Dynamic Pricing for Wireless Network Virtualization: A Stackelberg Game Based Approach

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Abstract
The infrastructure provider (InP) is required to deploy efficient and flexible resource allocation techniques to dynamically allocate the resources for the users associated with different mobile virtual network operators (MVNOs). Service contracts with different MVNOs and fairness among their users are crucial to the success of the virtualization scheme deployed by the InP. In this paper, a game-theoretic framework is proposed for resource allocation in OFDMA virtualized wireless network. The framework considers a market model consisting an InP and multiple MVNOs. Regarding the virtual resource for a virtualized wireless network as commodities, the InP wants to maximize its revenue by leasing the infrastructure to the MVNOs while meeting certain contract agreements. Moreover, MVNOs want to serve their users at the best performance and want to pay the minimum to InP. A two-stage Stackelberg game is applied to optimize the strategies of both the InP (the leader) and MVNOs (the followers). We show that this two-stage game has a unique Stackelberg equilibrium.

I. Introduction
In the information and communication technology (ICT) sector, virtualization has become a popular concept in different areas, e.g., virtual memory, virtual machines. Virtualization involves abstraction and sharing of resources among different parties. With virtualization, the overall cost of equipment and management can be significantly reduced due to the increased hardware utilization, decoupled functionalities from infrastructure, ease migration to newer services and products, and flexible management. Wireless network virtualization can have a very broad scope ranging from spectrum sharing, infrastructure virtualization, to air interface virtualization. Similar to wired network virtualization, in which physical infrastructure owned by one or more providers can be shared among multiple service providers, wireless network virtualization needs physical wireless infrastructure and radio resources to be abstracted and isolated to a number of virtual resource, which then can be offered to different service providers [1][2][3].

Wireless network virtualization is a means by which an infrastructure provider (InP) can slice the wireless and physical resources to slices. These slices are assigned to mobile virtual network operators (MVNOs) (or service providers SPs in some literatures) so that they can serve their subscribers. The main motivation behind wireless network virtualization is cost saving of network roll-out, maximization of revenue for InPs.

Resource allocation plays a very important role in achieving energy efficiency, spectrum efficiency and quality of service (QoS) provisioning in wireless networks in general. However, in wireless network virtualization, isolation has to be taken into account in resource allocation [1][2][3].

In this paper, we proposed a virtual resource allocation scheme for OFDMA based wireless virtualization networks, which considers the network benefits for InP and MVNOs simultaneously. We consider both the revenue maximization for InP and cost minimization for MVNOs while guarantee service contracts agreements between InP and MVNOs.

![Fig.1. System model](image-url)
II. System Model and Optimization Problem

We consider the downlink of a single cell consisting single base station (BS) scenario. The BS and spectrum are owned and managed by a single infrastructure provider (InP) who provides its network virtual service to a set of mobile virtual network operators (MVNOs) $\mathcal{M}$ by individual contracts. The InP owns the frequency spectrum with $C$ orthogonal subcarriers with the bandwidth size $\omega_0$ Hz. Each user $k$ of MVNO $m$ will be allocated an amount of bandwidth $c_{m,k}$ then the achievable data rates is as follows [5]:

$$R_{m,k} = c_{m,k} \alpha_k \ln \left(1 + \frac{P_m g_{m,k}}{c_{m,k} \alpha_k p_0}\right),$$

(1)

III. Stackelberg Game

The interactions between the InP and MVNOs can be characterized as a two-stage Stackelberg game model. The InP publishes the resource price in a first stage and then the MVNOs respond the resource demand in a second stage.

A. Stage II: MVNO model – Followers Game

We consider the net utility function of MVNO $m$ as follows

$$U_m(c_m,p_m) = \sum_{k=1}^{K_m} R_{m,k} - p_m \sum_{k=1}^{K_m} c_{m,k}$$

(2)

where $p_m$ is the price per unit of bandwidth charged by InP. The objective of the MVNO here is to maximize its users total throughput and minimize cost it has to pay to the InP. The optimization problem of MVNO $m$ is given as follows

$$\text{P}_{\text{MVNO}}: \text{maximize } U_m(c_m,p_m)$$

(3)

We assume that system operates in a high SINR regime, i.e., SINR is much larger than 1: thus, the data rate can be approximated as

$$R_{m,k} = c_{m,k} \alpha_k \ln \left(\frac{P_m g_{m,k}}{c_{m,k} \alpha_k p_0}\right).$$

Then, for given price $p_m$, the unique optimal solution for Stage-II is:

$$c_{m,k}^* = G_{m,k} e^{-\frac{\alpha_k + p_m}{\alpha_k}}, \forall m,k$$

(4)

where $G_{m,k} = \frac{P_m g_{m,k}}{\alpha_k p_0}$.

B. Stage I: InP model – Leader Game

We consider the revenue function of the InP as follows

$$\mathcal{R}(c,p) = \sum_{m=1}^{M} c_m p_m,$$

(5)

$$c_m = \sum_{k=1}^{K_m} c_{m,k}, \forall m$$

represents the total bandwidth sold by InP to the MVNO $m$. The InP objective is to maximize its revenue by setting the right resource price to satisfy the demand of MVNOs, while guarantees the contracts agreements.

With virtualization, each MVNO can schedule next serving users and allocate necessary bandwidth to users based its own QoS requirements. Assuming the pre-agreed bandwidth of slice allocated to MVNO $m$ is $\bar{R}_m$, MVNO can allocate any data rate $R_{m,k}$ to its serving user $k$ under the constrains

$$\sum_{k=1}^{K_m} R_{m,k} \leq \bar{R}_m, \forall m \in \mathcal{M}.$$  

(6)

The optimization problem of InP is given as follows

$$\text{P}_{\text{InP}}: \text{maximize } \mathcal{R}(c,p)$$

subject to

$$\sum_{m=1}^{M} c_m \leq C, \forall m \in \mathcal{M},$$

$$\sum_{k=1}^{K_m} R_{m,k} \leq \bar{R}_m, \forall m,$$

$$0 \leq p_m \leq p^\text{max}, \forall m,$$

(7)

Substituting (4) into problem (7), the InP problem in Stage-I can be reformulated as

$$\text{maximize } \sum_{m=1}^{M} \sum_{k=1}^{K_m} G_{m,k} e^{-\frac{\alpha_k + p_m}{\alpha_k}}$$

subject to

$$\sum_{m=1}^{M} \sum_{k=1}^{K_m} G_{m,k} e^{-\frac{\alpha_k + p_m}{\alpha_k}} \leq C,$$

$$\sum_{k=1}^{K_m} G_{m,k} (\alpha_k + p_m) e^{-\frac{\alpha_k + p_m}{\alpha_k}} \leq \bar{R}_m, \forall m,$$

$$0 \leq p_m \leq p^\text{max}, \forall m,$$

(8)

It is straightforward to show that problem (8) is a convex problem, then it can be easily solved by any standard solver. e.g., CVX.

IV. Numerical Results

In this section, we evaluate the system performance of the proposed framework using simulations. We consider a cellular network where MVNOs’ subscribed users are randomly located inside a macro cell of radius 500m belonging to the InP. We consider three MVNOs with 5 subscribed users for each MVNO. We assume the InP owns $C = 30$
OFDMA subchannels, each of which has a total bandwidth of 180 KHz. The noise power is assumed to be $10^{-13}$W. The small-scale fading coefficients of the BS-to-user links are generated as independent and identically distributed (i.i.d.) Rayleigh random variables with unit variance.

Channel gains are set as $g_{m,k} = \theta d_{m,k}^{-\beta}$ where $\theta$ is a random value generated according to the Rayleigh distribution, $d_{m,k}$ is the geographical distance between MBS and user $k$ of MVNO $m$, and $\beta = 3$ is the pathloss exponent. Here, all results presented are averaged over a large number of independent runs of random locations of users and resource gains.

![Fig. 2. Revenue versus transmit power](image)

In Fig. 2, we present the results obtained by varying the transmit power and achieving revenue. We can observe that as we increase the transmit power the revenue also increases.

![Fig. 3. Revenue versus maximum price](image)

In Fig. 3, we vary the maximum price threshold charged to MVNO and transmission power of the InP’s BS to observe the revenue achieved by the InP. It can be observed that, when the network has limited number of subchannels (i.e., 30), the revenue gets saturated after a threshold of maximum price $p_{\text{max}} > 6$. This trend is observed due to the fact InP owns limited resources which cannot fulfill the demands of all MVNOs. Therefore, increasing the price of the subchannel beyond a point will not increase the revenue.

V. Conclusions

In this paper, we have developed a dynamic pricing mechanism for resource allocation in wireless network virtualization. A hierarchical structure is adopted to model the business interaction between InP and multiple MVNOs. In this model, the InP wants to maximize its revenue by leasing the infrastructure to the MVNOs while meeting certain contract agreements. Moreover, MVNOs want to serve their users at the best performance and want to pay the minimum to InP. A two-stage Stackelberg game is applied to optimize the strategies of both the InP (the leader) and MVNOs (the followers). We have shown that the proposed game achieves a unique Stackelberg equilibrium.

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Reference


