Resource Sharing in Virtualized Wireless Networks: A Two-Layer Game Approach

Yan Kyaw Tun, Shashi Raj Pandey, Madyan Alsenwi, and Choong Seon Hong*
Department of Computer Engineering, Kyung Hee University,
Yongin, 17104 Korea
Email: {ykyawtun7, shashiraj, malsenwi, cshong}@khu.ac.kr

Abstract

Wireless network slicing (i.e., network virtualization) is one of the auspicious approaches to address the increasing demand of mobile data services for 5G wireless networks. It enables logical decoupling of the traditional cellular network into infrastructure providers (InPs) and mobile virtual network operators (MVNOs). It also offers a virtualized wireless network, efficient resource utilization, and isolation between network slices (i.e., between MVNOs). Here, we consider wireless network slicing for a single InP who owns radio resources and for multiple MVNOs who need radio resources to provide specific services to their mobile users. One of the challenges in wireless network slicing is how to efficiently allocate the limited radio resources available at the InP to the MVNOs. In this paper, we address the problem of efficient allocation of the InPs radio resources to the MVNOs which aims to maximize the total network capacity of the InP. To this end, we decompose our considered problem into two layers. The upper-layer is an efficient allocation of the InPs radio resources (bandwidth) to the MVNOs, and the lower-layer is an optimal allocation of MVNOs resources gained from the InP to their mobile users. We then propose a Generalized Kelly Mechanism framework and utilize the Karush-Kuhn-Tucker (KKT) conditions to solve the upperlayer and the lower-layer of our resource allocation problem, respectively. Finally, simulation results prove that the proposed algorithm outperforms other existing resource allocation schemes in virtualized wireless networks.

Keywords – *5GPP, wireless network virtualization, bandwidth allocation, two-layer game.*

I. Introduction

Mobile network operators (MNOs) can reduce the capital expenditure (CAPEX) and operational expenditure (OPEX) by slicing physical radio resources and base station (BS) hardware [1]. This is also a promising approach to address the issues associated with the growth of traffic in mobile data. Separation of traditional wireless cellular network into infrastructure providers (InPs) and mobile virtual network operators (MVNOs) is achieved in wireless network virtualization. Physical infrastructure such as base stations, physical resource blocks (RBs), cell sites are owned by InP. MVNOs lease these infrastructure and physical resources from multiple InPs to create their own virtual networks for providing specific services to their mobile users. By slicing (i.e., virtualizing) the wireless network, it is possible for MVNOs to share a physical infrastructure together with a flexible network operation. Although wireless network slicing technique has potential for future wireless networks, several issues such as interisolation, mobility management, intra-isolation, network management and control signaling need to be addressed before its deployment [2]. Furthermore, one of such critical concern in network slicing is to efficiently allocate resources such as physical resource blocks (RBs), bandwidth and transmission power to the mobile users [3] [4] [5] [8].

In this work, we propose an efficient bandwidth resource sharing to the users of MVNOs problem in the form of two layers. Then, we solve the the proposed problem by using Generalized Kelly Mechanism (GKM) and Karush-Kuhn-Tucker conditions [6] [7].

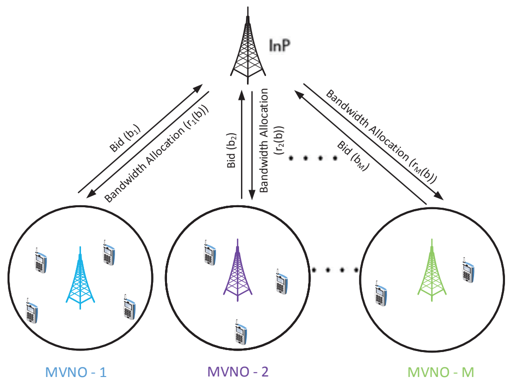

Fig. 1: System Model

II. System Model and Problem Formulation

A virtualized wireless network model with an InP that deploys a base station (BS) operating on the total system bandwidth R, and a set of MVNOs $\mathcal{M} = \{1, 2, \dots, M\}$ where each MVNO m is providing the specific mobile services to its mobile users, $\mathcal{S}_m = \{1, 2, \dots, S_m\}$ is shown in Fig. 1. In this virtualized wireless network model, MVNOs will lease fraction of bandwidth from the InP to provide services and satisfy the QoS requirement of their mobile users. Therefore, a fraction of the system bandwidth R of the BS that gets allocated to each MVNO $m \in \mathcal{M}$ is denoted as r_m. At BS, the InP deploys a hypervisor to virtualize physical resource (e.g., bandwidth and power) for leasing to MVNOs. Here, how the InP will virtualize its wireless bandwidth among multiple MVNOs to provide services to their mobile users becomes the central question. Because it is not possible for the InP to get direct access of user's information: channel state information (CSI), and QoS requirements. Therefore, a workable solution would be to allocate bandwidth to MVNOs first, and then each MVNO can allocate the wireless bandwidth for its users to provide specific services. This solution approach can be viewed as a two-layer solution approach.

A. Upper-layer of Bandwidth Allocation in a Virtualized Wireless Network

Based on the QoS requirements of mobile users, each MVNO $m \in \mathcal{M}$ establishes the demand of bandwidth. Let us denote the valuation function $v_m(r_m(\mathbf{b}))$ as the satisfaction of an MVNO $m \in \mathcal{M}$. According to reported bidding values of MVNOs, the InP allocates its wireless bandwidth to each MVNO. It means that the MVNO with a higher bidding value will receive more bandwidth from the InP. Thus, the cooperation between the InP and MVNOs can be formulated as a GKM framework, where an InP aims to maximize the aggregated valuation of all MVNOs. Therefore, the upper-layer of bandwidth allocation problem in a virtualized wireless network can be described as follows:

$$\max_{\mathbf{r_m}} \quad \sum_{m \in \mathcal{M}} v_m(r_m(\mathbf{b})) \tag{1}$$

$$\text{s.t.} \quad r_m(\mathbf{b}) \cap r_n(\mathbf{b}) = \emptyset, \text{for } m \neq n, \text{and } m, n \in \mathcal{M}, \tag{2}$$

$$\sum_{m=1}^{M} r_m(\mathbf{b}) \leq R, \tag{3}$$

$$r_m(\mathbf{b}) \geq 0, \quad \forall m \in \mathcal{M}, \tag{4}$$

where constraint (1) ensures an inter-slice isolation amongst MVNOs. As the system bandwidth of the base station (BS) is limited, constraint (2) guarantees that the allocated bandwidth of all MVNOs does not exceed the total system bandwidth of the BS.

Then, the bidding value of each MVNO $m \in \mathcal{M}$ can be calculated as follows:

$$b_m = \frac{1}{q_m} r_m(\mathbf{b}) v'(r_m(\mathbf{b}))(1-\mu_m), \quad \forall m \in \mathcal{M}. \tag{5}$$

After submitting the bidding value b_m to the InP, each MVNO $m \in \mathcal{M}$ receives a fraction of the total system bandwidth of BS $r_m(\mathbf{b})$ according to its bidding value b_m. Let $\mathbf{r} = \{r_1, r_2, \ldots, r_M\}$ be the vector of the allocated bandwidth to each MVNO which is determined by the weighted proportional allocation as:

$$r_m(\mathbf{b}) = \frac{b_m}{\sum_{m=1}^{M} b_m} R, \qquad \forall m \in \mathcal{M}, \tag{6}$$

Then, depending on the bidding value b_m, an InP imposes the cost function $c_m(\mathbf{b})$ of MVNO $m \in \mathcal{M}$ as $q_m b_m$, $\forall m \in \mathcal{M}$ where q_m is the penalty value for MVNO $m \in \mathcal{M}$. Finally, the payoff (i.e., utility) of the MVNO m can be expressed as:

$$u_m(\mathbf{b}) = v_m(r_m(\mathbf{b})) - q_m b_m, \qquad \forall m \in \mathcal{M}, \tag{7}$$

where $v_m(r_m(\mathbf{b}))$ is the valuation of the MVNO m when r_m is allocated according to the bidding value b_m. Moreover, let consider $\mathbf{q} = \{q_1, q_2, \ldots, q_M\}$ as the vector of penalty values of all MVNOs and it is as follows:

$$q_m = \frac{1}{\beta} v'_m(r_m)\left(1 - \frac{r_m}{R}\right), \qquad \forall m \in \mathcal{M}. \tag{8}$$

Here, in order to maximize its own payoff/utility, each MVNO will choose its best strategy i.e., bidding value. Therefore, the utility $u_m(b)$ of MVNO m when choosing its strategy b_m is as follows:

$$u_m(b_m; \mathbf{b}_{-m}, \mathbf{q}) = v_m(r_m(\mathbf{b})) - q_m b_m, \qquad m \in \mathcal{M}, \tag{9}$$

where $\mathbf{b}_{-m} = [b_1, \ldots, b_{m-1}, b_{m+1}, \ldots, b_M]$ is the strategy profiles of all other MVNOs except m. The strategy profile b^*_m is the best strategy of the MVNO $m \in \mathcal{M}$ and there exists a Nash equilibrium when the following condition is satisfied for all MVNOs:

$$u_m(b^*_m; \mathbf{b}^*_{-m}, \mathbf{q}) \geq u_m(b_m; \mathbf{b}^*_{-m}, \mathbf{q}), \qquad \forall b_m \geq 0. \tag{10}$$

B. Lower-layer of Bandwidth Allocation in a Virtualized Wireless Network

At the lower-layer of the bandwidth allocation in a virtualized wireless network, each MVNO $m \in \mathcal{M}$ aims to fulfill the rate requirement of its mobile users by allocating the bandwidth it receives from the InP. Then, the valuation of each MVNO $m \in \mathcal{M}$ can be expressed with the proportional fair allocation as follows:

$$v_m(r_m) = \max_{\mathbf{x^m_s}} \sum_{s=1}^{S_m} \log\left(x^m_s \log_2\left(1 + \frac{p^m_s h^m_s}{N_0}\right) - \rho^{\min}_{sm}\right) \tag{11}$$

$$\text{s.t.} \quad x^m_s \in [0, r_m], \forall s \in \mathcal{S}_m, \forall m \in \mathcal{M}, \tag{12}$$

$$\sum_{s=1}^{S_m} x^m_s \leq r_m, \forall m \in \mathcal{M}, \tag{13}$$

where $\rho^{\min}_{sm}$ is the minimum rate requirement of each user $s \in \mathcal{S}_m$ and p^m_s is the downlink transmitted power of the BS to the mobile user s. Moreover, h^m_s is the achievable channel gain of the mobile user s of MVNO m, N_0 is the noise power, and x^m_s represents a fraction of bandwidth of the MVNO m assigned to mobile user s where $x^m_s \in r_m$. (12) and (13) are the constraints for the fraction of wireless bandwidth allocated to each mobile user of MVNO $m \in \mathcal{M}$. By using, Lagrangian function and KKT conditions, we can get the closed-form solution of the problem (11) as follow:

$$x^{m*}_s = \frac{1}{|S_m|}\left[r_m - \sum_{s=1}^{S_m} \frac{\rho^{\min}_{sm}}{\alpha^*}\right] + \frac{\rho^{\min}_{sm}}{\alpha^*}, \forall s \in \mathcal{S}_m, \tag{14}$$

where $\alpha^* = \log_2\left(1 + \frac{p^m_s h^m_s}{N_0}\right)$. Due to the space page limitation, the detailed calculation cannot be expressed in this work.

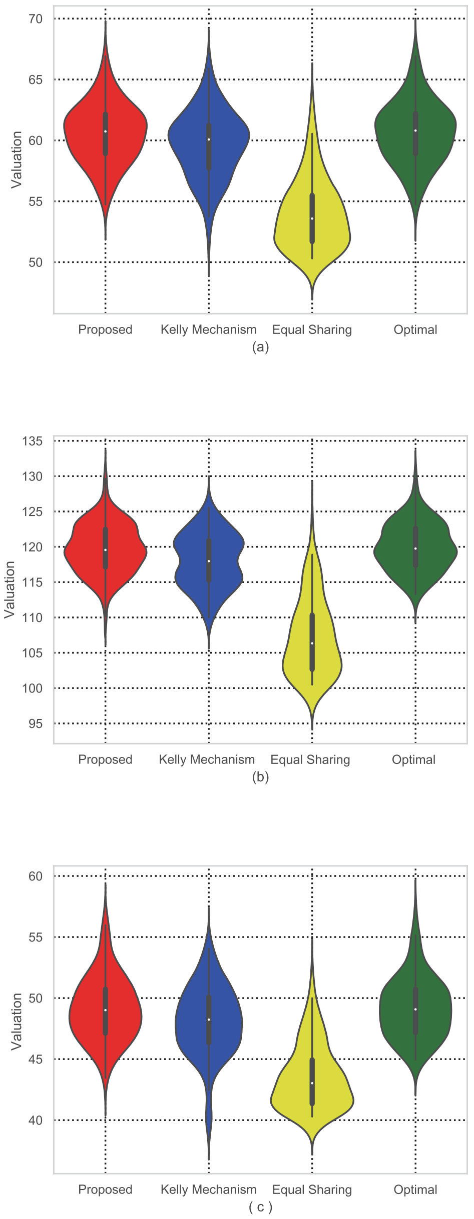

Fig. 2: Comparison of the achieved valuation for (a) MVNO-1, (b) MVNO-2, (c) MVNO-3.

III. Simulation Results

In this section, we demonstrate numerical results of our proposed GKM framework based bandwidth sharing to the users of MVNOs. Fig.2 demonstrates the valuation achievement of each MVNO as a function of allocated bandwidth using different algorithms: 1) proposed GKM algorithm, 2) traditional Kelly Mechanism, 3) equal sharing, where an InP allocates all bandwidth equally to all users of MVNOs, 4) optimal solution. From Fig.2, we can see that our proposed algorithm achieved higher valuation for all MVNOs where compared with traditional Kelly Mechanism, and equal sharing. Moreover, our proposed solution achieves near optimal solution.

IV. Conclusion

We have formulated a two-layer optimal bandwidth allocation problem for virtualized wireless network in this paper. At the upper-layer, the Generalized Kelly Mechanism (GKM) has been deployed to model MVNOs as bidders who compete for the bandwidth from the InP in order to serve their mobile users. The InP executes the bandwidth allocation process under the GKM to fulfill these requests. At the lower-layer, each MVNO adjusts the bandwidth allocation according to rate requirement of its users. Simulation results have confirmed the fairness of our proposed algorithm.

Acknowledgement

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (NRF-2017R1A2A2A05000995). *Dr. CS Hong is the corresponding author.

References

[1] Liang, Chengchao, and F. Richard Yu. "Wireless network virtualization: A survey, some research issues and challenges." IEEE Communications Surveys & Tutorials 17.1 (2014): 358-380.
[2] Haider, Aun, Richard Potter, and Akihiro Nakao. "Challenges in resource allocation in network virtualization." 20th ITC Specialist Seminar. Vol. 18. No. 2009. ITC, 2009.
[3] Tun, Yan Kyaw, et al. "Wireless Network Slicing: Generalized Kelly Mechanism-Based Resource Allocation." IEEE Journal on Selected Areas in Communications 37.8 (2019): 1794-1807.
[4] Tun, Yan Kyaw, et al. "Weighted Proportional Allocation Based Power Allocation in Wireless Network Virtualization for Future Wireless Networks." 2019 International Conference on Information Networking (ICOIN). IEEE, 2019.
[5] Tun, Yan Kyaw, Chit Wutyee Zaw, and Choong Seon Hong. "DownlinK power allocation in virtualized wireless networks." 2017 19th Asia-Pacific Network Operations and Management Symposium (APNOMS). IEEE, 2017.
[6] Boyd, Stephen, and Lieven Vandenberghe. Convex optimization. Cambridge university press, 2004.
[7] Ma, R. T., et al. "On resource management for cloud users: A generalized kelly mechanism approach." Electrical Engineering, Tech. Rep (2010).
[8] Pandey, Shashi Raj, et al. "A Downlink Resource Scheduling Strategy for URLLC Traffic." 2019 IEEE International Conference on Big Data and Smart Computing (BigComp). IEEE, 2019.