Enabling Crowd-sourced Mobile Internet Access

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Crowd-Sourced Mobile Internet Access

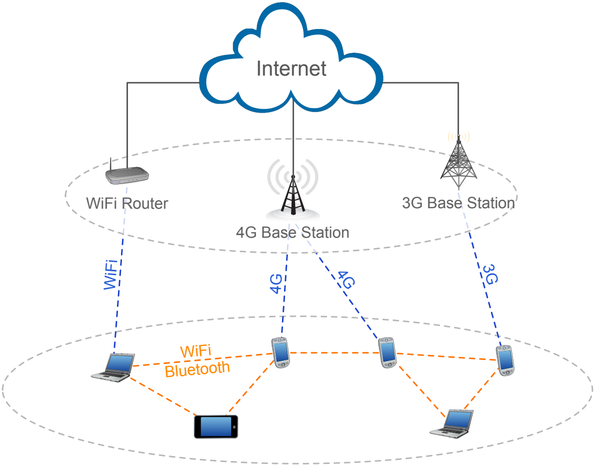


Fig. Illustration of Crowd-Sourced Mobile Internet Access: A set of mobile devices form a group/community (via WiFi or Bluetooth), sharing internet connections with each other.

Crowd-Sourced Mobile Internet Access

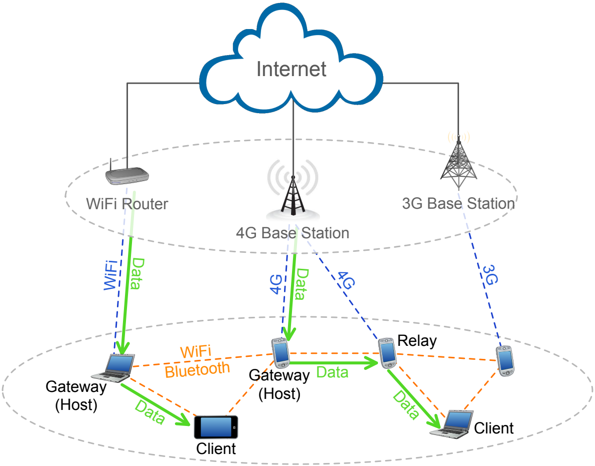


Fig. Illustration of Crowd-Sourced Mobile Internet Access: A device may act as a gateway/host downloading data for others, a relay forwarding data for others, and a client consuming data.

Key Problems in This Work

- How to achieve an efficient and fair network resource allocation?
  - who (hosts) will download data for whom (clients), and how much?
  - who (relays) will route data from each host to each client, and how much?
- How to encourage the user participation and cooperation?
  - how to compensate the hosts and the relays for their efforts?

Outline

1. Background
2. Model
3. Solution
4. Conclusion

Mobile Data Traffic Explosion

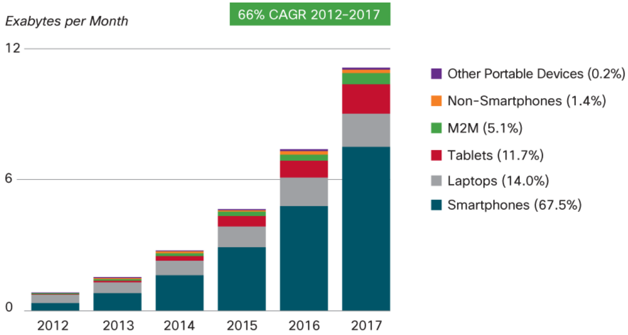


Fig. Global Mobile Data Traffic, 2012 to 2017 (from *Cisco VNI*)

- Mobile data traffic explosive growth: 66% annual grow rate
  - Reaching 11.2 exabytes per month by 2017, a 13-fold increase over 2012 or a 46-fold increase over 2010.

How about the network?

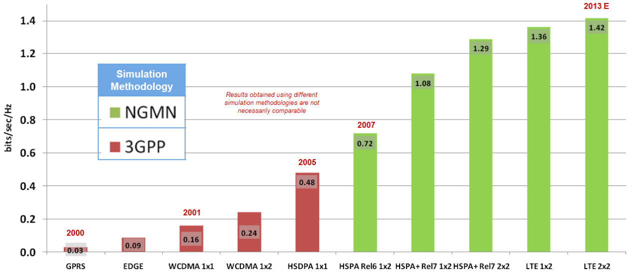


Fig. Historical Increases in Spectral Efficiency (from *Femtoforum*)

- Network capacity slow growth: less than 29% annual grow rate
  - Available spectrum band growth: 8% per year
  - Cell site increase: 7% per year
  - Spectrum efficiency growth: less than 12% per year from 2007 to 2013

$$108\% \cdot 107\% \cdot 112\% = 129\%$$

How to deal with the data explosion?

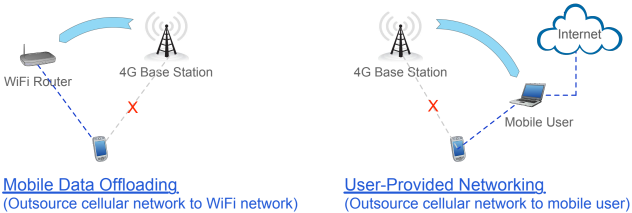
- Network capacity growth vs Data traffic growth

29% vs 66%

- Traditional approach: Network Expansion
  - Upgrading access technology (e.g., WCDMA $\rightarrow$ LTE $\rightarrow$ LTE-A)
  - Acquiring new spectrum license (e.g., TV white space)
  - Building more pico/micro/macro cell sites
- However, all of these methods are costly and time-consuming.

How to deal with the data explosion?

- Data usage is highly imbalanced, e.g., time-, location-, and network-dependent.
- One promising approach: Network Outsourcing
  - (A) Outsource network to network (N2N)
    - ★ Example: Mobile data offloading/onloading
  - (B) Outsource network to mobile user (N2MU)
    - ★ Example: User-provided networking

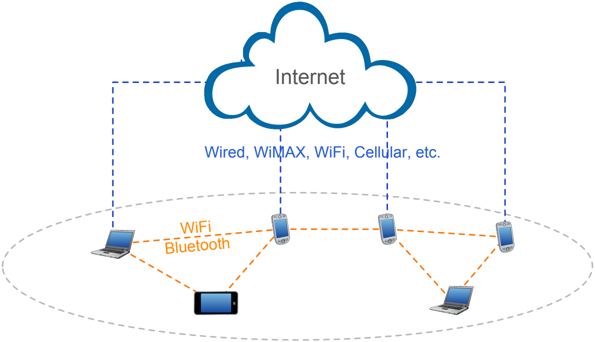


- In this work, we focus on the scenario B — N2MU.

A General Model of N2MU

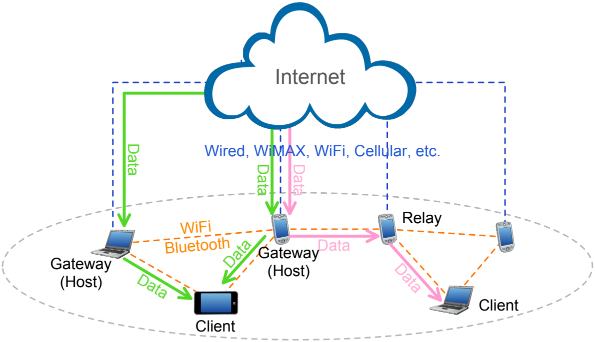
- A general model: A set of mobile users form a group/community, sharing internet connections with each other.

  —— Crowd-Sourced Mobile Internet Access



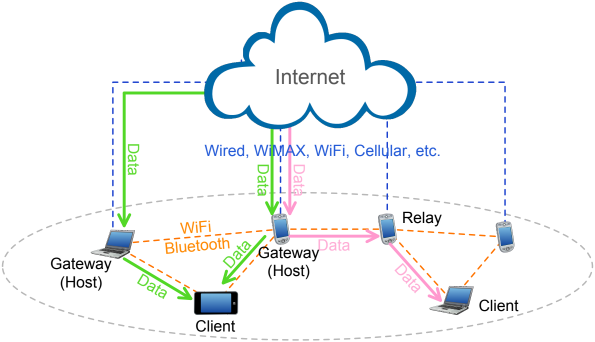
Crowd-Sourced Mobile Internet Access

- Key Features
  - (i) User-provided networking
    - ★ Mobile users can access internet through the hosting of other users.
  - (ii) Multi-hop accessing
    - ★ Mobile users can access internet through the relay of multiple devices.
  - (iii) Access bonding
    - ★ Mobile users can access internet through multiple access links.



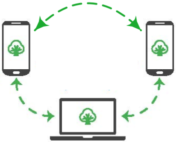
Crowd-Sourced Mobile Internet Access

- Roles of mobile users
  - Gateway (Host): Downloading data for others
  - Relay: Forwarding data for others
  - Client: Consuming data



Crowd-Sourced Mobile Internet Access

- Real Cases
  - Open Garden (http://opengarden.com)



  - M-87 (http://www.m-87.com/)

Key Problems in This Work

- How to achieve an efficient and fair network resource allocation?
  - who (hosts) will download data for whom (clients), and how much?
  - who (relays) will route data from each host to each client, and how much?
- How to encourage the user participation and cooperation?
  - how to compensate the hosts and the relays for their efforts?
- Our purpose: Design a mechanism to address both the incentive issue and the efficiency and fairness issues, i.e.,
  - Encourage the user participation and cooperation;
  - Achieve an efficient and fair network resource allocation.

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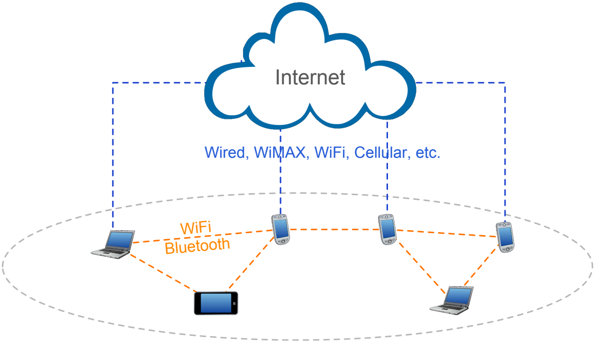
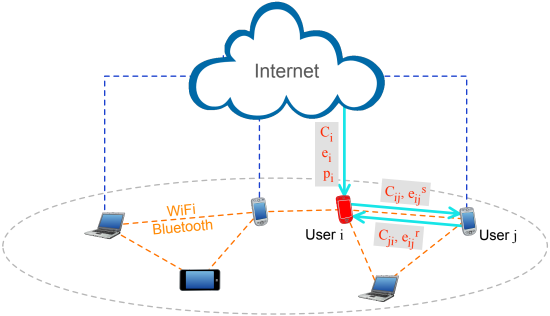
System Model

- A set of I mobile users: $\mathcal{I} = \{1, 2, ..., I\}$
  - Each user may act as a gateway/host downloading data for others, a relay forwarding data for others, and a client consuming data.
  - Users are heterogeneous in terms of their data requirements, internet connections, and energy budgets.



System Model

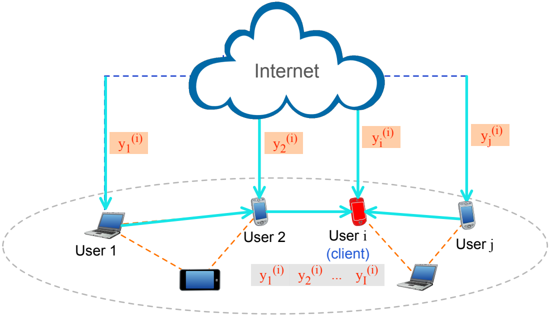
- Parameters related to each user $i \in \mathcal{I}$



  - $c_i, \ c_{ij}, \ c_{ji, \ j\in\mathcal{I}}$: link capacity;
  - $e_i, \ e^s_{ij}, \ e^r_{ij, \ j\in\mathcal{I}}$: unit energy consumption;
  - p_i: unit internet connection cost.

System Model

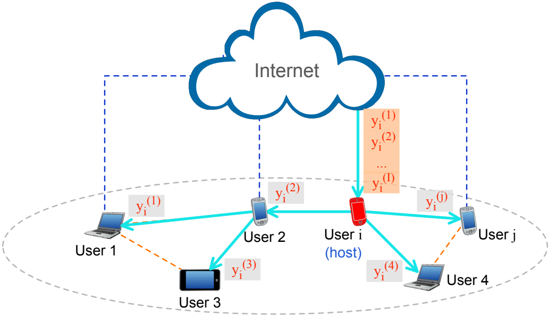
- Variables related to user $\mathrm{i} \in \mathcal{I}$ as a client.



  - $\mathrm{y}_{\mathrm{j},\ \mathrm{j}\in\mathcal{I}}^{(\mathrm{i})}$: the data downloaded via other hosts for client i;
  - $\mathrm{y}^{(\mathrm{i})} = \mathrm{y}_1^{(\mathrm{i})} + ... + \mathrm{y}_\mathrm{I}^{(\mathrm{i})}$: the total data consumed by client i;
  - $\mathrm{U}_\mathrm{i}\left(\mathrm{y}^{(\mathrm{i})}\right)$: the utility function of client i.

System Model

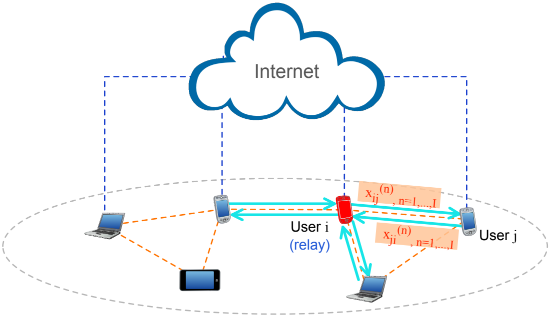
- Variables related to user $i \in \mathcal{I}$ as a host (gateway).



  - $y_{i,\ j\in\mathcal{I}}^{(j)}$: the data downloaded via host i for other clients;
  - $y_i = y_i^{(1)} + ... + y_i^{(I)}$: the total data downloaded via host i;
  - $e_i \cdot y_i$: the total energy consumption for downloading data;
  - $p_i \cdot y_i$: the total payment for downloading data;
  - Downloading capacity constraint: $y_i \leq c_i$.

System Model

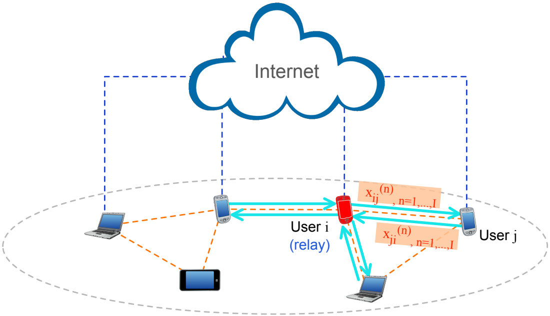
- Variables related to user $i \in \mathcal{I}$ as a relay.



  - $x_{ij,\ n\in\mathcal{I}}^{(n)}$: the data relayed from user i to user j, for client n;
  - $e_{ij}^{r} \cdot \sum_n x_{ji}^{(n)}$: the total energy consumption for receiving data from user j;
  - $e_{ij}^{s} \cdot \sum_n x_{ij}^{(n)}$: the total energy consumption for sending data to user j.

System Model

- Variables related to user $i \in \mathcal{I}$ as a relay.



  - Relaying capacity constraint: $\sum_n x_{ij}^{(n)} \leq c_{ij}, \quad \sum_n x_{ji}^{(n)} \leq c_{ji}$
  - Flow balance constraint: $\sum_j x_{ji}^{(n)} + y_i^{(n)} = \sum_j x_{ij}^{(n)}, \; n \in \mathcal{I}$
    - ★ For each relay i, its total received data (of client n) equals its total sent data (of client n).

System Model

- Payoff of each user $\mathrm{i} \in \mathcal{I}$:

$$\mathrm{J_i}(\mathbf{x}_\mathrm{i}, \mathbf{y}_\mathrm{i}) = \mathrm{U_i} - \mathrm{P_i} - \mathrm{E_i}$$

  - $\mathbf{x}_\mathrm{i} = \{\mathrm{x}_{\mathrm{ij}}^{(\mathrm{n})}\}_{\mathrm{j,n}\in\mathcal{I}}$: Relaying matrix;
  - $\mathbf{y}_\mathrm{i} = \{\mathrm{y}_{\mathrm{i}}^{(\mathrm{n})}\}_{\mathrm{n}\in\mathcal{I}}$: Downloading matrix;
  - $\mathrm{U_i}$: Utility of user i;
  - $\mathrm{P_i}$: Total payment of user i (for internet access);
  - $\mathrm{E_i}$: Total energy consumption of user i;

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Purpose of This Study

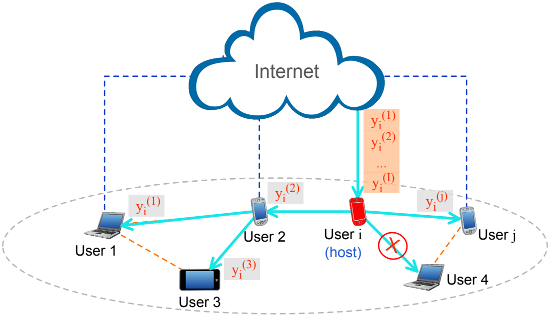
Objective

Our purpose is to design a mechanism to address the incentive, efficiency, and fairness issues in crowd-sourced mobile internet access, including

- Encouraging the user participation and cooperation;
- Achieving an efficient and fair network resource allocation.

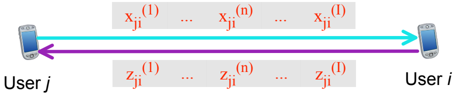
Incentive Issue

- How to encourage the user participation and cooperation?
  - Users may not want to participate in the crowd-sourced system;
    - ★ For example, those without the current demand;
  - Users may not want to download or relay data for others, especially those helpless to them.
    - ★ For example, user i may not want to download data for user 4.



Incentive Issue

- Our Solution: Virtual Currency
  - Key idea: User pays certain virtual currency to those who send data to him (i.e., I give you money, you give me data).



  - $z_{ji}^{(n)}$: the virtual price that user i pays j for receiving data (of client n);
  - $\sum_n z_{ji}^{(n)} \cdot x_{ji}^{(n)}$: the total virtual money that user i pays j for receiving data (of all clients) from j;

Modified Payoff with Virtual Currency

- Modified payoff of each user $i \in \mathcal{I}$:

$$J_i(\mathbf{x}_i, \mathbf{y}_i, \mathbf{z}_i) = U_i - P_i - E_i + V_i$$

  - $\mathbf{z}_i = \{z_{ij}^{(n)}\}_{j,n \in \mathcal{I}}$: Virtual price matrix;
  - V_i: Total virtual currency evaluation of user i;

Efficiency and Fairness Issues

- How to achieve an efficient and fair network resource allocation?
  - Efficiency: The aggregate payoff of all users is maximised or close to the maximum;
  - Fairness: Every user achieves a satisfactory payoff;
- Our Solution: Nash Bargaining Solution
  - Key idea: Users bargain for the network resource allocation and the virtual currency transfer based on the Nash bargaining framework.

Nash Bargaining Solution

Nash Bargaining Problem (NBP)

$$\max_{\mathbf{x}_i,\mathbf{y}_i,\mathbf{z}_i,\forall i} \quad \Pi_{i\in\mathcal{I}}(J_i - J_i^0)$$

$$\text{s.t.,} \quad \text{(a) } J_i \geq J_i^0 \qquad (J_i^0 : \text{disagreement point})$$

(b) *Capacity constraints*;

(c) *Flow balance constraint*;

(d) *Virtual current budget constraint*.

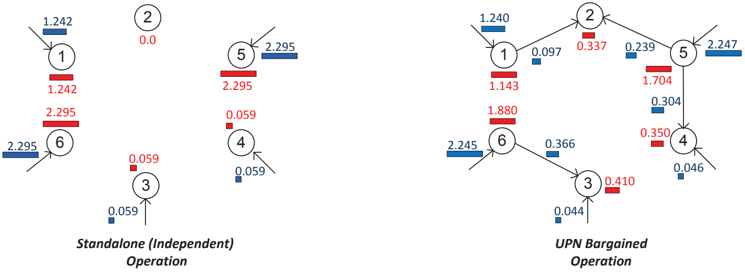
- The NBP problem has a unique optimal solution.

Nash Bargaining Implementation

- Centralized Implementation
  - A central control node collects all the required network information, and computes the Nash bargaining solution.
- Decentralized Implementation
  - Iterative updating: Users update their individual decisions sequentially and repeatedly, where in each updating period,
    - one user first updates its decision based on a local objective function and signals from its one-hop neighbors,
    - and then reports the necessary signals to its one-hop neighbors.

Simulation

- An example with 6 nodes
  - Blue Bar: Downloading/relaying data;
  - Red Bar: Consuming data;



Left: Independent Operation. Right: Crowd-sourced Operation.

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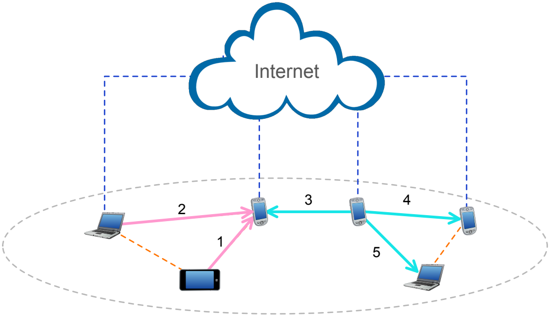
Conclusion

- We study the crowd-sourced mobile internet access system, in particular, we answer
  - How to achieve an efficient and fair network resource allocation?
  - How to encourage the user participation and cooperation?

- We propose a Nash bargaining solution with virtual currency, which addresses the incentive, efficiency, and fairness issues.

Future Extension

- Interference is a big problem !
  - Intra-node interference (RF constraint)
    - E.g., links 3, 4, and 5.
  - Inter-node interference (Transmission collision)
    - E.g., links 1 and 2.



Thank You

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