*DOI:*
10.1109/ICC.2017.7996490

*Document Version*
Peer reviewed version

# Network slicing in 5G: an Auction-Based Model

Menglan Jiang, Massimo Condoluci, Toktam Mahmoodi
Centre for Telecommunications Research
King's College London, London, UK
{menglan.jiang, massimo.condoluci, toktam.mahmoodi}@kcl.ac.uk

***Abstract*—The 5G mobile network is expected to meet the diverse demands from multiple types of business services. At the same time, some of the 5G use cases come with hard, and often expensive to meet, requirements in terms of latency and bandwidth. It is a common understanding that one system can not fit all and there is a need for customizing network according to the requirements of specific business use cases. Network slicing is introduced to partition the physical network to different slices to be configured for providing different quality of service as requested by the slice' operator and required by the slice' users. Since these slices will be used by the businesses, e.g. verticals, allocating physical resources to the network slices, is not anymore only a matter of performance but also a matter of revenue and business model. In this paper, we address a joint resource and revenue optimization a novel auction based model. Through extensive simulation study, we demonstrate our proposed auction model can allocate network resources to network slices for providing *(i)* higher satisfaction of requirements per network slice, and *(ii)* increased network revenue.**

***Index Terms*—5G; network slicing; auction model; resource allocation**

## I. Introduction

The next-to-come fifth generation (5G) mobile network is expected to open unprecedented business opportunities to telco operators by increasing their market to the business owners and providing not only business-to-customer service (B2C) services but also business-to-business (B2B) and and business to business to consumer (B2B2C) services. Large number of vertical industries are foreseen as natural users of 5G beyond the mobile broadband services, including healthcare automotive, smart cities, and industry automation [1]. In order to deliver services to such wide range of industries with diverse requirements, *network slicing* has been introduced in 5G networks, which can be then foreseen as a composition of multiple slices, each one designed with a set of functionalities tailored to serve a specific business.

From the network performance point of view, slicing implies that each 5G slice needs to have its own set of allocated resources and this aspect introduces a novelty in the management of network resources in mobile systems. Indeed, in the previous generations of mobile networks, the resources to be assigned to each application were mainly radio resources, while in the 5G network, resources represent both radio and core network [2], by means of computational and storage capabilities in addition to the over-the-air data rate. The definition by ITU in particular refers to a network slice as "a logically isolated network partitions comprising as programmable resources such as network, computation and storage" [3].From the business point of view, however, the issue of pricing a given slice is similar to pricing given spectrum, i.e., there is no clear way to value a given created slice by the operator. Therefore, there is a need for novel business model by the operators.

In order to consider the fact that slice allocation in 5G means allocating resources throughout the network, we model 5G network resources as multiple *chunks*, each one with a different capacity, spread across the whole physical network. This allows to take into consideration the management of resources in the core network in addition to the resources in the radio access. In order to optimize the network revenue by considering network utilization aspects, we focus on a resource management strategy based on a novel competitive auction mechanism combined with an optimization algorithm for network resources allocation. Therefore, objectives are increasing network utilization, enhancing satisfaction of requirements of network slices and increasing the incentive for operators by maximizing their revenue.

In this paper, we focus on a network slicing strategy based on a novel auction mechanism in order to maximize the network revenue. It is very well-suited compared with the other possible mechanisms. The network chunks and slices can interact with each other and our proposed auction mechanism can be viewed as an effective method for analysis of interactive decision making [4]. The proposed auction mechanism is applied to the problem of price decision in our proposed system model. Moreover, our proposed auction mechanism can be act as a key mechanism for resource allocating to network slices for maximising the network revenue. Compared with previous researches which mainly focus on price definition, our proposed auction mechanism considers the amount of network resources the network slices are requesting to the network. Therefore, our proposed auction mechanism can be used to enhance satisfaction of requirements of network slices and to maximize the network revenue.

In summary, the key contributions of this paper are summarized as follows.

- We formulate a novel business network model for providing 5G network slices computational and storage resources in order to satisfy their resource requirements optimally. The network slice manager has been designed to determine different prices of network chunks and provide a central view of the network information when required.

- By considering both the demand and provision in network chunks, we present a novel network slicing mechanism based on economic based auction mechanism for network slices. The proposed mechanism includes price auction mechanism which is designed to decide the selling price for different types of network chunks, and network slicing auction mechanism which is designed to maximize the network revenue.

The remainder of this paper is organized as follows. Section II briefly review the state of art in network virtualization for virtual resource sharing. After elaborating our system model and concept definitions in Section III, the problem formulations, our proposed resource sharing mechanism and pricing mechanism will be described in Section V. Section VI provides numerical results to verify our design objectives and analyses performance observations. Finally, summary of our work is detailed in Section VII.

## II. Related Works

In this section, we briefly overview the most relevant studies of auction based approaches for resource allocation.

From a resource allocation point of view, network slicing drives the business models behind 5G ecosystem and is strictly related to virtualization [5], enabling the management of network functionalities across the network. There are three different types of business models for network slicing which are B2B, B2C, and B2B2C [6]. In addition, several solutions for efficiently supporting network resource virtualization [7] and resource allocation by using auction approaches [8] have been proposed. They have been designed to improve the quality of experience (QoE) of mobile users and network utilization.

Focusing from a network resource slicing point of view, a resource allocation strategy of virtualized resources for Long Term Evolution (LTE) networks has been proposed in [9]. This work proposed a slicing scheme to allocate resource blocks to different service providers (SPs) in order to maximize the radio utilization. The proposed scheme was dynamic and flexible for addressing arbitrary fairness requirements of different SPs. In our previous work [10], we focused on the topic of slice association and resource allocation for mobile users with the aim of increasing the QoE the users.

From an auction point of view, game theory based resource auction mechanism have been widely investigated in existing works [11]. Nash equilibrium was considered as the solution for solving the problem of spectrum sharing in cognitive radio networks in [12]. Stackelberg game mechanism has been formulated for power control in wireless networks to maximize the capacity [13] [14]. In [15], an auction mechanism has been proposed to maximize the expected revenue of sellers. An auction-based scheme which can be used to develop a synchronous algorithm for solving the optimization problem of resource allocation has been proposed in [16]. The game theory based network virtualization framework has been described in [17] and an auction mechanism has been used for pricing the instantaneous rate consumption. Compared with the other game theory mechanisms, the auction mechanism was widely applied [16] [18] in the situation of competitive resource allocation. Meanwhile, effective allocation of network resources can improve the revenue of both users and networks. In [19], a competitive pricing model has been formulated in a dynamic spectrum access where a few primary services offer spectrum access opportunities to a secondary service.

## III. System Model

In this section, we will describe our system model in detail, also depicted in Fig. 1. The network resources are considered to be of different types, each referred to as network chunk (total number of network chunks is denoted by $\mathbb{M} = \{1, 2, ..., M\}$). The set of network chunk will shape a network slice, denoted by $\mathbb{K} = \{1, 2, ..., K\}$, to satisfy the requirements. Such augmentation of resources from radio access, core network and the cloud could be provided by different mechanisms, examples of which are in [20], [21] and [22].

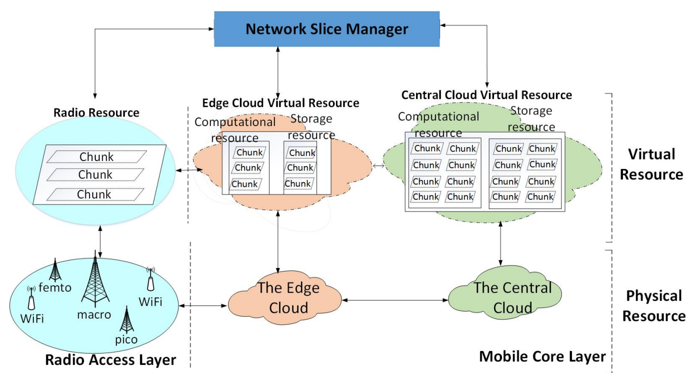


Fig. 1. Service and Network Slicing System Model

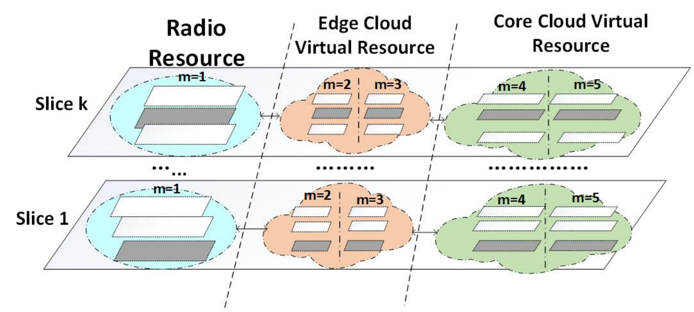


Fig. 2. Service Slice Model

For the allocation of resource chunks to network slices, we use the concept of priority level as according to the work in [10]. The priority level of each slice $k$ has been defined in the range of $\alpha_k = \{1, 2, ..., A\}$, where $A$ indicates the maximum priority level in our system model. The higher $\alpha_k$, the higher the priority level for the given slice $k$.

The system model supports allocation of different network resources to network slices, including resources from different radio access technologies, computational resource (i.e., CPU) and the storage resource. The capability of each network chunk $m$ is denoted by $\eta_m$ ($m \in \mathbb{M}$); this capacity has a different unit depending on the type of network chunk. The amount of resources assigned to each network slice $k$ from network chunk $m$ is denoted by $\sigma_{k,m}$ ($m \in \mathbb{M}$, $k \in \mathbb{K}$). The ratio of resource that slice $k$ receives from the chunk $m$ is denoted by $\frac{\sigma_{k,m}}{\eta_m}$. Moreover, in the real network environment, different network chunks will have different amount of resources, referred to as "weight value", and denoted as $\beta_m$ where $m \in \mathbb{M}$.

The network slice manager, within the depicted architecture in Fig. 1, is assumed to be an impartial entity [23]. In this case, cost values of different network chunks' per unit have been denoted as $\Omega_m = \{\omega_m | m \in \mathbb{M}\}$, and $C_m = \{c_m | m \in \mathbb{M}\}$ indicates the selling price per unit of the network chunk $m$.

Fig. 2 shows an example where an operator offers five different types of resource chunks to the slices. Such chunks are radio resource, the computational and the storage resource from the edge cloud, and the computational and the storage resource from the central cloud. The network resources required by slice $k$ from the network chunk $m$ is denoted by $\mathbb{R}_{k,m}$. $r_{k,m}$ and $R_{k,m}$ represent the minimum and maximum resource requirements by network slice $k$ from the network chunk $m$, respectively.

## IV. The Proposed Auction Model

The auction mechanism consists of two main parts: *a)* the price competition model; *b)* auction mechanism for network slicing.

In order to maximize the network revenue, the network slice manager should determine the price of network chunks $c_m$ by using auction mechanism. Then, the competitive auction mechanism for network slicing aims to achieve the optimal resource allocation. These two parts will be further elaborated below.

### A. Price Competition

The price competition model can be applied to achieve the equilibrium pricing, in a system where network chunks are willing to sell their resources to network slices based on slices' requirements. Therefore, the price strategy is determined by the network slice manager in terms of network utility values and capacity of network chunks, as well as the amount of resources requested by network slices.

The profit maximization of the network chunks is formulated as equation (1).

$$maximize \ \Theta(C_m, \sigma_{k,m}) \tag{1}$$

Where $\Theta(C_m, \sigma_{k,m})$ has been defined in equation (2),

$$\Theta(C_m, \sigma_{k,m}) = \sum_{m=1}^{M} \sum_{k=1}^{K} \sigma_{k,m} c_m - \omega_m \sum_{m=1}^{M} \eta_m \tag{2}$$

where $\omega_m$ is the cost value per unit of the virtual network resource chunk $m$, and the value of $\omega_m$ is defined as

$$\omega_m = \frac{\sum_{m=1}^{M} \eta_m}{\sum_{k=1}^{K} \sum_{m=1}^{M} \sigma_{k,m}}. \tag{3}$$

Then, the profit per unit of network chunk $m$ is given by

$$\theta_m(C_m, \sigma_{k,m}) = \sum_{k=1}^{K} \sigma_{k,m} c_m - \omega_m \tag{4}$$

where the partial differential of the price for the virtual chunk resource per unit is given by

$$\begin{aligned} \frac{\partial \theta_m(\eta_m)}{\partial c_m} &= \frac{\partial}{\partial c_m} (\sum_{k=1}^{K} \sigma_{k,m} c_m - \omega_m) \\ &= \sum_{k=1}^{K} \sigma_{k,m} + c_m \frac{\partial \sum_{k=1}^{K} \sigma_{k,m}}{\partial c_m} - \omega_m \frac{\partial \eta_m}{\partial c_m} \end{aligned} \tag{5}$$

In order to maximize the total profit of network chunks, we formulate the profit value so as to maximize the network chunks per unit. Therefore, $\frac{\partial \theta_m(\eta_m)}{\partial c_m} = 0$ and the equation (5) can be derived as,

$$\sum_{k=1}^{K} \sigma_{k,m} + c_m \frac{\partial \sum_{k=1}^{K} \sigma_{k,m}}{\partial c_m} = \omega_m \frac{\partial \eta_m}{\partial c_m} \tag{6}$$

$$\frac{\sum_{k=1}^{K} \sigma_{k,m}}{\frac{\partial \eta_m}{\partial c_m}} + c_m \frac{\partial \sum_{k=1}^{K} \sigma_{k,m}}{\partial \eta_m} = \omega_m \tag{7}$$

where we assume $\sum_{k=1}^{K} \sigma_{k,m} = \eta_m$. It means that the network resource of chunk $m$ has been totally sliced for all slices. Therefore,

$$\frac{c_m}{\frac{\partial \eta_m}{\partial c_m} \frac{c_m}{\eta_m}} + c_m = \omega_m \tag{8}$$

$$c_m \left( \frac{1}{\frac{\partial \eta_m}{\partial c_m} \frac{c_m}{\eta_m}} + 1 \right) = \omega_m \tag{9}$$

We assume that $\varepsilon = \frac{\partial \eta_m}{\partial c_m} \frac{c_m}{\eta_m}$, where $\varepsilon$ is a small positive value. Therefore, the value of $c_m$ is given by $c_m = \frac{\varepsilon}{\varepsilon+1} \omega_m$. Based on the price value $c_m$ of per unit network chunk $m$, we can also define our slice paid value based on their different priority level as in equation (10),

$$p_{k,m} = \alpha_k c_m \beta_m \tag{10}$$

where $p_{k,m}$ is the price paid by slice $k$ for the network chunk $m$. $c_m \beta_m$ indicates price of different network chunk $m$.

### B. Auction Mechanism for Network Slicing

In the state of the art, the auction mechanism has been widely used for price decision in order to improve the efficiency of network resource allocation. In the model described above, network slices can be considered as players and the aim of the auction mechanism is maximizing the network revenue for the owner (or operator) of the resource chunk.

To this end, our proposed auction based network slicing mechanism can be described as follows.

- Choosing the optimal amount of network resources to assign to network slice $k$ based on its resource requirements. The generated network revenue from network slice $k$ is denoted by $U_k(\sigma_{k,m}, p_{k,m}, \omega_m)$ as (11).

$$U_k = \sum_{m=1}^{M} p_{k,m} \sigma_{k,m} - \sum_{m=1}^{M} \omega_m \tag{11}$$

- Calculating the network revenue after removing the network slice $k$ from the system. It can be described as $U_{\mathbb{K}/\{k\}}(\sigma_{\mathbb{K}/\{k\},m}, p_{\mathbb{K}/\{k\},m}, \omega_m)$. Instead of allocating network resource to slice $k$ only based on its resource requirements, our auction mechanism forces the network slice manager to consider profit of the other slices $(K-1)$. The global objective of maximizing the total network revenue has been taken into account. The function of $U_{\mathbb{K}/\{k\}}$ has been defined in (12).

$$U_{\mathbb{K}/\{k\}} = \sum_{\mathbb{K}/\{k\}} \sum_{m=1}^{M} p_{\mathbb{K}/\{k\},m}\sigma_{\mathbb{K}/\{k\},m} - \sum_{m=1}^{M} \omega_m \quad (12)$$

- Maximizing the total network revenue by calculating $\sum_{k=1}^{K}(U_k - U_{\mathbb{K}/\{k\}})$.
- Finally, the network revenue generated by slice $k$ is described as equation (13).

$$U_k^{Auc} = U_k - (\max U_{\mathbb{K}/\{k\}}) \quad (13)$$

while the total network revenue is as follows,

$$U^{Auc} = \sum_{k=1}^{K} U_k^{Auc} \quad (14)$$

- Therefore, the optimized resource allocated to the network slice $k$ from the network chunk $m$ can be calculated according to (15).

$$\sigma_{k,m}^* = \arg U_k^{Auc} \quad (15)$$

## V. Problem Formulation

### A. Problem Formulation

In this paper, we aim to maximize the network revenue from both radio and cloud layers. The problem can be formulated as in (16).

$$\underset{\sigma_{k,m}^*}{\text{argmax}} \frac{U^{Auc}}{\sum_{k=1}^{K}[\sum_{m=1}^{M}\sigma_{k,m}^*]^{\alpha_k}} \quad (16)$$

$$\text{s.t.} \sum_{k=1}^{K}\sigma_{k,m}^* \leq \eta_m \quad (16a)$$

$$r_{k,m} \leq \sigma_{k,m}^* \leq R_{k,m}, \ \forall k \in K, \ \forall m \in M \quad (16b)$$

where $U^{Auc}$ is the network revenue and $\sigma_{k,m}^*$ is the amount of resources allocated to slice $k$ on chunk $m$ through the auction-based mechanism.

The aim of our proposed auction mechanism is to maximize the total network revenue while maximizing the capacity in terms of number of slices to be deployed. The constraint (16a) indicates that the amount of allocated resource cannot exceed the maximum available resources, while the constraint (16b) indicates that the received resource of the network slice $k$ must satisfy the resource requirements.

### B. Resource Slicing Mechanism

*1) Price Auction Mechanism:* The Bertrand based price auction mechanism has been proposed in order to receive the selling price of network chunks per unit. The players in each step are set of network chunks. The strategy of players is the price per unit which is non-negative.

According to the network resources required from the network slice $k$, the revenue of the network system can be expressed as in (14). In the price auction mechanism, a chunk cannot increase its profit by choosing a different action without affecting others [19]. In this case, the optimized result is obtained by defining a proper strategy for all participants from the whole view of the auction model. By the definition of the price auction mechanism in Section IV-A, we can receive the selling price of each network chunk.

*2) Resource auction Mechanism:* The auction-based resource allocation mechanism aims to maximize the network revenue and has been described in Algorithm 1. In the proposed mechanism, the benefit of using our auction mechanism is that it can guarantee to all the participants their QoS requirements, i.e., the assignment of, at least, the minimum amount of requested resources for each chunk. Moreover, while satisfying allocated network resources $\sigma_{k,m}$ to all participants, network revenue can be improved by our proposed auction mechanism as well.

**Algorithm 1:** Two-step Auction Mechanism for Resource Allocation

```
k: number of required service slices;
η_m^rest: the rest resource of chunk m;

for k := 1 to K do
    if R_{k,m} < η_m^rest then
        Calculate the network revenue because of slice k
          based on the Equation 11 where the value of
          received resource σ_{k,m} equals to the value of
          their maximized requirements R_{k,m};
        Then, calculate the network revenue value of the
          rest slices K − 1 according to the equation (12)
          where the value of received resource σ_{K/{k},m}
          equals to the value of their maximized
          requirements R_{K/{k},m};
    end
    if r_{k,m} < η_m^rest < R_{k,m} then
        Calculate the network revenue because of slice k
          based on the equation (11) ;
        Then, calculate the network revenue value of the
          rest slices K − 1 according to the equation (12);
    end
    Calculate the revenue value of slice k based on
      equation (14).
end
```

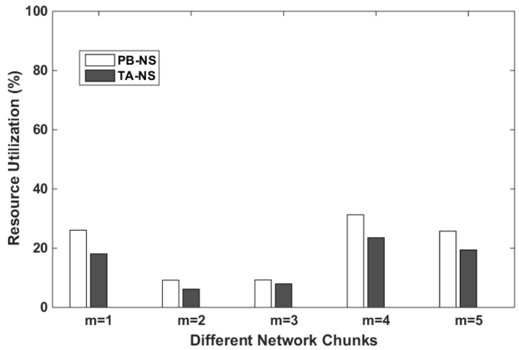


Fig. 3. Cumulative Network Resource Utilization (number of slices = 10)

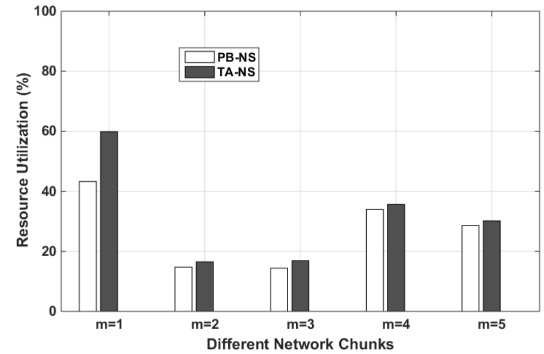


Fig. 4. Cumulative Network Resource Utilization (number of slices = 30)

## VI. Performance Investigation

In our simulation, we consider five different types of network chunks, as depicted in Fig. 2. Radio network chunks $(m = 1)$ are considered to take into account over the air resources. Values $m = 2, 3$ take into account storage and computational resources, respectively, at the edge network, while $m = 4, 5$ indicate such resources in the core network.

For the sake of simplicity, we assume that resources required by network slices is modeled as a ratio of the whole amount of resources available for each chunk. The amount of allocated resources to each network slice is described as $\sum_{k=1}^{K} \sigma^*_{k,m} \leq 100\%$. We set the amount of resources available in the radio network chunk to $100\%$. To take into consideration the fact that resources at the edge are scarcer than those in the core, we set the amount of storage and computational resources available at the edge to $40\%$, while we set these values to $60\%$ for the core network. Each slice requests a random portion of resources for each chunk. Finally, the priority of each slide is randomly chosen with the constraint that $\sum_{k=1}^{K} \alpha_k = 1$.

### A. Performance Strategies

In our evaluations, we evaluate the performance of two different strategies.

As a benchmark, we consider a *priced-based network slicing (PB-NS)* algorithm which is based only on price competitive mechanism, i.e., PB-NS implements (1).

Our proposed *two-step auction mechanism for network slicing (TA-NS)* is based on (16) and it is implemented as shown in Algorithm 1.

### B. Analysis of results

Fig. 3 and Fig. 4 show the performance in terms of resource utilization (i.e., the amount of assigned resources) for different network chunks. Fig. 3 considers a scenario with a limited number of slices (i.e., 10). In this case, the amount of allocated resources is lower for TA-NS w.r.t. PB-NS because the aim of TA-NS is to maximize the network revenue This means that TA-NS allocates more resources to slices generating more revenue (i.e., by taking into consideration slices' priority), while PB-NS tries to accommodate slices' requests without considering the priority and the related priority. In a scenario with few slices, increasing the amount of allocated resources does not meaningfully increase the revenue (this will be analyzed later). Fig. 4 consider a scenario with 30 slices. In this case, TA-NS shows higher resource utilization than PB-NS. That is due to the fact that, TA-NS minimizes the amount of resources allocated to slices generating less revenue in order to improve the allocation (and thus the revenue) for the slices with higher priority.

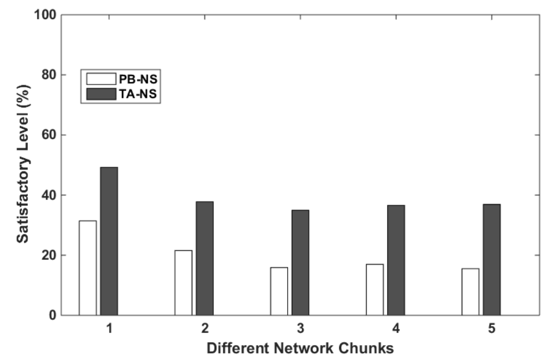


Fig. 5. Average Satisfactory Level of Slices from Each Network Chunks

Fig. 5 shows the average satisfactory level (for the case with 30 slices) for all network slices in different types of network chunks based on the equation $f_{k,m} = \frac{1}{k} \sum_{k=1}^{K} \frac{\sigma^*_{k,m} - r_{k,m}}{R_{k,m} - r_{k,m}}$. It can be noticed that TA-NS provides higher satisfactory level to network slices than PB-NS. This is because TA-NS takes into consideration the priority of slices and, as a consequence, it is able to maximize the satisfaction of slices with high priority while meeting the requirements of slices with lower priority. On the contrary, PB-NS has lower satisfactory levels as it does not consider the priority. Thus, PB-NS introduces higher dissatisfaction for slices with higher priority, and this consequently decreases the overall satisfaction.

Fig. 6 shows the cumulative network revenue by varying the number of network slices. Firstly, this analysis confirms the better behavior of our proposed TA-NS in being able to maximize the network revenue. Fig. 6 also shows that in scenarios with few number of slices (up to 6), TA-NS is able to offer a revenue equal to that of PB-NS even if the resource

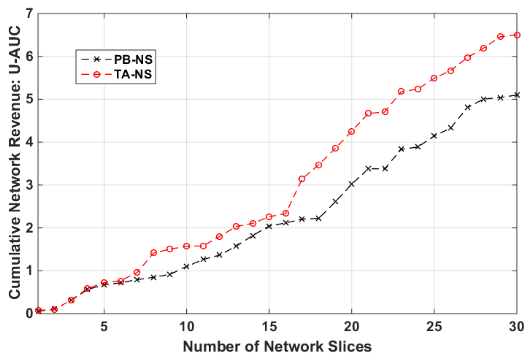


Fig. 6. Cumulative Network Revenue

utilization is lower (as shown in Fig. 3).

The results above testify that our proposed TA-NS is able to increase the network revenue by taking advantage of slices' priorities and without reducing the satisfaction experienced by the slices.

## VII. Conclusion

In this paper, we present a novel approach for network slicing in the 5G networks. Our proposed approach is an auction-based mechanism that considers radio network resources, the storage and the computational resources for performing resource and slice allocation. Our proposed auction based approach increases the network revenue and optimize the resource allocation by considering the limited network virtual resources. Extensive simulations show increase in total network revenue and efficiency in allocating network resources to network slices, as well as enhancement in satisfying their requirements.

## Acknowledgment

This work has been supported in part by the 5GPP VirtuWind (Virtual and programmable industrial network prototype deployed in operational wind park) Project.

## References

[1] "View on 5G Architecture." 5GPPP Architecture Working Group, White Paper, July 2016.

[2] P. K. Agyapong, M. Iwamura, D. Staehle, W. Kiess, and A. Benjebbour, "Design considerations for a 5G network architecture," *IEEE Communications Magazine*, vol. 52, pp. 65–75, Nov 2014.

[3] "Framework of Network Virtualization for Future Networks." ITU Y.3011, June 2012.

[4] J. Martyna, "Oligopoly bertrand model for price competition in cognitive radio networks," in *Communication Systems, Networks Digital Signal Processing (CSNDSP), 2014 9th International Symposium on*, pp. 227–231, July 2014.

[5] S. Abdelwahab, B. Hamdaoui, M. Guizani, and T. Znati, "Network function virtualization in 5g," *IEEE Communications Magazine*, vol. 54, pp. 84–91, April 2016.

[6] X. Zhou, R. Li, T. Chen, and H. Zhang, "Network slicing as a service: enabling enterprises' own software-defined cellular networks," *IEEE Communications Magazine*, vol. 54, pp. 146–153, July 2016.

[7] K. Zhu and E. Hossain, "Virtualization of 5g cellular networks as a hierarchical combinatorial auction," *CoRR*, vol. abs/1511.08256, 2015.

[8] Y. Zhang, C. Lee, D. Niyato, and P. Wang, "Auction approaches for resource allocation in wireless systems: A survey," *IEEE Communications Surveys Tutorials*, vol. 15, pp. 1020–1041, Third 2013.

[9] M. Kamel, L. B. Le, and A. Girard, "Lte wireless network virtualization: Dynamic slicing via flexible scheduling," in *Vehicular Technology Conference (VTC Fall), 2014 IEEE 80th*, pp. 1–5, Sept 2014.

[10] M. Jiang, M. Condoluci, and T. Mahmoodi, "Network slicing management and prioritization in 5g mobile systems," in *European Wireless, 2016*, May 2016.

[11] H. Zhang, C. Jiang, N. C. Beaulieu, X. Chu, X. Wang, and T. Q. S. Quek, "Resource allocation for cognitive small cell networks: A cooperative bargaining game theoretic approach," *IEEE Transactions on Wireless Communications*, vol. 14, pp. 3481–3493, June 2015.

[12] D. Niyato and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: a dynamic game approach," *IEEE Transactions on Wireless Communications*, vol. 7, pp. 2651–2660, July 2008.

[13] X. Kang, R. Zhang, and M. Motani, "Price-based resource allocation for spectrum-sharing femtocell networks: A stackelberg game approach," in *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pp. 1–5, Dec 2011.

[14] S. Guruacharya, D. Niyato, D. I. Kim, and E. Hossain, "Hierarchical competition for downlink power allocation in ofdma femtocell networks," *IEEE Transactions on Wireless Communications*, vol. 12, pp. 1543–1553, April 2013.

[15] J. Jia, Q. Zhang, Q. Zhang, and M. Liu, "Revenue generation for truthful spectrum auction in dynamic spectrum access," in *Proceedings of the Tenth ACM International Symposium on Mobile Ad Hoc Networking and Computing*, MobiHoc '09, (New York, NY, USA), pp. 3–12, ACM, 2009.

[16] Z. Suli, M. Zhongjing, and L. Xiangdong, "Efficient distributed resource allocation under synchronous auction-based algorithm," in *Control Conference (CCC), 2015 34th Chinese*, pp. 2720–2725, July 2015.

[17] F. Fu and U. C. Kozat, "Stochastic game for wireless network virtualization," *IEEE/ACM Transactions on Networking*, vol. 21, pp. 84–97, Feb 2013.

[18] P. Samadi, H. Mohsenian-Rad, R. Schober, and V. W. S. Wong, "Advanced demand side management for the future smart grid using mechanism design," *IEEE Transactions on Smart Grid*, vol. 3, pp. 1170–1180, Sept 2012.

[19] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of nash equilibrium, and collusion," *Selected Areas in Communications, IEEE Journal on*, vol. 26, pp. 192–202, Jan 2008.

[20] T. Mahmoodi and S. Seetharaman, "Traffic Jam: Handling the Increasing Volume of Mobile Data Traffic," *Vehicular Technology Magazine, IEEE*, vol. 9, pp. 56–62, Sept 2014.

[21] T. Mahmoodi and S. Seetharaman, "On Using a SDN-based Control Plane in 5G Mobile Networks," in *Wireless World Research Forum, 32nd Meeting*, May 2014.

[22] "Applying SDN Architecture to 5G Slicing." Technical Report, TR-526, April 2016.

[23] X. Li, G. Landi, J. Nez-Martnez, R. Casellas, S. Gonzlez, C. F. Chiasserini, J. R. Sanchez, D. Siracusa, L. Goratti, D. Jimenez, and L. M. Contreras, "Innovations through 5g-crosshaul applications," in *2016 European Conference on Networks and Communications (EuCNC)*, pp. 382–387, June 2016.