Proceedings Paper:

Nonde, L, Elgorashi, TEH and Elmirghani, JMH (2015) Cloud Virtual Network Embedding: Profit, Power and Acceptance. In: 2015 IEEE Global Communications Conference. GLOBECOM, 06-10 Dec 2015, San Diego, California. IEEE . ISBN 978-1-4799-5952-5

https://doi.org/10.1109/GLOCOM.2015.7417788

Cloud Virtual Network Embedding: Profit, Power and Acceptance

Leonard Nonde, Taisir E.H. Elgorashi and Jaafar M.H. Elmirgahni
School of Electronic and Electrical Engineering University of Leeds, LS2 9JT, United Kingdom

***Abstract*—In this paper, we investigate maximizing the profit achieved by infrastructure providers (InPs) from embedding virtual network requests (VNRs) in IP/WDM core networks with clouds. We develop a mixed integer linear programming (MILP) model to study the impact of maximizing the profit on the power consumption and acceptance of VNRs. The results show that higher acceptance rates do not necessarily lead to higher profit due to the high cost associated with accepting some of the requests. The results also show that minimum power consumption can be achieved while maintaining the maximum profit.**

Keywords—Cloud Networks; Virtual Network Embedding; Network Virtualization; MILP; Energy Efficient Networks; IP over WDM;

I. Introduction

The concept of network virtualization has provided a premise for the current and future Infrastructure as a Service (IaaS) provision in cloud networks [1]. Network virtualization enables through the provisioning of separate virtual networks (VNs) onto a shared physical platform, referred to as the substrate network, among other things, energy savings and efficient use of network resources by avoiding over provisioning and enabling consolidation [2]. A VN is a logical topology made up of a set of virtual nodes containing virtual machines and/or virtual routers which are interconnected by virtual links. This therefore sets up an architecture where two major players emerge in service provisioning in the Internet ecosystem; Infrastructure Providers (InPs) and Service providers (SPs). InPs manage the physical infrastructure (the substrate network) while SPs are the owners of VNs who interact directly with the end users of the cloud services. SPs send virtual network requests (VNRs) with node and link resource requirements to InPs who in turn map the VNRs onto the substrate network as illustrated in Fig. 1. The process of mapping a specific subset of nodes and links to adequately satisfy a VNR is known as virtual network embedding (VNE). The VNE problem can be either *Offline or Online.* In offline problems [3] all the virtual network requests (VNRs) are known and scheduled in advance while for the online problem, VNRs arrive dynamically and can stay in the network for an arbitrary duration [4], [5]. Both online and offline problems are known to be NP-hard with constraints on virtual nodes and links. The offline VNE problem can be reduced to the NP-hard multiway separator problem [6]. As a result most of the work done in this area has focused on the design of heuristic algorithms or the use of networks with minimal complexity when solving mixed integer linear programming (MILP) models.

The VNE problem has been investigated with the objective of minimizing energy consumption by means of resource consolidation [3], [7], [8].

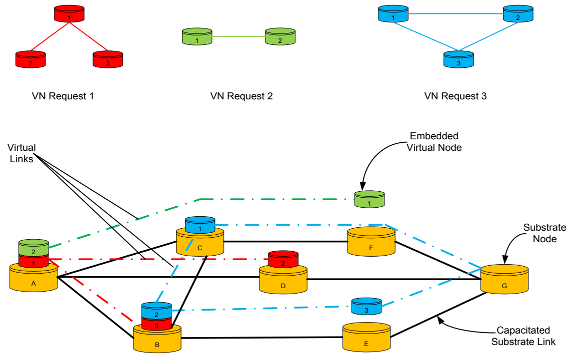


Fig. 1: Virtual Network Embedding

In [9] we proposed an energy efficient virtual network embedding approach for cloud computing networks where power savings are introduced by consolidating resources in the network and data centers. We addressed the link embedding problem as a multilayer problem that includes both the IP layer and the optical layer in an IP over WDM network and considered the granular power consumption of various network devices as well as the power consumption in data centers. In [10], we extended our study to investigate the energy efficiency of VNE in optical OFDM networks. In [11] and [12], we have looked at green IP over WDM networks with data centers where we employ renewable energy sources and consider data center location optimization to minimize energy consumption. We investigated the problem of physical network topology optimization to minimize power consumption in IP over WDM networks in [13] and in [14] we introduced a framework for the design of energy efficient cloud computing services over non-bypass IP over WDM networks. In [15] we studied caching and energy efficient future high-definition TV.

InPs aim to maximize the profit from the use of their infrastructure. The authors in [4], [16] and [17] have developed models to maximize the revenue obtained from embedding VNRs. All these models, however, have assumed equal cost and revenue of bandwidth and computing resources. In this work, we develop a profit maximized VNE MILP model taking into account the relative difference in cost and revenue of computing resources and bandwidth in today's cloud networks. We highlight the differences between maximizing profit and maximizing VNR acceptance and investigate the impact of maximizing the profit on the network power consumption.

The rest of this paper is organized as follows: The MILP model for profit maximized VNE in IP over WDM networks is introduced in Section II. We analyze the performance of the model and compare it with the power minimized model in Section III. The paper is concluded in Section IV.

II. MILP Model for Profit Maximized Virtual Network Embedding in IP over WDM Networks

In this section we extend the energy efficient VNE MILP model we developed in [9] where our goal was to minimize the overall power consumption of VNE in IP/WDM core networks with data centres through resource consolidation. Here, we investigate maximizing the profit of InPs offering IaaS cloud services.

The substrate network is modeled as a weighted undirected graph $G = (N, L)$ where N is the set of substrate nodes and L is the set of substrate links. Each node or link in the substrate network is associated with its own resource attributes. The VNR v is represented by the graph $G^v = (R^v, L^v)$ where R^v is the set of virtual nodes made up of virtual machines and/or virtual routers and L^v is the set of virtual links.

In the following we reintroduce the sets, parameters, variables and constraints defined in [9] for completeness and introduce the new objective functions and constraints developed to model the new profit maximized approach.

Sets:

V	Set of VNRs
R	Set of nodes in a VNR
N	Set of nodes in the substrate network
N_m	Set of neighbor nodes of node m in the optical layer

Parameters:

s and d	Source and destination of a traffic demand in a VNR
b and e	End points of a link in the virtual network
i and j	End points of a virtual link in the IP layer
m and n	End points of a physical fiber link in the optical layer
LOC_b^v	$LOC_b^v = 1$ if the master node of VNR v must be located at substrate node b, otherwise $LOC_b^v = 0$
α	The virtual nodes consolidation factor which defines the maximum number of virtual nodes of a VNR that can be co-located at a substrate node.
β	The virtual machines consolidation factor which defines the maximum number of virtual machines of a VNR that can be co-located in a data center
NDC	The total number of data centers in the network
$C^{v,s}$	The number of virtual cores requested by virtual machine s of VNR v
DP_b	$DP_b = 1$ if substrate node b is a data center, otherwise $DP_b = 0$
$H^{v,s,d}$	Bandwidth requested by VNR v on virtual link (s,d)
B	Wavelength rate
W	Number of wavelengths per fiber
$D_{m,n}$	Length of the physical link (m, n)
$EA_{m,n}$	Number of EDFAs in physical link (m, n). Typically $EA_{m,n} = \left\lfloor \left(\frac{D_{m,n}}{S}\right) - 1 \right\rfloor + 2$, where S is the distance between two neighboring EDFAs
$EG_{m,n}$	The number of regenerators on a physical link (m, n). Typically $EG_{m,n} = \left\lfloor \left(\frac{D_{m,n}}{RG}\right) - 1 \right\rfloor$, where RG is the reach of the regenerator.
PR	Power consumption of a router Port
PT	Power consumption of a transponder
PE	Power consumption of an EDFA
RG	Power consumption of a regenerator
PO_m	Power consumption of an optical switch at node m
PMD	Power consumption of a multi/demultiplexer
DM_m	Number of multi/demultiplexers at node m
$PPcore$	The price in US$ charged to the cloud client per single core
$CPcore$	The cost in US$ to the InP of hosting a single core in the cloud
$PPgbit$	The price in US$ per gigabit per second of network bandwidth charged to the cloud client
$CPgbit$	The cost in US$ to the InP of provisioning a gigabit per second of network bandwidth

Variables:

$\delta_b^{v,s}$	$\delta_b^{v,s} = 1$, if node s of VNR v is embedded in substrate node b, otherwise $\delta_b^{v,s} = 0$.
Ψ^v	$\Psi^v = 1$, if all the nodes of a VNR v are fully embedded in the substrate network, otherwise $\Psi^v = 0$
$\rho_{b,e}^{v,s,d}$	$\rho_{b,e}^{v,s,d} = 1$, if the embedding of virtual nodes s and d of virtual request v in substrate nodes b and e, respectively is successful and a link b, e is established if a virtual link s, d of VNR v exists.
$\omega_{b,e}^{v,s,d}$	$\omega_{b,e}^{v,s,d}$ is the XOR of $\delta_b^{v,s}$ and $\delta_e^{v,d}$, i.e. $\omega_{b,e}^{v,s,d} = \delta_b^{v,s} \oplus \delta_e^{v,d}$
$L_{b,e}$	Total traffic demand on virtual link (b, e) due to the embedded links of all VNRs
Φ^v	$\Phi^v = 1$, if all the links of VNR v are fully embedded in the substrate network, otherwise $\Phi^v = 0$
$L_{i,j}^{b,e}$	Bandwidth demand of link (b, e) in the virtual network passing through the lightpath (i, j) in the substrate network
$C_{i,j}$	Number of wavelengths in lightpath (i, j) in the substrate network
$W_{m,n}^{i,j}$	The number of wavelengths of lightpath (i, j) passing through a physical link (m, n)
$W_{m,n}$	Number of wavelengths in physical link (m, n)
$F_{m,n}$	Number of fibers in physical link (m, n)
$\Delta_b^{v,s}$	$\Delta_b^{v,s} = 1$ if virtual machine s of VNR v has been embedded at data center node b otherwise $\Delta_b^{v,s} = 0$
C_b	The total number of Virtual cores at data center b

The network power consumption under non-bypass where lightpaths passing through an intermediate node are terminated and forwarded to the IP router [18] is composed of:

Power consumption of router ports:

$$\sum_{m \in N} \sum_{n \in N_m} W_{m,m} \cdot PR$$

Power Consumption of transponders:

$$\sum_{m\in N}\sum_{n\in N_m} PT\cdot W_{m,n}$$

Power Consumption of regenerators:

$$\sum_{m\in N}\sum_{n\in N_m} RG\cdot W_{m,n}\cdot EG_{m,n}$$

Power Consumption of EDFAs:

$$\sum_{m\in N}\sum_{n\in N_m} PE\cdot EA_{m,n}\cdot F_{m,n}$$

Power Consumption of Optical Switches:

$$\sum_{m\in N} PO_m$$

Power Consumption of multi/demultiplexers:

$$\sum_{m\in N} PMD\cdot DM_m$$

Note that the objective function does not take into account the power consumption in data centers as we consider data centers with an energy efficient power profile and therefore the virtual machines will consume the same amount of power regardless of where they are embedded.

The revenue generated by the InP over a given duration T as a result of embedding a set of VNRs V is given as:

$$\sum_{v\in V}\sum_{s\in R} C^{v,s}\cdot\Psi^{v}\cdot PPcore+\sum_{v\in V}\sum_{s\in R}\sum_{d\in R:s\neq d}\mathrm{H}^{v,s,d}\cdot\Phi^{v}\cdot PPgbit$$

The cost associated with the embedding of V VNRs by the InP is given as:

$$\sum_{v\in V}\sum_{b\in N}\sum_{s\in R} C^{v,s}\cdot\Delta_b^{v,s}\cdot CPcore+\sum_{m\in N}\sum_{n\in N_m} W_{m,n}\cdot B\cdot CPgbit$$

Note that the cost per virtual core ($CPcore$) and the cost per 1Gbps of bandwidth ($CPgbit$) include both the OPEX, and CAPEX to be recovered over the lifetime of the network.

The profit gained by the InP is given as the difference between the revenue generated and the cost. The models are therefore defined as follows:

Objective (Profit Maximized):

Maximize the overall profit:

$$\left(\sum_{v\in V}\sum_{s\in R} C^{v,s}\cdot\Psi^{v}\cdot PPcore+\sum_{v\in V}\sum_{s\in R}\sum_{d\in R:s\neq d} H^{v,s,d}\cdot\Phi^{v}\cdot PPgbit\right)-\left(\sum_{v\in V}\sum_{b\in N}\sum_{s\in R} C^{v,s}\cdot\Delta_b^{v,s}\cdot CPcore+\sum_{m\in N}\sum_{n\in N_m} W_{m,n}\cdot B\cdot CPgbit\right)\quad (1)$$

In the objective, we maximize the revenue from the embedded VNRs and minimize the cost incurred thereby maximizing the profit.

Subject to:

Node Embedding Constraints:

$$\sum_{v\in V}\sum_{s\in R} C^{v,s}\cdot\Delta_b^{v,s}\le C_b\qquad\forall b\in N\qquad (4)$$

Constraint (4) ensures that the virtual cores embedded in a data center do not exceed the capacity of the data center.

$$\sum_{b\in N}\delta_b^{v,s}\le 1\qquad\forall v\in V,\ \forall s\in R\qquad (5)$$

Constraint (5) ensures that a virtual node is either rejected or only embedded once in a substrate network.

$$\sum_{b\in N}\Delta_b^{v,s}\le 1\qquad\forall v\in V,\qquad\forall s\in R\qquad (6)$$

Constraint (6) ensures that each virtual machine is either rejected or only embedded once in a data center.

$$DP_b\cdot\delta_b^{v,s}=\Delta_b^{v,s}\qquad\forall v\in V,\forall b\in N,\forall s\in R\qquad (7)$$

Constraint (7) ensures that virtual machines are only embedded in nodes with data centers.

$$\sum_{s\in R}\delta_b^{v,s}\le\alpha\qquad\forall v\in V,b\in N\qquad (8)$$

Constraint (8) defines how many nodes belonging to the same request can be co-located on the same substrate node.

$$\sum_{s\in R}\Delta_b^{v,s}\le\beta\qquad\forall v\in V,b\in N\qquad (9)$$

Constraint (9) defines how many virtual machines belonging to the same request can be co-located in the same data center.

Link Embedding Constraints:

$$\delta_b^{v,s}+\delta_e^{v,d}=\omega_{e,b}^{v,d,s}+2\cdot\rho_{b,e}^{v,s,d}$$
$$\forall v\in V,\qquad\forall b,e\in N,\qquad\forall s,d\in R:s\neq d\qquad (10)$$

Constraint (10) ensures that virtual nodes connected in the VNR are also connected in the substrate network. We achieve this by introducing a binary variable $\omega_{e,b}^{v,d,s}$ which is only equal to 1 if $\delta_b^{v,s}$and $\delta_e^{v,d}$ are exclusively equal to 1 otherwise it is zero.

$$\sum_{v\in V}\sum_{s\in N}\sum_{d\in N:s\neq d}\mathrm{H}^{v,s,d}\cdot\rho_{b,e}^{v,s,d}=L_{b,e}\ \forall b,e\in N\qquad (11)$$

Constraint (11) generates the traffic demand matrix resulting from embedding the VNRs in the substrate network and ensures that no connected nodes from the same VNR are embedded in the same substrate node.

$$\sum_{b\in N}\sum_{s\in R} C^{v,s}\cdot\delta_b^{v,s}=\Psi^{v}\sum_{s\in N} C^{v,s}\quad\forall v\in V\qquad (12)$$

Constraint (12) ensures that nodes of a VNR are completely embedded.

$$\delta_b^{v,1}=LOC_b^{v}\qquad\forall v\in V,b\in N\qquad (13)$$

Constraint (13) fixes the client's location in the network to the first node of the VNR.

$$\sum_{b\in N}\sum_{e\in N}\sum_{s\in R}\sum_{d\in R:s\neq d}\mathrm{H}^{v,s,d}\cdot\rho_{b,e}^{v,s,d}=\Phi^{v}\sum_{s\in R}\sum_{d\in R:s\neq d}\mathrm{H}^{v,s,d}$$
$$\forall v\in V\qquad (14)$$

Constraint (14) ensures the bandwidth demands of a VNR are completely embedded.

$$\Phi^{v} = \Psi^{v} \quad \forall v \in V \tag{15}$$

Constraint (15) ensures that both the nodes and links of a VNR are completely embedded. Constraints (12), (14) and (15) collectively ensure that a request is not partially embedded.

Flow conservation in the IP Layer:

$$\sum_{j \in N: i \neq j} L_{i,j}^{b,e} - \sum_{j \in N: i \neq j} L_{j,i}^{b,e} = \begin{cases} L_{b,e} & if \;\; i = b \\ -L_{b,e} & if \;\; i = e \\ 0 & otherwise \end{cases}$$
$$\forall b, e \in N: b \neq e \tag{16}$$

Constraint (17) represents the flow conservation constraint for the traffic flows in the IP Layer.

Lightpath capacity constraint

$$\sum_{b \in N} \sum_{e \in N: b \neq e} L_{i,j}^{b,e} \leq C_{i,j} \cdot B \qquad \forall i, j \in N: i \neq j \tag{17}$$

Constraint (17) ensures that the sum of all traffic flows through a lightpath does not exceed its capacity.

Flow conservation in the optical layer

$$\sum_{n \in N_m} W_{m,n}^{i,j} - \sum_{n \in N_m} W_{n,m}^{i,j} = \begin{cases} C_{i,j} & if \; m = i \\ -C_{i,j} & if \; m = j \\ 0 & otherwise \end{cases}$$
$$\forall i, j \in N: i \neq j \tag{18}$$

Constraint (18) ensures the conservation of flows in the optical layer.

Physical Link capacity constraints

$$\sum_{i \in N} \sum_{j \in N: i \neq j} W_{m,n}^{i,j} \leq W \cdot F_{m,n}$$
$$\forall m \in N, n \in N_m \tag{19}$$

$$\sum_{i \in N} \sum_{j \in N: i \neq j} W_{m,n}^{i,j} = W_{m,n}$$
$$\forall m \in N, n \in N_m \tag{20}$$

Constraints (19) and (20) represent the physical link capacity constraints. Constraint (19) ensures that the number of wavelengths in a physical link does not exceed the capacity of fibers in the physical links. Constraint (20) gives the total number of wavelength channels used in a physical link.

The mathematical model given above produces the maximum profit for the InP. However, it yields sub-optimal power consumption in the network. In order to achieve the minimum power consumption while maintaining the maximum profit, we evaluate the objective of minimizing the power consumption in the network [9] with a constraint on the achieved profit to be greater or equal to the maximum profit obtained from the model above.

Objective (Power Minimized) [9]:

$$\sum_{m \in N} \sum_{n \in N_m} W_{m,n} \cdot PR + \sum_{m \in N} \sum_{n \in N_m} W_{m,n} \cdot PT + \sum_{m \in N} \sum_{n \in N_m} PG \cdot W_{m,n} \cdot RG_{m,n} + \sum_{m \in N} \sum_{n \in N_m} PE \cdot EA_{m,n} \cdot F_{m,n} + \sum_{m \in N} PO_m + \sum_{m \in N} PMD \cdot DM_m \tag{21}$$

In addition to the above constrains, the power minimized objective is subject to the following constraint:

$$\left(\sum_{v \in V} \sum_{s \in R} C^{v,s} \cdot \Psi^{v} \cdot PPcore + \sum_{v \in V} \sum_{s \in R} \sum_{d \in R: s \neq d} H^{v,s,d} \cdot \Phi^{v} \cdot PPgbit \right) - \left(\sum_{v \in V} \sum_{b \in N} \sum_{s \in R} C^{v,s} \cdot \Delta_{b}^{v,s} \cdot CPcore + \sum_{m \in N} \sum_{n \in N_m} W_{m,n} \cdot B \cdot CPgbit \right) \geq Mx\_Prft \tag{22}$$

where Mx_Prft is the maximum profit obtained from the profit maximized model.

Constraint (22) ensures that the maximum profit is maintained while minimizing the power consumption.

III. PERFORMANCE EVALUATION

The 14 node and 21 link NSFNET network, shown in Fig. 2, is used as the substrate network to evaluate the performance of the MILP models. We take a practical approach to distribute VNRs in the substrate network where the cloud service enterprise client's location is fixed but the requested virtual machines could be embedded in any cloud data center. The concentration of clients at any substrate node is based on the population of the states where the node is located (see Fig. 2). In the case of California where we have two cities in one state (nodes 1 and 2), we have evenly distributed the population of the state between the two cities.

We evaluated an enterprise cloud service solution where enterprise clients request virtual networks consisting of virtual machines with a specific number of virtual cores and virtual links of specific bandwidth. A total of 50 enterprise clients send VNRs to the InP over a 24 hour period at two hour time intervals. The traffic generated by the VNRs over a 24 hour period is modelled according to the 2020 average business internet traffic between nodes in the US (served here by NSFNET) as projected by the GreenTouch Consortium [19]. The traffic distribution is as shown in Fig. 3. The requests once accepted stay in the network for 2 hours after which they will be torn down and adjusted according to the new arriving demands. The number of virtual machines per VNR is uniformly distributed between 1 and 5 and the number of virtual cores per VNR is uniformly distributed between 1000 and 8000. The substrate network is un-capacitated in terms of both node and link resources. The consolidation factors are set to $\alpha = \beta = 5$, i.e. all the virtual nodes and machines of a VNR can be co-located.

The current and future criterion for designing cloud infrastructure is to distribute the content among a number of data centers to minimize the delay experienced by the users and to avoid the scenario of having a single hot node in the network. We have therefore placed five data centers in the network located at nodes (2, 3, 6, 8 and 10) [20]. Table I shows the values of the parameters that have been used in the model.

TABLE I
EVALUATION SCENARIO PARAMETERS

Distance between two neighboring EDFAs (S) [21]	80 (km)
Distance between two neighboring Regenerators (RG)	2000 (km)
Number of wavelengths in a fiber (W)[22]	32
Power consumption of a transponder (PT) [23]	167 (W)
Power consumption of a regenerator (RG) [23]	334 (W)
Power consumption of a 40Gb/s router port (PR) [17]	1000(W)
Power consumption of an EDFA (PE) [23]	55 (W)
Power consumption of an optical switch (PO) [24]	85(W)
Power consumption of a multi/demultiplexer (PMD) [25]	16(W)
Price of a virtual core in the cloud per 2 hour usage (**PPcore**) [26]	$0.21
Price of 1Gbps of bandwidth in the cloud per 2 hour usage (**PPgbit**) [27]	$0.30
Profit margin per core and per Gbps	20%

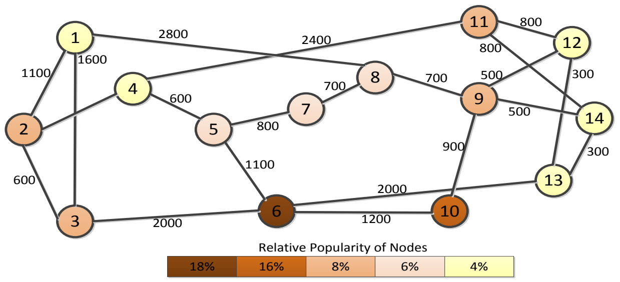


Fig. 2: NSFNET with Population Percentage Information

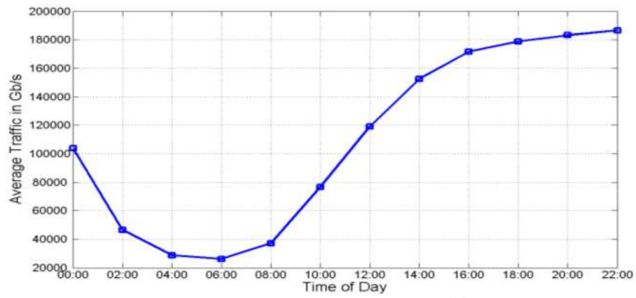
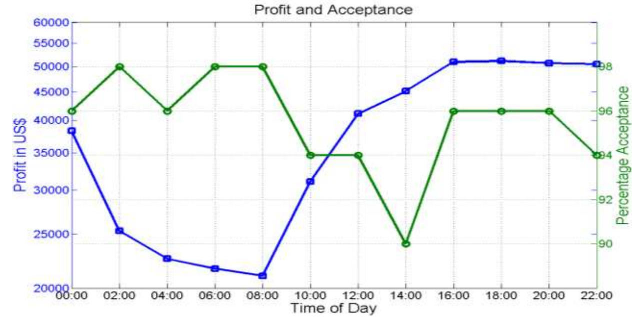


Fig. 3: 2020 Average Business Internet 24 hour Traffic Distribution

As discussed in Section II, we are not optimizing power consumption in data centers as we consider the power consumption of data centers to follow an energy efficient power profile. The actual cost of running a network is commercially sensitive and not publicly available. Therefore we adopt a "pay-as-you-use" revenue model to estimate $CPcore$ and $CPgbit$. We used the google cloud service pricing scheme in [26] and [27] with a typical profit margin for Internet providers of 20% [28].

The AMPL software with the CPLEX 12.5 solver is used as the platform for solving the MILP models on a PC with an Intel® Xeon™ CPU, running at 3.5 GHz, with 64 GB RAM. The running times for the models average 15 minutes for each solution (point on the curve).

Fig. 4(a) shows the profit and acceptance percentage of the profit maximized model over a 24 hour period. It shows that



(a)

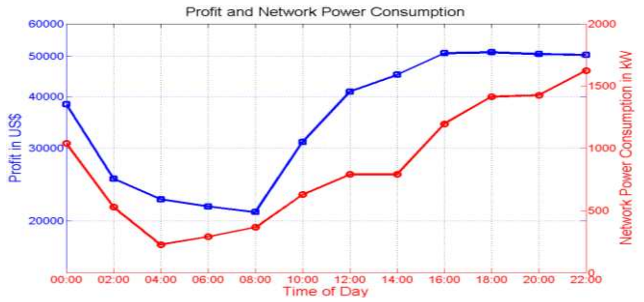
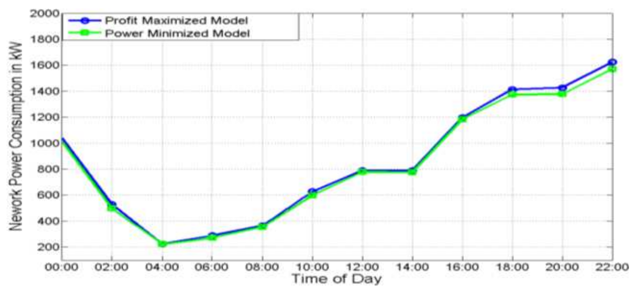


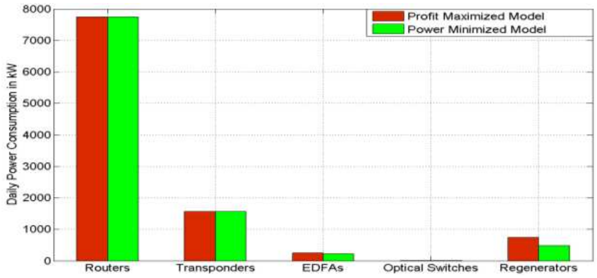
Fig. 4: (a) Profit and Acceptance Performance of the Profit Maximized Model, (b)Profit and Network Power Consumption Performance of the Profit Maximized Model

the profit achieved follows the traffic trend of Fig. 3. The profit is accrued from the minimal use of network resources (wavelengths) achieved through minimum hop routing, traffic grooming and the consolidation of data center resources.

VNRs are served locally as much as possible to save network resources. It should be noted that despite the network having sufficient resources (un-capacitated network) to accommodate all the VNRs in the network, some of the VNR requests are rejected. The rejected VNRs are those which are associated with high cost in terms of use of network resources. VNRs that can be served locally in a single data center are more likely to be accepted as they lead to higher profits as the number of network hops is reduced to the minimum (zero). On the other hand, VNRs that create multiple hops in the network are more likely to be rejected because of their high cost, i.e. low profit. It can therefore be concluded that higher acceptance ratios are not necessarily representative of increased profits. The network power consumption of the profit maximized model is shown in Fig. 4(b). Similar to the profit, the network power consumption follows the traffic trend of Fig. 3. This is because both the maximum profit and minimum network power consumption are obtained by optimizing the use of wavelengths.



(a)



(b)

Fig. 5: (a) Network Power consumption of the Power Minimized and Profit Maximized Models, (b) Device Network Power Consumption Comparison

Fig. 5(a) shows the power consumption obtained by minimizing the power consumption while maintaining the profit obtained by the profit maximized model. The results show that it is possible to save 300kW over a 24 hour time period compared to the profit maximized model. The actual network components where these savings are accrued from can be seen in Fig. 5(b) which shows the daily power consumption of individual components. The routers and transponders in both cases consume the same amount of power because as mentioned above the approaches taken by the profit and power models to achieve their objectives are similar in that they reduce the use of wavelengths. The power savings are accrued from the use of EDFAs and transponders. While the profit maximized model does not take EDFAs and regenerators into account when reducing the usage of network resources, the power minimized model selects shorter links for minimal usage of EDFAs and Regenerators.

IV. CONCLUSIONS AND FUTURE WORK

This paper has investigated maximizing the profit achieved by Infrastructure providers (InPs) from embedding VNRs. We have developed a MILP model to study the impact of maximizing profit on the power consumption and acceptance of VNRs. The results of the profit maximized model show that higher acceptance ratios are not necessarily representative of increased profits. We have also shown that the power consumption can be minimized without any compromize on the profit achieved as the approaches taken to maximize profit and minimize network power consumption are similar in that they both reduce the use of wavelengths. In our future work, we will also study maximizing the profit of embedding VNRs in a capacitated network and investigate the impact on power consumption and acceptance percentage.

V. REFERENCES

[1] N.M.M.K. Chowdhury and R. Boutaba, "A survey of network virtualization," Computer Networks, 2010. **54**(5): p. 862-876.

[2] N.M.M.K. Chowdhury and R. Boutaba, "Network virtualization: state of the art and research challenges," IEEE Communications Magazine, 2009, **47**(7): p. 20-26.

[3] B. Wang; X. Chang; J. Liu, J.K. Muppala, "Reducing power consumption in embedding virtual infrastructures," IEEE Globecom Workshops (GC Wkshps), 2012, pp.714, 718, 3-7 Dec. 2012

[4] M. Yu, et al., "Rethinking virtual network embedding: substrate support for path splitting and migration," SIGCOMM Comput., Commun., Rev., 2008, **38**(2): p. 17-29.

[5] C. Yang, et al., "Resilient Virtual Network Service Provision in Network Virtualization Environments," 16th International Conference in Parallel and Distributed Systems (ICPADS), 2010.

[6] D.G. Anderson, "Theoretical Approaches to Node Assignement," 2002 [cited 2013 11/03/2013]; Available from: http://repository.cmu.edu/cgi/viewcontent.cgi?article=1079&context=compsci

[7] J.F. Botero, et al., "Energy Efficient Virtual Network Embedding," IEEE Communication Letters, 2012. **16**(5): p. 756-759.

[8] S. Sen, et al., "Energy-aware virtual network embedding through consolidation," in IEEE Computer Communications Workshops (INFOCOM WKSHPS). 2012.

[9] L. Nonde, T.E.H. El-Gorashi, and J.M.H. Elmirghani, "Energy Efficient Virtual Network Embedding for Cloud Networks", IEEE Journal of Lightwave Technology, 2015. **33**(9): p. 1828-1849

[10] L. Nonde, T.E.H. El-Gorashi, and J.M.H. Elmirghani, "Green Virtual Network Embedding in Optical OFDM Cloud Networks," in 16th IEEE Conference on Transparent Optical Networks (ICTON), 2014.

[11] X. Dong., T.E.H. El-Gorashi, and J.M.H. Elmirghani, "IP Over WDM Networks Employing Renewable Energy Sources", IEEE Journal of Lightwave Technology, 2011. **29**(1): p. 3-14.

[12] X. Dong, T.E.H. El-Gorashi, and J.M.H. Elmirghani, "Green IP Over WDM Networks With Data Centers", IEEE Journal of Lightwave Technology, 2011. **29**(12): p. 1861-1880.

[13] X. Dong, T.E.H. El-Gorashi, and J.M.H. Elmirghani, "On the Energy Efficiency of Physical Topology Design for IP Over WDM Networks", IEEE Journal of Lightwave Technology, 2012. **30**(12): p. 1931-1942.

[14] A.Q. Lawey, T.E.H. El-Gorashi, and J.M.H. Elmirghani, "Distributed Energy Efficient Clouds Over Core Networks", IEEE Journal of Lightwave Technology, 2014. **32**(7): p. 1261-1281.

[15] N.I. Osman, T.E.H. El-Gorashi, L. Krug, J.M.H. Elmirghani, "Energy-Efficient Future High-Definition TV." IEEE Journal of Lightwave Technology, 2014. **32**(13): p. 2364-2381.

[16] M. Chowdhury, M.R. Rahman, and R. Boutaba, "ViNEYard: Virtual Network Embedding Algorithms With Coordinated Node and Link Mapping," Networking, IEEE/ACM Transactions, 2012. **20**(1): p. 206-219.

[17] G. Long, et al., "Toward profit-seeking virtual network embedding algorithm via global resource capacity," in IEEE INFOCOM, 2014.

[18] G. Shen and R.S. Tucker, "Energy-Minimised Design for IP Over WDM Networks" IEEE/OSA Journal of Optical Communications and Networking, , 2009. **1**(1): p. 176-186.

[19] J.M.H. Elmirghani, T. Klein, K. Hinton, T.E.H. El-Gorashi, A. Q. Lawey, X. Dong, "GreenTouch GreenMeter Core Network Power Consumption Models and Results," IEEE OnlineGreenComm 2014.

[20] AT&T, "AT&T's 38 Global Internet Data Centers", 2007 [cited 2015 01/04/2015]; Available from: http://www.business.att.com/content/productbrochures/eb_idcmap.pdf.

[21] Van Heddeghem, W., et al., "Power consumption modeling in optical multilayer networks," Photonic Network Communications, 2012. **24**(2): p. 86-102.

[22] Ciena. "DWDM vs. CWDM." 2015 [cited 2015; Available from: http://www.ciena.com/technology/dwdm-vs-cwdm/.

[23] Van Heddeghem, W., et al., "A power consumption sensitivity analysis of circuit-switched versus packet-switched backbone networks," Computer Networks, 2015. **78**(0): p. 42-56.

[24] Data sheet of Glimmerglass Intelligent Optical System 500.

[25] Data sheet of Cisco ONS 15454 100-GHz 4-CH Multi/Demultiplexer.

[26] Google. 2014; Available from: https://cloud.google.com/compute/.

[27] Google. 2014; Available from: https://support.google.com/fiber/answer/2657118?hl=en.

[28] Yahoo Business. 2014; Available from: https://biz.yahoo.com/p/8qpmu.html.