Provisioning Virtualized Cloud Services in IP/MPLS-over-EON Networks

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***Abstract*—Cloud computing enables the provisioning of resources in a reliable and on-demand manner. With the increasing importance of the network bandwidth in the Cloud environment, the networking related resources need to be optimally allocated together with the traditional Cloud computing resources. In addition, the significant growth of the global data center traffic poses the challenge of supporting demands with large bandwidth requirement for the Cloud provider. In our paper, we consider the network-efficient virtualized cloud infrastructure provisioning (NE-VCIP) problem in IP-over-EON network based on the data center as a service model. The elastic optical network (EON) is adopted to provide spectrum and cost efficient networking resources for large bandwidth requests in our work. We develop ILP formulations to construct the mathematical model for this problem and propose a cost-optimized heuristic to solve this problem. To investigate the cost and blocking rate for the served demands, different modulation formats are compared in the EON layer. The experimental results show that different modulation formats that are adopted in the EON layer will have different impacts on the total cost and demand blocking rate for the same data set size. In order to minimize the total cost and obtain a better system performance as well (e.g. low blocking rate), a trade-off needs to be considered between the two.**

I. INTRODUCTION

Cloud computing offers computing resources to a large amount of on-demand service applications. Customers can reserve the required resources through the infrastructure as a service (IaaS) to complete their computing intensive tasks. In the future, customers may not only want to reserve computing resources, such as virtual machines (VMs) and storage, but would also want to reserve their own Cloud environment. A new architecture proposed in [1] as data center as a service (DCaaS) for the future Cloud computing could satisfy such requirements from customers. DCaaS allows customers to create their own Cloud platform without constructing the physical DCs. The virtual data center (VDC) service which falls within IaaS enables users to quickly access Cloud infrastructure from a service provider such as vCloud Suite by VMware [2], VMDC by Cisco [3], etc. The reserved virtual Cloud environment consists of geographically distributed virtual data centers (VDCs) and backbone networks that connect these VDCs.

The Cisco Global Cloud Index (GCI) [4] is an ongoing effort to forecast the growth of global data center and cloud-based IP traffic. GCI indicates in the forecast and methodology report for 2013-2018 that, the global data center traffic and global Cloud traffic will increase significantly in the future years [4]. To support the large amount of traffic in the Cloud environment and satisfy the requirement of non-blocking bisection bandwidth among servers, huge bandwidth capacity should be provided by an efficient interconnection architecture. Therefore, optical networking with scalable bandwidth capacity, low cost and low latency would be desirable [5].

In this paper, we investigate the network-efficient virtualized Cloud infrastructure provisioning (NE-VCIP) in multi-layer network architecture. In our problem, a virtualized cloud infrastructure (VCI) demand submitted by a user consists of the VDC infrastructures and the virtualized network (VN) connectivity. Each VDC is provided with required amount of computing resources. The VNs are specified with certain amount of bandwidth for data transmission. The bandwidth requirement is an essential addition which provides the significant benefit of performance predictability for distributed computing [6]. The centralized controller needs to map the VDCs and VN to the geographically distributed physical DCs and backbone networks that both have enough related resources. To guarantee the bandwidth requirements by VN, optical circuits are established. In this paper, we consider the backbone network with IP-over-EON (elastic optical network) architecture. So one important task for the controller is to complete the routing and spectrum assignment (RSA) in the multi-layer network when doing VN mapping. The elastic optical network (EON) has become a promising approach for flexible bandwidth provisioning in optical networks. EON can provide high capacity bandwidth for the demands that cannot be well supported in current WDM networks.

II. RELATED WORK

The optimal resource provisioning in Cloud has been a challenge in Cloud computing. Various investigations have been conducted for the resource provisioning problems in the Cloud. The work in [7] studies the virtual resource allocation problem for networked cloud environments, incorporating heterogeneous substrate resources, and provides an approximation approach to address the problem. The work in [8] presents a system that makes use of virtualization technology to allocation DC resources dynamically and targets to optimizing the number of servers in use. A set of heuristics are developed to prevent overload in the system while saving energy used. Moreover, to get the maximum benefit from a distributed cloud system, efficient algorithms are needed for resource allocation which minimize communication costs and latency. The work in [9] develops efficient resource allocation algorithms to address such problems in distributed clouds. The target of this work is to minimize the maximum distance, or latency, between the selected DCs.

In addition, VDC networks has been considered as a feasible alternative to satisfy the requirements of advanced Cloud infrastructure services. Proper mapping of VDC resources to their physical counterparts can impact the revenue of cloud providers [10]. In addition to the VM resources, the work in [10] proposes a new embedding solution for DCs that considers the relation between switches and links, and allows multiple resources to be mapped to a single physical DC. Also a recent study in [11] about VDC embedding proposes *VDC Planner*, a migration-aware dynamic virtual data center embedding framework that aims at achieving high revenue while minimizing the total energy cost over-time. This work focuses on embedding VDCs into one physical data center. The work in [12] about VDC embedding proposes *Greenhead*, a holistic resource management framework for embedding VDCs across geographically distributed data centers connected through a backbone network. The goal of Greenhead is to maximize the cloud provider's revenue while ensuring that the infrastructure is as environment-friendly as possible. This work focuses on embedding VDCs into distributed infrastructures which is different from the work in [11] and [10].

Different from other works, we make use of the flexible optical network as the backbone network in the Cloud to investigate the virtual cloud resource provisioning problems. Our objective is to minimize the total cost (CapEx and OpEx) for resource provisioning in the cloud environment. To the best of our knowledge, this is the first work that investigates cost-optimized virtual cloud resource provisioning while utilizing the IP-over-EON network architecture.

III. NE-VCIP PROBLEM

As we mentioned above, in the NE-VCIP problem, a VCI demand submitted by a customer consists of VDC infrastructures and the VN interconnecting VDCs. Each VDC requires a certain amount of computing resources (e.g. CPU and storage) and IT resources (e.g. ports for infrastructure connections within a VDC). The VN that connects VDCs requires a certain amount of bandwidth for data transmission. The centralized scheduler needs to map the VDCs and VN to the geographically distributed DCs and backbone networks such that both have enough resources. To guarantee the bandwidth requirements for the VN, optical circuits are established and the spectrum is assigned to the demands. In this paper, we consider a backbone network which uses an IP-over-EON architecture as shown in Fig. 1. At the starting point of the data transmission path, the data traffic goes across the IP/MPLS layer node to the connected EON layer node (bandwidth-variable wavelength cross-connects (BV-WXCs)) through bandwidth-variable transponders (BVTs). Then the data traffic travels along the light path in the EON layer, arrives at the EON layer destination node and finally reaches the end point of IP/MPLS layer. Therefore, to perform the VN mapping, an important task is to complete the routing and spectrum assignment (RSA) in the multi-layer network. EON is one of the most exciting future directions for optical networks and also an efficient and cost-effective solution for provisioning of Cloud traffic [13].

A. VDC mapping

For the VDC mapping, we suppose that no two VDCs in a same demand will be mapped to the same physical DC since we would like to avoid the scenario of a disaster at one DC affecting multiple VDCs of a VCI demand. The geographically distributed DCs have different amount of resources with different rental prices. We assume that the DCs in the central region of the Cloud network have lower rental price compared those in west/east regions, because of the richer resources and lower construction costs.

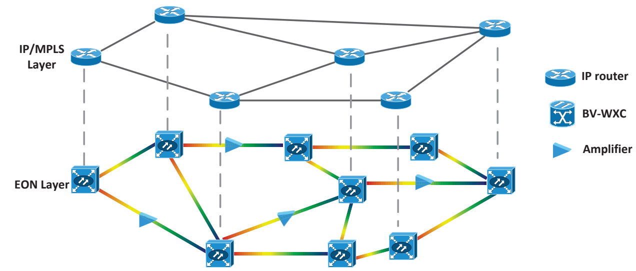

Fig. 1: The IP/MPLS-over-EON architecture

B. RSA in EON layer

The RSA problem in flexible grid optical networks contains both the routing decision for traffic demands and the subcarrier assignment to satisfy the requirements by corresponding traffic demands [14]. The VN mapping in the EONs is actually a RSA problem, which is NP-$hard$ [15]. For the VN requirement of a demand, the central scheduler needs to find the path between two geographically distributed DCs that has the lowest cost and make sure that all the fiber links along this path have enough spectrum resources. Then the scheduler assigns the related frequency slots (FSs) from each fiber link along the path for the demands. The required number of FSs must be contiguous in frequency domain and temporal domain for each link on the path. In addition, the links along the routing path must use the same FSs, which is called spectrum continuity. In our model the required bandwidth of a virtual link (VL) in VN is given in bit rate (Gbps). In order to estimate the number of FSs that each VL requires, we convert the required bit rate bandwidth into frequency (GHz) first according to the theoretical bandwidth efficiency limits for the main modulation formats [16]. Formula $F = B/M$ is used in the conversion. Here F is frequency; B is bit rate; M is log-2 value of modulation formats, $M = 1, 2, 3, 4$ for Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 8 Quadrature Amplitude Modulation (8-QAM) and 16 Quadrature Amplitude Modulation (16-QAM) respectively. The assumed transmission reaches of modulation formats BPSK, QPSK, 8-QAM and 16-QAM are 5000, 3000, 1500 and 700 km respectively [17]. Then according to the frequency grid of the EON, the required number of FSs of a VL can be obtained. In EON, the available optical spectrum is divided into a set of FSs of a fixed finer spectrum width (frequency grid), such as 25GHz, 12.5GHz and 6.25GHz. We use 12.5 GHz as the frequency grid for the operation of the EON in this work with a total of 320 FSs in the C-band on each fiber link.

IV. MATHEMATICAL FORMULATION

A. NE-VCIP Problem Setting

The objective of the NE-VCIP problem is to achieve the minimal cost while satisfying the input demands.

Given:
- A physical Cloud computing infrastructure, modeled as a weighted directed graph $G(V, E)$, V is the set of DCs with a set of computing resources and their unit costs, E is the set of network links. Each DC is described as a tuple data center $= (DC_v, C_v, S_v, P_v, \alpha_v, \beta_v, \gamma_v, i_v, e_v)$ with the capacity and unit cost of types of resources in this data center, the meaning of each item in the tuple is described in Table I. Each edge in E is described as a tuple $e = (u, v, d_{(u,v)})$, which indicates the link between DCs (u, v), and the link distance. The network in the modeled Cloud computing infrastructure is in multi-layer;
- A VCI demand d, modeled as a weighted directed graph $G^d(V^d, E^d)$, in which V^d is a set of VDCs with specified computing, storage and switch port requirements, E^d is a set of weighted VLs that indicate the required bandwidth. Each VDC of V^d is described as a tuple VDC $= (d, v', RC_d^{v't}, RS_d^{v't}, RP_d^{v't})$, in which d indicates the demand ID and v' indicates the VDC ID of demand d; the meaning of other items in the tuple is described in Table I. Each VL in E^d is described as $VL = (d, u', v', RB_d^{(u',v')t})$, in which u', v' indicate the two end VDCs of current virtual link.
- The cost for each optical amplifier (OA) and regenerator to be installed in the used fiber links and EON nodes respectively; and the cost for bandwidth-variable transponder (BVT) at each IP/MPLS node for connecting optical layer node. Both will be described in Section IV. B in detail.
- The modulation format for optical signals in EON layer.

Output:
- The mapping for the VDCs in each VCI demand to the physical DCs;
- The routing path for mapped VN with allocated FSs;
- The total cost for satisfying all demands.

Objective:
Minimize the total cost for all the VCI demands (Full Fit), or for satisfying the maximum number of VCI demands (Best Fit) if accepting all demands is not possible.

TABLE I: Parameters

C_v, S_v, P_v	CPU, storage and switch port capacities in DC v, $v \in V$
$\alpha_v, \beta_v, \gamma_v$	The unit cost of CPU, storage and switch port in DC v
i_v, e_v	The cost of IP/MPLS, EON layer terminals in DC_v
b	The unit cost (per Gbps) of bandwidth resource
d_e	The distance of link e, $e \in E$
ST_d, ET_d	The start and end time of demand d
V^d	The set of VDCs by demand d
E^d	The set of VN-links by demand d
Bud_d	The budget of demand d
$RC_d^{v't}, RS_d^{v't}, RP_d^{v't}$	The required amount of CPU, storage and switch port for VDC v' by demand d in time slot t, $v' \in V_d$
$RB_d^{(u',v')t}$	The required amount of bandwidth of virtual link between VDC (u', v') by demand d
$T_d^{(u',v')t}$	The required number of frequency slots by demand d between VDC (u', v')
$deg_d^{v'}$	The degree of VDC v' in VCI topology by demand d

B. Network Model

In this work we adopt the IP/MPLS-over-EON architecture for the cloud network as shown in Fig.1. In the IP/MPLS-over-EON network, the intermediate node along the routing path could be (1) a multi-layer node with both IP/MPLS and EON capability; (2) only a EON layer node if the transmitted optical signal is not needed to be processed by the IP/MPLS layer; (3) a patch field that only connecting the optical fibers such as optical amplifier if the transmitted optical signal is not needed to be processed by neither IP/MPLS layer nor EON layer.

In the IP/MPLS layer, an electrical node which can be seen as an IP/MPLS router, consists of the main building blocks: the basic node (including switching matrix, power supply and mechanics), line cards (LC), with a different number of ports for transceivers and the transceivers [18]. In the EON layer, a flexible EON node can be seen as a bandwidth variable wavelength cross-connect (BV-WXC), which is used to establish optical cross-connections with various frequency slot width. The BV-WXC which mainly consists of BVT and bandwidth-variable wavelength selective switch (BV-WSS) can provide both sub-wavelength and super-wavelength for the flexible optical network. The EON can provide a granularity of 12.5GHz instead of 50 GHz in current WDM systems. BVTs can adjust the optical signal transmission rate to the actual traffic demand, by expanding or contracting the bandwidth of an optical path (i.e. varying the number of sub-carriers) and by modifying the modulation format [19].

C. Cost Model

In this work, the cost we considered for the NE-VCIP problem comes from the renting cost for computing resources such as CPU and storage (noted as operating expenditure (OpEx) in this work), and the fixed cost for network equipments and fibers (noted as capital expenditure (CapEx) in this work). For the OpEx, we refer to the Amazon EC2 cost model to give the unit rental cost (cost per resource unit per time slot) of CPU, storage and bandwidth. For the CapEx, we refer to the cost model in [20] for the cost of IP/MPLS nodes, BVTs, optical amplifier, etc. We assume that the metro node in our topologies adopt a single-chassis router, which consists of a single shelf with 10 line-card slots. All the cost values in our work are normalized.

D. MILP Model

Next we will describe the MILP formulations of VCI mapping while considering RSA in EON problem. The MILP models we constructed for the VCIP problem is *Full-Fit*, in which we restrict that all VCI demands in the demand set must be accepted and the total cost of resource provisioning for all demands must be minimized. In general the physical frequency filtering requires that various spectrum paths are separated in the spectrum domain by guard frequencies when two spectrum paths share one or more common fiber links. In our problem, to simplify the model, we assume that the size of guard frequencies is zero. To construct MILP formulations, we define some variables as shown in the following.

- $x_d^{v'v}$, 1 if required VDC v' by demand d is mapped to DC v; 0 otherwise
- $y_{df(u',v')}^{(u,v)}$, 1 if the FS f is used on physical link (u, v), which is on the mapping path for virtual link (u', v') of demand d; 0 otherwise. $(u, v) \in E, (u', v') \in E^d$
- $COST_d$, the cost for demand d

Objective:

$$\text{Minimize} \sum_{d \in D} COST_d \quad (1)$$

$$COST_d = \sum_{t,v',v} (RC_d^{v't} \cdot \alpha_v + RS_d^{v't} \cdot \beta_v + RP_d^{v't} \cdot \gamma_v) \cdot x_d^{(v',v)} \quad (2)$$
$$+ \sum_{v',v} (i_v + e_v) \cdot x_d^{(v',v)} \cdot deg_d^{v'} + \sum_{t,e'} RB_d^{e't} \cdot b$$
$$+ \sum_{e',e} y_d^{(e',e)} \cdot d_e \cdot comCost \cdot \left\lceil RB_d^{e't}/10 \right\rceil$$

where $comCost$ integrates the OA, regenerator, etc. along the fiber links, $t \in [ST_d, ET_d], v' \in V^d, u, v \in V$

Computing Resource Capacity Constraints:

$$\sum_{d,v'} RC_d^{v't} \cdot x_d^{(v',v)} \leq C_v \quad (3)$$

$$\sum_{d,v'} RS_d^{v't} \cdot x_d^{(v',v)} \leq S_v \quad (4)$$

$$\sum_{d,v'} RP_d^{v't} \cdot x_d^{(v',v)} \leq P_v \quad (5)$$

where $t \in [ST_d, ET_d]$.

Equations (3)-(5) ensure that the assigned computing resources to the demand do not exceed the resource capacity of each node.

Resource Allocation Region Constraints:

$$\sum_{v} x_d^{(v',v)} = 1, \forall d \in D, v' \in V^d. \quad (6)$$

$$\sum_{v'} x_d^{(v',v)} \leq 1, \forall d \in D, v \in V. \quad (7)$$

Equation (6) guarantees that one VDC of a VCI demand can only obtain resources from a single physical DC. Equation (7) guarantees that a physical DC can only have at most one VDC of a demand to be assigned to itself.

Spectrum Continuity Constraint:

$$\sum_{f} y_{df(u',v')}^{(u,o)} - x_d^{u'u} \cdot T_d^{(u',v')t} = 0, \; y_{df(u',v')}^{(i,u)} = 0 \quad (8)$$

$$\sum_{f} y_{df(u',v')}^{(i,v)} - x_d^{v'v} \cdot T_d^{(u',v')t} = 0, \; y_{df(u',v')}^{(v,o)} = 0 \quad (9)$$

$$\sum_{f,j \neq v} y_{df(u',v')}^{(i,j)} = \sum_{f,j \neq u} y_{df(u',v')}^{(j,o)} \quad (10)$$

where $\forall i, o, j \in V, t \in [ST_d, ET_d]$. We indicate that u, v are the source and destination nodes of the mapping route for VL (u', v').

Equations in (8) guarantee that the number of output frequency slots from the source node equals the required number of frequency slots, and no input flows to the source node. Equations in (9) guarantee that the number of input frequency slots to the destination node equals the required input frequency slots, and no output flows from the destination node. Equation (10) ensures that the spectrum route uses the same spectrum along the routing path.

Frequency Slot Consecutiveness Constraint:

$$(y_{df(u',v')}^{(u,v)} - y_{d(f+1)(u',v')}^{(u,v)} - 1) * (-N) \geq \sum_{f'} y_{df'(u',v')}^{(u,v)} \quad (11)$$

where $f \in [1, F-1], f' \in [f+2, F], u', v' \in V^d, u, v \in V$.

Equation (11) ensures that the employed frequency slots are consecutive in the frequency domain. The FS consecutiveness constraint requires that, for a spectrum route, the allocated FSs are consecutive in frequency domain. This constraint can be equivalently converted to: if $y_{df(u',v')}^{(i,o)} = 1$ and $y_{d(f+1)(u',v')}^{(i,o)} = 0$, all FSs with index higher than $f+1$ will not be allocated to the VL (u', v') from fiber link (i, o). We introduce a large number N in this constraint.

Frequency Slot Capacity Constraint:

$$\sum_{d,u',v'} y_{df(u',v')}^{(i,o)} \leq 1, \forall f, i, o \quad (12)$$

Equation (12) ensures that one frequency slot on a fiber link can only be used by one route in a time slot.

$$\sum_{d,f,u',v'} y_{df(u',v')}^{(i,o)} \leq FN, \forall i, o \in V \quad (13)$$

Equation (13) ensures that the used frequency slots cannot exceed the spectrum capacity (noted as FN) of each fiber link.

V. Heuristic Algorithm

We propose a cost-optimized greedy heuristic for the NE-VCIP problem. The heuristic works for both *Full-Fit* and *Best-Fit* scenarios. In full-fit, all demands will be accepted and the total cost for all demands will be minimized. In best-fit, we accept as many demands as possible and minimize the total cost of accepted demands. Every VCI demand is generated randomly with start time, finish time in [0,24], with required bandwidth and computing resources. In our proposed heuristic, we do not separate the joint resource allocation into two phases: computing resource phase and bandwidth resource phase, but combine them together. The reason for this is to utilize the bandwidth resource more efficiently since we found from previous experiments that the network resource is the bottleneck (compared to computing resources in each DC) in completing the joint resource allocation for demands.

The general ideas of the proposed cost-optimized greedy heuristic are: (1) Map the first VDC (e.g. $v1$) of a demand, map it to the DC (e.g. u) which has enough computing resources and has lowest resource unit cost; (2) check if $v1$ has connections with other VDCs (e.g. $v2$) in the VCI demand graph; (3) if yes, for each connection, the Dijkstra algorithm is adopted to find the shortest path $p(u, des)$ between u and every other DC, and sort the paths in ascending order of distance; if no, go to (5); (4) map $v2$ to des which is the destination DC of the shortest path if des DC has enough computing resources and all links along path p have required number of FSs; (5) continues until a VCI demand is processed, then go for the next demand. The algorithm details are shown in Algorithm 1. We call the $Dijkstra$ algorithm whose time complexity is $O(|E|+|V|log|V|)$ in our proposed heuristic. The total time complexity of the proposed heuristic is $O((|E|+|V|log|V|+|V|^2)|D||V^d|)$.

Algorithm 1 Cost-optimized Greedy Algorithm

Input and Initializations:
  $G(V, E)$ // network topology
  D // demand set
  $G^d(V^d, E^d)$ // virtual topology of demand d
Output:
  Minimize $\sum_d Cost_d$.

```
Sort V in ascending order of computing resources cost
for all d ∈ D do
  for all v^d ∈ V^d do
    if v^d is not been processed then
      Map v^d on node v with enough resources for v^d;
      Allocate computing resources from v for v^d;
      Update Cost_d;
    end if
    Construct set P_v;
    for all u ∈ V, u ≠ v  do
      Find shortest path p(v, u), add p(v, u) into P_v;
    end for
    Sort paths in P_v in ascending order of distance;
    for all u^d ∈ Adjacent(v^d) do
      if u^d is not been mapped then
        for all p(v, u) ∈ P_v do
          if enough resources on node/path then
            Map u^d on node u;
            Allocate computing resources for u^d;
            Allocate spectrums and update Cost_d;
          end if
        end for
      else {// suppose u^d is already mapped to x ∈ V}
        if p(v, x) has enough spectrums then
          Allocate spectrums and Update Cost_d;
        else
          Drop demand d, release resources;
        end if
      end if
    end for
  end for
end for
return ∑_d Cost_d
```

VI. Experimental Results and Analysis

We carry out the simulations for ILP model (using IBM ILOG CPLEX Optimization studio) and cost-optimized greedy heuristic on a cluster node which has 2 CPUs/16 cores and 64GB memory with Linux system. Two network topologies are tested for the simulations: a 6-node topology (Google DC locations) and NSFNET topology shown in Fig. 2 with the distance in km. In the simulations, each VCI demand is generated randomly, which means the value of each item in a VCI demand tuple (as described in Section IV. A) is generated randomly. In general, in our simulation, we assume that each VCI demand consists of no more than 5 VDCs.

The correctness of the proposed greedy heuristic is verified by comparing its results with the ILP results for the small data set for the 6-node topology as shown in Table II. When given one demand, the heuristic can give the near optimal solution compared with that of CPLEX and the computing time is much more less than that of CPLEX. When given two or more demands, the CPLEX converges much slower to generate optimal solution compared to the heuristic method. In this case, in the later experiments, larger data sets are only tested by the heuristic on two topologies due to the slowness of ILP solution by CPLEX.

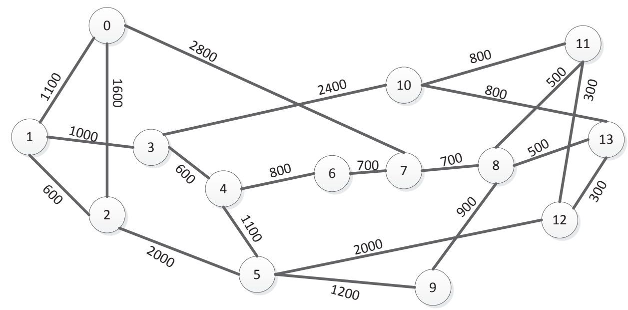

Fig. 2: NSFNET network topology

TABLE II: Cost and time comparison between CPLEX solver and heuristic

# of demands	Total Cost (normalized)		Running Time	
	CPLEX	Heuristic	CPLEX	Heuristic
1	1679.8	1692.31	1.2 hours	1.1384 s
2	4196.7461 (gap 18.56%)	4618.15	2 hours	1.1667 s
3	3547.4564 (gap 97.34%)	16788.3	12 hours	1.2685 s
4	*	17184.5	*	1.2841 s
5	*	17646.7	*	1.2943 s

We compare the total cost and demand blocking rate for different data sets with different modulation formats. Due to the space limitation, here we only list the comparison results for the NSFNET topology; similar results are also obtained on the 6-node topology.

In Fig. 3, all the demands can be accepted (full-fit) and allocated resources from the Cloud by the resource allocator. By observing Fig. 3 we can see that for different sizes of the demand set, the total costs decrease with the modulation format order of BPSK, QPSK and 8-QAM, since the required number of FSs of each demand is reduced. But the total cost with 16-QAM increases compared to that with 8-QAM, although each demand has the least number of required FSs with 16-QAM. We note that the required number of FSs for a given bit rate is reduced sequentially with the modulation format orders of BPSK, QPSK, 8-QAM and 16-QAM; and at the same time the optical signal reaches are reduced along the same modulation format order. In this case, more regenerators are needed along the optical path to regenerate the signals and the total cost increases instead. It seems that it is a better choice to adopt 8-QAM modulation format to get a lower total cost.

With the limited resource capacities, the resource scheduler will drop some demands that cannot be satisfied when the number of demands increases. During the experiment we found that the network resource is a bottleneck compared with other computing resources. Almost every demand that is dropped is due to lack of continuous spectrum resource along its optical path. We observe the blocking rate of different sizes of demand set with four types of modulation formats as shown in Fig. 4. It is obvious that for the modulation format order of BPSK, QPSK, 8-QAM and 16-QAM, the required number of FSs for each demand reduces significantly, so that the resource scheduler can accept many more demands. When the input number of demands reaches 1800, the blocking rates are nearly 13.6%, 0.7%, 0.022% and 0 with BPSK, QPSK, 8-QAM and 16-QAM respectively in Fig. 4.

Thus, while considering the total cost and blocking rate together, we found that 8-QAM in our experiment performs best, which has the lowest total cost and has the blocking rate close to 0 for larger data sets.

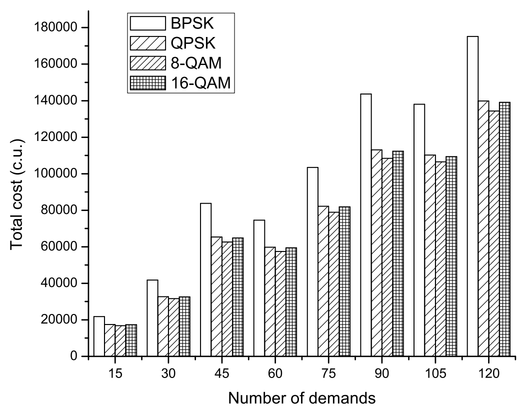

Fig. 3: Total cost comparison (NSFNET)

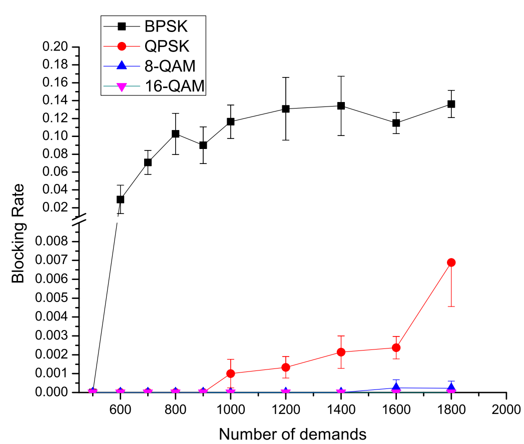

Fig. 4: Blocking rate comparison (NSFNET)

VII. Conclusion

In this work, we propose and investigate the NE-VCIP problem in IP-over-EON network architecture. An ILP mathematical model is constructed and a cost-optimized greedy heuristic is developed to solve the NE-VCIP problem. Different modulation formats that are adopted in the EON layer will have different results for the total cost and the demand blocking rate for the same data set size. So in order to minimize the total cost and also obtain a better system performance (e.g., low blocking rate, high resource utilization), a trade-off needs to be considered between the two. In our experiments, we conclude that adopting 8-QAM in EON layer would be a suitable choice for the resource scheduler to obtain the lowest total cost and also obtain an acceptable low blocking rate. In this work, we only consider using 10 Gbps BVT in EON layer, and we will investigate the effects of BVTs with different bit rates in our future work. In addition, we will consider the dynamic traffic for the demands and also the impact on the total cost by traffic grooming in EON.

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