Incentive Mechanism Design For Mobile Crowsensing

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Outline

- Motivation
- System Model
- Side-payment
- Content-restriction
- Combined Mechanism
- Conclusion
Motivation

- Waze uses an online crowdsensing platform for drivers to share real-time traffic and road information (e.g., accidents, road hazards and traffic jams) to provide a live map of auto traffic.
Motivation

- Providing information via crowdsensing comes at a cost to the mobile users.
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- Providing information via crowdsensing comes at a cost to the mobile users.
- Incentive mechanisms are crucial for crowdsensing!
User’s payoff from choosing H-path: \( \theta Q(x_H, x_L) - c_H \), from choosing L-path: \( \theta Q(x_H, x_L) \)

\( Q_0(x) = x^{0.5}, \ c_H = 5/24, \ \theta = 1 \)

NE: \( x_H = 0, \ x_L = 1, \ SW = \theta Q(0, 1) = 1 \)

Social optimum: \( x_H = 0.36, x_L = 0.64, \ SW = \theta Q(0.36, 0.64) - x_H c_H = 1.325 \)

How to remedy? a) side payments b) content restriction

Heterogeneous users: different \( \theta \) for different users
Two paths: H-path with cost $c_H > 0$; L-path with cost $c_L = 0$
System Model

- Two paths: H-path with cost $c_H > 0$; L-path with cost $c_L = 0$
- One unit mass of users
System Model

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- One unit mass of users
- $x_H$ mass on H-path, $x_L (= 1 - x_H)$ mass on L-path
Information Model

- Information aggregation function on a single path: $Q_0(x)$
Information Model

- Information aggregation function on a single path: $Q_0(x)$

Example: $Q_0(x) = \frac{N}{2} \left( 1 - \left( 1 - \frac{2\phi}{N} \right)^{nx} \right)$

- $N/2$ pieces of information available on a single path
- $nx$ users, each user pick $\phi$ pieces independently
Information Model

- Information aggregation function on two paths:

\[ Q(x_H, 1 - x_H) = Q_0(x_H) + Q_0(1 - x_H) \]
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- \( Q = Q(0, 1) \leq Q(x_H, 1 - x_H) \leq Q(0.5, 0.5) = \overline{Q} \)
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- \[ \frac{1}{2} \overline{Q} \leq Q \]
Equilibrium

- Two valuation types among users: $\theta_1$ and $\theta_2$ ($\theta_1 \leq \theta_2$)
- Both types with the same mass 0.5, average valuation: $\theta_0 = 0.5\theta_1 + 0.5\theta_2$
- User’s payoff function:

$$u_i(P, x_H) = \begin{cases} 
\theta_i Q(x_H, 1 - x_H), & \text{if } P = L; \\
\theta_i Q(x_H, 1 - x_H) - c_H, & \text{if } P = H.
\end{cases}$$

- **Definition 1** A feasible flow $\hat{x}_H$ in the content routing game is an equilibrium if no user traveling over the $H$-path or the $L$-path will profit by deviating from her current path choice to increase her payoff.

- **Proposition 1** There exists a unique equilibrium for our content routing game: $\hat{x}_H = 0$. 
Social welfare:

\[ SW(x_H) \stackrel{\text{def}}{=} (0.5 \theta_1 + 0.5 \theta_2)Q(x_H, 1 - x_H) - x_H c_H \]

Social optimum flow \( x^* \):

\[ x^* \in \text{arg max}_{0 \leq x_H \leq 1} \{ \theta_0 Q(x_H, 1 - x_H) - x_H c_H \} \]
Social Welfare

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\[ = \theta_0 Q(x_H, 1 - x_H) - x_H c_H \]

- Social welfare attained at equilibrium \( \hat{x}_H = 0 \):

\[ SW(\hat{x}_H) = \theta_0 Q \]
Social Welfare

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- Social optimum flow \( x^*_H \):

\[ x^*_H \in \arg \max_{0 \leq x_H \leq 1} \{\theta_0Q(x_H, 1 - x_H) - x_Hc_H\} \]
Price of Anarchy

- Price of anarchy (PoA): the ratio between the lowest social welfare at any equilibrium and the optimal social welfare $SW(\hat{x}_H)$, by searching over all possible system parameters and $Q_0(\cdot)$ functions:

$$PoA = \min_{\theta_i, Q_0(\cdot), c_H} \frac{SW(\hat{x}_H)}{SW(x^*_H)}.$$

**Proposition 2** The price of anarchy of the content routing game without incentive design is $PoA = 1/2$.

- $PoA = \min_{\theta_i, Q_0(\cdot), c_H} \frac{\theta_0 Q}{SW(x^*_H)} \geq \frac{Q}{Q} \geq \frac{1}{2}$

- $PoA \leq \frac{\theta_0 Q}{SW(x^*_H)} \leq \frac{\theta_0 Q}{SW(0.5)} = \frac{\theta_0 Q}{\theta_0 Q - 0.5 c_H} \xrightarrow{c_H \to 0} \frac{1}{2}$
Mechanism Design

- **Individual rationality (IR):** The payoff of each H- or L-path participant should be non-negative to guarantee participation.
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- **Incentive compatibility (IC):** Each user with type-i should truthfully decide routing according to her real valuation $\theta_i$. 

Many crowdsensing applications (e.g., Waze) want to maximize the social welfare and are not profitable in forming a community among users.
Mechanism Design

- **Individual rationality (IR):** The payoff of each H- or L-path participant should be non-negative to guarantee participation.

- **Incentive compatibility (IC):** Each user with type-i should truthfully decide routing according to her real valuation $\theta_i$.

- **Budget balance (BB):** The money collected from some users (if any) should be distributed to the rest of the users. Many crowdsensing applications (e.g., Waze) want to maximize the social welfare and are not profitable in forming a community among users.
Side-payment as incentive

\[
\text{subsidy/user} = \frac{1-x_H}{x_H} g(x_H)
\]

\[
c_H > 0
\]

\[
x_L = 1 - x_H
g(x_H)
\]

\[
\text{payment/user} = f(x_L)
= f(1 - x_H) = g(x_H)
\]

▶ Charge \( g(x_H) \) a user of L-path
Side-payment as incentive

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$\quad c_H > 0$

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- Charge $g(x_H)$ a user of L-path
- Subsidize by $\frac{1-x_H}{x_H} g(x_H)$ a user of H-path
Side-payment as incentive

- Charge $g(x_H)$ a user of L-path
- Subsidize by $\frac{1-x_H}{x_H}g(x_H)$ a user of H-path
- New payoff function:

$$u_i(P, x_H) = \begin{cases} 
\theta_i Q(x_H, 1 - x_H) - g(x_H), & \text{if } P = L; \\
\theta_i Q(x_H, 1 - x_H) - c_H + \frac{1-x_H}{x_H}g(x_H), & \text{if } P = H. 
\end{cases}$$
Side-payment as incentive

- Equilibrium condition for $\hat{x}_H$ being an equilibrium:

$$u_i(H, \hat{x}_H) = u_i(L, \hat{x}_H) \iff g(\hat{x}_H) = c_H \hat{x}_H$$
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- Equilibrium payoff:

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- **Stable equilibrium** (asymptotically stable): An equilibrium is stable if a small perturbation of the traffic on the two links does not move the system away from the equilibrium.
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▶ **Stable equilibrium** (asymptotically stable): An equilibrium is stable if a small perturbation of the traffic on the two links does not move the system away from the equilibrium.

▶ Without considering IR, $\hat{x}_H \in [0, 1)$ becomes a stable equilibrium under the linear side-payment function

$$g\hat{x}_H(x_H) = \frac{\hat{x}_H c_H}{1 - \hat{x}_H} (1 - x_H)$$
Social Welfare of Equilibrium

- Homogeneous users ($\theta_1 = \theta_2 = \theta_0$):

- The social optimum $x_H^*$ can be attained as an equilibrium using an appropriate payment function.
- IR is not an issue.
- PoA = 1.
Reduced User Participation

- Heterogeneous users ($\theta_1 < \theta_2$):

- Large $\theta_1$: ‘participating equilibria’ in $[0, x_{IR}^L]$

- Small $\theta_1$: ‘participating equilibria’ in $[0, x_{IR}^S]$

- Range of ‘participating equilibria’ decreases as $\theta_1$ decreases.
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Reduced User Participation

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Heterogeneous users ($\theta_1 < \theta_2$)

- Large $\theta_1$: $x_H^*$ can be achieved as a ‘participating equilibrium’
Heterogeneous users ($\theta_1 < \theta_2$)

- Large $\theta_1$: $x_H^*$ can be achieved as a ‘participating equilibrium’
- Small $\theta_1$: $x_H^*$ can not be achieved as a ‘participating equilibrium’
  - Best ‘participating equilibrium’: $x_{IR}^S$  
  - Keep only type $\theta_2$ users in the system, best equilibrium:

$$\tilde{x}_H \in \arg \max_{x_H \in [0,0.5]} \{0.5\theta_2 Q(x_H, 0.5 - x_H) - x_H c_H\}$$
Heterogeneous users ($\theta_1 < \theta_2$)

- **Case of** $x_{IR} < x^*_H$:
  - $SW(x_{IR}) \geq SW(\tilde{x}_H)$ (CD $\geq$ AB), optimally choose $\hat{x}_H = x_{IR}$
  - $SW(x_{IR}) < SW(\tilde{x}_H)$ (CD $<$ AB), optimally choose $\hat{x}_H = \tilde{x}_H$
Price of Anarchy ($\theta_1 < \theta_2$)

Note that $CD \geq OG$:

$$PoA = \frac{\max\{AB, CD\}}{MN} \geq \frac{OG}{MN} \geq \frac{OG}{KL} = \frac{\theta_0 Q}{\theta_0 Q} \geq \frac{1}{2}.$$
Price of Anarchy ($\theta_1 < \theta_2$)

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For some instance, $AB = OG, CD = OG$:

$$PoA \leq \frac{OG}{MN} \leq \frac{OG}{KJ} = \frac{\theta_0 Q}{\theta_0 Q - 0.5c_H} \xrightarrow{c_H \to 0} \frac{1}{2}.$$
Price of Anarchy \((\theta_1 < \theta_2)\)

- Note that \(CD \geq OG\):
  \[
P_{oA} = \frac{\max\{AB, CD\}}{MN} \geq \frac{OG}{MN} \geq \frac{OG}{KL} = \frac{\theta_0 Q}{\theta_0 Q} \geq \frac{1}{2}.
  \]
- For some instance, \(AB = OG, CD = OG\):
  \[
P_{oA} \leq \frac{OG}{MN} \leq \frac{OG}{KJ} = \frac{\theta_0 Q}{\theta_0 Q - 0.5 c_H} \xrightarrow{c_H \to 0, Q=2Q} \frac{1}{2}
  \]
- \(P_{oA} = \frac{1}{2}\)
Discussion

- Full participation: may require very low incentives $\Rightarrow x_H \downarrow \Rightarrow$ low path diversity but everybody benefits from higher participation
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- Only large type participate: we can optimally control the reduced system \( \Rightarrow \) more path diversity but less benefit from reduced total travel and number of users

How about incentivize users differently?
Discussion

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- Only large type participate: we can optimally control the reduced system $\Rightarrow$ more path diversity but less benefit from reduced total travel and number of users
- Need to choose between:
  - not admitting low types but increasing path diversity
  - or admitting more users at the expense of path diversity
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- High path diversity is valuable if paths are not very “content rich”, i.e., $Q = \text{concave function}$. If $Q = \text{linear}$, then path diversity not an issue.

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- High path diversity is valuable if paths are not very “content rich”, i.e., $Q = \text{concave function}$. If $Q = \text{linear}$, then path diversity not an issue.
- How about incentivize users differently?
Content-restriction as incentive

→ Restricted content for user of L-path: $aQ(x_H, 1 - x_H)$ where $0 \leq a \leq 1$
Content-restriction as incentive

- Restricted content for user of L-path: $aQ(x_H, 1 - x_H)$ where $0 \leq a \leq 1$
- Unrestricted content for user of H-path: $Q(x_H, 1 - x_H)$
Content-restriction as incentive

- Restricted content for user of L-path: \( aQ(x_H, 1-x_H) \) where \( 0 \leq a \leq 1 \)
- Unrestricted content for user of H-path: \( Q(x_H, 1-x_H) \)
- New payoff function:

\[
\begin{align*}
u_i(P, x_H) &= \begin{cases} 
a\theta_i Q(x_H, 1-x_H), & \text{if } P = L; \\
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\]
Homogeneous users \((\theta_1 = \theta_2 = \theta_0)\)

- Equilibrium condition:

\[
u_i(H, \hat{x}_H) = u_i(L, \hat{x}_H) \iff Q(\hat{x}_H, 1 - \hat{x}_H) = \frac{c_H}{(1 - a)\theta_0}
\]
Homogeneous users ($\theta_1 = \theta_2 = \theta_0$)

- Equilibrium condition:

  $$u_i(H, \hat{x}_H) = u_i(L, \hat{x}_H) \iff Q(\hat{x}_H, 1 - \hat{x}_H) = \frac{c_H}{(1 - a)\theta_0}$$

- Three regimes:
  - Strong content-restriction regime: small $a$
  - Medium content-restriction regime: medium $a$
  - Weak content-restriction regime: large $a$
Strong content-restriction regime: small $\alpha$

- Equilibrium: $\hat{x}_H = 1$
- Optimal equilibrium choice: $\hat{x}_H = 1$, $SW = \theta_0Q - c_H$
Medium content-restriction regime: medium $a$

- Equilibrium (stable): $\hat{x}_H = x_{H0}$
- Optimal equilibrium choice: $\hat{x}_H \rightarrow 0.5$, $SW = \theta_0 \overline{Q} - c_H$
Weak content-restriction regime: large $\alpha$

- Equilibrium: $\hat{x}_H = 0$
- Optimal equilibrium choice: $\hat{x}_H = 0, \ SW = \theta_0 Q$
Maximal Social Welfare of Equilibrium

- Homogeneous users ($\theta_1 = \theta_2$):
- If the travel cost over H-path is small (i.e., $c_H < \theta_0(Q - \overline{Q})$), we optimally approach perfect path diversity ($\hat{x}_H \to 0.5$) and optimum social welfare $\theta_0\overline{Q} - c_H$. 
Homogeneous users ($\theta_1 = \theta_2$):

- If the travel cost over H-path is small (i.e., $c_H < \theta_0(\overline{Q} - \underline{Q})$), we optimally approach perfect path diversity ($\hat{x}_H \to 0.5$) and optimum social welfare $\theta_0\overline{Q} - c_H$.

- If the travel cost over H-path is large (i.e., $c_H \geq \theta_0(\overline{Q} - \underline{Q})$), we optimally choose $a = 1$ and the corresponding social welfare $\theta_0\overline{Q}$.
Heterogeneous users ($\theta_1 < \theta_2$)

- Similar to the homogeneous case, when the travel cost is too high, we choose the zero path-diversity equilibrium; when the travel cost is small, we choose the perfect path-diversity equilibrium.
Heterogeneous users \((θ_1 < θ_2)\)

- Similar to the homogeneous case, when the travel cost is too high, we choose the zero path-diversity equilibrium; when the travel cost is small, we choose the perfect path-diversity equilibrium.

- When user types are diverse such that \(\frac{θ_2}{θ_1} > \frac{Q}{\bar{Q}}\), we can achieve higher social welfare at the perfect path-diversity equilibrium than the homogeneous case. **User diversity helps because we can choose an \(a\) not far from 1 to persuade type \(θ_2\) to use H-path**
  - type \(θ_1\) will use anyway the L-path
  - hence get the perfect path-diversity equilibrium with \(a\) near 1
Information aggregation function and price of anarchy

\[ Q(x_H, 1 - x_H) = Q_0(x_H) + Q_0(1 - x_H) \]

\[ Q_0(x_H) = \begin{cases} 
\frac{q x}{\delta}, & 0 \leq x \leq \delta \\
q, & \delta \leq x \leq 1 
\end{cases} \]

- zero path-diversity equilibrium: \( SW = \theta_0 Q = \theta_0 q \)
- perfect path-diversity equilibrium: \( SW \leq \theta_0 \overline{Q} - 0.5 c_H = 2\theta_0 q - 0.5 c_H \)
- social optimum: \( SW(\delta) = \theta_0 \overline{Q} - \delta c_H = 2\theta_0 q - \delta c_H \)
- \( PoA \geq \frac{Q}{\overline{Q}} \geq 1/2 \). Let \( c_H \) be large enough:

\[ PoA \leq \frac{\max\{\theta_0 q, 2\theta_0 q - 0.5 c_H\}}{2\theta_0 q - \delta c_H} = \frac{\theta_0 q}{2\theta_0 q - \delta c_H} \xrightarrow{\delta \to 0} \frac{1}{2} \]
Discussion

- It is optimal to either incentivize the perfect path-diversity equilibrium or just do nothing and stay at the zero path-diversity equilibrium (high $c_H$).
Discussion

- It is optimal to either incentivize the perfect path-diversity equilibrium or just do nothing and stay at the zero path-diversity equilibrium (high $c_H$).
- Diversity in the user types increases the optimum system efficiency: less restriction is needed to make users switch and obtain path diversity.
Combined mechanism

- Is only content-restriction or side-payment enough?
Combined mechanism

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- No! Combining them can achieve a strictly better performance.
Combined mechanism

- Is only content-restriction or side-payment enough?
- No! Combining them can achieve a strictly better performance.
- Better worst-case performance: $PoA \geq 0.7$. 
The ratio $SW_g/SW(x_H^*)$ between the maximum social welfare achieved by side-payment mechanism and the social optimum under different values of $\theta_1$ and $c_H$ (we fix $\theta_0$ as 0.5).

The ratio is larger than 70% globally and as long as $\theta_1$ is not too small, $SW_g/SW(x_H^*) = 100\%$. 
Numerical results: content-restriction

- The ratio $SW_a/SW(x_H^\ast)$ between the maximum social welfare achieved by content-restriction mechanism and the social optimum under different values of $\theta_1$ and $c_H$ (we fix $\theta_0$ as 0.5).
- The ratio is larger than 60% globally.

$$Q_0(x) = 50(1 - 0.01^x)$$
Numerical results: comparison

- Performance comparison between side-payment ($SW_g$) and content-restriction ($SW_a$) in terms of the achieved social welfare under different $\theta_1$ and $c_H$ values (we fix $\theta_0$ as 0.5).

- We have $SW_g > SW_a$ in most cases, and $SW_g < SW_a$ only when users are diverse (with small $\theta_1$) and $c_H$ is small.
Extensions

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- Our mechanism design is applicable to the case with more than 2 user types. We have extended our mechanisms to uniformly distributed user types in a continuous range.
- Our mechanism design is applicable to the case with more than 2 paths. We have extended our mechanisms to three-path model:
  - we can apply side-payment to incentivize a unique stable equilibrium
  - we can apply content-restriction to incentivize a stable set of equilibria
Conclusion

- We proposed a simple model of incentive-based routing where selfish users generate positive externalities from content aggregation. Without proper incentives, the system may end in a bad equilibrium.

- Assuming that user types are private information, we analyzed two different incentive mechanisms: side-payments and content-restriction, in terms of their stability of equilibria and efficiency.

- Our model captures the important effects of user type diversity, which can either help or weaken efficiency, depending on the type of mechanism used.

- In the case of incentive payments, there is a trade-off between path diversity and participation incentives that becomes important as user types become more diverse. In the case of content restriction, user type diversity helps incentives work easier and requires less 'content destruction'.
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