A Truthful Auction Mechanism for Mobile Crowdsourcing Systems

Vincent Wong

Department of Electrical and Computer Engineering

The University of British Columbia, Vancouver, Canada

Joint work with Hamed Shah-Mansouri

Embedded Sensors in Smartphones

- Smartphones are equipped with a set of embedded sensors, such as accelerometer, gyroscope, proximity sensor, ambient light sensor, and compass.
- Other conventional devices include front and back facing cameras, microphone, GPS, WiFi, and Bluetooth.

Applications and App Store

- Users can download different types of apps (e.g., games, healthcare, banking).

- The phone vendors offer app stores (e.g., Apple App Store) to distribute new apps.

Mobile Cloud Computing

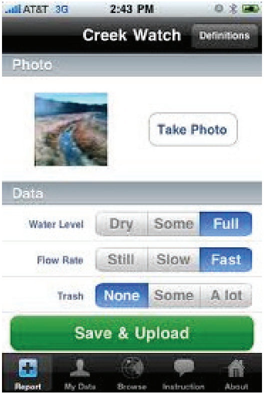
- The cloud enables us to offload resource intensive computations to the backend servers.

Mobile Crowdsourcing

- Mobile crowdsourcing or mobile crowdsensing is a new area which makes use of the pervasive smartphones for sensing and data collection.
- It opportunistically takes advantage of smartphone sensing capabilities to relieve the cost of deploying wireless sensor networks.
- The largest sensor network in the world can be formed by using smartphones.
- Question: What kind of large-scale applications can be developed by using mobile crowdsourcing?

Environmental Applications

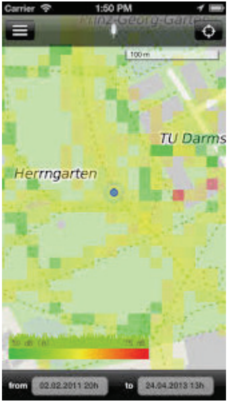
- CreekWatch for monitoring water levels and quality in creeks by collecting reports from individuals



[Creek Watch] IBM Research Creek Watch. http://ibmcreekwatch.tumblr.com/

Environmental Applications (cont.)

- Earphone for creating noise maps by recording noise level through microphone and tagging the location

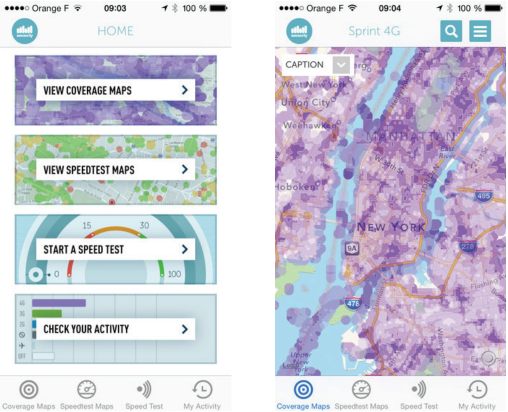


[Earphone] R. Rana, C. Chou, S. Kanhere, and W. H. N. Bulusu, "Earphone: An end-to-end participatory urban noise mapping," in *Proc. of ACM/IEEE IPSN*, Stockholm, Sweden, April 2010.

www.da-sense.de

Infrastructure Applications

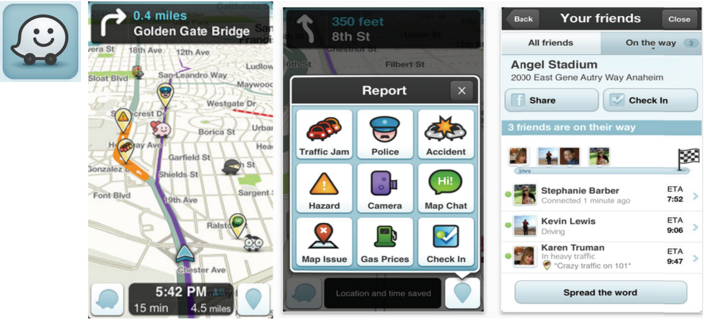
- Sensorly for making cellular/WiFi network coverage maps by measuring the received power level and tagging the location



Sensorly. http://www.sensorly.com

INFRASTRUCTURE APPLICATIONS (CONT.)

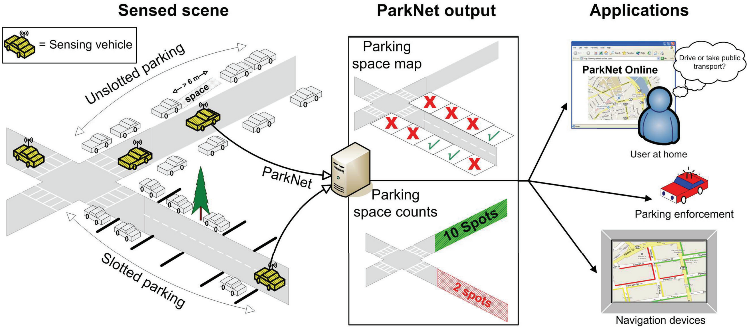
- Waze is a community-based traffic and navigation app.



www.waze.com.

INFRASTRUCTURE APPLICATIONS (CONT.)

- ParkNet for detecting available parking spots in cities by installing ultrasonic sensing devices on cars



[ParkNet] S. Mathur, T. Jin, N. Kasturirangan, J. Chandrashekharan, W. Xue, M. Gruteser and W. Trappe, "ParkNet: Drive-by sensing of road-side parking statistics," in *Proc. of ACM MobiSys*, San Francisco, CA, June 2010.

Characteristics

Compared to wireless sensor networks, mobile crowdsourcing systems have unique characteristics.

- Mobile device is a combination of computing, communication, and storage.
- Mobile devices are already deployed.
- The set of mobile devices and the results of sensing are dynamic.
- Sensed data can be reused across multiple applications on a mobile device.
- Human plays an important role.

Research Challenges

- Local analytics processes raw data and obtains intermediate results to
  - reduce energy and bandwidth consumption for communication,
  - decrease the amount of computation in cloud server.
- Aggregate analytics collects all sensing data from users to
  - analyze, process these data, and
  - identify some specific patterns to achieve the objective of application.

Research Challenges (cont.)

- Resource allocation determines the utilization of sensors to
  - identify the right set of mobile devices to perform a particular task, and
  - balance the trade off between data quality and energy consumption.
- Privacy and data integrity are to guarantee
  - individual specific privacy requirements, and
  - the integrity of sensing data provided by users.

Research Challenges (cont.)

- By participating in a mobile crowdsourcing system, smartphone users consume their own resources such as battery and computing power.

- They also expose themselves to potential privacy threats.

- Meanwhile, the performance of the system depends on the willingness of smartphone users to join the sensing system.

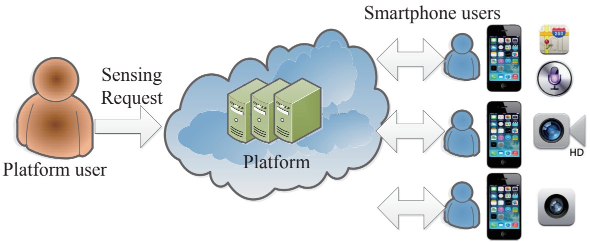
Question

Why a smartphone user would like to contribute to the system?

Incentive Mechanisms

- The mentioned existing applications assume that smartphones share their sensors voluntarily.
- Smartphone users may not be interested to share their sensors with the platform, unless they receive satisfying rewards.
- Incentive mechanisms encourage the smartphone users to contribute to the mobile crowdsourcing system.
- Such incentive mechanism must be immune against strategic behavior of selfish users. They may misreport their real cost in order to have more reimbursement.
- Auction theory provides a tool to manage such market models.

Mobile Crowdsourcing System



- The role of the platform is to
  - provide sensing and monitoring services to platform users and
  - encourage smartphone users to contribute to the system.
- The platform resides in a cloud.
- Once receiving the requests from platform users, the platform recruits smartphone users to collect data.
- The smartphone users are connected with the cloud server.

System Model

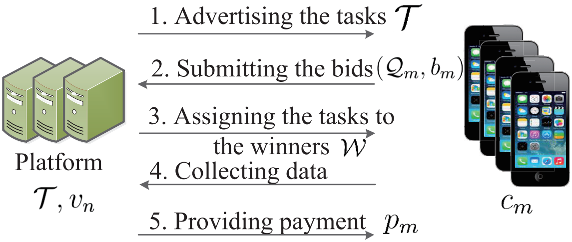
We model the interactions between the platform and smartphone users as a reverse auction mechanism:

- The platform is the single buyer and acts as the auctioneer .
- Smartphone users are sellers .
- Sensed data are goods of interest.

- Winner determination: The platform selects the smartphone users to perform tasks with the goal of maximizing its own profit.
- Design of payment scheme, which incentivizes the smartphone users and provides satisfying rewards to them.

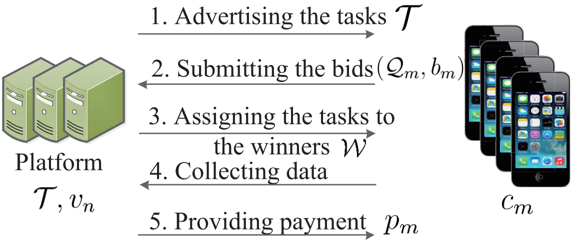
System Model

Consider a mobile crowdsourcing system consisting of a platform and M smartphone users.



- The set of sensing tasks is denoted by $\mathcal{T} = \{1, \ldots, N\}$.
- Each task $n \in \mathcal{T}$ represents a specific sensing service (e.g., taking photos at a specific location), which has a value $v_n > 0$ to the platform.
- Let $\mathcal{M} = \{1, \ldots, M\}$ denote the set of smartphone users.

SYSTEM MODEL (CONT.)



- Each user $m \in \mathcal{M}$ informs the platform
  - $\mathcal{Q}_m \subset \mathcal{T}$, which is a subset of tasks selected by user m according to the sensing capabilities of its smartphone and its preference.
  - b_m, which is the bid user m submits to the platform.
- The platform determines a subset of smartphone users as winners and provides the payment to them.
  - $\mathcal{W}$: set of the winners
  - $(p_m, m \in \mathcal{M})$: payment to user m

SYSTEM MODEL (CONT.)

- The utility of user m is

$$u_m = \begin{cases} p_m - c_m, & \text{if user } m \text{ wins} \\ 0, & \text{otherwise,} \end{cases} \quad (1)$$

where c_m denotes the cost incurred on user m when performing task $\mathcal{Q}_m$.

A user reveals its cost truthfully if it submits $b_m = c_m$ (i.e., bid = cost).

- The profit of the platform is

$$\sum_{n \in \cup_{w \in \mathcal{W}} \mathcal{Q}_w} v_n - \sum_{w \in \mathcal{W}} p_w = v(\mathcal{W}) - \sum_{w \in \mathcal{W}} p_w, \quad (2)$$

where $\mathcal{W}$ is the set of winners.

Auction Mechanism Design

- We propose ProMoT, which is a Profit Maximizing Truthful auction mechanism.
- ProMoT is composed of two major components, denoted by the pair $(\mathcal{A}, \mathcal{P})$.
- $\mathcal{A}$: the winner determination algorithm, which determines the winners.
- $\mathcal{P}$: the payment scheme, which determines the payment vector $\boldsymbol{p} = (p_1, \ldots, p_M)$.

Problem Formulation

- Let $x_n = 1$ if task $n \in \mathcal{T}$ is assigned to smartphone users. Otherwise, $x_n = 0$.
- Let $y_m = 1$ if user $m \in \mathcal{M}$ wins the competition. Otherwise, $y_m = 0$.
- The winner determination problem aims to maximize the profit of the platform.

$$
\begin{aligned}
\text{WD-ILP: } \underset{\boldsymbol{x},\boldsymbol{y}}{\text{maximize}} \quad & \sum_{n \in \mathcal{T}} v_n x_n - \sum_{m \in \mathcal{M}} b_m y_m && \text{(3a)} \\
\text{subject to } \quad & x_n \leq \sum_{m:\, n \in \mathcal{Q}_m} y_m, \quad \forall n \in \mathcal{T} && \text{(3b)} \\
& x_n, y_m \in \{0,1\}, \qquad \forall m \in \mathcal{M}, n \in \mathcal{T}, && \text{(3c)}
\end{aligned}
$$

where the first constraint forces x_n to be zero if task n is not assigned to any smartphones users.

Winner Determination

Theorem 1

The winner determination problem is NP-hard.

Sketch of proof: the winner determination problem can be reduced to the knapsack problem, which is known to be NP-hard.

As a result, the winners cannot be determined by an efficient algorithm with polynomial time computational complexity.

Winner Determination (cont.)

- To overcome the computation complexity of the winner determination problem, we relax the binary variables.

$$0 \le x_n, y_m \le 1, \qquad \forall m \in \mathcal{M}, n \in \mathcal{T}.$$

- Let $\boldsymbol{x}^*$ and $\boldsymbol{y}^*$ denote the optimal solution of the relaxed problem.
- $\boldsymbol{y}^*$ predicts which users are most likely to increase the profit of the platform.
- The larger value of y_m^*, the more contribution user m can provide.

Winner Determination (cont.)

- We introduce a novel greedy approach to determine the winners.

- Greedy mechanisms are based on a ranking function.

- We use the optimal solution of relaxed problem ($\boldsymbol{y}^*$) as the ranking function to sort users.

- This sorting implies that
$$y_1^* \geq y_2^* \geq \cdots \geq y_M^*.$$

- We gradually assign the tasks to the smartphone users, if they can increase the profit and make a progress towards finishing all the tasks.

Winner Determination (cont.)

Algorithm 1: Winner Determination Algorithm $\mathcal{A}$

Input: $\mathcal{T}, \boldsymbol{v}, \{(\mathcal{Q}_m, b_m)\}_{m \in \mathcal{M}}$
Initialize: $\mathcal{T}^{'} \leftarrow \emptyset$, $\mathcal{W} \leftarrow \emptyset$
Solve WD-LP problem (4), obtain optimal solutions $\boldsymbol{x}^*$ and $\boldsymbol{y}^*$
Sort y_m^* in the non-increasing order, denote the index list by $\mathcal{M}^s$
for $m = 1$ to M
  select user $m \in \mathcal{M}^s$
  if $v(\mathcal{W} \cup \{m\}) - v(\mathcal{W}) - b_m > 0$
    $\mathcal{T}^{'} \leftarrow \mathcal{T}^{'} \cup \mathcal{Q}_m$
    $\mathcal{W} \leftarrow \mathcal{W} \cup \{m\}$
  end if
end for
Output: Winning users set $\mathcal{W}$

Payment Scheme

- The payment scheme aims to ensure truthful bidding of smartphone users and motivate them to reveal their real cost.
- The following proposition presents the necessary and sufficient conditions to guarantee truthfulness.

Proposition

An auction mechanism is truthful if and only if [Nisan'07]:

- The winner selection algorithm is monotone. In other words, if user $m \in \mathcal{M}$ wins the auction by bidding b_m, it also wins by bidding $b'_m \leq b_m$.
- The pricing scheme is based on the critical payment. The critical payment is the highest bid that the bidder can submit in order to win.

[Nisan'07] N. Nisan *et al.*, Algorithmic Game Theory. Cambridge University Press, 2007.

Payment Scheme (cont.)

- We use the concept of critical payment to propose our payment scheme, denoted by $\mathcal{P}$.
- Let $\mathcal{M}_{-j}$ denote the set of smartphone users excluding user j.
- We execute the winner determination algorithm $\mathcal{A}$ with $\mathcal{M}_{-j}$ as input to find the winner set. The winner set is denoted by $\mathcal{W}_{-j}$.
- The critical payment p_j is the maximum value of b_j such that the following inequality holds.

$$v\left(\mathcal{W}\right) - \sum_{i \in \mathcal{W} \setminus \{j\}} b_i - b_j \geq v\left(\mathcal{W}_{-j}\right) - \sum_{i \in \mathcal{W}_{-j}} b_i.$$

Payment Scheme (cont.)

Algorithm 2: Payment Scheme $\mathcal{P}$

Input: $\mathcal{T}, \boldsymbol{v}, \{(\mathcal{Q}_m, b_m)\}_{m \in \mathcal{M}}$

Initialize $p_m \leftarrow 0, \quad \forall m \in \mathcal{M}$

Execute algorithm $\mathcal{A}$ with $(\mathcal{T}, \boldsymbol{v}, \{(\mathcal{Q}_m, b_m)\}_{m \in \mathcal{M}})$ as input, obtain $\mathcal{W}$

for each $j \in \mathcal{W}$

    Execute algorithm $\mathcal{A}$ with $\left(\mathcal{T}, \boldsymbol{v}, \{(\mathcal{Q}_m, b_m)\}_{m \in \mathcal{M}_{-j}}\right)$ as input, obtain $\mathcal{W}_{-j}$

    $p_j \leftarrow \left(v(\mathcal{W}) - \sum_{i \in \mathcal{W} \setminus \{j\}} b_i\right) - \left(v(\mathcal{W}_{-j}) - \sum_{i \in \mathcal{W}_{-j}} b_i\right)$

end for

Output: Payment vector $\boldsymbol{p} = (p_1, \ldots, p_M)$

Economic Properties

Theorem 2

Computational Efficiency: Both winner determination algorithm $\mathcal{A}$ and payment scheme $\mathcal{P}$ terminate in polynomial time.

Theorem 3

ProMoT is individually rational.

- Smartphone users have nonnegative utility.

Theorem 4

ProMoT achieves truthfulness.

- Reporting the true cost (i.e., $b_m = c_m,\ m \in \mathcal{M}$) is the dominant strategy of the bidders.

Performance Evaluation

- We compare our mechanism with MSensing mechanism [Yang'12].
- Tasks and users are randomly distributed in a $1000\ m \times 1000\ m$ region.
- Each user submits a bid to perform a subset of tasks located within a distance of r (sensing coverage radius) from it.

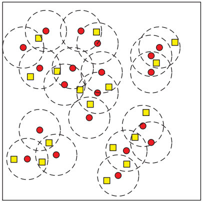
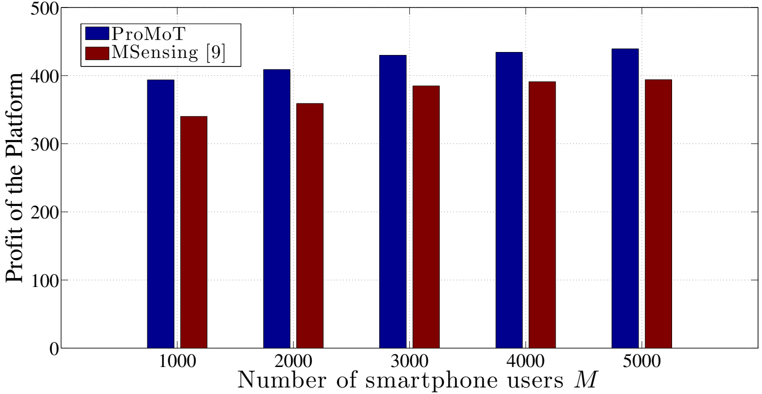


Figure: Squares represent tasks and circles represent users [Yang'12].

- The value of each task v_n is uniformly distributed over $[1, 10]$.
- The cost of user m is $\rho|\mathcal{Q}_m|$, where ρ is uniformly distributed over $[1, 5]$.

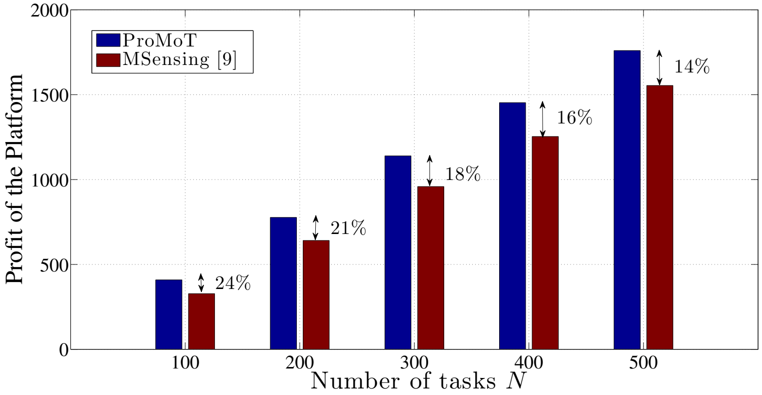
[Yang'12] D. Yang *et al.*, "Crowdsourcing to smartphones: Incentive mechanism design for mobile phone sensing," in *Proc. of ACM Mobicom*, Istanbul, Turkey, Aug. 2012.

Profit of the Platform



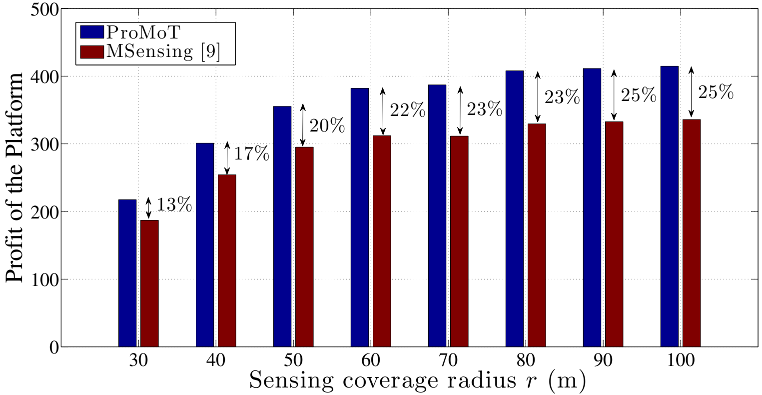
$N = 100$ tasks announced to the smartphone users and r (sensing coverage radius) is 80 m.

Profit of the Platform



The number of smartphone users is 1000 and $r = 80$ m.

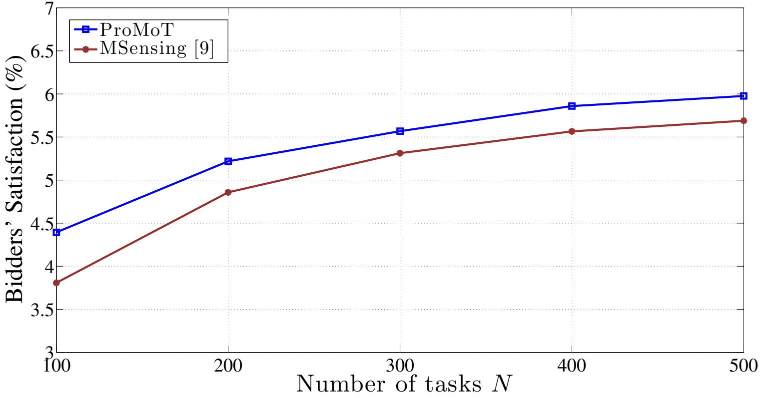
Profit of the Platform



100 tasks are announced to 1000 smartphone users.

Bidder's Satisfaction

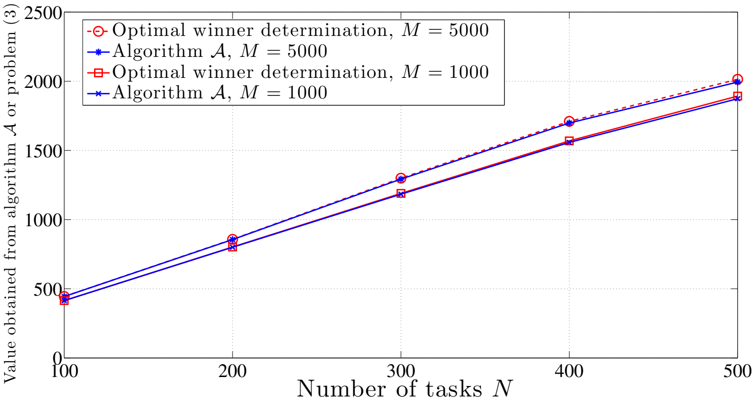
Bidder's satisfaction is defined as the ratio between the number of winners and the total number of bidders.



The number of smartphone users is 1000 and $r = 80$ m.

OPTIMAL VS. SUBOPTIMAL

Comparing the computationally efficient winner determination algorithm $\mathcal{A}$ with the optimal solutions of winner determination problem ($r = 80$ m).



CONCLUSION

- We proposed ProMoT, a truthful auction mechanism for mobile crowdsourcing systems.
- ProMoT motivates the smartphone users to contribute to the mobile crowdsourcing system by providing proper rewards to them.
- We proved that ProMoT achieves the main properties of an auction mechanism, namely, computational efficiency, individual rationality, and truthfulness.
- For future work, we will consider other task models and quality of sensing in the system.

Thank you!