The resource provision module (RPM) in OF-C then parses the message, and stores the request in the AR request queue (AR-Q). Meanwhile, RPM instructs the resource computation module (RCM) to calculate AR provisioning scheme for the request, i.e., determining the RSA, modulation-level and service window (i.e., the duration when the AR request should be active). During this process, RCM refers to the information in the accounting module (AM) and traffic engineering database (TED), for payment model and network status, respectively. After obtaining the AR provisioning scheme, RCM forwards it to RPM, where the AR scheme is encoded as flow-entries in *Flow-Mod* messages, and will be sent to all the OF-AGs on the routing path at the beginning of the service window (i.e., the time when the AR request should be provisioned). Meanwhile, RCM sends the revenue-gain from the request to AM for bookkeeping, and RPM updates TED to include the provisioned request's resource utilization. In each related OF-AG, OF-client parses the flow-entry, the equipment controller configures its data plane equipment accordingly to set up the lightpath, and the local traffic database (LTD) stores the request's information locally. If the request cannot be provisioned, RCM has the options to either block it immediately or store it in AR-Q for re-provisioning in the future, depending on the actual AR provisioning algorithm. The network abstraction module (NAM) talks with OF-AGs for abstracting data plane equipments and collecting the SD-EON's topology information for TED. In OF-C, TED communicates with an external network management system (NMS) for NC&M, while AM has the interface with a business support system (BSS).

III. REVENUE-DRIVEN AR PROVISIONING

We model an AR request in SD-EONs as $LR(s, d, C, t_a, d_{\max}, \Delta t, p_{\max})$, where $s - d$ is the source-destination pair, C is the capacity requirement in Gb/s, t_a is the arrival time, $d_{\max}$ is the maximum tolerable setup delay, Δt is the service duration, and $p_{\max}$ is the maximum payment from the client. To achieve AR provisioning for LR, the network operator first needs to determine the service window $[t_s, t_e]$, where t_s and t_e are the service start- and end-time and t_s should be within $[t_a, t_a + d_{\max}]$ to satisfy $d_{\max}$. Then, in the service window, a routing path $R_{s,d}$ is selected for LR, which has enough available contiguous FS' to carry C. Here, we assume that QoT-adaptive modulation-level selection is used, and hence the actual number of FS' to be allocated on $R_{s,d}$ depends on its transmission distance [8].

Algorithm 1: GRS for Revenue-gain AR Provisioning

```
for each pending request $LR$ in AR-Q in descending order of $p_{max}$ do
    RCM calculates $[\mathbf{RG}]_{K \times T}$ for $LR$ based on the network status in TED;
    RCM finds the maximum element $g_{k_m,t_m}$ in $[\mathbf{RG}]$;
    if $g_{k_m,t_m} > 0$ then
        RCM selects the $t_m$-th service window;
        RCM performs RSA with adaptive modulation selection on the $k_m$-th path;
        RCM forwards provisioning result to RPM;
        RCM sends revenue-gain from $LR$ to AM;
    else
        RCM instructs RPM to block $LR$;
    end
end
```

The payment model comes from the service-level agreement (SLA) between the operator and its clients, and we assume that the actual payment p for each AR request depends on its setup delay $d' = t_s - t_a$. In this work, we consider two payment models: 1) Fixed, as $p(d') = p_{\max}$ for $d' \leq d_{\max}$, otherwise $p(d') = 0$, 2) Linear, as $p(d') = p_{\max} - \beta \cdot d', d' \leq d_{\max}$, otherwise $p(d') = 0$, where β is a fixed coefficient. With a payment model, revenue-driven AR provisioning maximizes the total revenue-gain in a dynamic network scenario. To achieve this, we propose two algorithms, as the greedy request scheduling (GRS) and intelligent request scheduling (IRS), and both are implemented in RCM and AR-Q.

A. *Greedy Request Scheduling*

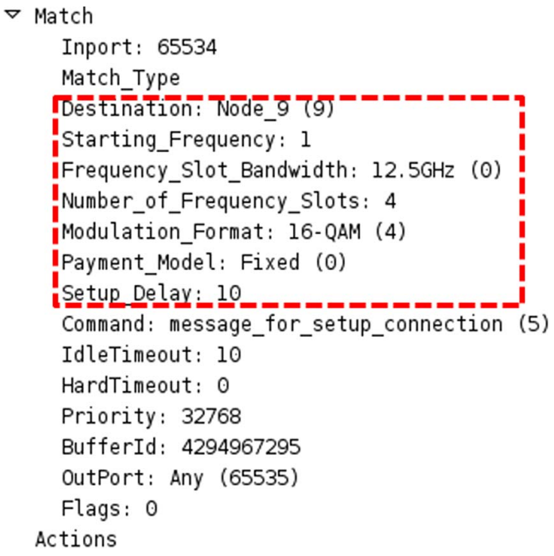
For simplicity, we assume that the SD-EON operates on discrete time-intervals, which means that for LR, the eligible service windows are countable, as $[t_a, t_a+\Delta t]$, $[t_a+1, t_a+1+\Delta t]$, $\cdots$, and $[t_a+d_{\max}, t_a+d_{\max}+\Delta t]$. When provisioning AR requests, greedy request scheduling (GRS) applies a greedy scheme for profit-seeking based on a revenue-gain matrix $[\mathbf{RG}]_{K\times T}$. Here, K is the number of pre-calculated paths for $s-d$, and $T=d_{\max}$ is the number of eligible service windows. Each element $g_{k,t}$ in $[\mathbf{RG}]$ represents the revenue-gain for serving an AR request over the k-th path during the t-th eligible service window, i.e., $[t_a+t-1, t_a+t-1+\Delta t]$. $g_{k,t}$ is calculated with the payment model if it can be provisioned there, otherwise, we set $g_{k,t}=0$. *Algorithm* 1 shows the detail procedure of GRS. By leveraging $[\mathbf{RG}]$, GRS tries to provision an AR request earlier, if its $p_{\max}$ is larger, and during the provisioning, GRS selects the scheme whose revenue-gain is the largest.

B. *Intelligent Request Scheduling*

GRS uses the greedy scheme for profit-seeking, but does not consider the competitions among requests arriving at different time. Therefore, we design intelligent request scheduling (IRS) to perform AR provisioning in a more considerable way for profit-seeking, whose procedure is illustrated in *Algorithm* 2. At each time instant, IRS calculates the expected payment of each pending request in AR-Q and tries to provision it with the least spectrum usage. If the request cannot be provisioned, IRS inserts it back to AR-Q for waiting for the next service time.

Algorithm 2: IRS for Revenue-gain AR Provisioning

```
for each pending request $LR$ in AR-Q in descending order of the expect payment $p(d')$ do
    $id = 0$, $f = +\infty$;
    for $k = 1$ to $K$ do
        if $LR$ can be provisioned with the k-th path $R_{s,d}^{(k)}$ from this moment then
            RCM performs RSA with adaptive modulation selection on $R_{s,d}^{(k)}$;
            RCM gets the number of FS' to be allocated on $R_{s,d}^{(k)}$ as $n_k$;
            RCM obtains the hop-count of $R_{s,d}^{(k)}$ as $h_k$;
            if $f > n_k \cdot h_k$ then
                $id = k$, $f = n_k \cdot h_k$;
            end
        end
    end
    if $id > 0$ then
        RCM instructs RPM to provision $LR$ right away on the $id$-th path;
        RCM sends revenue-gain from $LR$ to AM;
    else
        if $LR$ is eligible for the next service start-time then
            RCM puts $LR$ back to AR-Q;
        else
            RCM instructs RPM to block $LR$;
        end
    end
end
```



```
▽ Match
    Inport: 65534
    Match_Type
    Destination: Node_9 (9)
    Starting_Frequency: 1
    Frequency_Slot_Bandwidth: 12.5GHz (0)
    Number_of_Frequency_Slots: 4
    Modulation_Format: 16-QAM (4)
    Payment_Model: Fixed (0)
    Setup_Delay: 10
    Command: message_for_setup_connection (5)
    IdleTimeout: 10
    HardTimeout: 0
    Priority: 32768
    BufferId: 4294967295
    OutPort: Any (65535)
    Flags: 0
  Actions
```

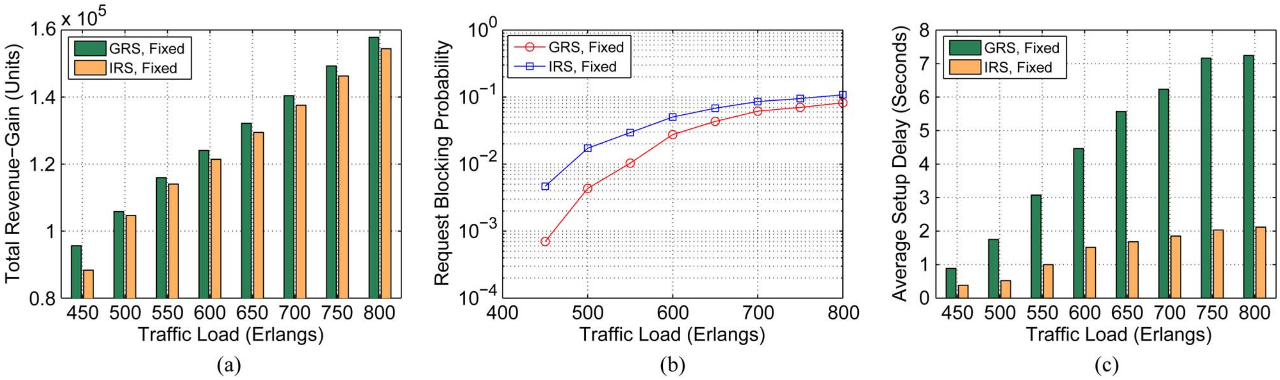
Fig. 4. *Flow-Mod* message for revenue-driven AR provisioning.

IV. EXPERIMENTAL DEMONSTRATIONS

To evaluate the performance of the proposed system and algorithms, we conduct experimental demonstrations in a control plane testbed built with high-performance Linux servers. We have 14 stand-alone servers that each works as an OF-AG, and they are connected in the way to mimic the 14-node NSFNET topology. These OF-AGs are implemented with Open-vSwitch running on Linux. Meanwhile, an OF-C is programmed with the POX platform, which runs on another independent server that is directly connected to all the OF-AGs. Since we focus on the control plane implementation, the data plane is emulated, where each fiber link is assumed to have 358 FS' that each has a bandwidth of 12.5 GHz. On each OF-AG, the AR requests are generated with the Poisson traffic model, where the $s-d$ pair of each request is randomly chosen, C is uniformly distributed within [25,500] Gb/s, $d_{\max}$ is within [30,50] seconds, Δt follows the negative exponential distribution with a mean of 100 seconds, and $p_{\max}$ is within [20,50] units. In the experiments, OF-C processes AR requests based on a discrete service interval, which is 10 seconds. Note that this service interval is just selected for saving the time of experiments. In practical SD-EONs, the interval can be much longer, and our system can take arbitrary service intervals.

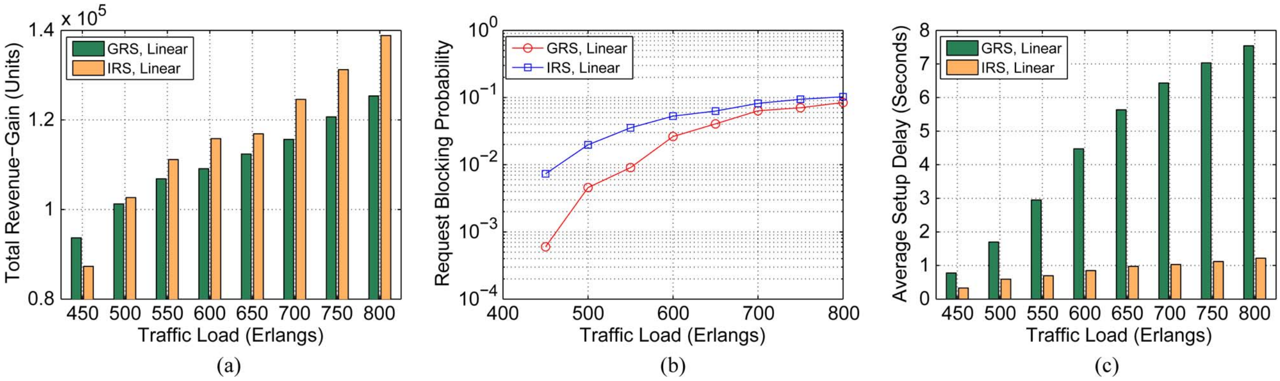
Fig. 3 shows the Wireshark capture for the OF messages involved in provisioning an AR request. The first line shows the *Packet-In* message from the source OF-AG to OF-C, and the rest lines show the messages from OF-C to all the OF-AGs on the routing path to install the lightpath. The details of a *Flow-Mod* message are in Fig. 4, which shows the new fields we insert for revenue-driven AR provisioning.

The results from the experiments with the fixed payment model are shown in Fig. 5. Fig. 5(a) compares GRS with IRS in terms of total revenue-gain, and shows that GRS achieves slightly higher profits than IRS. Apparently, total revenue-gain depends on two factors, i.e., the average revenue-gain from each request and the request blocking probability. With the fixed payment model, the revenue-gain from each request is independent of its setup delay and since GRS achieves lower blocking probabilities (as shown in Fig. 5(b)) with the greedy



(a) (b) (c)

Fig. 5. Results from experiments with fixed payment model. (a) Total revenue-gain. (b) Request blocking probability. (c) Average setup delay.



(a) (b) (c)

Fig. 6. Results from experiments with linear payment model. (a) Total revenue-gain. (b) Request blocking probability. (c) Average setup delay.

scheme, it provides higher revenue-gains. Fig. 5(c) shows the experimental results on average setup delay, which indicate that IRS provides much lower setup delays than GRS.

Fig. 6 shows the experimental results with the linear payment model. In Fig. 6(a), we observe that IRS achieves higher total revenue-gains than GRS for most of the traffic loads, except for 450 Erlangs. Note that when the traffic load is as low as 450 Erlangs, the average setup delay from GRS is almost comparable with that from IRS, while it provides much lower blocking probability than IRS, as shown in Figs. 6(c) and (b), respectively. Hence, GRS achieves higher revenue-gain than IRS when the traffic load is 450 Erlangs. However, when the traffic load keeps increasing, the revenue-gain from IRS becomes larger and the gap on the revenue-gains from the two algorithms increases too. This is because with the linear payment model, the greedy nature of GRS makes it provision the requests with prolonged setup delays (as shown in Fig. 6(c)). It is interesting to notice that the blocking probabilities from IRS are still higher than those from GRS while IRS' total revenue-gains are usually higher. This can be viewed as evidence that in this case, IRS performs revenue-driven AR provisioning better, as it can intelligently reject requests that only bring in small payments. Note that to obtain one data point in Figs. 5 and 6, OF-C serves around 4000 incoming AR requests from the OF-AGs.

V. CONCLUSION

This paper investigated how to realize OF-controlled revenue-driven AR provisioning in SD-EONs. We designed control plane framework, proposed two algorithms for OF-C, implemented the whole system in a semi-practical SD-EON testbed, and conducted experiments with two payment models. Experimental results indicated the proposed system performed well and could increase total revenue-gain effectively.

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