

STAR: Strategy-Proof Double Auctions for Multi-Cloud, Multi-Tenant Bandwidth Reservation

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Abstract—Bandwidth reservation has been recognized as a value-added service to the cloud provider in recent years. We consider an open market of cloud bandwidth reservation, in which cloud providers offer bandwidth reservation services to cloud tenants, especially online streaming service providers, who have strict requirements on the amount of bandwidth to guarantee their quality of services. In this paper, we model the open market as a double-sided auction, and propose the first family of Strategy-proof double Auctions for multi-cloud, multi-tenant bandwidth Reservation (STAR). STAR contains two auction mechanisms. The first one, STAR-Grouping, divides the tenants into groups by a bid-independent way, and carefully matches the cloud providers with the tenant groups to form good trades. The second one, STAR-Padding, greedily matches the cloud providers with the tenants, and fills the partially reserved cloud provider(s) with a novel virtual padding tenant who can be a component of the auctioneer. Our analysis shows that both of the two auction mechanisms achieve strategy-proofness and ex-post budget balance. Our evaluation results show that they achieve good performance in terms of social welfare, cloud bandwidth utilization, and tenant satisfaction ratio.

Index Terms—Data Center, Bandwidth Reservation, Double Auction.



1 INTRODUCTION

Cloud computing presents a new business model, in which Internet applications can rent computation, storage, and network resources by the means of virtual machines (VMs) from cloud providers, and pay for the usage of these resources. Attracted by much lighter burden of managing and maintaining fundamental service infrastructures, more and more Internet applications move their platforms to cloud providers, such as Netflix [1], a major online video streaming service provider in North America. Netflix moved its data storage system, streaming servers, encoding engine, and other major modules to Amazon Web Services (AWS) in 2010 [2].

However, many bandwidth-intensive application companies, especially online streaming service providers, are hesitating to move from their own infrastructures to the cloud providers, because

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- This work was supported in part by the State Key Development Program for Basic Research of China (973 project 2014CB340303 and 2012CB316201), in part by China NSF grant 61272443 and 61133006, in part by Shanghai Science and Technology fund 12PJ1404900 and 12ZR1414900, and in part by Program for Changjiang Scholars and Innovative Research Team in University (IRT1158, PCSIRT) China. The opinions, findings, conclusions, and recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the funding agencies or the government.

major cloud providers normally do not provide bandwidth guarantee. Thus, the bandwidth-intensive applications may not be able to maintain their quality of services(QoS) after moving to the cloud providers. Due to this reason, researchers from both industry and academia have started to design new cloud service architectures capable of supporting the need of bandwidth reservation [3]–[5]. As a value-added service, bandwidth reservation for guaranteeing various kinds of QoS requirements has been well recognized recently. For example, Niu *et al.* introduced a profit making broker to mix demands and negotiate the bandwidth prices with tenants in a free market [6], [7].

In this paper, we consider an open market of cloud bandwidth reservation, in which cloud providers (*e.g.*, Windows Azure [8], Amazon EC2 [9], and Google AppEngine [10]) offer bandwidth reservation services to cloud tenants (*e.g.*, Netflix, Hulu [11], and Youku [12]), who need certain amount of bandwidths to guarantee their QoS. Due to the fairness and allocation efficiency, auctions are attractive market-based mechanisms to distribute resource [13], and have been widely applied to solve the resource management in cloud computing [14], [15] and other research area [16]–[18]. We study the problem of cloud bandwidth reservation in a model of double auction, which enables multiple cloud providers and tenants to trade bandwidth dynamically.

However, designing a practical double auction mechanism for cloud bandwidth reservation has three

major challenges. One major challenge is strategy-proofness (please refer to Section 2.2 for the definition), which is inherited from traditional auction mechanisms. In a strategy-proof auction mechanism, simply reporting true valuation as a bid maximizes one's utility. Thus, any participant cannot benefit from manipulating the auction. Another major challenge is the divisibility of the bandwidth, which distinguishes it from traditional goods. Matching the cloud providers and the tenants is a combinatorial problem, in which an optimal allocation usually cannot be calculated in polynomial time. Therefore, classic strategy-proof auction mechanisms cannot be directly applied. Yet another major challenge is the ex-post budget balance (please refer to Section 2.2 for the definition), which guarantees that the auctioneer can benefit or at least do not lose anything from setting up an auction. Ex-post budget balance ensures that incentives of a trusted third party can be stimulated to build up a double auction for the cloud bandwidth reservation. We note that although several multi-unit double auction mechanisms have been proposed in the literatures (*e.g.*, [19], [20]) to solve similar allocation problems, none of them fully achieves both strategy-proofness and ex-post budget balance.

In this paper, we propose STAR, which is a family of Strategy-proof double Auctions for multi-cloud multi-tenant bandwidth Reservation. STAR contains two auction mechanisms, including STAR-Grouping and STAR-Padding. Both of the two auction mechanisms achieve strategy-proofness and ex-post budget balance. STAR-Grouping is a grouping-based strategy-proof double auction for cloud bandwidth reservation, in which tenants are grouped by a bid-independent way, and a trade is a match between a cloud provider and a tenant group. While STAR-Grouping can only be applied to some limited cases, the second auction mechanism, namely STAR-Padding, can be applied to general scenarios. STAR-Padding pads partially filled cloud provider(s) with a novel padding tenant, who has unlimited bandwidth demand, to guarantee strategy-proofness.

We make the following contributions in this paper.

- To the best of our knowledge, STAR is the first family of strategy-proof double auction mechanisms for multi-cloud multi-tenant bandwidth reservation.
- We model the problem of cloud bandwidth reservation as a double auction, and design practical auction mechanisms under this model.
- We first consider the scenario, in which the tenants' demands are indivisible and the cloud providers have the same bandwidth capacity, and propose STAR-Grouping, which is a grouping-based strategy-proof double auction for cloud bandwidth reservation. Specifically, STAR-Grouping divides the tenants into a number of groups by a bid-independent way, and careful-

ly matches the cloud providers with the tenant groups to form good trades.

- We further consider a general scenario, in which the bandwidth capacities of the cloud providers can be different and the tenants' demands are divisible, and propose a new double auction mechanism—STAR-Padding. STAR-Padding implements a virtual padding tenant with unlimited bandwidth demand to partially fill reserved cloud provider(s), and thus achieves strategy-proofness.
- Our analysis results show that both STAR-Grouping and STAR-Padding achieve ex-post budget balance in all the cases.
- Finally, we implement the two auction mechanisms and extensively evaluate their performance. Our evaluation results show that they both achieve good performance in terms of social welfare, cloud bandwidth utilization, and tenant satisfaction ratio.

The rest of this paper is organized as follows. In Section 2, we present technical preliminaries. In Section 3, we propose STAR-Grouping. In Section 4, we further propose STAR-Padding. In Section 5, we report evaluation results. In Section 6, we review related work. In Section 7, we conclude this work and discuss possible future work directions.

2 TECHNICAL PRELIMINARIES

In this section, we present our double auction model for the problem of multi-cloud multi-tenant bandwidth reservation, and review some important solution concepts used in this paper from classic mechanism design.

2.1 Auction Model

As shown in Fig. 1, we consider an open market of cloud bandwidth reservation, in which there are multiple cloud providers (*e.g.*, Windows Azure, Amazon EC2, and Google AppEngine), who offer guaranteed bandwidth reservation to cloud tenants, especially online streaming service providers (*e.g.*, Netflix, Hulu, and Youku). We introduce an auctioneer, who can determine the allocation of available bandwidth based on the supplies and demands of bandwidth.

We model the market of cloud bandwidth reservation as a double auction, in which there are m cloud providers, n tenants, and a trustworthy auctioneer. The auctioneer holds bandwidth reservation auction periodically. In each round, the cloud providers and the tenants simultaneously submit their sealed prices and bids to the auctioneer, respectively, so that no participant knows the prices/bids of any others. The auctioneer makes the decision on bandwidth reservation and payments/charges for the participants. We now give a detailed discuss with the entities in the double auction.

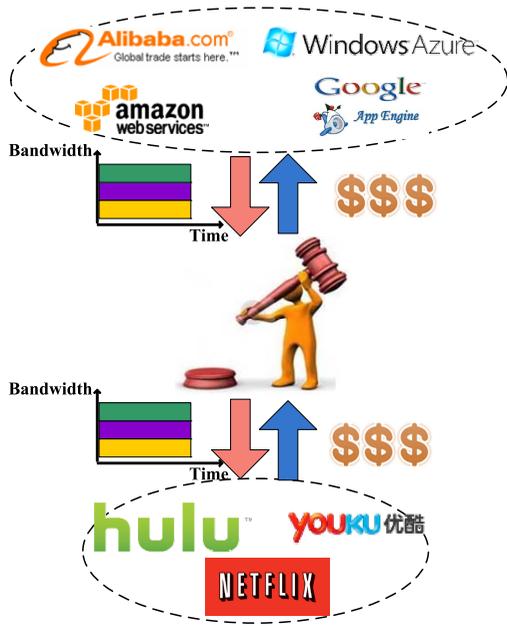


Fig. 1. An open market of bandwidth reservation between cloud providers and cloud tenants.

Cloud Provider: We denote the set of cloud providers by $\mathbb{M} = \{1, 2, \dots, m\}$. Each cloud provider $k \in \mathbb{M}$ has an outgoing bandwidth capacity B_k , and a per unit bandwidth serving cost c_k . Let $\vec{B} = (B_1, B_2, \dots, B_m)$ and $\vec{c} = (c_1, c_2, \dots, c_m)$ denote the profile of bandwidth capacities and per unit bandwidth costs, respectively. In the auction, each cloud provider $k \in \mathbb{M}$ submits her minimum per unit bandwidth selling price s_k and bandwidth capacity B_k to the auctioneer. We note that although the cloud provider k chooses a selling price s_k based on her real per unit bandwidth cost c_k , it is not necessary that s_k is equal to c_k , which is the private information of the cloud provider. Let $\vec{s} = (s_1, s_2, \dots, s_m)$ denote the profile of selling prices.

Tenant: There is a set of tenants, denoted by $\mathbb{N} = \{1, 2, \dots, n\}$, who are online streaming service providers. We assume that each tenant $i \in \mathbb{N}$ wants to reserve d_i units bandwidth to satisfy her requirement on QoS, and has a valuation v_i on each unit of reserved bandwidth. This valuation, which can be derived from the revenue gained by a tenant for serving her subscribers, is the private information of the tenant. We denote the valuation profile of the tenants by $\vec{v} = (v_1, v_2, \dots, v_n)$. Each tenant $i \in \mathbb{N}$ submits her per unit bandwidth bid b_i as well as her bandwidth demand d_i to the auctioneer. Similarly, b_i is not necessarily equal to v_i . Here, we assume that the tenants have strict requirements on the demands, meaning that the tenant i does not accept any bandwidth reservation less than d_i . Let $\vec{b} = (b_1, b_2, \dots, b_n)$ and $\vec{d} = (d_1, d_2, \dots, d_n)$ denote the profile of bids and bandwidth demands, respectively.

Auctioneer: The auctioneer is a trustworthy au-

thority, who determines the set of winning cloud providers $\mathbb{W}^M \subseteq \mathbb{M}$ and the set of winning tenants $\mathbb{W}^N \subseteq \mathbb{N}$, bandwidth reservation outcome matrix $A = (a_i^k)_{i \in \mathbb{N}, k \in \mathbb{M}}$, payment profile $\vec{p} = (p_1, p_2, \dots, p_m)$ for the cloud providers, and charge profile $\vec{q} = (q_1, q_2, \dots, q_n)$ for the tenants. Here, a_i^k denotes that the tenant i wins a_i^k units bandwidth from the cloud provider k .

We define the utility of a cloud provider $k \in \mathbb{M}$ be the difference between her payment and serving cost:

$$u_k^M \triangleq p_k - c_k \sum_{i \in \mathbb{N}} a_i^k.$$

Similarly, the utility of a tenant $i \in \mathbb{N}$ is the difference between her valuation on the reserved bandwidth and the charge:

$$u_i^N \triangleq v_i d_i - q_i.$$

We consider that the participants, including both the cloud providers and the tenants, are rational and selfish, thus their objectives are to maximize their own utilities. In contrast, the objective of the auctioneer is to prevent market manipulation (*i.e.*, guarantee strategy-proofness, which is defined in Section 2.2) and maximize the *social welfare*. Here, the social welfare is defined as follows.

Definition 1 (Social Welfare). *The social welfare in a double auction for cloud bandwidth reservation is the difference between the sum of winning tenants' valuations and the sum of winning cloud providers' serving costs on the bandwidth reserved.*

$$SW \triangleq \sum_{i \in \mathbb{N}} \sum_{k \in \mathbb{M}} (v_i - c_k) a_i^k. \quad (1)$$

We consider different auction scenarios in following sections. In Section 3, we consider the case, in which all the cloud providers have the same bandwidth capacity, *i.e.*, $B_1 = B_2 = \dots = B_m$ and the tenants' bandwidth demands are indivisible, *i.e.*, the reserved bandwidth only comes from one data center. In Section 4, we further extend to the general case, in which the bandwidth capacities of the cloud providers are different and the demands of the tenants are divisible, *i.e.*, the reserved bandwidth can come from different data centers.

In this paper, we assume that the cloud providers do not cheat their bandwidth capacities, and tenants do not lie about their bandwidth demands. This assumption restricts our mechanism falls into the family of conventional mechanism design with one-parameter domains [21], and make our problem tractable. We also assume that the participants, cloud providers and tenants as well as the auctioneer, do not collude with each other. We leave relaxation of these assumptions to our further work.

2.2 Solution Concepts

A strong solution concept from mechanism design is *dominant strategy*.

Definition 2 (Dominant Strategy [22], [23]). *Strategy* x_i is the player (cloud provider or tenant in this paper) i 's dominant strategy, if for any strategy (price or bid in this paper) $x'_i \neq x_i$ and any other players' strategy profile x_{-i} ,

$$u_i(x_i, x_{-i}) \geq u_i(x'_i, x_{-i}).$$

Intuitively, a dominant strategy of a player is the strategy that maximizes her utility no matter what strategy profile the other players choose.

The concept of dominant strategy is the basis of *incentive-compatibility*, which means that there is no incentive for any player to lie about her private information, and thus revealing truthful information is the dominant strategy for every player. An accompanying concept is *individual-rationality*, which means that for every player, truthfully participating in the game/auction is expected to gain no less utility than staying outside. We now can introduce the definition of *Strategy-Proof Mechanism*.

Definition 3 (Strategy-Proof Mechanism [24], [25]). *A mechanism is strategy-proof if it satisfies both incentive-compatibility and individual-rationality.*

Another critical property required to design economic-robust double auctions is *Ex-post Budget Balance*. We define auction profit Φ as the difference between the total charges collected from the tenants and the total payments given to the cloud providers:

$$\Phi \triangleq \sum_{i \in \mathbb{N}} q_i - \sum_{k \in \mathbb{M}} p_k.$$

A double auction is ex-post budget balanced if the profit of the auctioneer is non-negative, i.e., $\Phi \geq 0$.

Our objective of this work is to design strategy-proof double auctions for cloud bandwidth reservation, while guaranteeing ex-post budget balance. Note that the *Impossibility Theorem* [26] shows that no double auctions can simultaneously achieve strategy proofness, ex-post budget balance and maximum social welfare. Our designs first satisfy the economic properties while achieving the approximate maximum social welfare. This is also the general approach in double auctions design [20], [27].

2.3 McAfee Double Auction

McAfee double auction [28] is one of the most commonly used double auctions. It achieves strategy-proofness and ex-post budget balance for single-unit double auctions, but cannot be directly applied to auctions with divisible or multi-unit goods, such as bandwidth. Our designs follow the methodology of McAfee double auction, and successfully achieves both strategy-proofness and ex-post budget balance for cloud bandwidth reservation double auction.

We can summarize McAfee's design as follows.

- 1) It sorts the sellers (cloud providers) by their claimed prices in non-decreasing order:

$$s'_1 \leq s'_2 \leq \dots \leq s'_m,$$

and sorts the buyers (tenants) by their bids in non-increasing order:

$$b'_1 \geq b'_2 \geq \dots \geq b'_n.$$

Let $s'_{m+1} = +\infty$ and $b'_{n+1} = 0$.

- 2) It finds the maximum number of $k \leq \min\{m, n\}$, such that

$$b'_k \geq s'_k,$$

and

$$b'_{k+1} < s'_{k+1}.$$

- 3) Let

$$p_0 = \frac{b'_{k+1} + s'_{k+1}}{2}.$$

If $p_0 \in [s'_k, b'_k]$, the first k pairs of seller and buyer trade at price p_0 . Otherwise, only the first $k - 1$ pairs are valid trades, while the auctioneer pays each seller s'_k , charges each buyer b'_k , and keeps profit $(k - 1)(b'_k - s'_k)$.

Since McAfee double auction only matches a seller only to a single buyer, it cannot be directly applied to cloud bandwidth reservation double auctions, in which the bandwidth from a seller may satisfy the demands from multiple buyers. Therefore, we need to design new double auction mechanisms for cloud bandwidth reservation.

3 GROUPING-BASED AUCTION

In this section, we consider the case, in which the cloud providers have the same bandwidth capacity, i.e., $B_1 = B_2 = \dots = B_m = \beta$, and the bandwidth demands from the tenants are indivisible. Here, the demands are indivisible meaning that the tenants can only be allocated with the bandwidth from one data center. We present STAR-Grouping, which is a grouping-based strategy-proof double auction for cloud bandwidth reservation. STAR-Grouping follows the methodology of McAfee double auction. However, McAfee double auction only work with the scenarios of single-unit good, which is different from bandwidth. Unlike single-unit good, the bandwidth of a cloud provider can be allocated to multiple tenants, as long as the total demand of the tenants does not exceed the bandwidth capacity of the cloud provider. Therefore, major challenges in this problem are how to match each cloud provider with a group of tenants and how to design a pricing policy, such that both strategy-proofness and ex-post budget balance can be achieved. The design rationale is intuitive. We first form super buyers by grouping the tenants together, and carefully select a group bid for each super buyer.

After grouping, we can follow the design rationale of McAfee auction. We first present the details of STAR-Grouping and then analyze the properties of it, in this section.

3.1 Design Of STAR-Grouping

STAR-Grouping is composed of three parts: tenant grouping, winner determination, and price calculation.

3.1.1 Tenant Grouping

In order to prevent the tenants from strategically submitting untruthful bids to manipulate the auction, STAR-Grouping forms tenant groups in a bid-independent way. The grouping only depends on the bandwidth demands of the tenants. Specifically, STAR-Grouping iteratively applies a knapsack algorithm (e.g., [29]) on the set of remaining tenants to find a group of tenants that maximizes the sum of the bandwidth demands within the limit of cloud provider's bandwidth capacity β . The grouping process terminates when all the tenants are grouped. We denote the groups formed by

$$\mathbb{G} = \{G_1, G_2, \dots, G_g\},$$

s.t.,

$$G_j \cap G_l = \emptyset, \forall G_j, G_l \in \mathbb{G},$$

$$\text{and } \bigcup_{G_j \in \mathbb{G}} G_j = \mathbb{N}.$$

We now define each tenant group as a super buyer, and calculate the integrated bid Ω_l of each group $G_l \in \mathbb{G}$ as:

$$\Omega_l = \min\{b_i | i \in G_l\} \sum_{i \in G_l} d_i.$$

3.1.2 Winner Determination

STAR-Grouping sorts the cloud providers by the claimed selling prices in non-decreasing order:

$$\mathbb{L}_1 : s'_1 \leq s'_2 \leq \dots \leq s'_m,$$

and sorts the super buyers (tenant groups) by their integrated bids in non-increasing order:

$$\mathbb{L}_2 : \Omega'_1 \geq \Omega'_2 \geq \dots \geq \Omega'_g.$$

Let $s'_{m+1} = +\infty$ and $\Omega'_{g+1} = 0$.

STAR-Grouping finds the largest index $t \leq \min\{m, g\}$, such that

$$\Omega'_t \geq \beta s'_t, \quad (2)$$

and

$$\Omega'_{t+1} < \beta s'_{t+1}. \quad (3)$$

Then, STAR-Grouping calculates:

$$p_0 = \frac{\beta s'_{t+1} + \Omega'_{t+1}}{2}.$$

If $p_0 \in [\beta s'_t, \Omega'_t]$, then the first t matched pairs of cloud provider and tenant group are good trades, meaning that the first t cloud providers in the list \mathbb{L}_1 are winning cloud providers \mathbb{W}^M , and tenants in the first t groups in the list \mathbb{L}_2 are winning tenants \mathbb{W}^N :

$$\begin{aligned} \mathbb{W}^M &= \{\phi^s(1), \phi^s(2), \dots, \phi^s(t)\}, \\ \mathbb{W}^N &= \bigcup_{j=1}^t G_{\phi^b(j)}, \end{aligned}$$

where the function $\phi^s(t)$ and $\phi^b(t)$ return the t th cloud provider and the t th tenant group in \mathbb{L}_1 and \mathbb{L}_2 , respectively. Otherwise, the last match is sacrificed to guarantee strategy-proofness, and the first $t-1$ matches are good trades:

$$\begin{aligned} \mathbb{W}^M &= \{\phi^s(1), \phi^s(2), \dots, \phi^s(t-1)\}, \\ \mathbb{W}^N &= \bigcup_{j=1}^{t-1} G_{\phi^b(j)}. \end{aligned}$$

3.1.3 Price Calculation

If a participant, no matter a cloud provider or a tenant, does not win in the auction, she is free of any payment or charge. STAR-Grouping calculates the payments and charges for auction winners by distinguishing two cases:

- If $p_0 \in [\beta s'_t, \Omega'_t]$, then each winning cloud provider $k \in \mathbb{W}^M$ receives payment $p_k = p_0$, and each winning tenant group $G_l \subseteq \mathbb{W}^N$ is charged by p_0 . Every tenant $i \in G_l$ is charged proportionally to her amount of bandwidth reserved, which is equal to her bandwidth demand in this case:

$$q_i = \frac{d_i p_0}{\sum_{j \in G_l} d_j}.$$

- If $p_0 \notin [\beta s'_t, \Omega'_t]$, then each winning cloud provider $k \in \mathbb{W}^M$ receives payment

$$p_k = \beta s'_t,$$

and each winning tenant $i \in G_l \subseteq \mathbb{W}^N$ is charged:

$$q_i = \frac{d_i \Omega'_t}{\sum_{j \in G_l} d_j}.$$

The pseudo-code of above winner determination and price calculation is shown by Algorithm 1. In Algorithm 1, sorting is the most time consuming part. Algorithm 1's time complexity is $\mathcal{O}(n \log n + m \log m)$.

3.2 An Illustrative Example

Fig. 2 shows a toy example for using STAR-Grouping. As shown in Fig. 2, there are 4 cloud providers each with bandwidth capacity $\beta = 50$ units, and 11 tenants, which are divided into 4 tenant groups. The dashed eclipses represent the tenant groups. \mathbb{L}_1 and \mathbb{L}_2 indicate the sequence of the cloud providers and the tenant groups after sorting, respectively. The length

Algorithm 1: STAR-Grouping: Winner Determination and Price Calculation

Input: Set of cloud providers \mathbb{M} , bandwidth capacity β , set of tenants \mathbb{N} , vector of bandwidth demands \vec{d} , set of tenant groups \mathbb{G} , profile of the cloud providers' prices \vec{s} , and profile of the tenants' bids \vec{b} .

Output: Set of winning cloud providers \mathbb{W}^M , set of winning tenants \mathbb{W}^N , matrix of bandwidth reservation outcome A , profile of payments to cloud providers \vec{p} , and profile of charges for tenants \vec{q} .

```

1  $\mathbb{W}^M \leftarrow \emptyset$ ;  $\mathbb{W}^N \leftarrow \emptyset$ ;  $A \leftarrow 0^{n,m}$ ;  $\vec{p} \leftarrow 0^m$ ;  $\vec{q} \leftarrow 0^n$ ;
2 for  $l = 1$  to  $g$  do
3    $\Omega_l \leftarrow \min\{b_i | i \in G_l\} \sum_{i \in G_l} d_i$ ;
4 end
5 Sort cloud providers by claimed prices in
  non-decreasing order:  $s'_1 \leq s'_2 \leq \dots \leq s'_m$ ;
6 Sort tenant groups by integrated bids in
  non-increasing order:  $\Omega'_1 \geq \Omega'_2 \geq \dots \geq \Omega'_g$ ;
7  $s'_{m+1} \leftarrow +\infty$ ;  $\Omega'_{g+1} \leftarrow 0$ ;
8  $t \leftarrow \underset{t \leq \min\{m,g\}}{\operatorname{argmax}} \{\beta s'_t \leq \Omega'_t \wedge \beta s'_{t+1} > \Omega'_{t+1}\}$ ;
9  $p_0 \leftarrow (\beta s'_{t+1} + \Omega'_{t+1})/2$ ;
10 if  $p_0 \in [\beta s'_t, \Omega'_t]$  then
11    $p_0^s \leftarrow p_0$ ;  $p_0^b \leftarrow p_0$ ;
12 else
13    $t \leftarrow t - 1$ ;  $p_0^s \leftarrow s'_t$ ;  $p_0^b \leftarrow \Omega'_t$ ;
14 end
15 for  $l = 1$  to  $t$  do
16    $\mathbb{W}^M \leftarrow \mathbb{W}^M \cup \{\phi^s(l)\}$ ;  $\mathbb{W}^N \leftarrow \mathbb{W}^N \cup G_{\phi^b(l)}$ ;
17    $p_{\phi^s(l)} \leftarrow \beta p_0^s$ ;
18   foreach  $i \in G_{\phi^b(l)}$  do
19      $a_i^{\phi^s(l)} \leftarrow d_i$ ;  $q_i \leftarrow d_i p_0^b / \left(\sum_{j \in G_{\phi^b(l)}} d_j\right)$ ;
20   end
21 end
22 return  $\mathbb{W}^M$ ,  $\mathbb{W}^N$ ,  $A$ ,  $\vec{p}$ , and  $\vec{q}$ ;

```

of a rectangle indicates the amount of bandwidth capacity/demand from a cloud provider/tenant. The claimed selling prices and group bids are marked besides the cloud providers and the tenant groups, respectively. Since $\Omega'_2 \geq s'_2\beta$ and $\Omega'_3 < s'_3\beta$, the maximum index that satisfies constraints (2) and (3) is $t = 2$. The red box encloses the cloud provider and the tenant group with index t in their corresponding lists. Then, p_0 can be calculated

$$p_0 = \frac{\beta s'_3 + \Omega'_3}{2} = 560.$$

Since $p_0 \in [\beta s'_2, \Omega'_2]$, the first 2 pairs of cloud provider and tenant group are valid trades, and thus the participants involved in the first 2 pairs are auction winners. Each of the winning cloud provider gets payment 560. Suppose the tenant 1 demands 20 units of bandwidth, and the total demand of the group, to which the

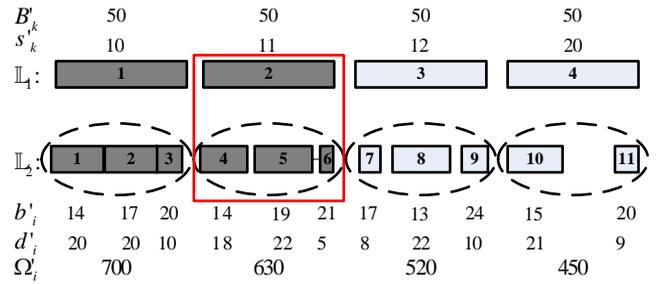


Fig. 2. An example for using STAR-Grouping.

tenant 1 belongs, is 50 units. Then, the charge for the tenant 1 is

$$q_1 = \frac{20p_0}{50} = 224.$$

While in this example STAR-Grouping does not sacrifice any potential trades, there exist bid profiles where STAR-Grouping has to sacrifice the last good trade to guarantee strategy-proofness.

3.3 Analysis

In this section, we prove that STAR-Grouping achieves both strategy-proofness and ex-post budget balance.

Before drawing the conclusion that STAR-Grouping is strategy-proof, we prove that STAR-Grouping satisfies individual rationality and incentive compatibility.

Theorem 1. *STAR-Grouping achieves individual rationality.*

Proof: Since a participant, who does not win in the auction, is free of any payment or charge, she still cannot be better by leaving the auction.

We then focus on the participants, who win in the auction. We distinguish two cases:

- $p_0 \in [\beta s'_t, \Omega'_t]$: For each winning cloud provider $k \in \mathbb{W}^M$, her utility is non-negative, when revealing truthful cost:

$$\begin{aligned}
 u_k^M &= p_k - c_k \sum_{i \in \mathbb{N}} a_i^k \\
 &= p_0 - c_k \sum_{i \in \mathbb{N}} a_i^k \\
 &\geq \beta s_k - c_k \sum_{i \in \mathbb{N}} a_i^k \\
 &= c_k \left(\beta - \sum_{i \in \mathbb{N}} a_i^k \right) \\
 &\geq 0.
 \end{aligned}$$

For each tenant i in winning tenant group $G_l \subseteq \mathbb{W}^N$, her utility is also non-negative, when bid-

ding truthfully:

$$\begin{aligned}
 u_i^N &= v_i d_i - q_i \\
 &= v_i d_i - \frac{d_i p_0}{\sum_{j \in G_l} d_j} \\
 &\geq v_i d_i - \frac{d_i \Omega_l}{\sum_{j \in G_l} d_j} \\
 &= d_i (v_i - \min\{b_j | j \in G_l\}) \\
 &\geq 0.
 \end{aligned}$$

- $p_0 \notin [\beta s'_t, \Omega'_t]$: Similarly, we can prove the non-negativity of the winning cloud providers' and tenants' utilities, by replacing p_0 with s'_t and Ω'_t in the previous proof, respectively. Due to limitations of space, we omit the proof here.

So any winner in the auction gets non-negative utilities when behaving truthfully, and her utility would be 0, if she stays out of the auction.

Therefore, STAR-Grouping achieves individual rationality. \square

Before proving the incentive compatibility of STAR-Grouping, we show that the winner determination is monotonic and the pricing is bid-independent, without detailed proof, due to limitations of space.

(1) Monotonic Winner Determination:

We present the following two lemmas to show that winner determination in STAR-Grouping is monotonic. Let \vec{b}_{-i} and \vec{s}_{-k} denote the bid profile of the tenants other than the tenants i and the price profile of the cloud providers other than the cloud provider k , respectively.

Lemma 1. *If the cloud provider k wins in STAR-Grouping by claiming price s_k , she also wins by claiming $s'_k < s_k$, given any \vec{s}_{-k} and \vec{b} .*

Lemma 2. *If the tenant i wins in STAR-Grouping by bidding b_i , she also wins by bidding $b'_i > b_i$, given any \vec{b}_{-i} and \vec{s} .*

(2) Bid-Independent Pricing:

Since the pricing is independent of the winners' bids or claimed prices, we have the following lemmas.

Lemma 3. *If the cloud provider k wins in STAR-Grouping by claiming price either s_k or s'_k , then the payment to her is the same in the two cases, given any \vec{s}_{-k} and \vec{b} .*

Lemma 4. *If the tenant i wins in STAR-Grouping by bidding either b_i or b'_i , then the charge to her is the same in the two cases, given any \vec{b}_{-i} and \vec{s} .*

We now prove the incentive compatibility of STAR-Grouping using the above lemmas.

Theorem 2. *STAR-Grouping achieves incentive compatibility.*

Proof: First, we prove that STAR-Grouping is incentive compatible for the tenants, by distinguishing two case:

- The tenant $i \in G_l$ wins in the auction and gets a non-negative utility u_i^N (by Theorem 1) when bidding truthfully, i.e., $b_i = v_i$. Suppose the tenant i manipulates her bid and loses in the auction, her utility is definitely no more than u_i^N . We then consider the other case, in which she cheats the bid (i.e., $b'_i \neq v_i$), and still wins in the auction. According to Lemma 4, STAR-Grouping charges the tenant i with the same price, so her utility remains the same.
- The tenant $i \in G_l$ loses in the auction and gets a zero utility when bidding truthfully, i.e., $b_i = v_i$. If she still loses, when manipulating her bid, her utility cannot be changed. We consider the case, in which the tenant i wins in the auction by manipulating her bid $b'_i > b_i$, and let p_0^b be the charge for the group G_l in this case. Let Ω_l and Ω'_l be the integrated bid of the group G_l , when the tenant i bids truthfully and not, respectively. Because the tenant i changes the auction result by increasing her bid, i must have the minimum bid in her group G_l when she bids truthfully, and then we have $\Omega'_l \geq p_0^b \geq \Omega_l$. We now show her utility still cannot be positive:

$$\begin{aligned}
 u'_i &= v_i d_i - q'_i \\
 &= v_i d_i - \frac{d_i p_0^b}{\sum_{j \in G_l} d_j} \\
 &= \frac{d_i}{\sum_{j \in G_l} d_j} \left(v_i \sum_{j \in G_l} d_j - p_0^b \right) \\
 &= \frac{d_i}{\sum_{j \in G_l} d_j} (\Omega_l - p_0^b) \\
 &\leq 0.
 \end{aligned}$$

Second, we can prove STAR-Grouping is also incentive compatible for the cloud providers, similarly. Due to limitations of space, we do not repeat the proof here.

Therefore, STAR-Grouping is incentive compatible for both the tenants and cloud providers. \square

By integrating Theorem 1 and Theorem 2, we can draw the following theorem.

Theorem 3. *STAR-Grouping is a strategy proof double auction for cloud bandwidth reservation.*

We next prove that STAR-Grouping is ex-post budget balanced.

Theorem 4. *STAR-Grouping achieves ex-post budget balance.*

Proof: We analyze the auction profit Φ by distinguishing two cases:

- $p_0 \in [\beta s'_t, \Omega'_t]$: Since the total payment and the total charge are the same in this case, the auction

profit is 0:

$$\Phi = \sum_{l=1}^t (p_0 - p_0) = 0.$$

- $p_0 \notin [\beta s'_t, \Omega'_t]$: The t th match of cloud provider and tenant group is used to set the clearing price. We have

$$\Phi = \sum_{l=1}^{t-1} (\Omega'_l - \beta s'_l) \geq 0.$$

So, no matter in which case, we always have $\Phi \geq 0$. This completes our proof. \square

We observe that some winning cloud providers may not be fully filled due to the tenant grouping method. The auctioneer proposes a virtual padding tenant, which will be discussed in detail in the next section, to collect these unallocated marginal bandwidths.

4 PADDING-BASED AUCTION

In this section, we consider the problem of cloud bandwidth reservation in a general scenario, in which the bandwidth capacities of the cloud providers can be different and the demands of the tenants are divisible. Here, demands are divisible meaning that a tenant can obtain bandwidth from different data centers as long as the sum of bandwidth meets her demand. In this case, grouping the tenants statically can no longer fit various bandwidth capacities of the cloud providers. Therefore, we propose a new strategy-proof double auction, namely STAR-Padding in this section.

When the cloud providers have various bandwidth capacities and the tenants have divisible demands, the major challenge for designing a strategy-proof double auction is the incentive compatibility for the partially filled cloud provider(s). A cloud provider may benefit by manipulating her claimed per unit bandwidth selling price to decrease her bandwidth allocated to tenants, and thus decrease her total serving cost. To address this problem, we propose a virtual *padding tenant*, who has unlimited bandwidth demand, to fully fill all the winning cloud providers' unallocated bandwidth. By introducing the virtual *padding tenant*, we can handle the manipulated behaviors of cloud providers, and make our mechanism strategy-proofness. The padding tenant can be implemented by the auctioneer herself, and thus the padding bandwidth can be counted as additional profit gained from organizing the auction. The auctioneer may further sell the padding bandwidth to her subscribers, who do not have strict bandwidth requirements, out of the cloud bandwidth reservation auction.

4.1 Design of STAR-Padding

The STAR-Padding contains two components: winner selection and price calculation.

4.1.1 Winner Selection

Similar to STAR-Grouping, STAR-Padding first sorts the cloud providers by the claimed selling prices in non-decreasing order:

$$\mathbb{L}_1 : s'_1 \leq s'_2 \leq \dots \leq s'_m,$$

and then sorts the tenants, instead of the tenant groups, by their bids in non-increasing order:

$$\mathbb{L}_2 : b'_1 \geq b'_2 \geq \dots \geq b'_n.$$

Let $s'_{m+1} = +\infty$ and $b'_{n+1} = 0$.

After sorting, STAR-Padding greedily reserves the bandwidth of the cloud providers for tenants using the water filling method. STAR-Padding "fills" the cloud providers one by one following the order specified in \mathbb{L}_1 , with tenants by the order of \mathbb{L}_2 . We note that the bandwidth demand of a tenant may be used to fill two or more consecutive cloud providers, and the bandwidth capacity of a cloud provider may be filled with one or more tenants' bandwidth demands.

STAR-Padding finds the largest indexes t and f in \mathbb{L}_1 and \mathbb{L}_2 , respectively, satisfying the following constraints:

$$\sum_{i=1}^f d'_i \leq \sum_{k=1}^t B'_k, \quad (4)$$

$$b'_{f+1} \cdot \sum_{i=1}^f d'_i \geq s'_{t+1} \cdot \sum_{k=1}^t B'_k, \quad (5)$$

where B'_k is the bandwidth capacity of the k th cloud provider in list \mathbb{L}_1 , and d'_i is the bandwidth demand of the i th tenant in list \mathbb{L}_2 . Here, constraint (4) indicates that the first t cloud providers have sufficient bandwidths to satisfy the demands of the first f tenants. Constraint (5) guarantees the ex-post budget balance. Then, the winners in the auction are the first t cloud providers and the first f tenants.

In STAR-Padding, the first t cloud providers' bandwidths are all sold out. Noting from constraint (4), there may be left over bandwidth if

$$\sum_{i=1}^f d'_i < \sum_{k=1}^t B'_k.$$

In this case, the auctioneer creates a padding tenant, and reserves bandwidth \bar{d} on the t th cloud provider for the padding tenant:

$$\bar{d} = \sum_{k=1}^t B'_k - \sum_{i=1}^f d'_i.$$

The bandwidth \bar{d} reserved for the padding tenant is taken by the auctioneer.

Algorithm 2: STAR-Padding: Winner Determination and Price Calculation

Input: Set of cloud providers \mathbb{M} , profile of bandwidth capacity \vec{B} , set of tenants \mathbb{N} , vector of bandwidth demands \vec{d} , profile of cloud providers' prices \vec{s} , and profile of tenants' bids \vec{b} .

Output: Set of winning cloud providers \mathbb{W}^M , set of winning tenants \mathbb{W}^N , matrix of bandwidth reservation outcome A , profile of payments to cloud providers \vec{p} , and profile of charges for tenants \vec{q}

- 1 $\mathbb{W}^M \leftarrow \emptyset; \mathbb{W}^N \leftarrow \emptyset; A \leftarrow 0^{n,m}; \vec{p} \leftarrow 0^m; \vec{q} \leftarrow 0^n;$
 - 2 Sort cloud providers by their selling prices in non-decreasing order: $s'_1 \leq s'_2 \leq \dots \leq s'_m;$
 - 3 Sort tenants by their bids in non-increasing order: $b'_1 \geq b'_2, \dots, \geq b'_n;$
 - 4 $s'_{m+1} \leftarrow +\infty; b'_{n+1} \leftarrow 0;$
 - 5 Find the largest indexes f and t satisfying constraints (4) and (5);
 - 6 Let $\phi^s(k)$ and $\phi^b(i)$ return the k th cloud provider and the i th tenant in \mathbb{L}_1 and \mathbb{L}_2 , respectively;
 - 7 $k \leftarrow 1; i \leftarrow 1;$
 - 8 **while** $k \leq t$ and $i \leq f$ **do**
 - 9 $\mathbb{W}^M \leftarrow \mathbb{W}^M \cup \{\phi^s(k)\}; \quad \mathbb{W}^N \leftarrow \mathbb{W}^N \cup \{\phi^b(i)\};$
 - 10 $p_{\phi^s(k)} \leftarrow s'_{t+1} \cdot B_{\phi^s(k)}; \quad q_{\phi^b(i)} \leftarrow b'_{f+1} \cdot d_{\phi^b(i)};$
 - 11 $a_{\phi^b(i)}^{\phi^s(k)} \leftarrow \min(B'_k, d'_i);$
 - 12 $B'_k \leftarrow B'_k - a_i^k; d'_i \leftarrow d'_i - a_i^k;$
 - 13 **if** $B'_k = 0$ **then**
 - 14 $k \leftarrow k + 1;$
 - 15 **end**
 - 16 **if** $d'_i = 0$ **then**
 - 17 $i \leftarrow i + 1;$
 - 18 **end**
 - 19 **end**
 - 20 **return** $\mathbb{W}^M, \mathbb{W}^N, A, \vec{p},$ and $\vec{q};$
-

4.1.2 Price Calculation

STAR-Padding pays each winning cloud provider $k \in \mathbb{W}^M$ by the $(t+1)$ th selling price in list \mathbb{L}_1 multiplying her capacity:

$$p_k = s'_{t+1} \cdot B_k.$$

Each winning buyer $i \in \mathbb{W}^N$ is charged by the $(f+1)$ th bid in the list \mathbb{L}_2 multiplying her demand:

$$q_i = b'_{f+1} \cdot d_i.$$

If a participant does not win in the auction, then she is free of any payment or charge.

The pseudo-code of above winner determination and price calculation is shown by Algorithm 2. The runtime of Algorithm 2 is $\mathcal{O}(n \log n + m \log m)$.

4.2 An illustrative Example

Fig. 3 shows a toy example for applying STAR-Padding. There are 4 cloud providers and 8 tenants,

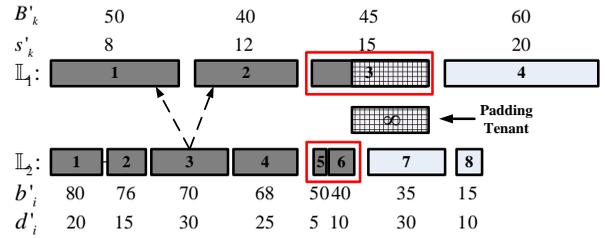


Fig. 3. An example for using STAR-Padding.

whose bandwidth capacities and demands are denoted by bars with different lengths, respectively. The claimed selling prices (bids) are marked besides the cloud providers (tenants). \mathbb{L}_1 and \mathbb{L}_2 indicate the sequence of the cloud providers and the tenants after sorting, respectively. STAR-Padding finds the largest index $f = 3$ and $t = 6$ according to constraints (4) and (5). So the first 3 cloud providers and the first 6 tenants are auction winners. Each winning cloud provider k gets payment $s'_t \cdot B_k$, where B_k is her bandwidth capacity, while each winning tenant i is charged $b'_f \cdot d_i$, where d_i is her bandwidth demand. Since the last winning cloud provider is not fully filled by the winning tenants' demands, the auctioneer generates a virtual padding tenant to fully fill the third cloud provider's bandwidth capacity.

4.3 Analysis

Since STAR-Padding pays each winning cloud provider with a higher price in list \mathbb{L}_1 and charges each winning tenant with a lower price in list \mathbb{L}_2 , we have the following theorem.

Theorem 5. STAR-Padding achieves individual rationality.

Similarly, we get that STAR-Padding has the properties of monotonic winner determination and bid-independent pricing.

(1) Monotonic Winner Determination:

Lemma 5. If the cloud provider k wins in STAR-Padding by claiming price s_k , she also wins by claiming $s'_k < s_k$, given any \vec{s}_{-k} and \vec{b} .

Lemma 6. If the tenant i wins in STAR-Padding by bidding b_i , she also wins by bidding $b'_i > b_i$, given any \vec{b}_{-i} and \vec{s} .

(2) Bid-Independent Pricing:

Lemma 7. If the cloud provider k wins in STAR-Padding by claiming price either s_k or s'_k , then the payment to her is the same for the two cases, given any \vec{s}_{-k} and \vec{b} .

Lemma 8. If the tenant i wins in STAR-Padding by bidding either b_i or b'_i , then the charge to her is the same for the two cases, given any \vec{b}_{-i} and \vec{s} .

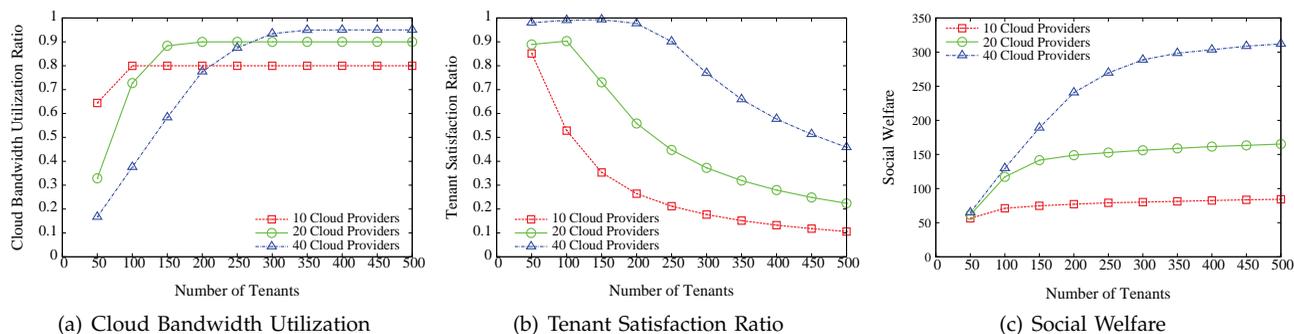


Fig. 4. Performance of STAR-Grouping, when the bandwidth capacity of each cloud provider is fixed at 3 units.

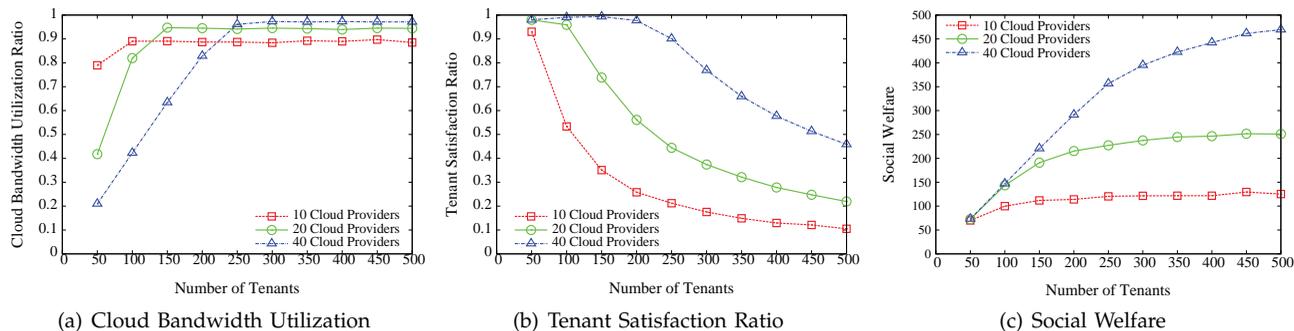


Fig. 5. Performance of STAR-Padding, when the bandwidth capacity of each cloud provider is uniformly distributed over (1,5].

Using the way to prove Theorem 2, we can prove the following theorem.

Theorem 6. *STAR-Padding achieves incentive compatibility.*

Due to limitations space, we omit the proof here.

Since STAR-Padding satisfies both individual rationality and incentive-compatibility, we can draw the following conclusion.

Theorem 7. *STAR-Padding is a strategy proof double auction for cloud bandwidth reservation.*

Finally, constraint (5) guarantees the ex-post budget balance.

Theorem 8. *STAR-Padding achieves ex-post budget balance.*

5 EVALUATION RESULTS

We implement STAR and conduct a series of simulations to evaluate its performance. In this section, we present our evaluation results.

5.1 Methodology

We consider a set of cloud providers offer bandwidth reservation to numbers of tenants. The cloud provider's cost of per unit bandwidth is normalized and uniformly distributed over $c_k \in (0, 1]$, while the tenant's valuation on per unit bandwidth is randomly selected in the interval $v_i \in [0.8, 5]$. Similarly, each

tenant's demand for bandwidth is also uniformly distributed over the normalized interval $d_i \in (0, 1]$. When we evaluate the performance of STAR-Padding, the reserved bandwidth amount of each cloud provider is randomly selected in the range of $B_k \in (1, 5]$. And we fixed the bandwidth capacity of each cloud provider at $B_k = 3$ units (i.e., the mean of 1 and 5) when studying the performance of STAR-Grouping. We conduct another experiment, in which all the random values are generate by a normal distribution¹. All the results on performance are averaged over 1000 runs.

We evaluate the performance of STAR in terms of the following three metrics.

- *Cloud bandwidth utilization:* Cloud bandwidth utilization is the proportion of the total bandwidth that is utilized/reserved in the auction. It also reflects the satisfaction ratio of cloud providers. Here, we use cloud bandwidth utilization and cloud provider satisfaction ratio interchangeably.
- *Tenant satisfaction ratio:* Tenant satisfaction ratio is the ratio of bandwidth demands that can be satisfied in the auction.
- *Social welfare:* As defined in Section 2.1, the social welfare is the difference between the sum of winning tenants' valuations and the sum of winning

1. The ranges of parameters can be different from the ones used here. However, the evaluation results of using different ranges are identical. Therefore, we only show the results of the above ranges in this paper.

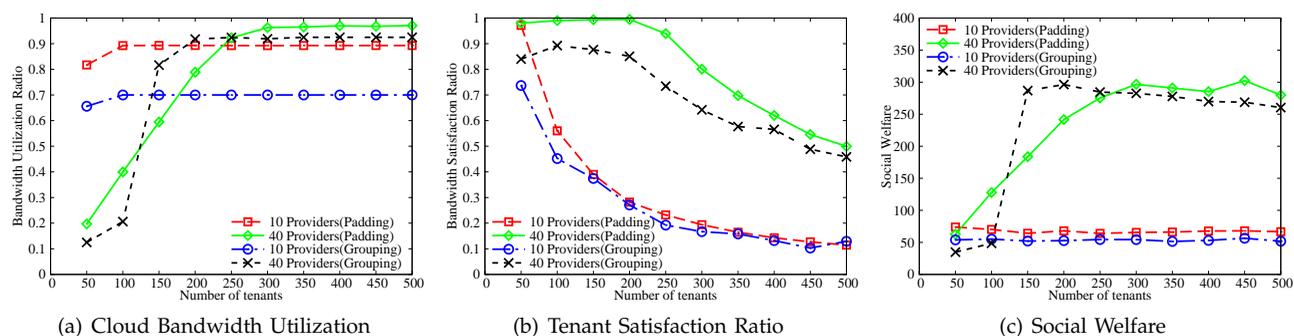


Fig. 6. Performance of STAR, when the bandwidth capacity of each cloud provider is normally distributed over (1,5].

providers' costs on the reserved bandwidths.

5.2 Performance on Bandwidth Reservation

Figure 4 shows the evaluation results of STAR-Grouping as a function of the number of tenants, when there are 10, 20 and 40 cloud providers and the bandwidth capacity of each cloud provider is fixed at 3 units.

Figure 4(a) illustrates the cloud bandwidth utilization of STAR-Grouping as a function of the number of tenants. We can see that STAR-Grouping bandwidth utilization almost linearly increases until the turning point is reached, and then stays in a stable saturation state. Furthermore, the bandwidth utilization ratio in saturation state is a constant less than 1, this is due to that STAR may sacrifice one potential trade to guarantee strategy-proofness. The saturation bandwidth utilization ratio of STAR-Grouping increases with the growth of cloud providers, because larger amount of bandwidth leads to smaller sacrifice ratio against the number of tenants. Generally, the tenant satisfaction ratio is relatively stable when the number of tenants is small, and then decreases as the number of tenants increases. The reason is that more tenants in the auction leads to more intense competition, and thus the tenant satisfaction ratio decreases. We notice that the tenant satisfaction ratio is higher when there are larger cloud providers. This is because the higher supply of bandwidth leads to more trades in the auction and more tenants are allocated bandwidth.

In Fig. 4(c), we study the social welfare, the goal, achieved by STAR-Grouping. It is shown that the social welfare grows with the number of tenants, but the speed of growth slows down, and gradually enter a saturation state as we mentioned in Fig. 4(a). Meanwhile, more cloud providers lead to higher social welfare, which fits our intuitions that more cloud providers can provide more bandwidth reservation.

In Fig. 5, we show the performance of STAR-Padding as the number of tenants increases, when there are 10, 20 and 40 cloud providers and the bandwidth capacity of each cloud provider is uniformly distributed over (1,5].

Figure 5(a) shows that STAR-Padding bandwidth utilization increases with the number of tenants, but the speed of growth is slowing, and gradually become saturated. The cloud provider leads to saturation state, because almost all bandwidth resource is reserved, when there are a large number of tenants. Similar to STAR-Grouping, more cloud providers lead to higher bandwidth utilization in the saturation state. Compared with STAR-Grouping, STAR-Padding achieves higher saturation bandwidth utilization ratio, since it sacrifices less bandwidth to guarantee strategy-proofness.

Figure 5(b) indicates that the bandwidth satisfaction ratio decrease as the scale of tenants grows. Again, the larger number of cloud providers leads to the higher tenant satisfaction ratio. This is because when the number of tenants is fixed, more cloud providers means higher supply of bandwidth, leading to more winning tenants. Therefore, the tenant satisfaction ratio increases.

Figure 5(c) shows the social welfare we can obtain when running STAR-Padding algorithm. Generally speaking, more tenants and more cloud providers lead to higher social welfare, as it was discussed in Fig. 4(c). On one hand, we can allocate the fixed bandwidth more efficiently when there are more tenants in the auction. On the other hand, for fixed number of tenants, more bandwidth would be reserved when the number of cloud providers increases, and thus the social welfare becomes larger.

Figure 6 shows the evaluation results of STAR when all the random values are generate by a normal distribution. We can see that the evaluation results are similar to that before. We do not repeatedly describe the explain here.

6 RELATED WORKS

In this section, we first review related work on bandwidth reservation for cloud computing, and then review the pricing mechanism for network resource sharing. Finally, we review the work with auction mechanisms design.

6.1 Bandwidth Reservation for Cloud Computing

A number of work have been proposed to solve the problem of bandwidth reservation for cloud computing in these years. Here, we briefly enumerate some practical systems for bandwidth reservation in cloud computing. NetShare [30] is a hierarchical max-min bandwidth allocation. It relies on a centralized bandwidth allocator to divide link bandwidth among tenants. In [31], the authors started from three requirements for cloud network sharing: min-guarantee, high utilization and payment proportionality, and then they propose three allocation policies to navigate these tradeoffs. Network virtualization technology has been widely used to provide the bandwidth sharing in cloud computing. SecondNet [4] is the first architectures to provide bandwidth guarantees for VMs through data center network virtualization. Oktopus [3] proposes two simplified virtual network abstractions: virtual clusters and virtual oversubscribed clusters, to explore the trade-off between bandwidth guarantees, costs and the provider revenue. Since SecondNet and Oktopus both offer the fixed bandwidth guarantees, Xie *et al.* [5] developed PROTEUS to capture the temporal dimension of bandwidth requirements. The proposed Time-Interleaved Virtual Clusters (TIVC) abstraction increases the overall datacenter utilization. Seawall [32] is a hypervisor-based framework that allows data center administrators to divide network and fairly share bandwidth among VM-pairs. Guo *et al.* considered the effects of larger numbers of short flows and massive bursty traffic in the datacenter, and designed a novel distributed bandwidth allocation algorithm based on the Logistic model [33].

Recently, some works considered the fairness of multiple resources (including CPU, memory and bandwidth) allocation in data center. Mesos [34] is a platform for multiple diverse cluster computing frameworks to share resources in a fine-grained manner. Fairness should be considered in designing resource allocation algorithms in a system containing multiple resource types. To address this problem, Ghodsi *et al.* proposed a novel game theoretic concept: Dominant Resource Fairness (DRF), a generalization of max-min fairness to multiple resource types [35]. Wang *et al.* generalized the notion of dominant resource fairness from a single server to multiple heterogeneous servers, and design a multi-resource allocation mechanism, called DRFH [36]. Guo *et al.* modeled the data center bandwidth allocation as a bargaining game and proposed Falloc, which is a new bandwidth allocation protocol for VM-based fairness across the data center [37].

6.2 Pricing Mechanism for Cloud Computing

The traditional cloud pricing model is pay-as-you-go [38], and the practical reservation models often

ignore the bandwidth resource. The traditional pricing and reservation models are not suitable for the needs of online streaming service providers. Cloud bandwidth reservation and charging has been identified as an important problem [6], [7], [14], [39]. Hitesh *et al.* [40] proposed a pricing scheme, considering location independent tenant costs in datacenters. Wang *et al.* [41] propose a optimal capacity segmentation for cloud providers to maximize their revenue in hybrid cloud pricing. Zhao *et al.* [39] considered the problem of dynamic pricing for the cloud with geodistributed data centers. To address the problem, they designed an efficient online algorithm, together with job scheduling and server provisioning in each data-center, to maximize the profit of the cloud provider. Game theory has been considered an effective method of resource allocation for cloud services [42]. Niu *et al.* introduced a profit making broker to statistically mix demands and negotiate the bandwidth prices with tenants in a free market [6], [7]. However, their approaches inherit shortcomings of Nash equilibrium. One collusion-resistant cloud resource pricing scheme based on combinatorial auction is introduced in [14], and achieve a stronger solution concept: dominant equilibrium. In [43], a randomized combinatorial auction is designed for dynamic resource provisioning in cloud computing. Zhang *et al.* [15] designed a novel bidding language for users to express their heterogeneous demands. Besides, building on top of the bidding language, the authors propose COCA, an incentive compatible online cloud auction mechanism. Considering several types of available resources in cloud, Mashayekhy *et al.* [44] designed online mechanisms for VM provisioning and allocation.

In contrast to these work, we propose a family of strategy-proof auction mechanisms for cloud bandwidth reservation in this paper. Our approaches achieve not only strategy-proofness, but also ex-post budget balance.

6.3 Auction Mechanisms Design

We study the problem of cloud bandwidth reservation in a model of double auction, which has been studied for decades. Conventional double auction mechanisms can be partitioned into single-unit [28], [45] and multi-unit auctions [19], [20]. Most of previous work follow the design rational of McAfee's mechanism [28], sacrificing one effective trade to ensure strategy-proofness. Huang *et al.* [20] simply assume that the buyers' demands are divisible and un-strict, *i.e.*, the buyers can accept part of demands. None of these mechanisms can be applied directly into cloud bandwidth reservation market.

Many strategy-proof mechanisms have been proposed to address different kinds of resource allocation problems, such as spectrum allocation in wireless network [16], [27], [46]–[51], influence maximization

in social network [18], incentive mechanism design in mobile crowdsensing [17], [52].

7 CONCLUSION AND FUTURE WORK

In this paper, we have modeled the problem of cloud bandwidth reservation as a double-sided auction, and propose STAR, which is the first family of strategy-proof double auctions for multi-cloud, multi-tenant bandwidth reservation. STAR contains two auction mechanisms, namely STAR-Grouping and STAR-Padding. STAR-Grouping is applied in the scenario, in which the cloud providers have the same bandwidth capacity and the tenants' demands are indivisible, while STAR-Padding can be used in the general scenario, in which the bandwidth capacities of the cloud providers can be different and the tenants' demands are divisible. We have theoretically proven that both of the two auction mechanisms achieve strategy-proofness and ex-post budget balance. To the best of our knowledge, STAR is the first multi-unit double auction mechanism, achieving both strategy-proofness and ex-post budget balance. We also extensively evaluated the performance of STAR. Our evaluation results have shown that STAR achieve good performance in terms of social welfare, cloud bandwidth utilization, and tenant satisfaction ratio.

As for future work, one direction is to design double auction mechanisms that can prevent false-name bidding for cloud bandwidth reservation. Another direction is extending our work to online double auctions to adapt dynamic bandwidth demands/supplies changing from the tenants/cloud providers. Extending STAR to address cheating on bandwidth demands and capacities is also an interesting research problem.

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