ESTRA: Incentivizing Storage Trading for Edge Caching in Mobile Content Delivery

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***Abstract*—The explosion of mobile content and usage imposes enormous pressures on mobile communication networks. To reduce content delivery latency and to ease the burden on network bottlenecks (*e.g.*, backhaul networks), besides upgrading the infrastructures, it is promising to cache popular contents at the edge-storage on BSs (Base Stations), APs (Access Points) or other third-party devices associated with BSs and APs, which have been widely deployed in mobile networks. Then it is a challenge here to effectively match such demands of CPs (Content Providers) and the supplies of edge-storage owners because of the complexity caused by the two-fold matching requirements on both coverage and quantity combined with the multi-buyer multi-seller scenario and the divisibility of heterogeneous edge-storages. In this paper, we propose *ESTRA* (Edge Storage TRading Auction) mechanism to tackle such a challenge. By proposing a region-based model for edge-storage trading, we design a demand cover mechanism to transfer subscriber coverage demands into edge-storage bundle demands and design a *truthful, weakly budget balanced* and *individually rational* auction mechanism under the constraints of enabling multi-unit asks and bundle bids. Our theoretical analysis proves the economic robustness, and the simulation result shows that *ESTRA* achieves $74\% \sim 91\%$ of the maximum social welfare and maintains the sustainability of the trading platform through a proper distribution of social welfare.**

I. Introduction

Even with the rapid development of mobile communication technologies, mobile network capacities are still limited compared with the exploding mobile content demands, especially on bandwidth consuming requests like videos. To meet the expanding demands and improve user experience, MNOs (Mobile Network Operators) can upgrade the mobile communication technologies, and CPs (Content Providers) can optimize the content delivery in mobile networks.

The bottlenecks of mobile data transmission are at the backhaul networks or content servers because they are the places where the data streams aggregate [1]. To ease the burden on these bottlenecks and significantly reduce the latency of delivering contents, it is a promising solution to place contents on the highly distributed edge networks of the mobile network [1][2][3]. Moreover, such caching will eliminate the burdens on backhaul networks, which will help reduce the operational costs of MNOs.

However, it is expensive for CPs, who have the demands of edge caching, to deploy highly distributed cache servers in all edge networks. Fortunately, with the development of mobile communication, there are already many built-in and third-party storages at edge networks [2][3][4], such as those on Femtocell BSs (Base Stations), smart WiFi APs (Access Points), *etc*. Then these CPs, who are planning to place popular contents at the edge networks, can buy caching storage from these storage owners.

Effective mechanisms should be designed to match such demands and supplies on edge-storage, an important type of network resource in future mobile networks [1][3], and the auction is an efficient market-based mechanism to allocate network resources [5]. However, several significant challenges exist due to the specific constraints in edge-storage trade. *First*, CPs focus on their *subscriber coverage demands* over broader area while the storage providers publish their storage supplies over isolated edge networks, each of which covers a limited region. A two-fold matching requirement on both edge-storage coverage and quantity need to be satisfied. *Second*, there exist heterogeneous edge-storages due to their different coverage and edge network connectivity. The direct applications of classical economic-robust mechanisms, such as VCG and McAfee, cannot guarantee the truthfulness in a heterogeneous commodity trade [6]. *Third*, it is an intrinsic property of edge-storage to be continuously-divisible, which brings more complexity and difficulties in designing an economic-robust trading mechanism, compared with single-unit indivisible commodities. *Fourth*, in this work, we consider that there are multiple CPs (*buyers*) who prefer to take advantage of edge-storage, and there are multiple storage providers (*sellers*). It is more challenging to design economic-robust mechanisms for multi-seller multi-buyer scenarios than for one-sided markets.

In this paper, we propose an edge-storage trading framework that tackles the above challenges. The key contributions are listed as follows. **1)** We design a region-based model for edge-storage trading and then propose a demand cover mechanism to transfer subscriber coverage demands into edge-storage bundle demands for conducting the edge-storage auction. **2)** We propose an auction mechanism for multi-unit divisible edge-storage and prove that it is *truthful*, *weakly budget balanced* and *individually rational* under the constraints of enabling bundle bids. The factors that will affect efficiency loss are also analyzed. **3)** Our extensive simulation shows that our mechanism achieves reasonable level of social welfare compared with optimal allocation and it provides

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utility incentives to attract more participants.

Section II sets up the system model and provides problem formulation. Section III demonstrates the proposed trading framework in detail and proves the economic properties of the proposed mechanism. The edge-storage trading simulation and the mechanism performance evaluation are shown in Section IV. We introduce the related works in Section V, before we conclude the paper in Section VI.

II. System Model and Problem Formulation

A. Overview of Edge Caching

The overview of edge caching in mobile content delivery is shown in Figure 1, from which we can see various edge caching scenarios defined by the types of edge network and edge storage. For example, the edge networks include cell networks of various coverage areas, WLANs, *etc.* And edge storage can be the built-in storage of BSs and APs, third-party storage (*e.g.*, PC) that is connected to edge networks, *etc.*

If certain economic properties are guaranteed, the mechanism will motivate the participation of the trading. CPs reduce bandwidth costs on their own content servers or CDNs through edge caching of popular contents. Storage owners earn profits through selling idle storage and the auctioneer earn a nonnegative revenue through matching demands and supplies. The interaction between the participants and other related roles who are not involved in the trade, such as benefit distribution among CPs and operators [7], is left to future works.

B. System Model and Bidding Language

The edge caching in mobile networks is closely related to locations because of the mobility of mobile users and the geographically distributed content demands. Therefore, we set up a region-based model to discuss the caching storage trading, as shown in Fig. 2. The whole considered area $\mathbb{R}$ is divided into a set of M *disjoint* small regions R_m ($m \in \mathbb{M} = \{1, 2, \cdots, M\}$). Upon these regions, there are K edge networks denoted by N_k ($k \in \mathbb{K} = \{1, 2, \cdots, K\}$), which have a one-to-one correspondence with edge network infrastructures (*i.e.*, BSs and APs). $\mathcal{C}(\cdot) \subseteq \mathbb{R}$ refers to the valid *coverage* of an edge network, for example, $\mathcal{C}(N_1) = \{R_1, R_2\}$ in Fig. 2. Every region is *atomic*, which means that for every single edge network, the region is either totally or not at all covered, instead of being partially covered.

The number of storage entities is J and S_j denotes the corresponding seller of storage j ($j \in \mathbb{J} = \{1, 2, \cdots, J\}$). The *type* of storage j, $K_j \in \mathbb{K}$, is determined by its associated edge network, which means that multiple storage entities associated with the same edge network are treated as *homogeneous*, such as S_4 and S_5 in Fig. 2. The *coverage* of storage j is defined as $\mathcal{C}(S_j) = \mathcal{C}(N_{K_j})$. $\mathbf{A}_j = (a_j, s_j)$ is the *ask* profile of seller j, where a_j is the *unit ask* and s_j is the *amount* of supply.

Buyers are denoted by Y_i ($i \in \mathbb{I} = \{1, 2, \cdots, I\}$). In reality, buyers (*e.g.*, CPs) care about their content delivery to subscribers over broader regions (*subscriber coverage demands*) rather than focusing on every atomic region, so the bid profile of buyer i is defined as $\mathbf{B}_i = (\mathbb{R}_i, d_i, b_i)$. $\mathbb{R}_i \subseteq \mathbb{R}$ denotes buyer i's *demand region*, d_i denotes the *amount* of demand and b_i denotes his *bid*. That is to say, buyer i is willing to pay b_i for caching contents of volume d_i to meet the requests of subscribers within region $\mathbb{R}_i$. Buyer i's demands on each type of storage is denoted by $\mathbf{B}_i^T = (d_i^1, \cdots, d_i^k, \cdots, d_i^K)$, where d_i^k is the demands on storage of type k.

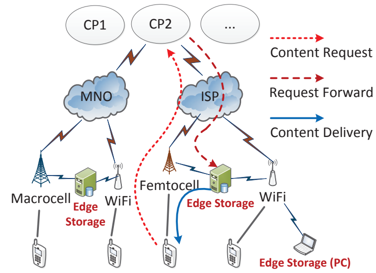


Fig. 1. Overview of Edge Caching

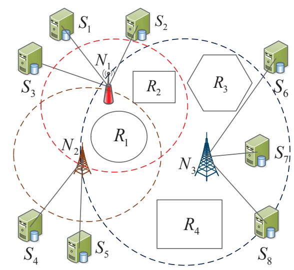


Fig. 2. Region-Based Model

C. Problem Formulation

The purpose of this paper is to explore an effective trading framework to match the demands and supplies of edge-storage. It is important for the proposed trading mechanism to be *truthful/incentive compatible (IC)*, *weakly budget-balanced (BB)* and *individual rational (IR)*. *IC* guarantees the truthful revelation of buyers' and sellers' values on the storage. The region and amount of demands are assumed to be public knowledge and the analysis on their truthfulness is left to future works. *BB* guarantees that the profit of the auctioneer is nonnegative, which is necessary for the sustainability of the trade. *IR* guarantees that all buyers and sellers will gain a nonnegative utility through participating the trade, which is of vital importance for attracting buyers and sellers.

The utilities of the participants are defined as their trading surpluses. *We assume all bids and asks to reveal their true values for the convenience of analysis, and we will prove the truthfulness of the proposed mechanism in Section III-D.* The bundle demands of buyers can be partially met because the contents can be cached as divided blocks and the number of cached blocks can be reduced if the demand is partially met. The *ex post* popularity ranks of contents cannot be determined before caching due to the uncertainty of consumer requests. Therefore, buyers' gained values are assumed to have a linear relationship with the proportion of met demand. Then the utility of buyer i can be denoted by $u_i = b_i x_i - p_i$, where $x_i \in [0, 1]$ refers to the proportion of demand that is met in the trade and p_i refers to the payment of buyer i. Seller j's utility can be denoted by $u_j = p_j - a_j y_j$, where p_j refers to the charge of seller j and $y_j \in [0, s_j]$ refers to the sold-out amount. The utility of the auctioneer can be denoted by $u_a(\mathbb{I}, \mathbb{J}) = \sum_{i \in \mathbb{I}} p_i - \sum_{j \in \mathbb{J}} p_j$. The *social welfare* is defined as the sum of all participants' utilities, *i.e.*, $U(\mathbb{I}, \mathbb{J}) = \sum_{i \in \mathbb{I}} u_i + \sum_{j \in \mathbb{J}} u_j + u_a(\mathbb{I}, \mathbb{J}) = \sum_{i \in \mathbb{I}} b_i x_i - \sum_{j \in \mathbb{J}} a_j y_j$.

According to *Myerson-Satterthwaite theorem* [8], we cannot achieve *efficiency* when the above three properties hold. Therefore, our goal is to achieve maximum social welfare under the three property constraints, which can be expressed by:

$$
\begin{aligned}
\max \quad & U(\mathbb{I}, \mathbb{J}) \\
s.t. \quad & \textstyle\sum_{i \in \mathbb{I}} d_i^k x_i = \sum_{j \in \mathbb{J}, K_j = k} y_j, & \forall k \in \mathbb{K} \\
& 0 \leqslant x_i \leqslant 1, & \forall i \in \mathbb{I} \\
& 0 \leqslant y_j \leqslant s_j, & \forall j \in \mathbb{J} \\
& \textit{IC},\ \textit{BB and IR}
\end{aligned}
$$

III. Edge Storage Trading Framework

In this section, *ESTRA* (Edge Storage TRading Auction mechanism) is proposed for edge-storage trading.

A. Design Rationale

As discussed in Section II-B, the demands of buyers focus on broader areas while the supplies of sellers are restricted in the defined atomic regions. We design a two-step allocation mechanism *ESTRA* to match the demands and supplies.

First, a demand cover mechanism is designed to satisfy subscriber coverage demand with a proper bundle of seller supplies. The demand over broader areas is divided into region-based demands, which will then be transferred into bundle demands over edge-storages.

Second, an edge-storage double auction mechanism is proposed to meet the bundle demands with sellers' multi-unit supplies. Inspired by the trade reduction approach [9] and the multistage design approach [10], we propose a truthful double auction mechanism, which allocates the storage through two linear program optimizations and prices participants according to their roles and allocation result. As mentioned in Section II-C, to guarantee *IC*, *BB* and *IR*, the social welfare has to be sacrificed. So we introduce a trade reduction in the storage allocation. After the allocation, the payments of buyers are determined by their "winning thresholds" and the charges of sellers are derived by their VCG-like prices.

B. Demand Cover Mechanism

The demand cover mechanism should satisfy the following two properties. 1) *Bid independency*. The transfer from subscriber coverage demands to bundle storage demands should be independent of the buyer bids, so as to guarantee the truthfulness of *ESTRA*. 2) *Subscriber coverage*. The ultimate goal of CPs to cover an area is to meet the requests of all the subscribers within the area. However, the subscribers could be connecting to any edge network that covers the area. Therefore, the demand cover mechanism should guarantee that the demands over a specific area will be transferred into the demands over all the associated edge networks.

The demand cover problem can be solved by Algorithm 1, which satisfies the two properties as mentioned above.

C. Edge Storage Double Auction Mechanism

After solving the demand cover problem, the original problem has been transferred into a multi-unit double auction. To introduce the proposed mechanism, optimization problem $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I}^+,\mathbb{J}^+)$ is defined as:

$$\max \quad U(\mathbb{I},\mathbb{J})=\sum_{i\in\mathbb{I}} b_i x_i-\sum_{j\in\mathbb{J}} a_j y_j$$

$$\begin{aligned} s.t. \quad & \textstyle\sum_{i\in\mathbb{I}} d_i^k x_i = \sum_{j\in\mathbb{J},K_j=k} y_j-\Delta_k, && \forall k\in\mathbb{K}\\ & 0\leqslant x_i \leqslant 1, && \forall i\in\mathbb{I}^+\\ & x_i=0, && \forall i\in\mathbb{I}\backslash\mathbb{I}^+\\ & 0\leqslant y_j\leqslant s_j, && \forall j\in\mathbb{J}\backslash\mathbb{J}^+\\ & y_j=s_j, && \forall j\in\mathbb{J}^+ \end{aligned}$$

where $\mathbb{I}^+\subseteq\mathbb{I}$ and $\mathbb{J}^+\subseteq\mathbb{J}$. $\Delta_k>0$ is the sacrificed trading storage amount of type k for guaranteeing truthfulness and $\mathbf{\Delta}=(\Delta_1,\cdots,\Delta_k,\cdots,\Delta_K)$ refers to the trade reduction of all types of storage. The optimal solutions to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ and $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$ are denoted by $(\mathbf{x}^*,\mathbf{y}^*)$ and $(\mathbf{x}^{**},\mathbf{y}^{**})$, respectively, where $\mathbb{I}'=\{i\in\mathbb{I}|x_i^*=1\}$.

1) Storage Allocation: The storage allocation is determined by Algorithm 2. To guarantee economic properties of the mechanism, $\Delta_k\geqslant\max\{s_j|K_j=k\}$, $\forall k\in\mathbb{K}$ should be satisfied, and the proofs of the properties will be provided in Section III-D. The detailed procedures for solving $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ and $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$ are omitted here because they are both linear optimization and have well-investigated solutions. Note that when the buyer demand is partially met, the demands on each edge network (*i.e.*, of each storage type) are met with the same proportion.

2) Payments and Charges: The winning buyer set $\mathbb{I}''=\{i\in\mathbb{I}'|x_i^{**}>0\}$. The *payment* of buyer i is $p_i=\min\{b_i|x_i^*=1\}$ if $i\in\mathbb{I}''$ and $p_i=0$ otherwise. The derivation of p_i $(i\in\mathbb{I}'')$ is shown in Algorithm 3 and a proper precision threshold ϵ can be set to meet the precision requirement. The winning seller set $\mathbb{J}''=\{j\in\mathbb{J}|y_j^{**}>0\}$. The *charge* of seller j is $p_j=a_jy_j+U^*(\mathbb{I},\mathbb{J})-U^*(\mathbb{I},\mathbb{J}\backslash\{j\})$ if $j\in\mathbb{J}''$ and $p_j=0$ otherwise, where $U^*(\mathbb{I},\mathbb{J})$ and $U^*(\mathbb{I},\mathbb{J}\backslash\{j\})$ are the optimal value of $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$ and $\mathcal{P}(\mathbb{I},\mathbb{J}\backslash\{j\},\mathbf{0},\mathbb{I}',\emptyset)$, respectively.

Algorithm 1 Demand Cover

Input: $\mathbf{B}_i$ $(\forall i\in\mathbb{I})$
Output: $\mathbf{B}_i^T$ $(\forall i\in\mathbb{I})$
1: $\forall i\in\mathbb{I},k\in\mathbb{K}$, $d_i^k\leftarrow 0$;
2: $\forall i\in\mathbb{I}$, go through step 3 to step 4;
3: $\forall k\in\mathbb{K}$, go through step 4;
4: If $\mathcal{C}(N_k)\bigcap\mathbb{R}_i\neq\emptyset$, $d_i^k=d_i$;
5: **return** $\mathbf{B}_i^T$ $(\forall i\in\mathbb{I})$;

Algorithm 2 Storage Allocation

Input: $\mathbf{A}=(\mathbf{A}_1,\cdots,\mathbf{A}_J)$, $\mathbf{B}^T=(\mathbf{B}_1^T,\cdots,\mathbf{B}_I^T)$, $\mathbf{\Delta}$
Output: $(\mathbf{x}^{**},\mathbf{y}^{**})$, buyers' transaction proportions and sellers' sold-out amounts
1: Solve $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ and get $(\mathbf{x}^*,\mathbf{y}^*)$;
2: Derive $\mathbb{I}'$ according to $\mathbb{I}'=\{i\in\mathbb{I}|x_i^*=1\}$;
3: Solve $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$ and get $(\mathbf{x}^{**},\mathbf{y}^{**})$;
4: **return** $(\mathbf{x}^{**},\mathbf{y}^{**})$;

Algorithm 3 Payment Determination

Input: $\epsilon>0$, the precision threshold
Output: p_i $(i\in\mathbb{I}'')$
1: $\underline{b}\leftarrow 0,\overline{b}\leftarrow b_i$;
2: $b_i'\leftarrow(\underline{b}+\overline{b})/2$;
3: Solve $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ with buyer i bidding b_i', and get the optimal solution $(\mathbf{x}',\mathbf{y}')$;
4: If $x_i'<1$, $\underline{b}\leftarrow b_i'$; Else, $\overline{b}\leftarrow b_i'$;
5: If $|\overline{b}-\underline{b}|\leqslant\epsilon$, continue to step 6; Else, go back to step 2;
6: **return** $\overline{b}$;

D. Property Analysis

1) Complexity: The bottleneck of the whole mechanism is Algorithm 3, which contains dichotomy and linear programming. The b_i $(\forall i\in\mathbb{I})$ is a constant and the linear optimization has polynomial-time solutions [11]. Therefore, the computational complexity of *ESTRA* is polynomial.

2) Economic Robustness: *ESTRA* is proved to be *truthful*, *individual rational* and *weakly budget balanced*. To guarantee economic properties, the trade reduction $\mathbf{\Delta}$ is introduced in *ESTRA*. All the analysis below is under the constraint that $\Delta_k\geqslant\max\{s_j|K_j=k\}$, $\forall k\in\mathbb{K}$.

Lemma 1: $\forall i\in\mathbb{I}$, $x_i^*=1$ if and only if $x_i^{**}=1$.

Proof: $x_i^*=1$ means that buyer i can get all the demands in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$. Then in $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$, the demands reduction by excluding buyer set $\mathbb{I}\backslash\mathbb{I}'$ and the supply increase coming from $\mathbf{\Delta}>\mathbf{0}$ will further ensure that all $i \in \mathbb{I}'$ get their whole demands in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$, *i.e.*, $x_i^{**}=1$.

If $x_i^* \neq 1$, $i \notin \mathbb{I}'$ according to $\mathbb{I}'$'s definition, and $x_i^{**}=0$ according to the constraints of $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$. Then based on the equivalence between mutually inverse negative propositions, $x_i^{**}=1 \Rightarrow x_i^*=1$.

Therefore, $x_i^*=1$ if and only if $x_i^{**}=1$. ■

Lemma 2: Bidding truthfully is a weakly dominant strategy for all the buyers.

Proof: We assume all the buyers bid truthfully and then will prove they cannot benefit from lying. The demand cover mechanism is independent of buyer bids, so we focus on the auction rules. $\forall i \in \mathbb{I}$, $p_i' = \min\{b_i | x_i^*=1\}$.

If $b_i < p_i'$, then $x_i^* < 1$, *i.e.* $i \notin \mathbb{I}'$ and buyer i gets nothing in the auction with $p_i=0$ and $u_i=0$. Claiming an untruth bid $\tilde{b}_i$ will not change the result unless $\tilde{b}_i \geqslant p_i'$, where buyer i will get all his demands (according to Lemma 1), resulting in a negative utility $u_i = b_i - p_i'$. If $b_i \geqslant p_i'$, then $x_i^*=1$ and buyer i will get all his demands (according to Lemma 1) with $u_i = b_i - p_i' \geqslant 0$. Modifying his claimed bid $\tilde{b}_i$ within $[p_i', +\infty)$ will not change the result because the payment p_i is independent of the winner's bid according to the derivation. If $\tilde{b}_i < p_i'$, the buyer will gain a zero utility. Therefore, bidding truthfully is a weakly dominant strategy for all the buyers. ■

Lemma 3: The optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ will not change when seller j lower his ask if $y_j^* = s_j$.

Proof: $y_j^*=s_j$ means that all supplies of seller j have been allocated in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$, so lowering the ask will not allocate more storage from seller j and therefore will not change the optimal solution. ■

Lemma 4: $y_j^{**}=0$ if $y_j^* < s_j$, $\forall j \in \mathbb{J}$.

Proof: We consider a specific seller $\tilde{j}$ here, and the same is with other sellers. According to the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$, $\Sigma_{i\in\mathbb{I}} d_i^k x_i^* = \sum_{j\in\mathbb{J},K_j=k} y_j^* - \Delta_k$. According to Lemma 1, the final trading amount of type $K_{\tilde{j}}$ is $\sum_{i\in\mathbb{I}'} d_i^{K_{\tilde{j}}} \leqslant \sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* = \sum_{j\in\mathbb{J},K_j=K_{\tilde{j}}} y_j^* - \Delta_{K_{\tilde{j}}} \leqslant \sum_{j\in\mathbb{J},K_j=K_{\tilde{j}}} y_j^* - \max\{s_j | K_j = K_{\tilde{j}}\} \leqslant \sum_{j\in\mathbb{J},K_j=K_{\tilde{j}}} y_j^* - s_{\tilde{j}} < \sum_{j\in\mathbb{J},K_j=K_{\tilde{j}}} y_j^* - y_{\tilde{j}}^* = \sum_{j\in\mathbb{J}\backslash\{\tilde{j}\},K_j=K_{\tilde{j}}} y_j^*$.

$y_{\tilde{j}} < s_{\tilde{j}}$ means that the storage of seller $\tilde{j}$ is of the lowest priority to trade for maximizing $U(\mathbb{I},\mathbb{J})$. And $\sum_{i\in\mathbb{I}'} d_i^{K_{\tilde{j}}} < \sum_{j\in\mathbb{J}\backslash\{\tilde{j}\},K_j=K_{\tilde{j}}} y_j^*$ means that the supplies of sellers without seller $\tilde{j}$ can also meet the demands of winning buyers. Therefore, seller $\tilde{j}$ will not be included in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{0},\mathbb{I}',\emptyset)$, *i.e.*, $y_{\tilde{j}}^{**}=0$. ■

Lemma 5: $\forall i \in \mathbb{I}, j \in \mathbb{J}$, $x_i^{'*}=1$ in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J}\backslash\{j\},\mathbf{0},\mathbb{I}',\emptyset)$ if $x_i^*=1$.

Proof: Suppose that the sellers who provide storage of type k are sorted by their asks in ascending order. Define $p_{|s|}^k = a_{j(s(j-1)<s\leqslant s(j))}$, where $s(j)$ refers to the supplies of the first j sellers in the sorted list with $s(0)=0$. Then $p_{|s|}^k \leqslant p_{|s'|}^k$ if $s \leqslant s'$.

The storage amount of type k in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ is $\sum_{i\in\mathbb{I}} d_i^k x_i^* + \Delta_k \geqslant \sum_{i\in\mathbb{I}'} d_i^k + \max\{s_j | K_j = k\}$. Assume $\tilde{i} \in \mathbb{I}'$, $x_{\tilde{i}}^* = 1$ generates an equal or higher social welfare than $x_{\tilde{i}}' \to 1^-$, from which we can infer that $b_{\tilde{i}} \geqslant \sum_{k\in\mathbb{K}} d_{\tilde{i}}^k p^k_{|\sum_{i\in\mathbb{I}} d_i^k x_i^* + \Delta_k|} \geqslant \sum_{k\in\mathbb{K}} d_{\tilde{i}}^k p^k_{|\sum_{i\in\mathbb{I}'} d_i^k + \max\{s_j|K_j=k\}|}$.

Similarly, the amount of type k in the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J}\backslash\{j\},\mathbf{0},\mathbb{I}',\emptyset)$ is $\sum_{i\in\mathbb{I}} d_i^k x_i^{'*}$. Notice that $\sum_{i\in\mathbb{I}'} d_i^k + \max\{s_j|K_j=k\} \geqslant \sum_{i\in\mathbb{I}'\backslash\{\tilde{i}\}} d_i^k x_i^{'*} + d_{\tilde{i}}^k + \max\{s_j|K_j=k\}$, so $b_{\tilde{i}} \geqslant \sum_{k\in\mathbb{K}} d_{\tilde{i}}^k p^k_{|\sum_{i\in\mathbb{I}'\backslash\{\tilde{i}\}} d_i^k x_i^{'*} + d_{\tilde{i}}^k + \max\{s_j|K_j=k\}|}$. Then it is impossible that $x_{\tilde{i}}^{'*} < 1$ because we can gain higher objective by increasing it to 1. Therefore, $x_{\tilde{i}}^{'*}=1$. ■

Define $\hat{p}_j = \max\{a_j | y_j^* = s_j\}$. For a specific seller $\tilde{j}$, $(\mathbf{x}^{\tilde{j}*}, \mathbf{y}^{\tilde{j}*})$ denotes the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\{\tilde{j}\})$ and $\mathbb{I}'_{\tilde{j}} = \{i \in \mathbb{I} | x_i^{\tilde{j}*} = 1\}$. After sorting all the sellers except $\tilde{j}$ who supply storage of type $K_{\tilde{j}}$ by their asks in ascending order, we define $p_{|s|}^{-\tilde{j}} = a_{j(s(j-1)<s\leqslant s(j))}$, where $s(j)$ refers to the supplies of the first j sellers in the sorted list with $s(0)=0$.

Lemma 6: $\hat{p}_{\tilde{j}} \geqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$, $\forall \tilde{j} \in \mathbb{J}$.

Proof: In the optimal solution to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$, the storage amount of type $K_{\tilde{j}}$ is $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* + \Delta_{K_{\tilde{j}}}$. By the extra constraint $y_{\tilde{j}} = s_{\tilde{j}}$, the storage amount becomes $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^{\tilde{j}*} + \Delta_{K_{\tilde{j}}}$ in $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\{\tilde{j}\})$. If the optimal solutions to $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$ and $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\{\tilde{j}\})$ are the same, $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^{\tilde{j}*} + \Delta_{K_{\tilde{j}}} = \sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* + \Delta_{K_{\tilde{j}}}$. Otherwise, the demands in $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\{\tilde{j}\})$, except those met by $s_{\tilde{j}}$, will still match their optimal supplies as in $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\emptyset)$, therefore, $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^{\tilde{j}*} + \Delta_{K_{\tilde{j}}} = \sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* + \Delta_{K_{\tilde{j}}}$ still holds.

Now we show that $a_{\tilde{j}} \leqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|} \Rightarrow a_{\tilde{j}} \leqslant \hat{p}_{\tilde{j}}$. If $a_{\tilde{j}} \leqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$, note that $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^{\tilde{j}*} + \Delta_{K_{\tilde{j}}} - s_{\tilde{j}} \geqslant \sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} + \max\{s_j | K_j = K_{\tilde{j}}\} - s_{\tilde{j}} \geqslant \sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}$, we have that $a_{\tilde{j}} \leqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^{\tilde{j}*} + \Delta_{K_{\tilde{j}}} - s_{\tilde{j}}|} = p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* + \Delta_{K_{\tilde{j}}} - s_{\tilde{j}}|}$, which means seller $\tilde{j}$'s ask is within the lowest $\sum_{i\in\mathbb{I}} d_i^{K_{\tilde{j}}} x_i^* + \Delta_{K_{\tilde{j}}} - s_{\tilde{j}}$ asks. Therefore, $y_{\tilde{j}} = s_{\tilde{j}}$. Considering the definition of $\hat{p}_{\tilde{j}}$, we know that $a_{\tilde{j}} \leqslant \hat{p}_{\tilde{j}}$. Through $a_{\tilde{j}} \leqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|} \Rightarrow a_{\tilde{j}} \leqslant \hat{p}_{\tilde{j}}$, it is obvious that $\hat{p}_{\tilde{j}} \geqslant p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$. ■

Lemma 7: Claiming the truthful ask is a dominant strategy of seller $\tilde{j}$ ($\forall \tilde{j} \in \mathbb{J}$).

Proof: We assume that seller $\tilde{j}$ asks truthfully, *i.e.*, $a_{\tilde{j}}$ is his true value and we will prove that he will gain no more charge by lying. The demand cover mechanism is independent of sellers' asks, so we focus on the auction process.

When $a_{\tilde{j}} > p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$. If $y_{\tilde{j}}^* < s_{\tilde{j}}$, $y_{\tilde{j}}^{**}=0$ according to Lemma 4. If $y_{\tilde{j}}^* = s_{\tilde{j}}$, $\mathbb{I}' = \mathbb{I}'_{\tilde{j}}$ according to the definitions of $\mathcal{P}(\mathbb{I},\mathbb{J},\mathbf{\Delta},\mathbb{I},\{\tilde{j}\})$ and $\mathbb{I}'_{\tilde{j}}$. The amount of demands in the optimal solution is then $\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}$. So $a_{\tilde{j}} > p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$ is not within the lowest $\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}$ asks, $y_{\tilde{j}}^{**}=0$.

When $a_{\tilde{j}} < p^{-\tilde{j}}_{|\sum_{i\in\mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$, according to Lemma 6, $a_{\tilde{j}} < \hat{p}_{\tilde{j}}$ and $\mathbb{I}' = \mathbb{I}'_{\tilde{j}}$. Then according to Lemma 5, the allocations of buyers are the same in the optimal solutions of $\mathcal{P}(\mathbb{I}, \mathbb{J}, \mathbf{0}, \mathbb{I}', \emptyset)$ and $\mathcal{P}(\mathbb{I}, \mathbb{J}, \mathbf{\Delta}, \mathbb{I}, \{\tilde{j}\})$ with $\mathbb{I}_{\tilde{j}}$ being the winning buyer set. If $p^{-\tilde{j}}_{|\underline{s}|} < a_{\tilde{j}} < p^{-\tilde{j}}_{|\overline{s}|}$ with $\underline{s} \geqslant \sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - s_{\tilde{j}}$ and $\overline{s} \rightarrow \underline{s}^+$, seller $\tilde{j}$'s sold-out amount is $\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - \underline{s}$ and his charge is $\int_{\underline{s}}^{\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}} p^{-\tilde{j}}_{|s|} \mathrm{d}s$ according to the derivation. If $a_{\tilde{j}} < p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - s_{\tilde{j}}|}$, seller $\tilde{j}$ will sell out all his supplies and the charge will be $\int_{\underline{s}}^{\underline{s}+s_{\tilde{j}}} p^{-\tilde{j}}_{|s|} \mathrm{d}s$. If $a_{\tilde{j}} = p^{-\tilde{j}}_{|\underline{s}|}$ with $\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - s_{\tilde{j}} < \underline{s} \leqslant \sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}$, it is uncertain if seller $\tilde{j}$ will sell out his supplies.

In conclusion, when $a_{\tilde{j}} > p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$, bidding truthfully will prevent seller $\tilde{j}$ from the trade and get a zero utility. If he lowers his ask $a'_{\tilde{j}} < p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|}$ to sell out amount s', he will get a charge of $\int_{\underline{s}}^{\underline{s}+s'} p^{-\tilde{j}}_{|s|} \mathrm{d}s < s' p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}|} < s' a_{\tilde{j}}$, which will result in a negative utility, because $\underline{s} < \underline{s} + s' \leqslant \sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}}$ belongs to the part that should be traded without seller $\tilde{j}$. Similarly, if $p^{-\tilde{j}}_{|\underline{s}|} < a_{\tilde{j}} < p^{-\tilde{j}}_{|\overline{s}|}$ with $\underline{s} \geqslant \sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - s_{\tilde{j}}$ and $\overline{s} \rightarrow \underline{s}^+$, ask untruthfully to sell out amount not equal to $\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - \underline{s}$ will generate negative utilities. If $a_{\tilde{j}} < p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'_{\tilde{j}}} d_i^{K_{\tilde{j}}} - s_{\tilde{j}}|}$, selling out all his supplies is the optimal choice, which can also be ensured by asking truthfully. Therefore, claiming the truthful ask is a dominant strategy of all the sellers. ■

***Theorem** 1: ESTRA* is *truthful*, *individual rational* and *weakly budget balanced* under the constraint that $\Delta_k \geqslant \max\{s_j | K_j = k\}, \forall k \in \mathbb{K}$.

Proof: According to Lemma 2 and Lemma 7, *ESTRA* is *truthful*. Then all the sellers and buyers will reveal their true values to gain maximum utilities, which are all nonnegative according to the details of analysis. Therefore, *ESTRA* is *individual rational*.

According to the definition of buyer payment p_i, suppose that $b_{\tilde{i}} \geqslant p_{\tilde{i}}$, we have $x^*_{\tilde{i}} = 1$. Then based on the analysis in Lemma 5, we can infer that $b_{\tilde{i}} \geqslant \sum_{k \in \mathbb{K}} d^k_{\tilde{i}} p^k_{|\sum_{i \in \mathbb{I}'} d_i^k + \Delta_k|}$. Through $b_{\tilde{i}} \geqslant p_{\tilde{i}} \Rightarrow b_{\tilde{i}} \geqslant \sum_{k \in \mathbb{K}} d^k_{\tilde{i}} p^k_{|\sum_{i \in \mathbb{I}'} d_i^k + \Delta_k|}$, we can infer that $p_{\tilde{i}} \geqslant \sum_{k \in \mathbb{K}} d^k_{\tilde{i}} p^k_{|\sum_{i \in \mathbb{I}'} d_i^k + \max\{s_j | K_j = k\}|}$. Therefore, the total payment of buyers for storage type k is $P_k \geqslant (\sum_{i \in \mathbb{I}'} d_i^k) \cdot p^k_{|\sum_{i \in \mathbb{I}'} d_i^k + \Delta_k|}$. According to the derivations of seller charge and $p^{-\tilde{j}}_{|s|}$, the highest unit charge of seller $\tilde{j}$ is $p^{-\tilde{j}}_{|\sum_{i \in \mathbb{I}'} d_i^{K_{\tilde{j}}}|} \leqslant p^{K_{\tilde{j}}}_{|\sum_{i \in \mathbb{I}'} d_i^{K_{\tilde{j}}} + s_{\tilde{j}}|} \leqslant p^{K_{\tilde{j}}}_{|\sum_{i \in \mathbb{I}'} d_i^{K_{\tilde{j}}} + \max\{s_j | K_j = K_{\tilde{j}}\}|}$. So the total charges of sellers for storage type k is $C_k \leqslant (\sum_{i \in \mathbb{I}'} d_i^k) \cdot p^{K_{\tilde{j}}}_{|\sum_{i \in \mathbb{I}'} d_i^k + \max\{s_j | K_j = k\}|}$. In conclusion, $\forall k \in \mathbb{K}$, $P_k \geqslant C_k$. Therefore, the auctioneer will gain nonnegative utility and *ESTRA* is *weakly budget balanced*. ■

3) Efficiency Loss: To guarantee *IC*, *IR* and *BB*, an efficiency loss caused by trade reduction is introduced in the mechanism. According to the definition of $\mathbf{\Delta}$, the reduced trade amount of each storage type is the amount of the maximum supply of this type. When the trade attracts more and more sellers, the effect of trade reduction will shrink. Evaluations on the efficiency loss will be provided in Section IV.

IV. Simulation and Evaluation

A. Simulation Setup

The regions and the associated edge networks are generated from public trace data set[1] on mobile users. A mobile node at a specific time is used to define an atomic region, and the available cells and APs are referred as the edge networks that cover the region. The number of buyers that have demands over each region is assumed to follow normal distribution, which reflects the existence of a few busy regions and a few unpopular ones.

A total of 2000 sellers are assigned to the generated cell networks and the number of sellers of each edge network follows normal distribution, which creates a scenario where most of the edge networks have a medium number of storages. 100 buyers with randomly generated region-based demands represent the CPs who want to employ edge cache.

The market is set up as a buyer market, where the supply is relatively sufficient and the demands is relatively deficient. The performance of *ESTRA* under such market will be evaluated in Section IV-B, and that under a seller market is similar.

B. Evaluation

The efficiency of *ESTRA*, the effect of ask and bid distributions on the performance, and the distribution of social welfare among different participants are evaluated in the simulation.

Fig. 3 shows the social welfare under *ESTRA* and that under optimal allocation with different buyer and seller scales. The optimal allocation is derived by directly solving a linear optimization without considering the economic robustness. The result shows that *ESTRA* achieves $74\% \sim 91\%$ of the optimal social welfare. The increase of both buyer scale and seller scale produce a trend of higher social welfare, although the generated bids and asks from certain distributions may cause some exceptions.

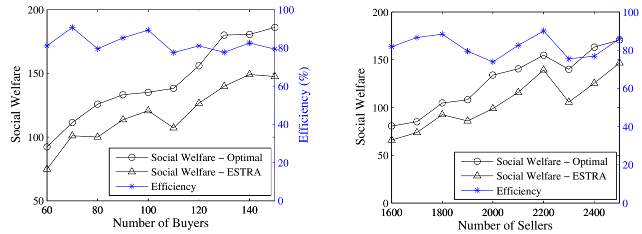
The effect of ask and bid distributions on the social welfare is shown in Fig. 4. The cases under each configuration are sorted in ascending order according to the social welfare. The configuration with both uniform asks and uniform bids are the most smooth in social welfare. And the configurations with other combinations of ask and bid distribution differ obviously in best cases in social welfare.

The utilities and utility shares of different participants are shown in Fig. 5. It is obvious that buyers gain a larger share of utility compared with sellers under the buyer market configuration. The high level profit of auctioneer will benefit the sustainability of the trading platform.

V. Related Work

To meet the exploding mobile data demands, mobile content placement is studied [12] and novel content delivery techniques are proposed, many of which focus on edge caching. Spagna *et al.* [13] discuss the design principles for highly distributed operator-owned CDN. Poularakis *et al.* [14] design multicast-aware popular files caching at small cell stations.

[1]http://crawdad.cs.dartmouth.edu/yonsei/lifemap/



(a) Buyer Scale (2000 Sellers) (b) Seller Scale (100 Buyers)

Fig. 3. Social Welfare with Different Buyer and Seller Scales

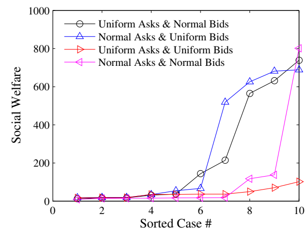


Fig. 4. Social Welfare with Different Ask/Bid Distributions

Dai *et al.* [15] propose a mechanism for collaborative caching at mobile switching centers. Golrezaei *et al.* analyse video caching on femtocell stations in [2]. With the development of edge networks, there emerge many edge-storages, which can be utilized to cache contents for CPs. However, there is no study on the matching of such demands and supplies so far.

Auction is a promising approach to allocate network resources, such as spectrum and cloud resources. Zhou *et al.* [16] design a truthful double auction that enables spectrum reuse. Feng *et al.* [6] propose a double auction mechanism for heterogeneous spectrums. Dong *et al.* [17] design double auctions for dynamic spectrum allocation. However, these works all focus on single-unit scenarios. Xu *et al.* [18] study several versions of multiple spectrum channels allocation with different contract duration and demand expression. Chu [19] proposes multi-unit double auction mechanisms for indivisible commodity under single-minded assumption, which is not applicable for edge-storage. Gao *et al.* [20] study the integrated contract and auction design for secondary spectrum trading under one-seller scenario. Xu *et al.* [21] propose a combinatorial double auction for mobile cloud computing, focusing on allocation efficiency rather than economic robustness.

VI. Conclusion

In this paper, *ESTRA* is proposed to match edge caching demands and edge-storage supplies. We design a region-based model for edge-storage trading and propose a demand cover mechanism to transfer subscriber coverage demands into bundle storage demands. The proposed double auction for divisible heterogeneous edge-storage is proved to be truthful, weakly budget balanced and individually rational. The simulation result shows the effectiveness and efficiency of *ESTRA*.

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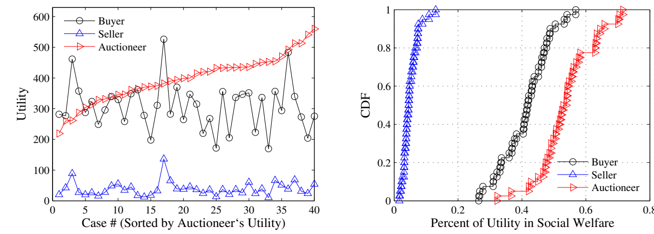

(a) Utilities (b) Utility Shares

Fig. 5. Utility Shares of Participants

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