Incentive Design and Market Evolution of Mobile User-Provided Networks

Mohammad Mahdi Khalili†, **Lin Gao***, Jianwei Huang*, and Babak Hossein Khalaj†

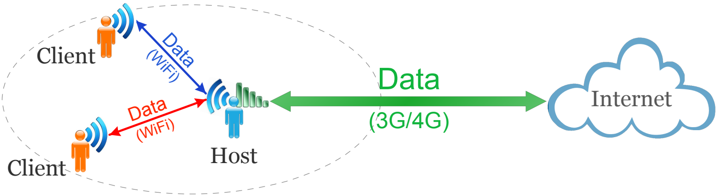
† **Department of Electrical Engineering**
Sharif University of Technology (SUT), Iran

* **Network Communications and Economics Lab (NCEL)**
The Chinese University of Hong Kong (CUHK), Hong Kong

Outline

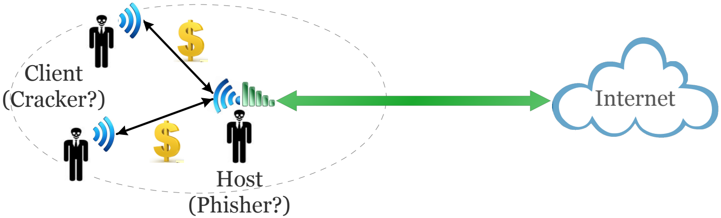
What is Mobile UPN?

- **Mobile User-Provided Network (UPN)**
  - Mobile users act as micro-providers (hosts) through their personal devices (e.g., smartphones and customized portable devices), and provide Internet connections for others (clients).



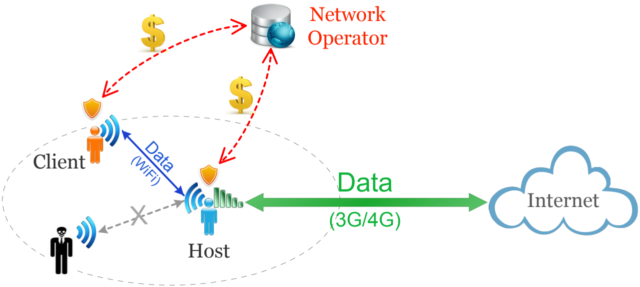
Key Challenges

- **Security**
  - E.g., a host may be a phishing user, or a client may be a hacker.
  - *It is difficult for a mobile user to detect a phishing user or a hacker.*
- **Incentive**
  - When acting as hosts, mobile users will incur certain hosting cost, such as energy cost and cellular data payment.
  - *Direct money transfer among anonymous users is difficult.*



Current Solution

- **Operator-Assisted Mobile UPN**
  - A network operator is introduced to address the security and incentive issues in mobile UPN.
    - ★ Security: Achieved via certificates provided by the operator (i.e., users with certificates can operate as UPN);
    - ★ Incentive: Achieved via the agency of operator (i.e., no direct money transfer among users → money transfer among each user and operator);

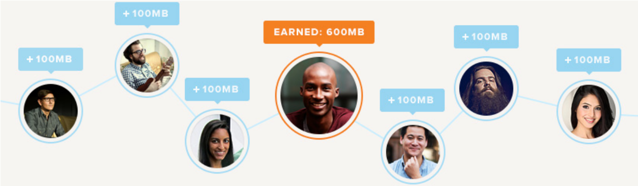


A Real Case — Karma

- **Karma** (https://yourkarma.com)
  - A recent mobile virtual network operator (MVNO) in USA;
    - ★ Providing 4G services (with usage-based pricing) to its customers, using cellular networks leased from traditional mobile network operators;
  - Offer a (certified) custermized device to its customers;
    - ★ Enabling its customers to operate as WiFi hotspots (hosts) and provide Internet connections for others (clients) → Operator-Assisted UPN

A Real Case — Karma

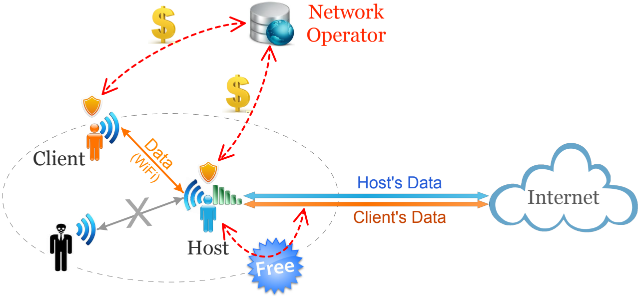
- **Karma's Incentive Approach**
  - Connectivity Sharing (Not Data Sharing)
    - ★ Hosts only pay the data they actually consume, and clients pay their own data usage on hosts' cellular links.
  - Free Data Quota
    - ★ Every host gets 100MB of free data when sharing its Internet connection with every new mobile user at the first time.



- Drawbacks
  - *Easy to employ, but fail to provide consistent incentives!*

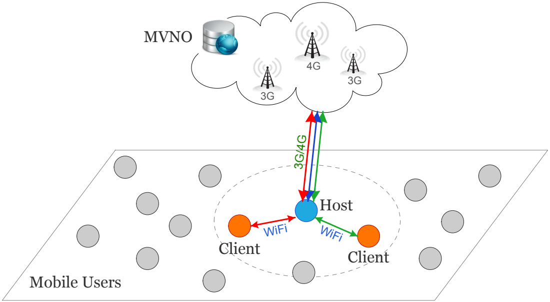
A Generalized Karma Model

- **Generalized Karma Model** in [Gao et al. INFOCOM 2014]
  - Connectivity Sharing (same as Karma)
    - ★ Hosts only pay the data they actually consume, and clients pay their own data usage on hosts' cellular links.
  - **Flexible** Free Data Quota (more general than Karma)
    - ★ Key Idea: The free data quota for a host is not fixed, but proportional to the data that the host routes for clients.



A Generalized Karma Model

- **Generalized Karma Model** in [Gao et al. INFOCOM 2014]
  - Focus only on *the interaction of a particular host (and its clients) in a fixed network*, without considering
    - ★ Network Topology Change: Due to user mobility, a client connecting to a host may not be able to connect to the host in the future;
    - ★ User Membership Change: Due to the varying of incentive level or QoS requirement, a user may change its membership, e.g., a host (client) may choose to be a client (host) with a reduced (increased) incentive.



Our Focus in This Work

- In this work, we will study the generalized Karma model from a system perspective, considering both the network topology change and user membership change.

Key Problems

1. What is the *best membership choice* for each mobile user, and how different users' membership choices affect each other?
2. What is the operator's *best pricing and free data quota rewarding strategy*, considering the network topology change and user membership change?

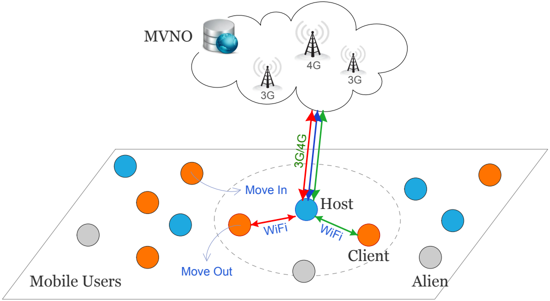
Outline

System Model

- One MVNO
  - Provide 4G service to mobile users, and enable operator-assisted UPN;
    - ★ Incentivize mobile users to operate as hosts and provide Internet connections for other users (clients);
  - Charge hosts and clients a usage-based data price;
  - Reward hosts a flexible free data quota;
- Multiple Mobile Users
  - Move randomly in a certain area;
  - Request service (data transmission) with a certain probability;
  - Choose different memberships $s \in \{\text{H}, \text{C}, \text{A}\}$:
    - ★ Host (H): Connect to the MVNO's network at any time; Gain free data quota via providing Internet connection for others (clients);
    - ★ Client (C): Connect to the MVNO's network through a nearby host;
    - ★ Alien (A): Not connect to the MVNO's network at all;

System Model

- Illustration of Operator-Assisted Mobile UPN



  - Mobile Users: Hosts (Blue), Clients (Red), Aliens (Gray).

System Model

- MVNO Parameters
  - $p \in [0, p_{\text{MAX}}]$: the usage-based price changed to hosts and clients;
  - $\delta \in [0, 1]$: the free data quota ratio rewarded to hosts.
- User Parameters
  - $\mathcal{N} = \{1, 2, ..., N\}$: the set of mobile users;
    - ★ We assume a large network with $N \to \infty$;
  - $\rho \in [0, 1]$: the meeting (encountering) probability of any two users;
    - ★ We assume the homogeneous mobility pattern for users;
  - $\lambda = N \cdot \rho$: the average number of other users that a user encounters;
    - ★ We assume that λ is a finite value;
  - $\theta \in [0, 1]$: the **service request probability** of each user, referred to as the user type;
    - ★ We assume that different users may have different types, which are independent and identically distributed (i.i.d) according to a probability distribution function $f(\theta)$.

System Model

- User Payoff: For a type-θ user,
  - (i) When choosing to be an alien $(s = \mathrm{A})$, its expected payoff is

$$U_\theta(\mathrm{A}) = 0$$

  - (ii) When choosing to be a client $(s = \mathrm{C})$, its expected payoff is

$$U_\theta(\mathrm{C}) = \theta \cdot P_{\mathrm{H}} \cdot \underbrace{(v_{\mathrm{C}} - \gamma_{\mathrm{C}} - p)}_{\textit{consumption benefit}} - \phi_{\mathrm{C}}$$

  - ★ v_{C}: the average data value of clients;
  - ★ γ_{C}: the average transmission cost of clients;
  - ★ ϕ_{C}: the time-average cost of clients (e.g., subscription fee);
  - ★ P_{H}: *the probability of a client meeting at least one host (to be derived);*

System Model

- User Payoff: For a type-θ user,
  - (iii) When choosing to be a host ($s = \mathrm{H}$), its expected payoff is

$$U_\theta(\mathrm{H}) = \theta \cdot \underbrace{(v_\mathrm{H} - \gamma_\mathrm{H} - p)}_{consumption\ \ benefit} + \bar{\theta}_\mathrm{C} \cdot Y_\mathrm{C} \cdot \underbrace{(\delta \cdot p - \gamma_\mathrm{HC})}_{sharing\ \ benefit} - \phi_\mathrm{H}$$

★ v_H: the average data value of hosts;

★ γ_H: the average transmission cost of hosts for its own data;

★ γ_HC: the average transmission cost of hosts for client data;

★ ϕ_H: the time-average cost of clients (e.g., the device cost);

★ $\bar{\theta}_\mathrm{C}$: *the average service request probability of clients (to be derived);*

★ Y_C: *the average number of clients that a host serves (to be derived);*

System Model

- MVNO Profit
  - Pay a usage-based wholesale price ω to traditional MNOs;
  - Earn a usage-based service price p from hosts and $p \cdot (1-\delta)$ from clients;
  - Hence, its expected profit is

$$V(p,\delta) = \underbrace{\mu_{\mathrm{H}} \cdot \bar{\theta}_{\mathrm{H}} \cdot (p-\omega)}_{profit\ \ from\ \ hosts} + \underbrace{P_{\mathrm{H}} \cdot \mu_{\mathrm{C}} \cdot \bar{\theta}_{\mathrm{C}} \cdot (p \cdot (1-\delta) - \omega)}_{profit\ \ from\ \ clients}$$

    - ★ μ_{H} and μ_{C}: the percentages of hosts and clients;
    - ★ $\bar{\theta}_{\mathrm{H}}$ and $\bar{\theta}_{\mathrm{C}}$: the average service request probabilities of hosts and clients;
    - ★ $\mu_{\mathrm{H}} \cdot \bar{\theta}_{\mathrm{H}}$: the total data requested and consumed by hosts;
    - ★ $\mu_{\mathrm{C}} \cdot \bar{\theta}_{\mathrm{C}}$: the total data requested by clients;
    - ★ $P_{\mathrm{H}} \cdot \mu_{\mathrm{C}} \cdot \bar{\theta}_{\mathrm{C}}$: the total data consumed by clients;

System Model

- **Two-stage Game Formulation**
  - Stage I — MVNO Pricing Strategy
    - ⋆ The MVNO decides the price p and the free data quota ratio δ, aiming at maximizing the expected profit $V(p, \delta)$;
  - Stage II — User Membership Selection
    - ⋆ The mobile users with each type-θ decide their memberships $s(\theta) \in \{\mathrm{H}, \mathrm{C}, \mathrm{A}\}$, aiming at maximizing the expected payoff $U_\theta(s)$;

- **We will derive the Subgame Perfect Equilibrium (SPE).**

Outline

Preprocessing

- **Derivation of Important Variables**
  - Let Θ_{A}, Θ_{C}, Θ_{H} denote the sets of users (types) choosing to be aliens, clients, and hosts, respectively.
  - (i) μ_{A}, μ_{C}, μ_{H}: *the percentages of aliens, clients, and hosts*

$$\mu_s = \int_{\theta \in \Theta_s} f(\theta) \mathrm{d}\theta, \quad \forall s \in \{\mathrm{A}, \mathrm{C}, \mathrm{H}\}$$

  - (ii) $\bar{\theta}_{\mathrm{C}}$, $\bar{\theta}_{\mathrm{H}}$: *the average service request probabilities of clients and hosts*

$$\bar{\theta}_s = \frac{1}{\mu_s} \cdot \int_{\theta \in \Theta_s} \theta \cdot f(\theta) \mathrm{d}\theta, \quad \forall s \in \{\mathrm{C}, \mathrm{H}\}$$

Preprocessing

- **Derivation of Important Variables**
  - (iii) P_{H}: *the probability of a client meeting at least one host*

$$P_{\mathrm{H}} = 1 - (1 - \rho\mu_{\mathrm{H}})^{N-1} = \underbrace{1 - e^{-\mu_{\mathrm{H}}\lambda}}_{when\ N\to\infty}$$

    - ★ $\rho\mu_{\mathrm{H}}$: the probability of meeting an user and meanwhile the latter is a host;
    - ★ P_{H} increases with the percentage of hosts μ_{H};

  - (iv) Y_{C}: *the average number of clients connected to a host*

$$Y_{\mathrm{C}} = (N-1) \cdot \rho\mu_{\mathrm{C}} \cdot P_{\mathrm{C}}^{\mathrm{CON}} = \underbrace{\frac{\mu_{\mathrm{C}}}{\mu_{\mathrm{H}}} \cdot (1 - e^{-\mu_{\mathrm{H}}\lambda})}_{when\ N\to\infty}$$

    - ★ $P_{\mathrm{C}}^{\mathrm{CON}}$: the probability that a host is chosen by a client that he meets;
    - ★ Y_{C} increases with the percentage of clients μ_{C}, and decreases with the percentage of hosts μ_{H};

Stage II – User Membership Selection

- **User Best Response**
  - Given the MVNO's strategy (p, δ), and under a particular membership distribution $\{\Theta_{\mathrm{A}}, \Theta_{\mathrm{C}}, \Theta_{\mathrm{H}}\}$, the payoff of a type-$\theta$ user is:

$$U_\theta(s) = \begin{cases} 0, & \text{if } s = \mathrm{A}, \\ \theta P_{\mathrm{H}} \Pi_{\mathrm{C}} - \phi_{\mathrm{C}}, & \text{if } s = \mathrm{C}, \\ \theta \Pi_{\mathrm{H}} + \bar{\theta}_{\mathrm{C}} Y_{\mathrm{C}} \tilde{\Pi}_{\mathrm{H}} - \phi_{\mathrm{H}}, & \text{if } s = \mathrm{H}. \end{cases}$$

    - ⋆ *P_{H}, $\bar{\theta}_{\mathrm{C}}$, Y_{C} depend on the choices of other users;*

  - A type-θ user will choose to be a client, if and only if

$$U_\theta(s = \mathrm{C}) \geq \max\{0,\ U_\theta(s = \mathrm{H})\},$$

  - A type-θ user will choose to be a host, if and only if

$$U_\theta(s = \mathrm{H}) \geq \max\{0,\ U_\theta(s = \mathrm{C})\}.$$

Stage II – User Membership Selection

- **Membership Selection Equilibrium**
  - Existence: There exists at least one equilibrium in the membership selection game in Stage II.
  - Shape of Equilibrium:

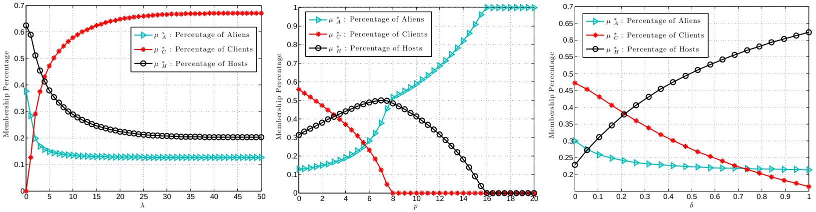
  - Equilibrium Condition:

$$\begin{cases} \mu_{\mathrm{C}} = \theta_{\mathrm{H}}(\mu_{\mathrm{C}}, \mu_{\mathrm{H}}) - \theta_{\mathrm{A}}(\mu_{\mathrm{C}}, \mu_{\mathrm{H}}), \\ \mu_{\mathrm{H}} = 1 - \theta_{\mathrm{H}}(\mu_{\mathrm{C}}, \mu_{\mathrm{H}}), \end{cases} \tag{1}$$

    - ★ θ_{A}: the largest θ that a type-θ user prefers to be an alien;
    - ★ θ_{H}: the smallest θ that a type-θ user prefers to be a host;
    - ★ Users with a type between θ_{A} and θ_{H} prefer to be clients;

Stage II – User Membership Selection

- Illustration of Membership Selection Equilibrium
  - Green: Aliens; Red: Clients; Black: Hosts.
  - (a) $\lambda \nearrow$: Clients $\nearrow$, Host $\searrow$;
  - (b) $p \nearrow$: Clients $\searrow$, Host first $\nearrow$ and then $\searrow$;
  - (c) $\delta \nearrow$: Clients $\searrow$, Host $\nearrow$;



Stage I – MVNO Pricing Strategy

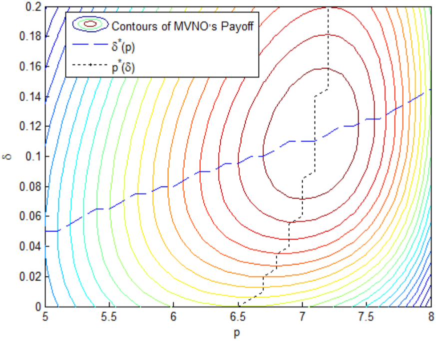
- **MVNO Profit Optimization Problem**

$$\max_{\{p,\delta\}} \underbrace{\mu_{\mathrm{H}} \cdot \bar{\theta}_{\mathrm{H}}}_{X_{\mathrm{H}}} \cdot (p-\omega) + \underbrace{P_{\mathrm{H}} \cdot \mu_{\mathrm{C}} \cdot \bar{\theta}_{\mathrm{C}}}_{X_{\mathrm{C}}} \cdot (p \cdot (1-\delta) - \omega)$$

- ★ X_{H}: the total amount of data consumed by hosts *under the membership selection equilibrium in Stage II*;
- ★ X_{C}: the total amount of data consumed by clients *under the membership selection equilibrium in Stage II*;
- ★ Both X_{H} and X_{C} are functions of p and δ.

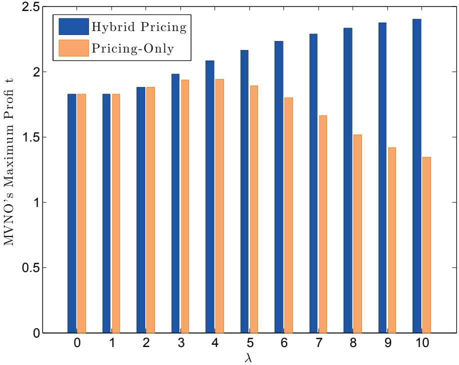
Stage I – MVNO Pricing Strategy

- Illustration of MVNO's Best Pricing Strategy
  - The contours of MVNO profit under different p and δ;
  - Blue Dash Curve $\delta^*(p)$: The best δ under different p;
  - Black Dot Curve $p^*(\delta)$: The best p under different δ;



Performance Evaluation

- **MVNO's Maximum Profit**
  - Hybrid Pricing Policy (proposed in this work)
    - ⋆ The MVNO's maximum profit *always increases* with λ;
    - ⋆ *Exploit the benefit of a larger λ for both hosts and clients;*
  - Pricing-Only Policy
    - ⋆ The MVNO's maximum profit *first increases then decreases* with λ;
    - ⋆ *Exploit the benefit of a larger λ for clients only;*



Outline

Conclusion

- Model an operator-assisted mobile UPN from a system perspective;
- Analyze the user membership selection equilibrium and the operator's best hybrid pricing strategy.

- **Future Extension**
  - Practical mobility model based on real data traces;
  - Practical service model based on real data traces;
  - Whether the price discrimination is profitable, and how to discriminate prices in the best way?

Thank You

LGAO@IE.CUHK.EDU.HK

Network Communications and Economics Lab (NCEL)

The Chinese University of Hong Kong (CUHK)