TCO Game in 5G Multi-Tenant Virtualized Mobile BackHaul (V-MBH) Network

1st Nassim Haddaji
Ecole de Technologie Superieure
Montreal, QC, CANADA
nassim.haddaji.1@ens.etsmtl.ca

2nd Kim-Khoa Nguyen
Ecole de Technologie Superieure
Montreal, QC, CANADA
Kim-Khoa.Nguyen@etsmtl.ca

3rd Mohamed Cheriet
Ecole de Technologie Superieure
Montreal, QC, CANADA
Mohamed.Cheriet@etsmtl.ca

Abstract*—Raising density and ever-increasing traffic demand within future 5G Heterogeneous Networks (HetNets) will result in huge deployment, expansion and operating costs for upcoming Mobile Backhaul (MBH) networks. Multi-tenancy and network slicing based on virtualized resources are promising solutions to satisfy MBH network greediness while reducing related expenditures. Nevertheless, there is no appropriate model that fairly distributes costs over multiple Mobile Network Operators (MNO), and also optimizes physical resource planning. In this paper, we introduce a new model of 5G multi-tenant MBH costs (CapEx and OpEx). Then, we drive a novel pay-as-you-grow and optimization model called Virtual-Backhaul-as-a-Service (VBaaS) as a planning tool optimizing the Project Profit Margin (PPM) while considering the Total-Cost-of-Ownership (TCO) and the yearly generated Return-on-Investment (ROI). We also formulate an MNO pricing game (MPG) for TCO optimization to calculate the optimal Pareto-Equilibrium pricing strategy for offered Tenant Service Instances (TSI). Finally, we compare the PPM for a specific use-case known in the industry as CORD project using Traditional MBH (T-MBH) versus Virtualized MBH (V-MBH) as well as using randomized versus Pareto-Equilibrium pricing strategies. Numerical results show more than three times increase in network profitability using our proposed solutions compared with Traditional MBH (T-MBH).

***Index Terms*—5G, SDN, NFV, TCO, ROI, Virtualized Mobile BackHaul (V-MBH), Multi-tenancy, Game theory.**

I. Introduction

5G and IoT era are bringing tremendous data explosion with stringent traffic requirements. Large network modernization and expansions are unavoidable. Many Mobile Network Operators (MNO) keep expanding their optical transport network infrastructure to deal with recent challenges of coming 5^{th} generation of mobile networks such as capacity, flexibility and costs. These transport networks will definitely cease being profit-making due to massive growth in traffic demand, limited generated revenues as well as raising deployment and operating expenses [1]. One of the emerging solutions for host MNOs is to start leasing their infrastructure as isolated network slices to a number of Mobile Virtual Network Operators (MVNOs) or Tenants who are competing to serve their own end-users using MNO's shared resources. In this context, each MNO is trying to maximize his profits by maximizing his network Return-on-Investment (ROI) while reducing his Total-Cost-of-Ownership (TCO). Traditional Mobile Backhaul (T-MBH) transport networks [2] are deploying expensive purpose-built devices consuming tremendous amounts of CapEx and OpEx even before they start generating revenues. Initial high deployment costs make it very hard for most MNOs to kick-off their projects on-time [3]. As shown in Fig. 1, the T-MBH which is defined as the access network collecting traffic from several hundreds of high density eNodeB and small cells within 5G HetNets (Heterogeneous Networks) and forwarding it towards the core. Several OLTs (Optical Line Termination) are connecting residential remote ONTs (Optical Network Termination) and CPEs (Customer Premisse Equipment, such as home routers). The novel concepts of Software-Defined Networks (SDN) [5] and Network Function Virtualization (NFV) [6] offer openness, portability, and efficient resource management. Costly purpose-built middle-boxes in the T-MBH (Fig. 1) are being replaced by commodity hardware devices controlled by centralized Virtual Network Functions (VNF) running in compute instances (such as Virtual Machines (VM) or micro-service containers). These compute instances are deployed on top of large-scale commodity servers and creating the intelligence part of the Virtual MBH (V-MBH) networks (Fig. 2). It results in new challenges for TCO calculation, because V-MBH are shared among various mobile base stations [4].

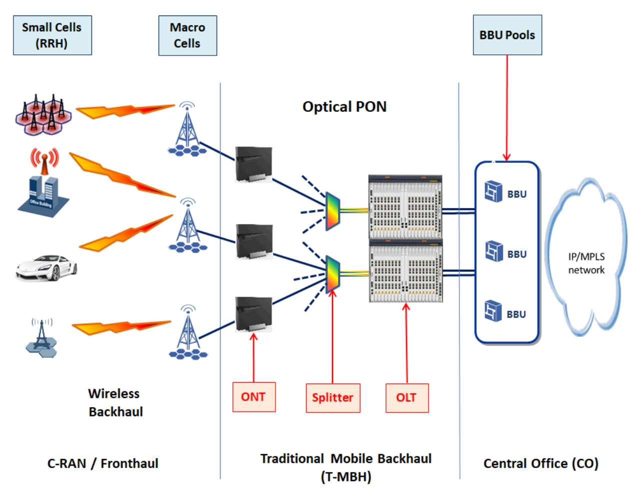

Fig. 1: Traditional Mobile BackHaul (T-MBH) network.

In this paper, we investigate TCO planning for V-MBH based on the so-called Central-Office-Re-architected-as-a-

Datacenter (CORD) [7] architecture. CORD offers flexible provisioning and end-to-end control of multi-tenant connectivity and elastic cloud services for residential, enterprise, and mobile network applications. We focus on R-CORD (residential) use-case which is based on commodity ONTs and low-cost slide-in I/O access blades controlled by Virtual OLT (vOLT) software. The vOLT software is running in commodity servers connected by several leaf-and-spine switching fabric (Fig.2). We extend TPaaS cost model discussed in [13] to software-based multi-tenant V-MBH. Planning of such raising V-MBH networks shall also be optimized on yearly resource activation and related revenue generation. Network expenditures need to be scattered over the planned project runtime span to help MNOs expand their networks at suitable paces. The remainder of this paper is as follows. Section II reviews related work. In Section III-A1, we introduce a novel concept called *Virtual backhaul-as-a-Service (VBaaS)* to optimize PPM. We also define an MNO Pricing Game (MPG) to calculate the optimal equilibrium price. In Section IV, we compare results of optimized PPM for T-MBH versus V-MBH and using randomized prices versus Equilibrium price. Section V concludes the paper.

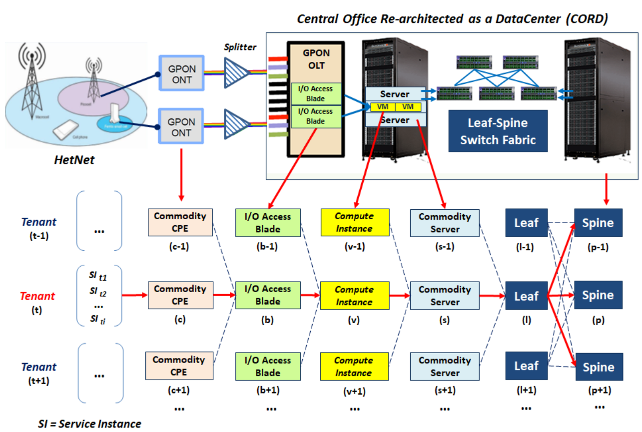

Fig. 2: Virtualized Mobile BackHaul (V-MBH) network (based on R-CORD architecture).

II. Related Work

Several efforts were carried out in previous works to optimize infrastructure resources and drop costs of coming 5G optical backhaul networks. However, most of the focus was offered to the technical issues until some recent studies that has been carried out on the economic aspects in optimizing MBH networks. [8] introduces a Mixed Linear Integer Program (MILP) optimization algorithm to generate - while minimizing CapEx - a detailed Bill of Materials (BoM) and an optimum network design in transport networks. German and US backbone sample networks are used as examples to evaluate the performance of proposed heuristic method and compare generated BoM with realistic ones. [9] presents a comprehensive cost modeling methodology to assess TCO of MBH networks including both microwave and fiber technology options. The authors introduce a first complete assessment of the entire TCO and the impact of a given backhaul technology on a HetNet deployment using small cells. Detailed CapEx and OpEx breakdown is proposed and can be used for different backhaul technologies and architectures. [10] defines a detailed techno-economic model for LTE networks including a novel comprehensive TCO analysis for real and virtualized network components. Various project life-cycle phases are considered in TCO calculation. CapEx and OpEx cost models take into account various SDN/NFV based scenarios: i) equipment can be owned or rented, ii) real or virtual devices, iii) globally or individually, and iv) VNFs running on top of Virtual Machines (VMs) can be outsourced/rented based on a VNF-as-a-Service (VNFaaS) model. Resulting CapEx and OpEx cost analysis investigates the profitability of a fully virtualized versus a traditional mobile network. [11] presents a techno-economic analysis for integration of recent technologies such as SDN, NFV and Cloud Computing in 5G mobile networks. CapEx and OpEx are compared between traditional and proposed network architecture to estimate TCO based on number of deployed Base Station (BS) sites in Sweden. On the other side, [12] presents a game theoretic compromise of quality versus price competition among MNOs and analyse price dynamics in a real world. An optimization problem is defined based on a two-stage competition model combining Cournot (quality and investment) and Bertrand (price and revenue) competition games. The outcome is an equilibrium point between quality-of-service (QoS) offered by MNO networks and competing service prices driven by end-users. [13] introduces a novel network planning and TCO analysis method, called BackHauling-as-a-Service (BHaaS) based on You-pay-only-for-what-you-use approach. BHaaS maximizes the project profit margin ($PPM = ROI - TCO$) by introducing a detailed model for invested TCO and generated ROI. TCO calculation is proportional to yearly satisfied traffic demands and activated MBH resources. ROI calculation is proportionl to MNO wholesale prices and yearly generated ARPUs.

With a target to reduce TCO of optical MBH networks, prior work focused on optimizing the number of planned network elements and related costs of their specific technologies. Existing TCO analysis do not pay attention to Service Level Agreements (SLA) between MNOs and their customers. Cost models proposed in prior work do not consider Average-Revenue-Per-User (ARPU) values generated by satisfying each connected Tenant Service Instances (TSI) and the total ROI generated by yearly activated network services. Moreover, to the best of our knowledge, no prior work has considered the TCO planning and pricing games for SDN/NFV based virtualized MBH networks. In this paper, we extend BHaaS models to consider the raising software-based network virtualization technologies such as SDN and NFV. Thus, we propose the *Virtual-backhaul-as-a-Service (VBaaS)* model to optimize the PPM for multi-tenant V-MBH. We also apply game theoretic models to define the best wholesale pricing strategy for MNOs to optimize related ARPUs and also the yearly generated ROI.

III. System Model

A. VBaaS TCO Optimization

*1) **Framework definition** :* Given a number of macro and small cells from various Tenants (MVNOs) or Tower $t \in T$, (see Fig. 2 and Table I) within a new 5G high-density HetNet. Consider a host MNO who is planning to build and lease slices of his MBH transport network to these MVNOs. Total number of required TSIs to connect the towers in the RAN is globally forecasted by MNOs based on the number of his customers (MVNOs) and their connectivity requirements. A randomly generated matrix of Tenant Service Instances $TSI[t,i], \ \forall \ (t,i) \in T \cap I$ is provided as input where related traffic needs to be backhauled from each Tenants/Tower $t \in T$ to the core network. The target is to plan, maximize and validate the project profitability for deploying and operating a new multi-tenant V-MBH optical network over the project runtime Y. Optimal quantities for resource deployment and activation are calculated prior to the network installation phase. Unlike Traditional MBH (T-MBH) projects where TCO analysis are based on expensive hardware infrastructure, MNOs are trying to drop MBH costs thanks to software components running on cost-effective commodity ONTs / CPEs $c \in C$, universal I/O access Blades $b \in B$ and commodity Servers $s \in S$. Network functions are moved to VNFs instantiated in compute instances $v \in V$ such as VMs (Virtual Machines), Containers and Containers-in-VMs. Compute instances are hosted in commodity servers $s \in S$ organized into a rackable unit called a POD (Point-of-Delivery). Various components of each POD such as commodity servers and access blades are connected via a leaf-spine switch fabric (Fig. 2). Each commodity server $s \in S$ is usually connected to two separate Leaf switches $l \in L$ for redundancy. Each leaf switch $l \in L$ is connected to ALL available spine switches $p \in P$ in the higher layer for maximum redundancy as shown in Fig. 2. Leaf switches are not connected to leaf switches. Same, spine switches are not connected to spine switches.

TABLE I: Symbol Notation

Symbol	Meaning
Y	Number of years in project runtime (usually $Y = 5$)
T	Set of Tenants served by the multi-tenant network
I	Set of Tenant Service Instances (TSI) to be connected
C, B	Respectively sets of CPEs and access blades
V	Set of compute instances, $V = \{vm^{owned}, \ vm^{rented}\}$
S, L, P	Respectively sets of servers, leaves and spines
H	Set of all hardware types within V-MBH, H = $\{CPE, \ Blade, \ Server^{owned}, \ Server^{rented}, \ Leaf, \ Spine\}$

The use of recent concepts such as multi-tenancy and network slicing is added to the complexity of the TCO problem. Payments for constructing and operating new networks are avoided / delayed by maximizing infrastructure sharing and resource utilization among multiple tenants. In particular, an isolated set of 5G physical and virtual transport resources is dynamically assigned upon demand as a dedicated network slice to each tenant. Therefore, a smart planning and efficient cost analysis for data center resources is required to optimize new project TCO and enhance V-MBH profitability and scalability. Infrastructure resources should not be switched-on in V-MBH network unless corresponding service is active, carrying traffic and generating revenue. Forthcoming 5G V-MBH networks should move from always-on" dummy pipes to "always-available" and "service-aware" resource commissioning.

*2) **Assumptions**:* We assume all hosting servers contain a fix number of compute instances (VMs, containers, etc) with comparable memory resources and CPU (Central Processing Unit) requirements. Each commodity server $s \in S$ is connected to only one Leaf switches $l \in L$ with no redundancy. A server is shutdown when there is no compute instances running. Network bandwidth is always affordable since we use multiple 100G connectivity cables to connect application servers to leaf switches and leaf-to-spine switches. A new leaf switch is added to the networking fabric when no more leaf ports are available to connect application servers. The number of spine switches depends on the number of leaf switches and is defined by a given leaf-to-spine ratio. ONTs / CPEs are connected to I/O access blades using 10G-PON technology. A new access blade is added to OLT racks when no more PON ports are available to connect remote ONTs. The objective is to activate the minimal number of devices and software components (ONTs, access blades, compute instances, servers, leaf and spine switches) to afford traffic demand. In other words, we try to delay as long as possible the activation of each of above hardware and software components until the moment when revenue is highest.

*3) **Problem Formulation** :* The proposed VBaaS model distributes the deployment and activation of software and hardware components over the number of years Y to maximize the project PPM. Deployment and operating costs related to each component are considered in TCO calculation only when they are selected by VBaaS for activation. VBaaS model is defined as a MILP optimization problem (named TCO_OPT problem) whose objective function defined in Eq. (1) is to optimize PPM of the V-MBH project which is the difference between consumed TCO versus generated ROI.

$$maximize \ PPM[Y] = ROI^{TSI}[Y] - TCO^{VB}[Y] \tag{1}$$

s.t.

$$ROI^{TSI}[Y] = \sum_{y \in Y} \sum_{t \in T} \sum_{i \in I} ARPU^{TSI}[y,t,i] \tag{2}$$

$$ARPU^{TSI}[y,t,i] = \frac{Pw[y,t,i] * D^{TSI}[y,t,i]}{|I_{y,t,i}|} \tag{3}$$

Eq. (2) calculates the total ROI generated by adding ARPUs of satisfied TSIs $i \in I$ of all tenants $t \in T$ during the project runtime Y. Eq. (3) calculates the ARPU as defined in [3] for each tenant on yearly basis where $Pw[y,t,i]$ is the Wholesale price of the offered TSI service, $D^{TSI}[y,t,i]$ represents the yearly demand of activated TSIs and $|I_{y,t,i}|$ represents the cardinality (total number of TSIs) of a group of TSIs $i \in I$ for a tenant $t \in T$ in year $y \in Y$.

$$TCO^{VB}[Y] = \sum_{y \in Y} (\delta_{CX}[y] * CX[y] + \delta_{OX}[y] * OX[y]) \quad (4)$$

$$CX[y] = \sum_{m \in H \cup V} \left([1 - \phi(m,y)] \sum_{n=1}^{N[m]} \psi[m,n,y] * CX[m,y] \right) \quad (5)$$

$$OX[y] = \sum_{m \in H \cup V} \left([1 - \phi(m,y)] \sum_{n=1}^{N[m]} D[m,n,y] * OX[m,y] \right) \quad (6)$$

$$\psi(m,n,y) = D[m,n,y] - D[m,n,y-1], \quad \forall\ n = 1..N[m] \quad (7)$$

$$D_j[n,y] - D_j[n,y-1] \geq 0, \quad \forall j \geq 1,\ \forall n \in G_j \quad (8)$$

$$\sum_{y \in Y} D_{tsi}[i,y] \geq 1, \quad \forall i \in I \quad (9)$$

$$\frac{\sum_{n=1}^{N[l]} D[l,n,y]}{\sum_{n=1}^{N[s]} D[s,n,y]} = \alpha, \quad \forall y \in Y \quad (10)$$

$$CX[y] + OX[y] \leq TCO_{MAX}[y], \quad \forall y \in Y \quad (11)$$

Eq. (4) calculates the TCO for V-MBH network by considering the yearly evolution of CapEx and OpEx during the project runtime Y. A yearly discount δ is usually offered and considered in our model. Eq. (5) and (6) respectively calculate CapEx and OpEx for Hardware and Software network components in V-MBH. The function $\phi(m,y)$ represents the incremental quantity discount (IQD) offered to MNOs for high ordered quantities [13]. Eq. (7) shows that CapEx costs for any network component are calculated only once i.e. only during the year when activated. On the other hand, OpEx costs are counted every year since activation date as shown in Eq. (6). Eq. (8) imposes that the network evolve in one-direction by maintaining deployed CPEs and related TSIs active for coming years during the project runtime. We assume that an activated service instance in year y will not be disconnected in coming years within the project runtime Y. Eq. (9) assures that there is always initial service instances $i \in I$ requested from at least one tenant $t \in T$. The coefficient α in Eq. (10) is a given leaf-to-spine ratio that defines the required number of spine switches. Eq. (11) shows that yearly project TCO is limited by a maximum allowed budget for each year $y \in Y$.

*4) **Control parameters**:* We define two "ordered" sets, the group G for network component and the group D for related activation demand.

$$G = (G_1, G_2, G_3, G_4, G_5, G_6, G_7) = (I, C, B, V, S, L, P)$$
$$D = (D_1, D_2, D_3, D_4, D_5, D_6, D_7) = (D_{tsi}, D_{cpe}, D_{bld}, D_{vm}, D_{srv}, D_{leaf}, D_{spine})$$

$\forall y \in Y;\ \forall j \geq 2;\ \forall n \in G_j$:

$$D_j(n,y) = \mathbb{1}\ \{ \sum_{m \in G_{j-1};\ B(m)=n} D_{j-1}(m,y) \geq 1 \} \quad (12)$$

Eq. (12) assures that costs of any idle (not activated) network component $n \in G_j$ where $j = 1..7$ are excluded from the cost calculation until related offered service is provisioned and started generating revenue. The functions in Eq. (12) are defined as follows:

- $\mathbb{1}$ { A } is the Indicator Function (also called Characteristic Function) that takes the value 1 if the condition A is satisfied and the value 0 otherwise.
- $D_j(n,y)$ is the Demand Function of deployed and activated network component n within G_j in year y.
- $B(m) = n$ is a Binding Function that attaches the network component $m \in G_{j-1}$ to the next level component $n \in G_j$ as per the resource mapping tree presented in Fig. 2 (e.g. the function binds a number of compute instance $v \in V$ to a certain commodity server $s \in S$, etc)

In VBaas, a leaf switch $l \in L$ is counted, if and only if, at least one server is connected to it. The number of spine switches is defined by the number of leaf switches and the leaf-to-spine ratio α. Moreover, if no compute instances are executed in a server $s \in S$, then the server is considered as idle and therefore it is not considered. Same applies for access blades and commodity CPEs. Costs of a compute instance are excluded from the total cost if it is not serving any access blades in year Y. An access blade $b \in B$ is idle if no CPE is connected to it and it is forwarding no traffic. Finally, a CPE $c \in C$ is included, if and only if, it is serving / satisfying a TSI $i \in I$ for a tenant $t \in T$.

B. MNO Pricing Game (MPG)

*1) **Problem statement**:* The problem of MNOs leasing isolated slices of their networks to several tenants (MVNOs) can be viewed as a non-cooperative transportation game [14]. MNOs have different price strategies and try always to minimize their investment costs and maximize their profits (payoffs) as rational players in the price competition game. Each MNO will always have incentives to undercut his TSI prices given the price strategies of his competitors. This complex competitive interaction among different MNO price strategies is often driving to fall in a prisoner's dilemma issue where competing MNOs are facing big challenges in defining the most appropriate and efficient pricing strategy. The resolution of this linear generalized Nash equilibrium problem (LGNEP) helps to find the optimal wholesale price equilibrium and stabilize the oligopoly market by modeling and correlating the best response strategies of all competing players in their price competition game. The target is to define the Nash-equilibrium when no more improvement becomes possible from all competing MNOs [3], [14]. Standard VBaaS proposed in Section III-A focuses in optimizing the TCO defined in Eq. (4) while the values of TSI wholesale prices

$Pw[y,t,i]$ are given (fixed) in Eq. (3). We optimize in Section III-B the ROI (Eq. (2)) as well by correlating the best pricing strategies for all competing MNOs and calculating the yearly pareto-Equilibrium prices for $Pw[y,t,i]$. These prices are then used to calculate the optimal ARPUs for each tenant and each TSI in Eq. (3) and used in Eq. (2) for the ROI calculation.

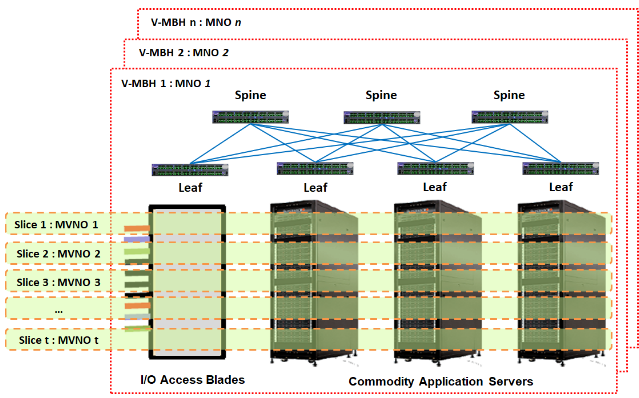

Fig. 3: Slicing MNO V-MBH networks to MVNOs

*2) **Game definition**:* Given the MBH network which is virtualized, sliced and is exploited by a set N of MNOs as shown in Fig. 3. We assume all MNOs have the same budget for CAPEX and OPEX, using the same types of network equipment, and same network architecture. There is a set of MVNOs / Tenants $t \in T$ who are renting V-MBH slices (represented as TSIs $i \in I$ in VBaaS model) at a wholesale price $Pw[y,t,i]$ from a host MNO $n \in N$ to connect a set of towers. Thus, each TSI $i \in I$ rented by tenant $t \in T$ may bring a certain revenue per each year. Each MNO $n \in N$ has to choose a strategy to activate its hardware equipment in order to maximize its revenue according to Eq. (1), but taken into account the competition of other MNOs. So, a MNO may have to activate its equipment earlier (or later) than the optimal time in Eq. (1). The problem is to find the best schedule for all MNOs to activate their equipment and to meet Nash-equillibrium (if any MNO activates an equipment earlier or later of this time, some others will have to suffer). Indeed, if an MNO activates his network equipment sooner (e.g. in the first years of the project), higher traffic demand will be afforded, and more customers can be served earlier. However, his price will also be higher as a result of high CAPEX investment and low revenue as seen in the TCO_OPT problem. Such higher price may eventually result in customer lost in subsequent years. On the other hand, if the MNO delays the deployment of his network equipment to later years, he may offer a lower price but risks loosing customers in the first years. The optimal time (activation year) is relying on the network capacity $k_m[y,t,i]$ yearly dedicated by MNO $n \in N$ to each of his tenants as well as the yearly revenue $ARPU^{TSI}[y,t,i]$ generated by each TSI. Each competing player (host MNO $n \in N$) sets his own strategy in a non-cooperative transportation problem (NTP) [14] to plan his network deployment and increase his market share. In real world, network capacities may be planned and fixed but prices increase and decrease all the time. This makes the market instable without a pure Nash Equilibrium as highlighted by *Proposition 1* in [12].

*3) **Mathematical model**:* We use *Proposition 2* in [12] that limits the number of price changes within a certain period of time in order to push prices to merge into a Pareto-optimal equilibrium point. MNOs' best responses are driven by different service ARPUs for each tenant which is proportional to the wholesale prices as defined in Eq. (3). We define the optimal activation time for the V-MBH resources by calculating the equilibrium point $(P_n^{eq}[y,t,i], \ \forall n \in N)$ for a certain TSI $i \in I$ offered by several competing MNOs $n \in N$ to a tenant (customer) $t \in T$. We use the model defined by *Lemma 4* in [12] which is the outcome of the introduced two-stage Cournot and Bertrand competition model to study the price dynamics among several competing MNOs. We generalize in our work the definition of the normalized network capacities respectively calculated for MNOs $m,n \in N$ in the Cournot stage (quantity competition) to consider the capacities $k_m[y,t,i]$ and $k_n[y,t,i]$ dedicated for the TSI $i \in I$ offered to the tenant $t \in T$ on yearly basis. Then the prices $P_m^{eq}[y,t,i]$ and $P_n^{eq}[y,t,i]$ are calculated in the Bertrand stage (price competition) for these given network capacities. The pareto-equilibrium prices are calculated in the model defined in Eq. (13). These prices are used to optimize ARPUs in Eq. (3) and ROI in Eq. (2).

$$(\, P_m^{eq}[y,t,i] \ , \, P_n^{eq}[y,t,i]) =$$

$$\begin{cases} (\dfrac{1}{k_m[y,t,i]+2}, \dfrac{k_m[y,t,i]+1}{k_m[y,t,i]+2}) \quad if \quad k_m[y,t,i] < 2k_n[y,t,i] \\ \\ (\dfrac{1}{k_m[y,t,i]+2}, \dfrac{k_m[y,t,i]+1}{k_m[y,t,i]+2}) \quad or \\ (\dfrac{2k_n[y,t,i]+1}{2(k_n[y,t,i]+2)}, \dfrac{1}{2}) \qquad if \quad k_m[y,t,i] = 2k_n[y,t,i] \\ \\ (\dfrac{2k_n[y,t,i]+1}{2(k_n[y,t,i]+2)}, \dfrac{1}{2}) \qquad if \quad k_m[y,t,i] > 2k_n[y,t,i] \end{cases} \tag{13}$$

IV. Validation and Results

The TCO analysis is executed as part of the network planning phase to plan the resources distribution over the coming number of years (e.g. five years). Thus, no real-time solution of the problem is required and we can use mathematical solver to compute optimal solutions. In this paper, IBM ILOG CPLEX has been used as a solver for our VBaaS ILP problem on simulation scenarios. The solver is running on a Windows 7 HP machine with i7-4790 CPU @ 3.6 GHz and 8 GB RAM.

A. Use case definition

We use GPON-based V-MBH as defined in R-CORD project to validate the performance of our proposed VBaaS cost model detailed in Section III-A. A GPON splitting ratio of 1:32 is applied which corresponds to the number of GPON ONTs (CPEs) per each OLT I/O access blade port ($c_{max} =$ 32). Cost of PON ports implicitely includes costs of fiber connectivities required to connect remote CPEs. Costs related to deploy fiber cable infrastructure are excluded from our models and are subject to separate TCO analysis project. We apply VBaaS to various scenarios of software based optical V-MBH networks and compare with traditional hardware based MBH (T-MBH) scenario. Cost values used in our study are based on published costs and industry-based estimates.

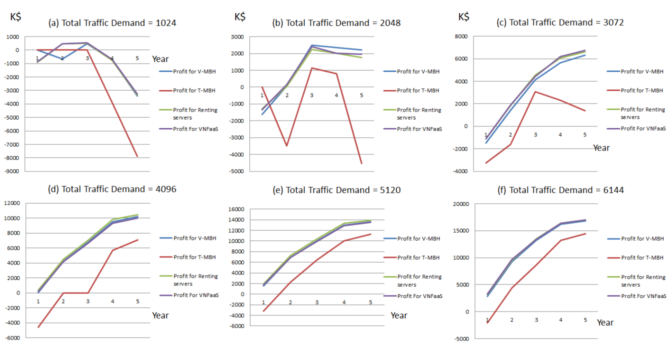

Fig. 4: Project Profit Margin (PPM) yearly evolution for T-MBH versus V-MBH, Renting servers and VNFaaS scenarios

B. T-MBH vs V-MBH

We compare the PPM for PON based T-MBH versus V-MBH with various scenario (where MNO owns his own infrastructure) versus the Renting servers and VNFaaS scenarios (MVNOs). Fig. 4 summarizes the yearly evolution of PPM for T-MBH versus V-MBH. Results show that for very low traffic demand (TDD = 1024), both T-MBH and V-MBH profit margins are negative. Thus the project is not yet profitable. Although V-MBH presents a positive PPM for the second and third year, the increasing TCO in the fourth year without enough revenue generation is driving to a negative profit for coming years. Furthermore, results show that renting VMs (VNFaaS) and/or servers offers a slight advantage in the second and third year compared with the standard V-MBH scenario where MNO deploys his own network. For TTD = 2048, software-based MBH scenarios offer a clear advantage over T-MBH. The project starts to be profitable in the second year while T-MBH is still presenting negative PPM. Deploying its own network resources presents a slight advantage to MNO compared with the scenario where renting VMs and/or servers from a third-part provider. At TTD = 3072, T-MBH starts to have a positive PPM on the third year while software networks are generating a positive profit before the second year. Results also show that VNFaaS (and renting servers) offers a higher PPM compared to the standard V-MBH scenario. For high traffic demand (starting from TTD = 4096), PPM graphs of software-based scenarios (standard V-MBH, VNFaaS and renting servers) start merging with a much higher values compared to T-MBH. For TTD = 6144, the three curves of previous software-based scenarios are merging showing that - for very high traffic demand - it does not matter anymore if the MNO buys/deploys or rents his VMs and/or servers. In fact, most of TCO is consumed on the access components such CPEs, access blades and not on the computing side of the network.

C. Pareto-equilibrium price

We consider the Canadian market as an example with three (3) major competing MNOs (Bell, Rogers and Telus). We use the MNO Pricing Game (MPG) defined in Section III-B to calculate the Equilibrium prices. We consider the case where all MNOs are sharing the yearly traffic demand in an equitable way with no monopolism. Thus, we assume the simplest case where the normalized network capacities for all competing MNOs are equal to 1, meaning that, $k_n[y,t,i] = 1,\ \forall\ n \in N,\ y \in Y,\ t \in T\ and\ i \in I$. We use the first case (i.e. $k_m[y,t,i] < 2\ k_n[y,t,i]$) in the Equilibrium model defined by Eq. (13) to calculte the pareto-equilibrium prices for MNO 2 and 3 based on the randomized prices of MNO 1. The normalized pareto-equilibrium prices are calculated as follows $(P_m^{eq}[y,t,i], P_n^{eq}[y,t,i] = (1/3, 2/3))$. Thus, knowing the wholesale pricing strategy of MNO 1, his competitor MNO 2 will define his best strategy by leasing his TSIs with higher price and enhance his revenues in a pareto-equilibrium market situation. Same, MNO 3 will define his prices based on the calculated prices of MNO 2. We exclude the case where all MNOs define their pricing strategies at exactly the same time with no knowledge about competitors behavior. Fig. 5 presents

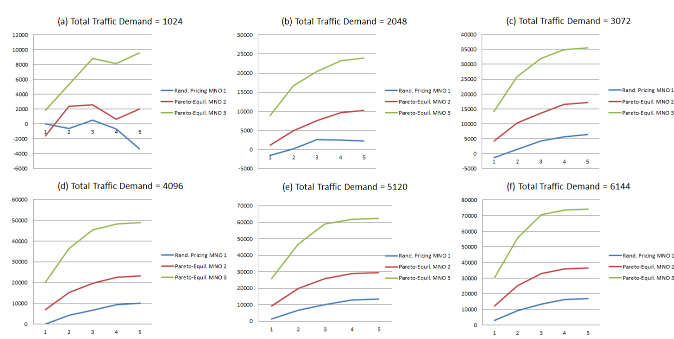

Fig. 5: Project Profit Margin (PPM) yearly evolution for V-MBH using Randomized pricing versus Equilibrium pricing

the yearly evolution for V-MBH Project Profit Margin (PPM) for Randomized pricing (MNO 1) versus Pareto-Equilibrium pricing (MNO 2 and 3). Results show the big advantage of using the Pareto-Equilibrium pricing strategy to define MNO service prices and enhances the profitability of V-MBH for all traffic demand volumes. For instance, V-MBH is not profitable for very low traffic demand (TTD =1024) when using randomized pricing strategy (MNO 1) while it becomes profitable with Pareto-Equilibrium pricing strategy (MNO 2 and 3). Furthermore, MNO 3 generate more profit than MNO 2 concluding that the MNO making later decision based on previous ones will have more chances for higher profit margins. We conclude also that the profitability of V-MBH project increases with high traffic demand. Fig. 6 summarizes

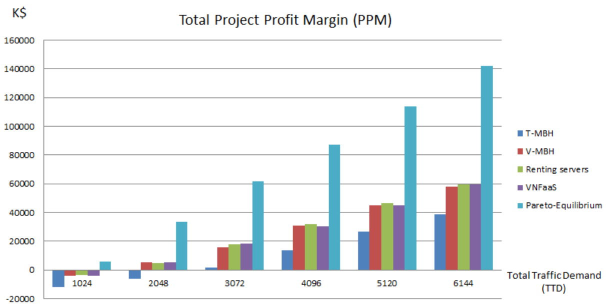

Fig. 6: Total Project Profit Margin (PPM) for T-MBH versus V-MBH using Randomized pricing and Equilibrium pricing

and validates previous conclusions for the Total PPM for the entire project runtime (Y). Unlike the evolution of PPM on yearly basis discussed in Fig. 5, results in this paragraph focus on the final PPM of the whole project without considering detailed yearly behavior. At the end of the project lifetime, the project is either profitable enough or not. The outcome of this result helps the MNO decide which strategy to use for building his future MBH network. Thus, he may decide to build his own infrastructure as a host MNO (e.g. T-MBH or standard V-MBH) or to go for renting resources (servers, VNFaaS) as an MVNO. He can also decide on which pricing strategy to adopt based on his competition best strategy. By comparing the Total PPM for all previously discussed scenarios, Fig. 6 shows that for TTD = 1024, only V-MBH with Pareto-Equilibrium pricing is profitable while all remaining PPMs are negative. For TTD = 2048, only T-MBH is still not profitable. Starting from TTD = 3072, all project scenarios become profitable with a very big advantage to V-MBH with Pareto-Equilibrium pricing.

V. Conclusion

Future 5G multi-tenant Mobile BackHaul networks (MBH) are facing a continuous increase in traffic demand, particularly with coming greedy applications like IoT, smart cities and connected cars. Building and operating such networks require huge inverstments while generated revenues remain flat. Thus, a combination of efficient choice of technology, optimized resource planning and smart service pricing strategy is urging to guaranty the MBH network profitability and enhance the Project Profit Margins (PPM). In this paper, we proposed an optimization model to optimize the network PPM for a typical SDN- and NFV-based Virtualized MBH (V-MBH) use-case (called CORD project) while considering the yearly consumed Total-Cost-of-Oweneship (TCO) and generated Return-on-investement (ROI). Simulation results provide useful understanding on various factors affecting the MBH network profitability. We applied the model on various scenarios where the Mobile Network Operator (MNO) may deploy its own network or rent computing resources such as servers and/or VMs. Then, we used game theory to find the Pareto-Equilibrium pricing strategy that optimizes the MNO's TCO planning based on competition strategies. Techno-economic analysis show the ability of recent SDN and NFV technologies such as centralized cloud computing to reduce deployment costs (CapEx) and operation costs (OpEx). Furthermore, network slicing and multi-tenancy business models help to enhance network resources sharing and generate more revenues for MNOs. We conclude that the combination of deploying an MBH with software-based virtualized resources and using game theory to define the best pricing strategy significantly enhance the MNO generated revenues and increase the project profitability.

In the future, we will study the game theoretic problem of pricing for application providers that use MVNO networks. We will also consider an efficient demand prediction which takes into account market behaviors with various MNOs.

Acknowledgment

The authors thank NSERC and Ciena for funding the project CRDPJ 461084. This research also receives support from the Canada Research Chair, Tier 1, hold by Mohamed Cheriet.

References

[1] M. Fiorani et al., "Challenges for 5G transport networks," 2014 IEEE International Conference on Advanced Networks and Telecommuncations Systems (ANTS), New Delhi, 2014, pp. 1-6.
[2] N. Haddaji, K. Nguyen and M. Cheriet, Towards End-to-End Integrated Optical Packet Network: Empirical Analysis, Elsevier, Optical Switching and Networking, June 2017.
[3] F. Sun, F. Hou, H. Zhou, B. Liu, J. Chen, and L. Gui, Equilibriums in the Mobile-Virtual-Network-Operator-Oriented Data Offloading, IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY, VOL. 67, NO. 2, FEBRUARY 2018.
[4] M. Jaber, M. A. Imran, R. Tafazolli and A. Tukmanov, "5G Backhaul Challenges and Emerging Research Directions: A Survey," in IEEE Access, vol. 4, pp. 1743-1766, 2016.
[5] H.-H. Cho, C.-F. Lai, T. K. Shih, and H.-C. Chao, "Integration of SDR and SDN for 5G," IEEE Access, vol. 2, pp. 1196 - 1204, 2014.
[6] S. Sun, M. Kadoch, L. Gong and B. Rong, "Integrating network function virtualization with SDR and SDN for 4G/5G networks," in IEEE Network, vol. 29, no. 3, pp. 54-59, May-June 2015.
[7] L. Peterson et al., "Central office re-architected as a data center", in IEEE Communications Magazine, vol. 54, no. 10, pp. 96-101, October 2016.
[8] M. S. Zefreh, A. Tizghadam, A. Leon-Garcia, H.Elbiaize, W. Miron, CAPEX Optimization in Multi-Chassis Multi-Rate IP/Optical Networks, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 13, NO. 9, SEPTEMBER 2014.
[9] M. Mahloo, P. Monti, J. Chen and L. Wosinska, "Cost modeling of backhaul for mobile networks," 2014 IEEE International Conference on Communications Workshops (ICC), Sydney, NSW, 2014, pp. 397-402.
[10] T. M. Knoll, "Life-cycle cost modelling for NFV/SDN based mobile networks," 2015 Conference of Telecommunication, Media and Internet Techno-Economics (CTTE), 2015, pp. 1-8.
[11] C. Bouras, P. Ntarzanos and A. Papazois, "Cost Modeling for SDN/NFV Based Mobile 5G Networks", 8th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2016.
[12] S. M. Yu and S.-L. Kim, Game-Theoretic Understanding of Price Dynamics in Mobile Communication Services, IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 13, NO. 9, SEPTEMBER 2014.
[13] N. Haddaji, A. Bayati, K. Nguyen, and M. Cheriet, "Backhauling-as-a-Service (BHaaS) for 5G Optical Sliced Networks: An Optimized TCO Approach", IEEE OSA Journal of Lightwave Technology, July 2018.
[14] O. Stein and N. Sudermann-Merx, "The noncooperative transportation problem and linear generalized Nash games", Elsevier, European Journal of Operational Research, 2018.