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A truthful double auction for two-sided heterogeneous mobile crowdsensing markets

Shuang Chen [a,b], Min Liu [a,*], Xiao Chen [a,b]

[a] Institute of Computing Technology, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Computer and Control Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Incentive mechanisms are critical for the success of mobile crowdsensing (MCS). Existing mechanisms mainly focus on scenarios where all sensing tasks are belong to a monopolistic campaign, while ignoring the situation where multiple campaigns coexist and compete for potential sensing capacities. In this paper, we study mechanisms in a two-sided heterogeneous MCS market with multiple requesters and users, where each requester publishes a sensing campaign consisting of various tasks whereas each user can undertake multiple tasks from one or more campaigns. The mechanism design in such a market is very challenging as the demands and supplies are extremely diverse. To fairly and effectively allocate resources and facilitate trades, we propose a novel truthful double auction mechanism named TDMC. By introducing a carefully designed virtual padding requester, a two-stage allocation approach and corresponding pricing schemes for both requesters and users are developed in TDMC. Through theoretical analysis, we prove that TDMC has the properties of truthfulness, individual rationality, budget balance, computational tractability, and asymptotic efficiency as the workload supply compared with demand becomes more and more sufficient. To make TDMC more adaptable, we further introduce two more flexible bid profiles for both requesters and users, and two adjustment methods to control the sensing quality. Extensive simulations demonstrate the effectiveness of TDMC.

1. Introduction

Mobile Crowdsensing (MCS) [1] has become a promising paradigm to solve large-scale and complex data collection problems by leveraging pervasive sensor-equipped mobile devices of the crowd (e.g., smartphones, Tablet PCs, wearable devices). In a MCS platform, a big data collection problem is usually divided into small tasks, thus mobile device users can contribute their relatively small sensing capacities to accomplish the problem in a *crowdsourcing* way. So far, a number of crowd sensing applications have been developed for a variety of purposes, such as traffic information collecting [2], environment monitoring [3], crowdsourced commercial activities [4], and so on.

One critical issue in practical MCS applications is how to stimulate users to participate in the sensing campaigns, as executing sensing tasks will undoubtedly consume physical resources of devices, time, and even human intelligence. Similar to the employment relationship in a labor market, appropriate incentives are needed to compensate users in order to recruit enough sensing workforce.

However, current incentive mechanisms are mainly based on a *monopoly campaign scenario*, which means they simply assume all sensing tasks are belong to a globally unique campaign, and all participating users are working for the same campaign. This may be reasonable for some specific-purpose applications, but things become different in an *integrated MCS platform*. In such a platform, many kinds of MCS applications are available, and different requesters can publish multiple sensing campaigns in a unified platform concurrently. Some platforms such as *Medusa* [5] and *gPS* [6] have been designed in this way. Integrated MCS brings significant benefits, including total overhead reduction and more efficient management. What is more, it also relieves the users from switching between various MCS platforms and provides them more sensing choices.

In this paper, we consider the case where multiple campaign requesters demand for sensing workforce and multiple users supply their sensing capacities. Besides, both requesters and users are self-interested and want to maximize their own benefits *strategically*. This actually builds up a further developed *two-sided market*, which is fundamentally different from the traditional monopoly campaign scenario. As multiple requesters with different interests may *compete* for potential sensing capacities, it is unsuitable to regard all

* Corresponding author. Tel.: +86 10 62565533; fax: +86 10 62533449.
E-mail addresses: chenshuang@ict.ac.cn (S. Chen), liumin@ict.ac.cn (M. Liu), chenxiao3310@ict.ac.cn (X. Chen).

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campaigns as a whole and apply a single incentive mechanism in a monopolistic way. Letting each campaign apply an independent incentive mechanism is also inconvenient, since users have to contemplate different strategies among various campaigns to maximize their utilities. Indeed, none of existing incentive mechanisms [7–19] can work well in the multiple-campaign competing situations.

In order to fairly and effectively allocate resources and facilitate trades between requesters and users, we propose a Truthful Double auction mechanism for the two-sided Mobile Crowdsensing market (TDMC). However, the design is challenging as the market is intrinsically *heterogeneous*. Further to say, requesters demand for tasks with diverse requirements in aspects of locations, time and sensing methods, while users have different availabilities and preferences for different tasks based on their spatio-temporal and device states. This makes it extremely difficult to allocate tasks and achieve *efficiency*, i.e., the total valuation of all allocated resources of all requesters and users, or called the *social welfare*, is maximum. Besides, *truthfulness* is critical for an auction, which means bidders should truthfully reveal their private information for the items they bid. However, to fully stimulate the sensing capacities, users should be allowed to freely bid for multiple heterogeneous tasks as long as they can undertake. Their private information is actually multi-dimensional, which makes it harder to ensure truthfulness. What is more, it is also important for a double auction to guarantee: (i) *individual rationality*: bidders have non-negative utilities by reporting truthfully, (ii) *budget balance*: auctioneer would not suffer a deficit, and (iii) *computational tractability*: auction runs in polynomial time.

To overcome above challenges, we first categorize all tasks from different campaigns into orthogonal *sensing patterns* to characterize the heterogeneity of the market. Then we allow users to bid personalized maximum available workload and associated (unit) costs for different patterns based on their sensing capacities. Finally, we adopt a two-stage allocation approach to determine the trading results and optimize the social welfare. In stage one, by introducing a carefully designed virtual padding requester, we intentionally intensify the competition among requesters and screen out a set of more competitive requesters to be the winners. In stage two, we match these selected requesters with users who offer the cheapest workload and get the final allocation. Novel pricing schemes are also designed for both requesters and users, which ensures the truthfulness as well as budget balance. Furthermore, we also show TDMC can asymptotically approach the efficiency as the workload supply compared with demand becomes more and more sufficient. The contributions of this paper are as follows.

- To the best of our knowledge, TDMC is the first truthful auction mechanism for a two-sided heterogeneous MCS market, where multiple requesters and users have diverse demands and supplies. A joint consideration of competition among requesters and heterogeneity in the market significantly complicates the design.
- Utilizing a padding idea, TDMC develops a two-stage allocation approach and corresponding pricing schemes for requesters and users to achieve approximate efficiency while preserving truthfulness and budget balance.
- We theoretically prove that TDMC possesses the attractive properties of truthfulness, individual rationality, budget balance, computational tractability, and asymptotic efficiency as the workload supply compared with demand becomes more and more sufficient.
- We further consider several practical issues to make TDMC more adaptable, including more flexible bid profiles for both requesters and users, and two adjustment methods of *price intervention* and *workload quota* to control the sensing quality.

The rest of the paper is organized as follows. In Section 2, we review the related work. In Section 3, we introduce the model and formulate the problem. In Section 4, we elaborate the details of TDMC and provide theoretical proofs of desired properties. Then in Section 5 we consider several practical issues of TDMC. In Section 6 we show some simulation results. In Section 7, we conclude the paper.

2. Related Work

2.1. Incentive mechanisms for mobile crowdsensing

A number of incentive mechanisms [7–19] have been developed for MCS. In [8,9], the platform (also the campaign organizer) applies a stackelberg game to maximize its utility by deciding an optimal total reward. Koutsopoulos [7] proposes a reverse auction in which the platform determines users' participation levels based on their reported unit costs to minimize the total payments under certain service quality limits. An all-pay auction is introduced in [10], where the platform allocates a contribution-dependent prize and only the user who makes the highest contribution can win. After that a Tullock context model is designed in [11], which gives weak players more opportunities to win compared with all-pay auctions to attract more users to participate. These works consider that the market is homogeneous and single user has a uniform cost to all tasks. Some works [8,12–18] also deal with the heterogeneity of MCS from different aspects. In [8], each user bids for a bundle of tasks with a single private cost and the platform selects a subset of users to maximize its submodular utility function. Following this way, Zhao et al. [12] develop two online auctions by adopting a multiple-stage sampling-accepting process. The work in [13] considers the location-awareness of tasks while in [14] considers the dynamic arrivals of users and tasks. Sun and Ma [16] focus on designing long-term user participation incentives by modelling the problem as a restless multi-armed bandit process. He et al. [15] study a unified platform where multiple tasks are distributed in different locations and focuses on optimal task allocation to maximize the total reward for the platform. Cheung et al. [17] develop a finite-step task selection game for users to make their plans of undertaking location-based and time-sensitive tasks. Jin et al. [18] introduce a critical metric of information quality into the design of reverse auction mechanisms for MCS systems. However, all above works regard that tasks in MCS are belong to a unique campaign without caring whether tasks are from multiple self-interested requesters. As far as we know, there is only one work [19] that is related to our two-sided MCS market, where the platform recruits workers to participate in multiple sensing processes, but its target is to maximize total number of satisfied users without considering the processes' utilities and consequent competition among them.

2.2. Double auctions for two-sided markets

In economics, double auctions are widely used for a two-sided market with multiple buyers and sellers. Traditional VCG mechanism is truthfulness, individual rationality and efficiency, but it cannot guarantee budget balance. McAfee double auction [20] is truthful and budget balanced to trade single units of items, and [21] extends it to the multi-unit situation, but the items they study are homogeneous. When trading multiple heterogeneous items, the problem becomes more difficult. Actually, the general form is a multi-unit combinatorial auction, whose optimal allocation problem is NP-hard [22]. Only a few truthful and budget balanced mechanisms with approximate efficiency have been designed in specific cases. Babaioff and Walsh [23] and Chu and Shen [24] consider a scenario where each buyer wants a bundle of items while each seller only offers single unit of one item. Chu [25] studies the case where a buyer's demand is a bundle while a seller can offer multiple units of one item. The padding idea in our work is inspired by Chu [25], but it cannot be directly applied to our work, as we further allow each seller (user) to offer multiple heterogeneous items (maximum available workload for different sensing patterns).