Computer Networks 141 (2018) 1–16

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Truthful incentive mechanisms for mobile crowd sensing with dynamic smartphones

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ARTICLE INFO

Article history:
Received 30 September 2017
Revised 25 April 2018
Accepted 18 May 2018
Available online 20 May 2018

ABSTRACT

The emergence of ubiquitous mobile devices has given rise to mobile crowd sensing, as a new data collection paradigm to potentially produce enormous economic value. Fully aware of the paramount importance to incentivize smartphone users' participation, a wide variety of incentive mechanisms have been proposed, however, most of which have made the *impractical* assumption that smartphones remain static in the system and sensing tasks are known in advance. Designing truthful incentive mechanisms for mobile crowd sensing system has to address four major challenges, *i.e.,* dynamic smartphones, uncertain arrivals of tasks, strategic behaviors, and private information of smartphones. To jointly address these four challenges, we propose two truthful auction mechanisms, *OT-OFMCS* and *NOT-ONMCS*, with respect to the offline and online case of mobile crowd sensing, aiming at selecting an optimal set of winning bids with low costs for maximizing the social welfare. The *OT-OFMCS* mechanism features an optimal task allocation algorithm with the polynomial-time computational complexity where the information of all smartphones and tasks are known a priori. The *NOT-ONMCS* mechanism is comprised of a critical payment scheme and an online allocation algorithm with a $\frac{1}{2}$-competitive ratio, where the real-time allocation decisions are made based on current active smartphones. To improve the theoretical competitive ratio, we investigate a modified online approximation algorithm *RWBD* with the ratio of $(1-\frac{1}{e})$. Rigorous theoretical analysis and extensive simulations have been performed, and the results demonstrate our proposed auction mechanisms achieve truthfulness, individual rationality and computational efficiency.

1. Introduction

These years have witnessed the rapid adoption of mobile devices [1]. The proliferation of smartphones brings new opportunities to reinforce the impact of mobile crowd sensing application on global society. Being embedded with a variety of sensors such as accelerometer, gyroscope, camera, and digital compass, a smartphone is able to read various sensing data about its surroundings. As being attached to a user who may roam in different places, a smartphone collects sensing data that can be valuable to other users in the world.

Mobile crowd sensing with smartphones, as illustrated in Fig. 1, has become a promising paradigm for collecting and sharing data, leveraging the unique advantage of distributed mobile smartphones. Within a mobile crowd sensing system, there is a platform locating on the cloud and a pool of dynamically available smartphones. Those users who want to collect sensing data about a distributed phenomenon can send sensing tasks to the platform which then recruits smartphones to provide the desired sensing services. A number of useful applications and systems have been investigated, such as noise mapping [2,3], cellular/WiFi coverage maps [4], and traffic information collection [5].

Stimulating smartphone participation is of paramount importance to evaluate achieved service quality of mobile crowd sensing application. In general, smartphone users are reluctant to provide sensing services for others. *On the one hand*, performing sensing services consumes considerable resources on a resource-limited smartphone, such as energy and memory. *On the other hand*, as a smartphone shares sensing data, it may be subject to the possible privacy breach. However, without enough contributing smartphones, one is not able to receive desirable sensing services from the mobile crowd sensing application. As a result, mobile crowd sensing would not be practical for wide adoption. Although a number of existing mobile crowd sensing applications and systems [2–

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https://doi.org/10.1016/j.comnet.2018.05.016
1389-1286/

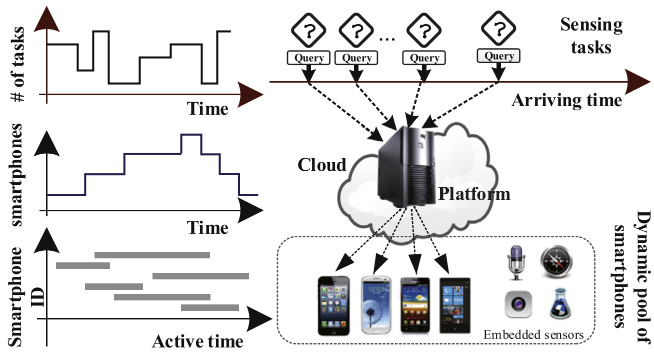

Fig. 1. Illustration of a mobile crowd sensing system. The platform residing on the cloud receives sensing tasks and assigns the tasks to smartphones. Both tasks and smartphones arrive to the system dynamically.

6] have been developed, they usually assume that smartphones voluntarily contribute their resources to provide sensing services. This assumption does not hold in reality, suggesting such mobile crowd sensing systems cannot be sustained in the long run. Thus, it is nontrivial to design reward-related incentive mechanisms for contributing smartphones as compensation.

A wide variety of truthful incentive mechanisms [7–13] has been designed for mobile crowd sensing. *However, most of them have made the impractical assumption that both smartphones and sensing tasks are static in the system*. Clearly, such assumption is untrue in practice. In the real world, a smartphone may be opportunistically available for providing sensing services and hence may join the system for a certain duration of time, when, *e.g.*,the smartphone is idle. When the smartphone user returns to use the phone, it may leave the system. On the other hand, sensing tasks also arrive at the system dynamically, and arrivals of tasks can be busty and unpredictable. As a result, existing incentive mechanisms may fail and become untruthful when being applied to mobile crowd sensing systems with dynamic smartphones and random arrivals of tasks.

It is particularly challenging to design incentive mechanisms given the unique characteristics of mobile crowd sensing with dynamic smartphones. *First*, smartphones may dynamically join and leave the system, and sensing tasks may arrive at the system at random. Such uncertain and unpredictable behaviors further complicate the design of incentive mechanisms. *Second*, the key information about the real cost, arriving time and departure time are typically *private* and unknown to others. *Finally*, smartphone users are both rational and strategic. A smartphone takes actions solely for maximizing its own utility. Although existing mechanisms [14–17] investigate the design of online incentive mechanisms, they focus on diverse models or objectives, failing to be applied to solve our online assignment problem. For example, different from the existing works [14,17], the random arrivals of sensing tasks further increase the complexity of the online incentive mechanism design.

In response to the challenges, we propose two truthful auction mechanisms, *OT-OFMCS* and *NOT-ONMCS*, as well as a modified approximation algorithm. The *NOT-ONMCS* mechanism explicitly take both dynamic smartphones and random arrivals of tasks into consideration. *First*, as a benchmark of the online case, we design the *OT-OFMCS* mechanism in which the optimal maximum weighted matching algorithm produces the maximum social welfare with a polynomial complexity of $O((n+\gamma)^3)$. *Second*, we propose the suboptimal *NOT-ONMCS* mechanism, which is comprised of a winning bids decision algorithm and a critical payment scheme. Moreover, the near-optimal allocation algorithm can approximate the offline optimal solution within a factor of $\frac{1}{2}$. *As a complementary*, we further introduce a randomized winning bids decision algorithm *RWBD*, where the competitive ratio is increased to $(1-\frac{1}{e})$. Solid theoretical analysis and extensive simulations demonstrate that both *OT-OFMCS* and *NOT-ONMCS* mechanisms can achieve the desired properties of truthfulness, individual rationality and computational efficiency.

The preliminary result of this work was reported in 2014 IEEE ICDCS [18]. The rest of the paper proceeds as follows. The next section reviews related work. Section 3 presents the system model, the reverse auction model, and the mathematical formulation. We demonstrate the *OT-OFMCS* and *NOT-ONMCS* mechanism in Section 4 and Section 5 respectively. In Section 6, we propose a modified online algorithm *RWBD*. Section 7 presents evaluation results. Section 8 concludes the paper.

2. Related work

The related works about existing incentive mechanisms are demonstrated as the following two categories: *Offline Incentive Mechanisms* and *Online Incentive Mechanisms*. Especially, each category is divided into incentive mechanisms with strategic behaviors and without strategic behaviors.

2.1. Offline incentive mechanisms

A number of existing works [7,10,11,19,20] have made the impractical assumption on static smartphones and given tasks. All the information has been revealed before the task allocation is initially made.

2.1.1. Incentive mechanisms with strategic behaviors

Existing works [7,9–11,19–22] design auction-based incentive mechanisms to induce smartphones to disclose their real cost. Yang et al. [7] propose two incentive mechanisms for the user-centric model and platform-centric model, respectively. Li et al. [10] propose a randomized auction mechanism to increase the diversity of sensing devices and prevent the starvation of some users, however, only achieving the approximate truthfulness. Feng et al. [11] solve the location-aware sensing tasks allocation problem, modeled as the modified minimal weighted set cover problem, to minimize the social cost. Meanwhile, the critical payment scheme is proposed according to the work [23]. However, the mentioned works [7,10,11] only consider the smartphones with single-parameter bids, and the proposed mechanisms simply run in the offline settings. Especially, Koutsopoulos [9] aim to minimize the total expected payment under the known cost distribution of smartphones, where the prior distribution cannot be adapted to our setting.

In particular, Jin et al. [21] take it into consideration, that the quality of sensed data collected by the smartphones, aiming at maximizing the social welfare under the constraint of the task quality requirement. Based on the prior work, Jin et al. [24] further propose a payment mechanism, where a non-cooperative game is adopted to model the strategic behaviors of smartphones. Each smartphone can maximize its utility only when it determines to complete the assigned sensing task with the maximum effort. In addition to guarantee the truthfulness of smartphones, the existing work [25] further considers the probable misreporting of multiple task requesters. Jin et al. [25] adopt a double auction mechanism to stimulate the participation of both sides. However, none of the referred works [21,24,25] has considered dynamic arrivals of both smartphones and sensing tasks.

2.1.2. Incentive mechanisms without strategic behaviors

Many related work [8,12,26] have assumed that smartphones are cooperative and participate in mobile crowd sensing system voluntarily. He et al. [12] offer an approximation algorithm *LRBA*