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Dynamic pricing incentive for participatory sensing

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ABSTRACT

User participation is one of the most important elements in participatory sensing application for providing adequate level of service quality. However, incentive mechanism and its economic model for user participation have been less addressed so far in this research domain. This paper studies the economic model of user participation incentive in participatory sensing applications. To stimulate user participation, we design and evaluate a novel reverse auction based dynamic pricing incentive mechanism where users can sell their sensing data to a service provider with users' claimed bid prices. The proposed incentive mechanism focuses on minimizing and stabilizing the incentive cost while maintaining adequate level of participants by preventing users from dropping out of participatory sensing applications. Compared with random selection based fixed pricing incentive mechanism, the proposed mechanism not only reduces the incentive cost for retaining the same number of participants but also improves the fairness of incentive distribution and social welfare. It also helps us to achieve the geographically balanced sensing measurements and, more importantly, can remove the burden of accurate price decision for user data that is the most difficult step in designing incentive mechanism.

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1. Introduction

There has been a growing body of studies on sensor networks; however commercialization of sensor network technologies has never been successfully deployed (or introduced) in the real world due to the expensive installation cost for sufficient number of sensors. Considering the issue, several groups [1,2] have recently proposed to incorporate human carrying smart phones in a sensing data collecting loop. Such a novel approach is shortly called '*Participatory Sensing*'. In participatory sensing, a large number of users carrying smart phones contribute to monitoring the environments with their sensing measurements (e.g., Mobile Millennium [3], Nokia Simple Context [4], Urban Atmosphere [5]). Smart phones carried by users transmit the sensing data to service providers, thereby replacing dedicated infrastructure and sensors. [2] However, currently existing deployments have suffered from insufficient participants because participants who voluntarily submit their sensing data found no interest to remain actively in the system without being rewarded. From the viewpoints of service providers that collect and utilize user sensing data, a well designed incentive mechanism increases user participation for the service and helps address privacy concerns that arise in the data collection step. A participant may drop out of the collecting loop unless his *Return on Investment (ROI)* in participatory sensing application is greater than their expectations. The expected ROI is dependent on true valuation of user's investment that includes all efforts for collecting data such as battery power consumption, device resources, and privacy. However, such a true valuation dynamically changes among

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[2] It is projected that mobile device subscriptions pass the four billion mark in 2009. Thanks to an increasing number of built-in sensors on mobile devices, about 40 billion mobile sensors are expected by 2009 [1].

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individuals, different types of sensing data, and user's contexts (e.g., spatial–temporal situations). In such environments, we observed that fixed price incentive mechanisms cannot adapt to dynamic distributions of user's true valuations and lead users to dropping out of participatory sensing applications. Additionally, it is hard to infer optimal incentive price for user sensing data in the fixed price incentive mechanism. In this study, we address the problem of designing an incentive mechanism that removes the burden of accurate pricing for user sensing data, adapts itself to dynamic change of user's true valuation, and minimizes the user drop out with minimal cost spent. Motivated by several inherent advantages of the dynamic pricing scheme such as its dynamic adaptation to market environments [6], we introduce a Reverse Auction based Dynamic Price (RADP) incentive mechanism in which users sell their sensing data to the service provider with their claimed bids, and a service provider selects multiple users and purchases their sensing data. The selected users receive their bid prices as a reward for their sensing data. A reverse auction for participatory sensing application is a recurring one since a service provider recurrently and continuously requires users' sensing data. In such a recurring reverse auction, we observe that the users with higher true valuations become starved frequently for being winners who sell their sensing data. Therefore the users with higher true valuations lose their interest in continuous participation and drop out of the reverse auction. The dropped out participants weaken price competitions, thereby they cause incentive cost explosion because remaining participants constantly win and, as a result, increase their bid prices for selling their sensing data for the future auction rounds to maximize their expected profits. To overcome the challenge, we let the service provider give a virtual credit to the participants who lost in the previous reverse auction as a reward for their participation only. The virtual participant credit (VPC) can only be used for lowering bid price and the bid price after the deduction increases the wining probability of the user in future auction rounds. With this mechanism, the bidders who have higher true valuations can be winners by continuous participation and they can still remain active in the reverse auction. Such participation incentives maintain enough active bidders (i.e., desired level of participatory sensing service quality) and stabilizes the incentive cost by keeping the price competitions. We envision that the presented incentive mechanism effectively fits to commercial participatory sensing applications that will be popular soon upon many requests of environmental sensing. For its successful deployment in the real world, we have many issues to be resolved, but the incentive mechanism explored in this study plays an essential role as a cornerstone in achieving high level service quality in participatory sensing applications.

This paper is extended from our previous work [7] and the reminder of this paper is organized as follows. In the next section, we briefly describe participatory sensing applications and motivations of our work. Section 3 analyzes participatory sensing in terms of market structure perspective and describes challenging problems that arise when applying traditional market mechanism into participatory sensing applications. Section 4 illustrates the novel reverse auction based incentive mechanism for participatory sensing application. The proposed incentive mechanism is evaluated by various experimentations in Section 5. The additional advantages of the proposed incentive mechanism in the participatory sensing application services are evaluated in Section 6. Section 7 discusses open challenges in real deployments and future works. The previous related works about auction mechanism and marketplaces for trading personal data are described in Section 8. Finally, in Section 9, we conclude with a summary of our contributions.

2. Backgrounds

2.1. Participation sensing applications

Traditional sensor networks require application-specific sensors deployed over a large area to monitor the environment such as air quality or automotive traffic jam. However, its performance is heavily dependent on the number of sensors. If sensor networks fail to lower the sensor cost, they cannot provide enough sensors to cover a wide area. As smart phones are getting prevalent in mobile industry, they are expected to replace application-specific sensors. Wireless connectivity, GPS-based localization capability, and OS can provide a platform for general-purpose sensors. Furthermore, smart phones carried by users add mobility to static sensors, covering a dynamic range. Each user transmits what he or she senses through the phone to nearby wireless access points (e.g., cellular base stations or WLAN access points). The infrastructure service provider aggregates sensing measurements from a large number of users through access networks, and then delivers raw data or statistics to application service providers. Examples of participatory sensing applications can be categorized into two groups, environment monitoring (e.g., traffic [8–12], air pollution [5], and noise [13]) and personal monitoring (e.g., phone data [4], user activity [14], and context [15]). In environment monitoring, the predefined number of user sensing data is required for a given geographic region at a given time in order to guarantee desired level of service quality. This paper focuses on environment monitoring participatory sensing applications in which a service provider collects the predefined number of user sensing data that includes geographical and temporal features.

2.2. Motivations

User participation is the most important element in participatory sensing application since application services (e.g., environmental sensing services) are truly dependent on users' sensing data. Additionally, user participation includes sensing and transmitting the measurements to a service provider. During the participation, a user consumes his own private resource such as battery and computation power of his device. Also, he may expose himself to potential location privacy threats

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