User-Provided Networks (UPN)

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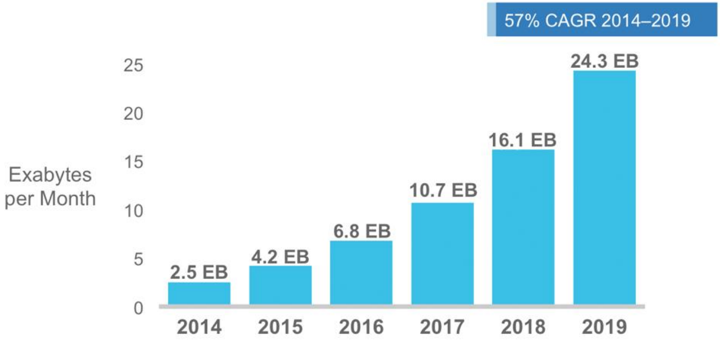
Outline

Part I: Introduction of UPN

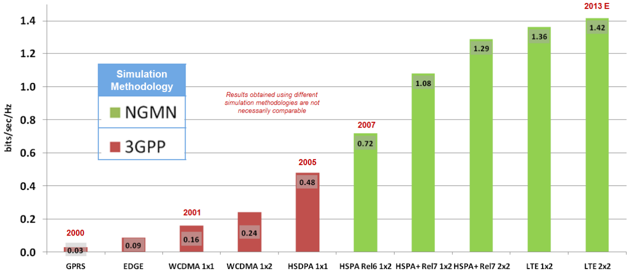
Global Mobile Data Traffic



Global Mobile Data Traffic Growth Projection (source: Cisco VNI Mobile 2015)

- Annual growth rate $\sim$ 57%
  - Expected to reach 24.3 exabytes per month by 2019
  - Nearly 10-fold increase over 2013

Cellular Mobile Network Capacity



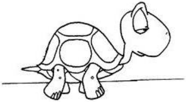
Historical Increases in Spectral Efficiency (source: Femtoforum)

- Annual grow rate $\sim$ 36%
  - Available spectrum band growth: 8% per year
  - Cell site increase: 7% per year
  - Spectrum efficiency growth: $<$ 18% per year (2007 – 2013)

$$108\% \cdot 107\% \cdot 118\% = 136\%$$

Widening Supply-Demand Gap

36% vs. 57%



Slow network capacity growth vs. Fast data traffic growth

What is User Provided Networks?

- Traditional infrastructure networks:
  - Users obtain network connectivity and services from network providers
  - Clear distinction between "providers" and "users"
- User provided networks (UPN):
  - Users can serve as providers, directly offering connectivity to other users
  - UPN exploits the diversity of user devices
  - UPN extends coverage and service of traditional providers
  - Connectivity becomes an infrastructure independent commodity
- Next we show some commercial examples of UPN.

Fon: Wireless Community Network

(Source: www.Fon.com)

- Managed by Fon.
- Sharing home fixed WiFi, and get free access to other Fon hotspots.
- More than 13 million Fon hotspots worldwide.

BeWiFi: Recycling WiFi Connectivity

(Source: www.xataka.com)

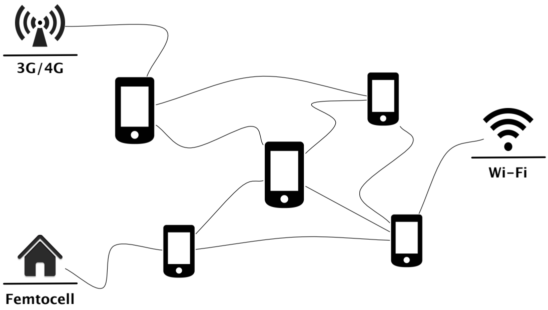
- Managed by Telefonica: support a sharing similar as Fon.
- Also support autonomous sharing
  - Close-by fixed WiFi routers form a mesh without operator intervention.
  - Share each other's unused bandwidth.

Karma: Social Bandwidth Sharing

(Source: yourkarma.com)

- Managed by Karma.
- Karma mobile device turns 4G into WiFi.
- Share Internet access to friends and earn free data.

Open Garden: Crowd-Souring Connectivity



- Software provided by Open Garden with No central management.
- Close-by mobile devices form a mesh.
- Share mobile Internet connectivity.

Taxonomy of UPN

	Fixed Hosts	**Mobile Hosts**
Network Assisted	Fon, BeWiFi	Karma
Autonomous	BeWiFi	Open Garden

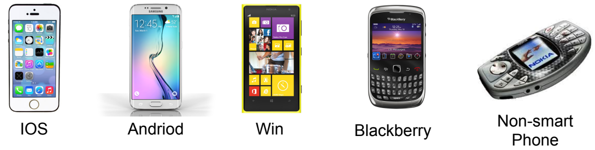
Part II: Technical Challenges of UPN Design

Main Technical Challenges

- Implementation Challenges
- Security and Privacy Issues
- Performance Limitations

Implementation Challenges

- Incompatibility of Equipments
  - Devices may be equipped with different hardware and software.
    - Operating systems, network interfaces, protocols, etc.
  - Commercial devices are usually not programmed to work together.
    - One-hop relaying; require user intervention; not optimized (e.g., no flow control)
  - Additional supporting infrastructure may be necessary.
    - E.g., provisioning tailored routers such as in FON and Karma.



Different Types of Mobile Phones

Implementation Challenges

- Lack of Automated Procedures
  - Discover the local devices that provide the UPN service automatically.
    - Time and resource-consuming process.
    - Even more challenging for dynamic systems.
  - Create user connections in a user-transparent fashion.
    - Minimum-possible user intervention, but also enough control to users to decide their participation mode.
  - Additional software may be necessary.
    - E.g., Open Garden and Whisher.

Implementation Challenges

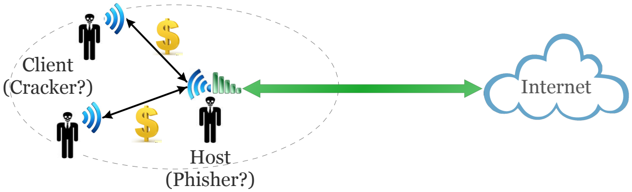
- Limited Resources of Host Devices.
  - Limited battery energy.
    - Perhaps the most critical resource of mobile devices.
    - Users have high aversion in battery energy consumption.
  - High Internet access cost.
    - Data plan costs vary and can be very high in certain countries.
    - Most applications are data hungry and hence expensive (e.g., video conferencing).

Implementation Challenges

- Dynamic Network Environment.
  - Fast changing network conditions (especially in mobile UPN).
    - ⋆ Capacity and quality of device-to-device wireless links changes.
    - ⋆ Internet access and battery resources of each user changes.
    - ⋆ Environment interference changes, e.g., from other Wi-Fi APs.
  - Fast changing traffic demand of users.
    - ⋆ Previous demands are satisfied; new demands are created.

Security and Privacy Issues

- Lack of Centralized Authentication/Security Mechanisms
  - Cooperative users are often associated/authenticated by different network operators.
  - Difficult to implement a cross-platform security mechanism.
  - Mechanisms such as Hotspot 2.0 help, but still an open issue.



Security Issue: It is difficult for a mobile user to detect a phishing user or a hacker.

Security and Privacy Issues

- Lack of Decentralized (off-grid) Trust Mechanisms
  - Users often need to trust each other and cooperate without intervention from 3rd parties;
  - Decentralized security mechanisms may be necessary.
    - ★ E.g., crowdsourced trusting methods.

Security and Privacy Issues

- Lack of Privacy Protection Mechanisms
  - Users may disclose their privacy information when providing or consuming the UPN service.
    - ★ Disclosure of information, such as location and communication needs, improve the performance of the service.
    - ★ Inherent trade off between privacy preservation and quality of the UPN service.
  - Decentralized privacy protection mechanisms may be necessary, especially for mobile UPN.

Performance Limitations

- Actual performance limits of such systems are unexplored.
  - How fast can the devices communicate?
  - What is the impact of multi-hop operation on the end-to-end data transfer capability?
  - Current implementations are mainly one-hop, and often application-layer connection services.
    - Large system overheads, and poor performance.

Performance Limitations

- Implementation overheads need to be quantified.
  - What is the energy consumption of a mobile device for relaying traffic?
  - What is the overhead, in terms of battery energy consumption and bandwidth, of a UPN system?
    - Sophisticated UPN mechanisms may be resource-consuming and hence eventually impact the performance.

Performance Limitations

- How adaptive such system can be in practice?
  - How fast is it possible to update the configuration of such systems?
    - Devices need to exchange messages in order to keep the UPN status updated.
    - Frequent updates may consume a lot of bandwidth and battery.
    - Fast reconfigurations allow the system's adaptation to changing network conditions, but may impact performance.
    - Less often reconfiguration prolong battery duration.
  - What are the optimal design choices?

Part III: Incentive Issues of UPN design

Incentive Issues of UPN

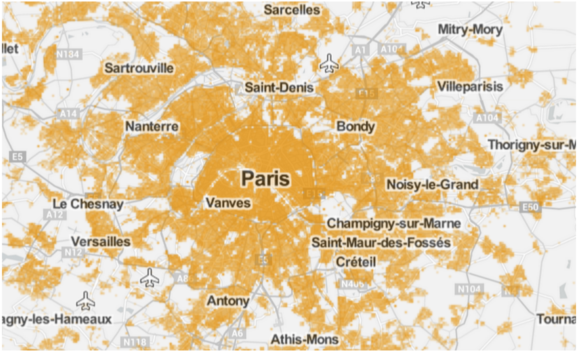
- Resource sharing induces costs:
    - Reduced internet access bandwidth
    - Increased data usage cost
    - Reduced battery energy of mobile devices
- Incentive issues not adequately considered in the current designs
- We will study incentive issues for both network-assisted and autonomous UPNs.

Part III Outline

1. Pricing and network evolution of wireless community networks
2. Membership selections in wireless community networks
3. Hybrid pricing and reward optimization for social bandwidth trading
4. Bargaining-based crowd-sourced network connectivity
5. Cloud-based SDN assisted mobile UPNs
6. Service exchange in UPNs

Network evolution of wireless community networks

Wireless Community Networks



FoN coverage around Paris (source: fon.com)

- WiFi owners constitute a community
- Community members share WiFi with each other
- Capable of covering a large area with a relatively small cost

Main Issues

- User Behavior
  - Who will join the community network?
- Network Evolution
  - How would the network dynamically evolve?
- Social Impact
  - How would the community network and cellular network interact?

M. Manshaei, J. Freudiger, M. Flegyhzi, P. Marbach, and J. Hubaux, *On Wireless Social Community Networks,* IEEE INFOCOM, 2008.

Network Model

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  - Involves the WiFi APs operated by individual users;
  - Only provide limited coverage: depending on the number of WiFi users
- Multiple WiFi AP Owners (Users): $n = 1, 2, ..., N$
  - Subscribe to one network operator (or not subscribe to any operator) based on the subscription fee and the network coverage.

User's Payoff

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- A sequence of discrete time slots: $t = 1, 2, ..., \infty$
- At each time slot t, each user n makes the network subscription decision $i \in \{L, S, 0\}$
  - Each user n's payoff $u_n^i[t]$ at slot t:

$$u_n^i[t] = a_n \cdot Q_i[t] - P_i[t], \quad i \in \{L, S\}$$

  - a_n: the user n's sensitivity to network coverage;
  - $Q_i[t]$: the network i's coverage at the beginning of slot t;
  - $P_i[t]$: the network i's subscription fee at slot t;

Network Operator's Payoff

- The payoff of each network operator $i \in \{L, S\}$ at slot t:

$$v_i[t] = N \cdot n_i[t] \cdot P_i[t] - C_i$$

  - $n_i[t]$: the percentage of users choosing network i at slot t;
  - C_i: the operational cost of network operator i.

Network Pricing Schemes

- Static Pricing Scheme: $P_i[t]$ does not change over time:

$$P_i[1] = P_i[2] = ... = P_i$$

- Dynamic Pricing Scheme: $P_i[t]$ may change over time

Key Problems

- Operators' Pricing Decisions
  - How to make the optimal pricing decisions over time, to maximize the total payoff?
- Users' Subscription Dynamics and Network Evolution
  - How to make the best network subscription decisions in each time slot, and how will this affect the network evolution?

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Case 1: Monopoly LBO (Cont.)

- The optimal subscription fee P_L^* that maximizes the LBO's payoff is

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$$P_L^* = \max\left\{\alpha,\ \frac{\beta}{2}\right\}$$

  - When $\beta \leq 2\alpha$ (narrow distribution of a_n): low $P_L^* = \alpha$, and all users subscribe to its service;
  - When $\beta > 2\alpha$ (wide distribution of a_n): high $P_L^* = \frac{\beta}{2}$, only users with $a_n \geq P_L^*$ subscribe to its service.

Case 2: Monopoly SCO

- Assume that only the SCO provides wireless access service:
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  - Examples of equilibrium: $Q_S^{eq} = 0$ (no user subscribes to the SCO), and $Q_S^{eq} = 1$ (all users subscribe to the SCO).

Case 2: Monopoly SCO (Cont.)

- When $\beta \leq 2\alpha$ (narrow distribution of a_n), there exist three equilibrium points $Q_S^{eq} \in \{0, Q_{S,1}, 1\}$;

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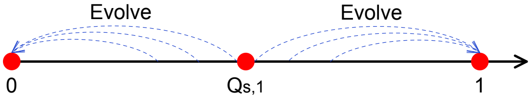
- Network Evolution



  - $Q_S < Q_{S,1}$: the network evolves to equilibrium $Q_S^{eq} = 0$;
  - $Q_S > Q_{S,1}$: the network evolves to equilibrium $Q_S^{eq} = 1$;
  - $Q_S = Q_{S,1}$: the network stays at equilibrium $Q_S^{eq} = Q_{S,1}$.

Case 2: Monopoly SCO (Cont.)

- When $\beta > 2\alpha$ (wide distribution of a_n), there exist four equilibrium points $Q_S^{eq} \in \{0, Q_{S,1}, Q_{S,2}, 1\}$;

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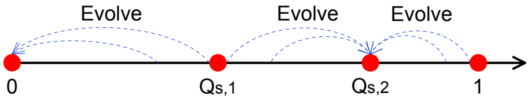

  - $Q_S < Q_{S,1}$: the network evolves to equilibrium $Q_S^{eq} = 0$;
  - $Q_S \in (Q_{S,1}, Q_{S,2})$: the network evolves to equilibrium $Q_S^{eq} = Q_{S,2}$;
  - $Q_S \in (Q_{S,2}, 1)$: the network evolves to equilibrium $Q_S^{eq} = Q_{S,2}$.

Case 2: Monopoly SCO (Cont.)

- For both $\beta < 2\alpha$ and $\beta > 2\alpha$, we can compute the optimal static and dynamic prices
- Key idea: steer to the proper Network Equilibrium.

General Case 3: LBO and SCO

- One LBO and one SCO compete for providing wireless access service:
  - Non-cooperative pricing game

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- One LBO and one SCO compete for providing wireless access service:
  - Non-cooperative pricing game
- Main Results
  - If $\beta \geq \frac{3\alpha}{2}$: there is a Nash equilibrium in which both operators have subscribers;
  - If $\beta < \frac{3\alpha}{2}$: no Nash equilibrium.

Insights

A wireless operator does not have an economic incentive to deploy both a social community and a licensed band wireless access network.

A Two Price Model

- A two-price policy: the first price is an introductory price that expires once service adoption reaches a certain level.
- Key question: How to address the trade-off among setting high prices to increase the direct revenue, and low-prices to increase membership?

M. Afrasiabi, R. Guerin, *Pricing Strategies for User-Provided Connectivity Services*, IEEE INFOCOM, 2012.

Model

- Basic model parameters
  - Service coverage k, level adoption x, user propensity to roam $\theta \in [0, 1]$
  - Parameter θ captures a user's sensitivity to service coverage
- Generic utility model

$$U(\theta) = F(\theta, k) + G(\theta, m) - p(\theta)$$

- Under some simplified assumptions:

$$U(\theta) = \gamma(1-\theta) - cm + \theta rx - p(\theta)$$

where

  - γ is the utility of base connectivity,
  - m is the volume of the roaming traffic, cm disutility for serving roaming traffic,
  - r is the utility of roaming connectivity,
  - $p(\theta)$ price that is charged to users with roaming profile θ .

Total Welfare

- What is the total welfare the service can create for the members and the operator?
- It depends on the system parameters and the service cost
  - If the service cost is low, i.e., $e < (\gamma + r - c)/2$:

$$V^* = \frac{\gamma + r - c}{2} - e$$

    that is realized for $x^* = 1$, i.e., full adoption.
  - If the service cost is high, i.e., $e \geq \frac{\gamma + r - c}{2}$:

$$x^* = 0, \;\; V^* = 0\,.$$

Pricing Policies

- Usage-based pricing policy:

$$p_z(z_h, z_r) = z_h \cdot p_h + z_r \cdot p_r - \alpha$$

  where the different cost components are:
  - z_h is the home usage cost
  - z_r is the roaming usage cost
  - α is the fixed usage allowance per user

- Fixed pricing policy:

$$p(\theta) = p\,,$$

  where p is the price that each user pays independently from the usage or roaming.

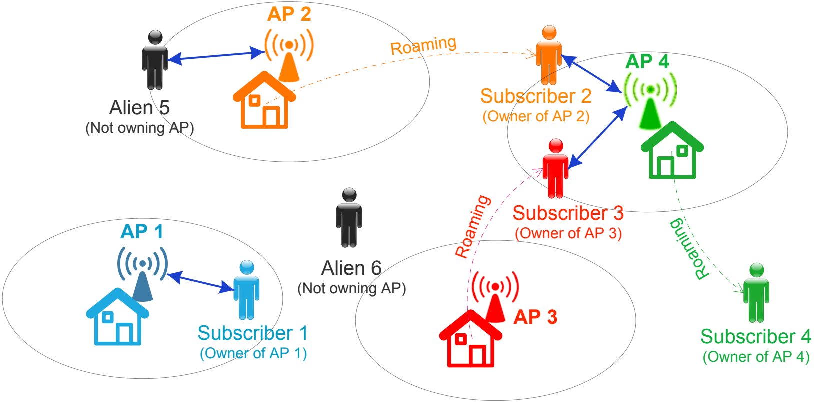
Membership selections in wireless community networks

Incentive Issues

- What role should a user choose in such a network?
- How would the operator incentivize the proper behavior from users?

Q. Ma, L. Gao, Y. Liu, J. Huang, *A Game-Theoretic Analysis of User Behaviors in Crowdsourced Wireless Community Networks*, IEEE WiOpt, 2015.

System Model



Wireless Community Network

Operator and Users

- One wireless community operator announces fixed
  - Usage-base price $p \in [0, p_{\mathsf{max}}]$
  - revenue sharing ratio $\delta \in [0, 1]$

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- Subscribers (AP owners): $\mathcal{K}_s = \{1, 2, \ldots, K\}$
  - Share WiFi APs with other members
  - Each AP's spectrum is split into two channels
    - ★ Private channel: dedicated usage by the AP owner
    - ★ Public channel: shared by vistors
  - Two types of subscriber memberships: Linus and Bill

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  - Two types of subscriber memberships: Linus and Bill
- Aliens: $\mathcal{K}_A = \{K + 1, \ldots, K + K_A\}$
  - Do not own WiFi APs
  - Pay according to usage-based pricing p

Subscriber Memberships

Membership	Pay for Roaming Access	Paid for Sharing
Linus	No	No
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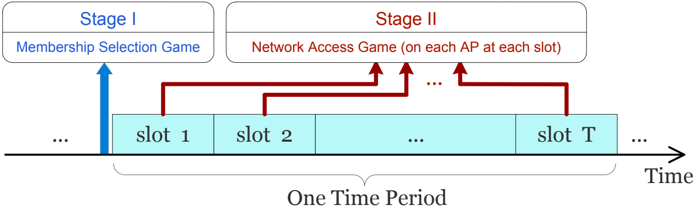
  - Do not obtain revenue when sharing his own AP
    - All payments from other users go to the operator
- Bill:
  - Pay when accessing others' APs (based on usage-based price p)
  - Obtain δ fraction of the total revenue when sharing his own AP
    - The rest $1-\delta$ fraction of the total revenue goes to the operator

User Mobility Pattern

- For each user i: $\boldsymbol{\eta}_i = (\eta_{i,l}, l = 0, 1, \ldots, K)$
  - $\eta_{i,0}$: probability of not covered by any AP
  - $\eta_{i,k}$: probability of within the coverage of AP k

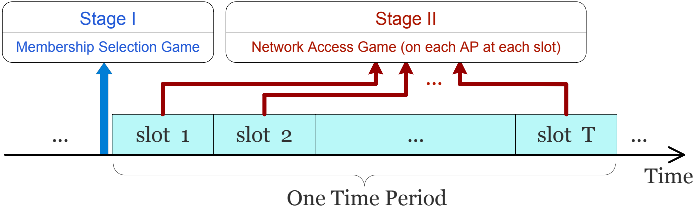
$$\eta_{i,0} + \sum_{k=1}^{K} \eta_{i,k} = 1$$

Two-Stage Dynamic Game



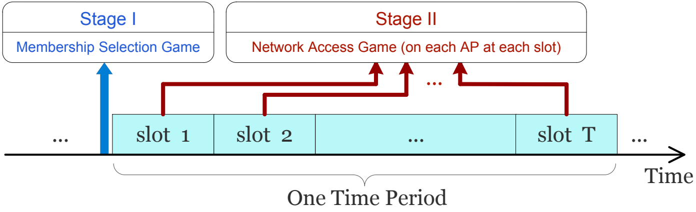
- A time period including a sequence of T discrete time slots

Two-Stage Dynamic Game



- A time period including a sequence of T discrete time slots
- Two-stage dynamic game
  - Stage I: subscribers choose their memberships simultaneously at the beginning of the time period $\Rightarrow$ A Membership Selection Game
  - Stage II: users (subscribers and aliens) decide how to access Wi-Fi APs in each time slot $\Rightarrow K \times T$ Network Access Games

Two-Stage Dynamic Game



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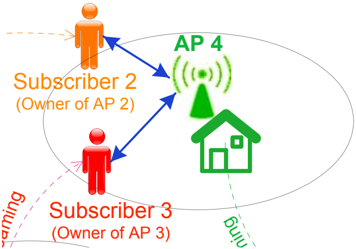
- Analysis through backward induction

Stage II: Network Access Game on AP k



Stage II Game

- Consider users who travel to AP k in time slot t

$$\mathcal{K}(k,t) = \mathcal{K}_s(k,t) \bigcup \mathcal{K}_a(k,t)$$

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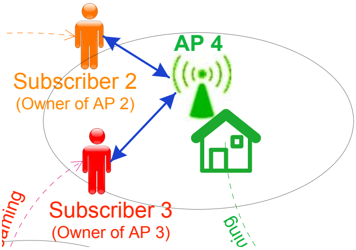

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- AP owner k does not participate in the game
  - As he transmits over a separate private channel

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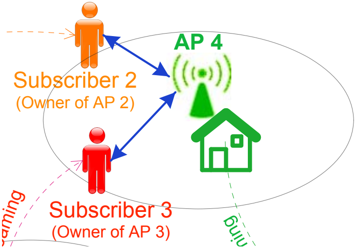


Stage II Game

Game (Network Access Game on AP k in A Time Slot)

- *Players: the set $\mathcal{K}(k)$ of users;*
- *Strategies: network access time $\sigma_{i,k} \in [0,1]$, $\forall i \in \mathcal{K}(k)$;*
- *Payoffs: $v_{i,k}(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k})$, $\forall i \in \mathcal{K}(k)$.*

User Payoff

- Bills and Aliens' payoff = utility minus payment

$$v_{i,k}(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k}) = u_i(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k}) - p \cdot \sigma_{i,k}$$

- Linus' payoff = utility

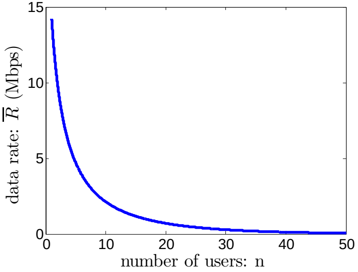
$$v_{i,k}(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k}) = u_i(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k})$$

User Utility

$$u_i(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k}) = \rho_i \log(1 + \bar{r}_k(\boldsymbol{\sigma}_{-i,k})\sigma_{i,k})$$

- ρ_i: user i's network access valuation
- $\bar{r}_k(\boldsymbol{\sigma}_{-i,k})$: user i's expected data rate at AP k

$$\bar{r}_{i,k}(\boldsymbol{\sigma}_{-i,k}) = \sum_{n=0}^{|\mathcal{K}(k)|-1} P_{i,k}(n) \cdot \bar{R}(n+1).$$



(source: [Chiang'2012])

User Best Response: Linus

Lemma (Linus Best Response)

For a Linus i, his best response in Network Access Game on AP k is:

$$\sigma_{i,k}^* = 1,$$

which is independent of other users' strategies.

- Fully utilization since there is no payment.

User Best Response: Bill and Alien

Lemma (Bill and Alien Best Response)

For a Bill or Alien i, his best response in Network Access Game on AP k is:

$$\sigma_{i,k}^{*} = \min\left\{1, \max\left\{\frac{\rho_i}{p} - \frac{1}{\bar{r}_{i,k}(\boldsymbol{\sigma}_{-i,k})}, 0\right\}\right\},$$

which is dependent of other users' strategies $\boldsymbol{\sigma}_{-i,k}$.

- A tradeoff between utility and payment.

Nash Equilibrium

Definition (Nash Equilibrium)

A Nash equilibrium of the Network Access Game on AP k is a profile $\boldsymbol{\sigma}_k^*$ such that for each user $i \in \mathcal{K}(k)$,

$$v_{i,k}(\sigma_{i,k}^*, \boldsymbol{\sigma}_{-i,k}^*) \geq v_{i,k}(\sigma_{i,k}, \boldsymbol{\sigma}_{-i,k}^*), \quad \forall \sigma_{i,k} \in [0,1].$$

Nash Equilibrium: Existence and Uniqueness

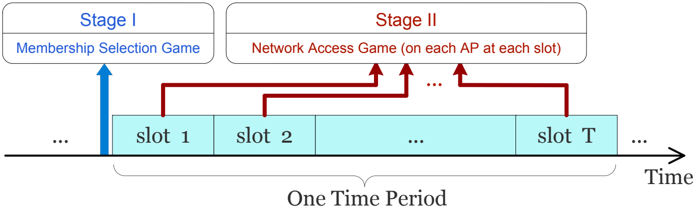
Theorem (Existence and Uniqueness of Nash Equilibrium)

- *There exists at least one pure strategy Nash equilibrium in the Network Access Game on AP k.*
- *For a two-player game, the Nash equilibrium is unique under the following condition:*

$$c \equiv \frac{R(1) - R(2)}{R(2)^2} < 1,$$

which is always satisfied in practical WiFi networks.

Recall: Two-Stage Dynamic Game



- Two-stage dynamic game
  - Stage I: subscribers choose their memberships simultaneously at the beginning of the time period $\Rightarrow$ A Membership Selection Game
  - Stage II: users (subscribers and aliens) decide how to access Wi-Fi APs in each time slot $\Rightarrow$ $K \times T$ Network Access Games

Stage I: Membership Selection Game

Game (Membership Selection Game)

- *Players: the set $\mathcal{K}_s$ of subscribers.*
- *Strategies: $x_i \in \{Linus(0), Bill(1)\}, \forall i \in \mathcal{K}_s$.*
- *Payoffs: $V_i(x_i, \boldsymbol{x}_{-i}), \forall i \in \mathcal{K}_s$.*

User Payoff

$$V_i(x_i, \boldsymbol{x}_{-i}) = T \cdot \left(x_i \cdot \delta \cdot \underbrace{\bar{\Pi}_i(\boldsymbol{x}_{-i})}_{\text{revenue from own AP}} + \sum_{k=0}^{K} \eta_{i,k} \cdot \underbrace{V_{i,k}(x_i, \boldsymbol{x}_{-i})}_{\text{payoff on AP } k} \right).$$

User Best Response

Proposition (Best Response)

A subscriber i's best response is $x_i = 1$ (to be a Bill) if his probability of staying at home is above a threshold,

$$\eta_{i,i} > \underline{\eta}_i.$$

Pure Strategy Nash Equilibrium

Definition (Pure Strategy Nash Equilibrium - PNE)

A PNE of the Membership Selection Game is a profile $\boldsymbol{x}^*$ such that for each user $i \in \mathcal{K}_s$,

$$V_i(x_i^*, \boldsymbol{x}_{-i}^*) \geq V_i(x_i, \boldsymbol{x}_{-i}^*), \quad \forall x_i \in \{0, 1\}.$$

- A PNE does not always exist in the Membership Selection Game.

Mixed Strategy

- Mixed strategy profile:

$$\boldsymbol{\alpha} = \{\alpha_i \in [0,1], \forall i \in \mathcal{K}\}$$

- The expected payoff:

$$\omega_i(\alpha_i, \boldsymbol{\alpha}_{-i}) = \alpha_i \widetilde{V}_i(1, \boldsymbol{\alpha}_{-i}) + (1-\alpha_i)\widetilde{V}_i(0, \boldsymbol{\alpha}_{-i})$$

Mixed Strategy Nash Equilibrium

Definition (Mixed Strategy Nash Equilibrium - MNE)

A MNE of the Membership Selection Game is a probability profile $\boldsymbol{\alpha}^*$ such that for each AP owner $i \in \mathcal{K}$, we have:

$$\omega_i(\alpha_i^*, \boldsymbol{\alpha}_{-i}^*) \geq \omega_i(\alpha_i, \boldsymbol{\alpha}_{-i}^*), \quad \forall \alpha_i \in [0, 1].$$

Theorem (Existence of MNE)

In the Membership Selection Game, there exists at least one MNE.

Hybrid Pricing and Reward for Social Bandwidth Trading

The Karma Model

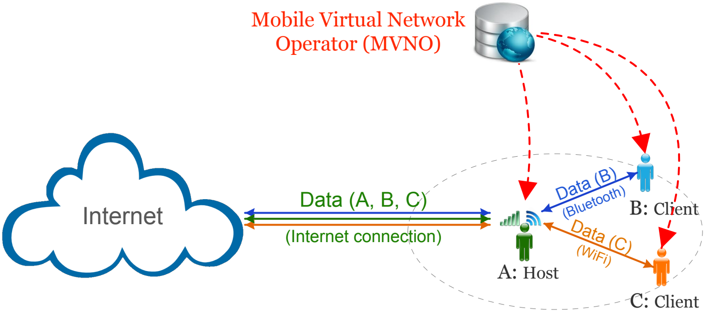


Illustration of the Karma model

- MVNO (Karma) purchases network resources from MNO (Sprint), and charges the users a usage-based pricing ($14 per GB).

The Karma Model

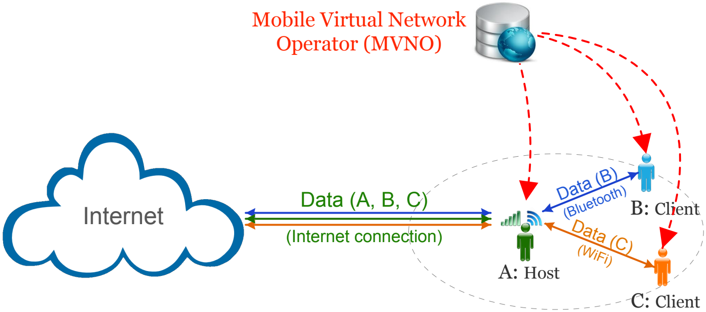


Illustration of the Karma model

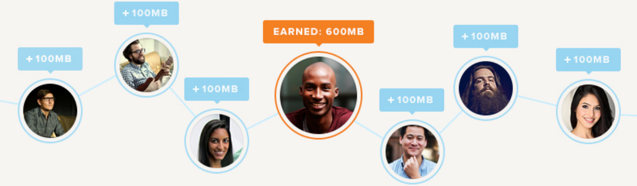
- MVNO (Karma) purchases network resources from MNO (Sprint), and charges the users a usage-based pricing ($14 per GB).
- Subscriber device (host) converts 4G cellular signal to WiFi, and can share the connectivity with clients.

Karma's Innovations

- Connectivity sharing, not data sharing (not simple tethering)
  - A host does not pay for clients' data
- Free data quota for sharing (extra incentives)
  - A host is rewarded with free data for sharing

Current Practice: One-Time Free Data Reward

- A host gets 100MB of free data when sharing connectivity with a client for the first time.



(source: karma.com)

- Easy to deploy, but fail to provide consistent incentives.

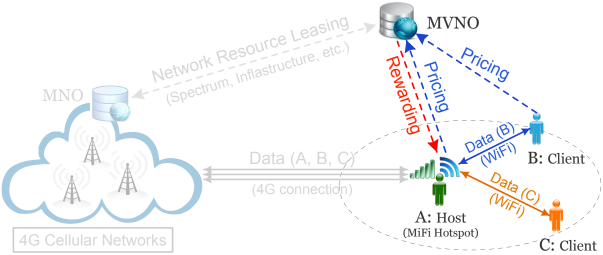
Our Purpose

- We want to design a pricing and rewarding strategy that provides consistent incentives to hosts.

L. Gao, G. Iosifidis, J. Huang, L. Tassiulas, *Hybrid Data Pricing for Network-assisted User-provided Connectivity*, IEEE INFOCOM, 2014.

Our Purpose

- We want to design a pricing and rewarding strategy that provides consistent incentives to hosts.
- Key questions:
  - How should the MVNO price the hosts and clients?
  - How should the MVNO reward the hosts with free data quota?
  - How much data would a host forward for the clients?



L. Gao, G. Iosifidis, J. Huang, L. Tassiulas, *Hybrid Data Pricing for Network-assisted User-provided Connectivity*, IEEE INFOCOM, 2014.

System Model

- One MVNO (Karma)
  - Pay MNO (Sprint) a usage-based data wholesale price w.
  - Charge subscribers (hosts and clients) a usage-based data price p.
  - Reward hosts a free data quota ratio $\theta \in [0, 1]$.

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  - Transmit their own traffic;
  - Operate as WiFi hotspots and route traffic for clients.

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  - Transmit their own traffic;
  - Operate as WiFi hotspots and route traffic for clients.
- Clients: $\mathcal{N} \triangleq \{\mathcal{N}_1, ..., \mathcal{N}_I\}$
  - $\mathcal{N}_i$: The set of clients accessing Internet through host i.

System Model

- A period of T time slots: $\mathcal{T} = \{1, ..., T\}$

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  - $\boldsymbol{\xi}_i \triangleq \{\xi_{it}\}_{t \in \mathcal{T}}$: the unit energy cost incurred by host i for transceiving one byte of data via the WiFi connection;

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  - $\boldsymbol{\xi}_i \triangleq \{\xi_{it}\}_{t \in \mathcal{T}}$: the unit energy cost incurred by host i for transceiving one byte of data via the WiFi connection;
  - $\boldsymbol{D}_i \triangleq \{D_{it}\}_{t \in \mathcal{T}}$: the total client demand to host i;
    - Can be shiftable or non-shiftable
    - Assumed to be price insensitive

MVNO

- Strategy: Decide price p_i and free data quota ratio θ_i to every host i
- The choices will affect the hosts' decisions:
  - $x_{it}(p_i, \theta_i)$: the total data that host i's consumes for himself at slot t;
  - $y_{it}(p_i, \theta_i)$: the total data that host i routes for his clients $(\mathcal{N}_i)$ at slot t;

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  - $y_{it}(p_i, \theta_i)$: the total data that host i routes for his clients ($\mathcal{N}_i$) at slot t;
- Objective: Maximize the total profit (revenue - cost)

MVNO's Profit

$$V(\boldsymbol{p}, \boldsymbol{\theta}; (\boldsymbol{x}_i, \boldsymbol{y}_i)_{i \in \mathcal{I}}) = \sum_{i=1}^{I} \sum_{t=1}^{T} \Big(p_i \cdot (x_{it} - \theta_i \cdot y_{it}) + p_i \cdot y_{it} - w \cdot (x_{it} + y_{it}) \Big)$$

Host i

- Strategy
  - x_{it} and y_{it} for all t
- Objective: Maximize the total payoff, including
  - Utility from consuming data
  - Payment to the MVNO
  - Energy consumption

Host i's Payoff

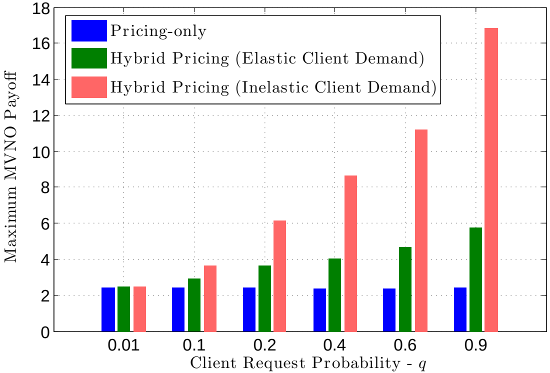
$$J_i(\boldsymbol{\alpha}_i, \boldsymbol{\beta}_i; p_i, \theta_i) = U_i(\boldsymbol{x}_i) - \sum_{t=1}^{T} p_i \cdot (x_{it} - \theta_i \cdot y_{it}) - \left(\sum_{t=1}^{T} \epsilon_{it} x_{it} + \sum_{t=1}^{T} (\epsilon_{it} + \xi_{it}) \cdot y_{it} \right)$$

Problem Formulation

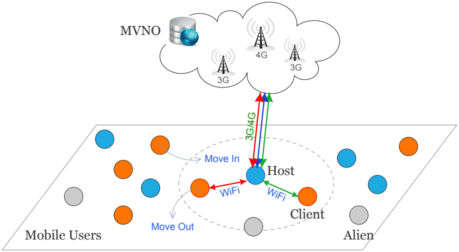
- Hybrid Pricing Game
- Leader: the MVNO makes decisions in Stage I
  - Deciding price and free data quota reward to every host;
- Followers: Hosts makes decisions in Stage II
  - Deciding the data consumption for themselves, and the data routed for their clients.
- Closed-form analysis through backward induction

Simulation

- MVNO's Optimal Revenue
  - Increase 20% to 135% under the elastic client demand (GREEN bar).
  - Increase 50% to 550% under the inelastic client demand (RED bar).



A Generalized System Model



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

- Large network with randomly moving users

M. Khalili, L. Gao, Jianwei Huang, and B. Khalaj, *Incentive Design and Market Evolution of Mobile User-Provided Networks*, IEEE INFOCOM SDP Workshop, 2015.

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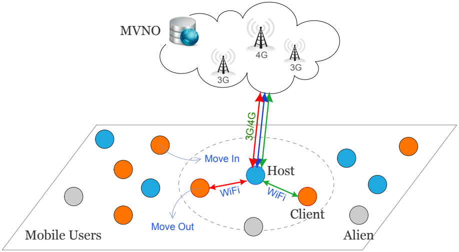

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- Each user's membership choice: a host, a client, or an alien.

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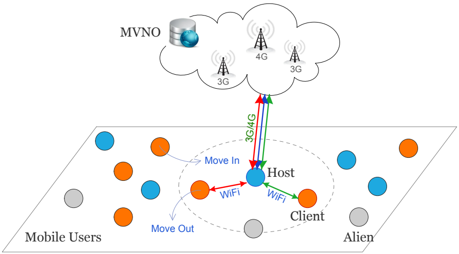

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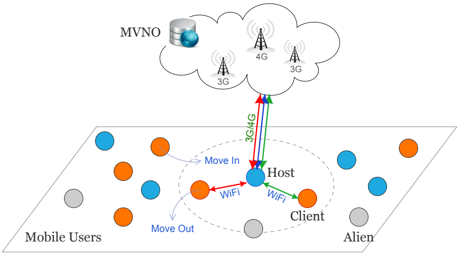

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- Large network with randomly moving users
- Each user's membership choice: a host, a client, or an alien.
- Population of each type will affect the benefit of other types of users
- We will characterize the membership selection equilibrium

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System Model

- MVNO Parameters
  - Usage-based price $p \in [0, p_{\mathrm{MAX}}]$
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    - Homogeneous mobility pattern for users;
  - $\lambda = N \cdot \rho$: the average number of other users that a user encounters;
    - A finite value;
  - $\delta \in [0, 1]$: the **service request probability** of each user (user type);
    - I.I.D. with pdf $f(\delta)$.

User Payoff

- A type-δ user's payoff:
  - When choosing to be an alien $(s = \mathrm{A})$, its expected payoff is

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

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

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

    - ★ P_{H}: *the probability of a client meeting at least one host;*
    - ★ 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);

User Payoff (Cont.)

- A type-δ user's payoff:
  - When choosing to be a host ($s = \mathrm{H}$), its expected payoff is

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

    - ★ $\bar{\delta}_\mathrm{C}$: *the average service request probability of clients;*
    - ★ Y_C: *the average number of clients that a host serves;*
    - ★ 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);

MVNO Expected 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, MNO's expected profit is

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

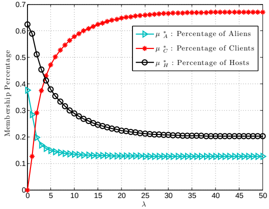
  - μ_{H} and μ_{C}: the percentages of hosts and clients;
  - $\bar{\delta}_{\mathrm{H}}$ and $\bar{\delta}_{\mathrm{C}}$: the average service request probabilities of hosts and clients;
  - $\mu_{\mathrm{H}} \cdot \bar{\theta}_{\mathrm{H}}$: the total data requested and consumed by hosts;
  - $\mu_{\mathrm{C}}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

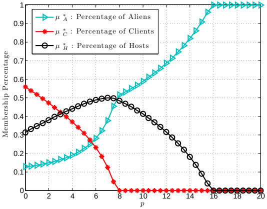
Two-stage Game Formulation

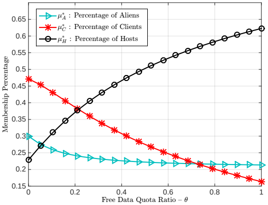
- Stage I — MVNO Pricing Strategy
  - The MVNO decides the price p and the free data quota ratio δ, aiming at maximizing the expected profit $V(p, \delta)$;
- Stage II — User Membership Selection
  - The mobile users with each type-θ decide their memberships $s(\theta) \in \{\mathrm{H}, \mathrm{C}, \mathrm{A}\}$, aiming at maximizing the expected payoff $U_\theta(s)$;
- We can derive the Subgame Perfect Equilibrium (SPE).

Stage II – User Membership Selection

- Illustration of Membership Selection Equilibrium
  - Blue: Aliens; Red: Clients; Black: Hosts.
  - Average number of user encounters $\lambda \nearrow$: Clients $\nearrow$, Host $\searrow$;
  - Usage-based price: $p \nearrow$: Clients $\searrow$, Host first $\nearrow$ and then $\searrow$;
  - Reward ratio $\theta \nearrow$: Clients $\searrow$, Host $\nearrow$;





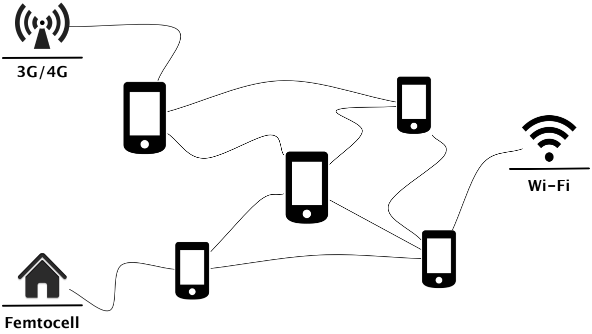


Bargaining-based Crowd-sourced Network Connectivity

Imbalance of Mobile Internet Access

- Different users have different access technologies and access speeds: 3G/4G, femtocell, Wi-Fi.
- Different networks have different congestion levels even at the same time and location.
- How to effectively take advantage of and integrate heterogeneous network access capabilities?

Open Garden

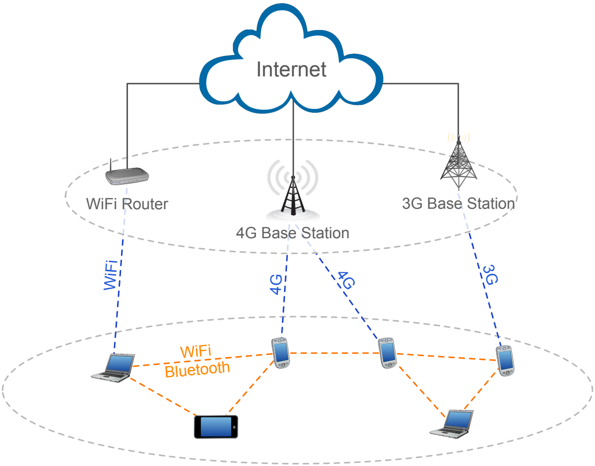


- Share the best mobile internet connection(s) among users.

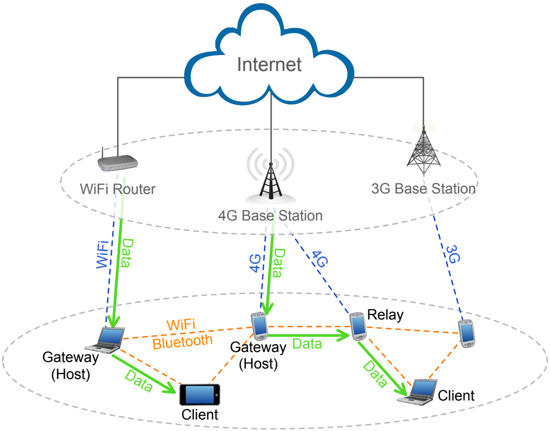
Key Problems

- How to achieve an efficient and fair network resource allocation?
  - Who will download data for whom, and how much?
  - Who 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?

Crowd-Sourced Mobile Internet Access



Crowd-Sourced Mobile Internet Access



- Host (Gateway): Downloading data from Internet
- Relay: Forwarding data for others
- Client: Consuming data

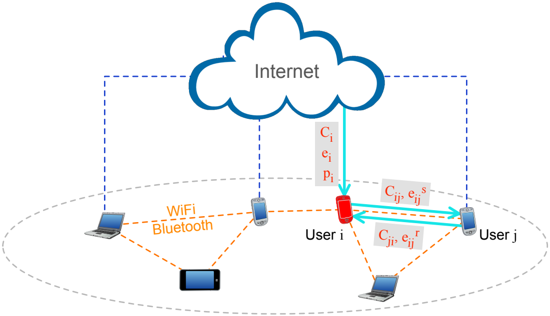
G. Iosifidis, L. Gao, J. Huang, L. Tassiulas, *Enabling Crowdsourced Mobile Internet Access*, IEEE INFOCOM, 2014.

Key Features

- A mobile user may have multiple concurrent roles
- Multi-hop accessing
  - Mobile users can access internet through the relay of multiple devices.
- Access bonding
  - Mobile users can access internet through multiple access links.

System Model

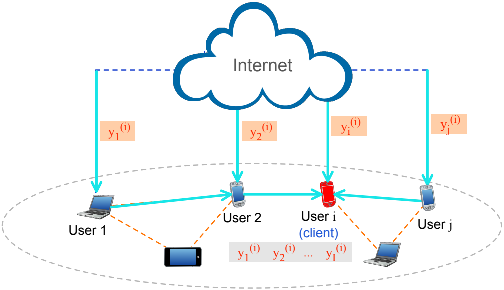
- A set of mobile users: $\mathcal{I} = \{1, 2, ..., I\}$
- For each user $i \in \mathcal{I}$:



  - $c_i,\ c_{ij},\ c_{ji},\ j \in \mathcal{I}$: link capacity;
  - $e_i,\ e_{ij}^s,\ e_{ij}^r,\ j \in \mathcal{I}$: unit energy consumption;
  - p_i: usage-based pricing for accessing Internet.

Client Model

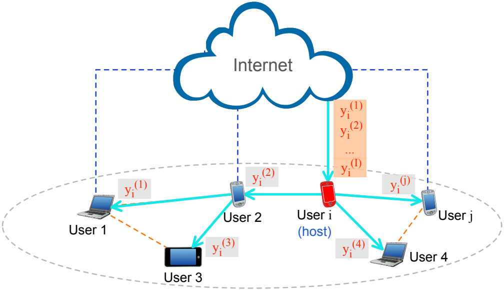
- When user $i \in \mathcal{I}$ is a client.



  - $y_j^{(i)}$: the data downloaded via host j for client i;
  - $y^{(i)} = \sum_{j\in\mathcal{I}} y_j^{(i)}$: the total data consumed by client i;
  - $U_i\left(y^{(i)}\right)$: the utility function of client i.

Host Model

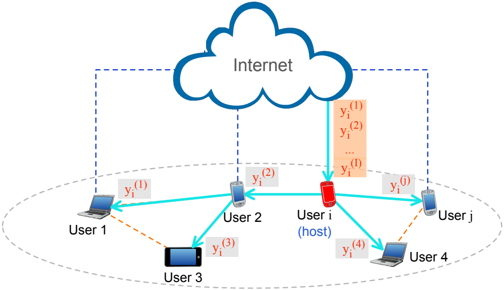
- When user $i \in \mathcal{I}$ is a host (gateway).



  - $y_i^{(j)}$: the data downloaded via host i for a client j;
  - $y_i = \sum_{j \in \mathcal{I}} y_i^{(j)}$: 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;

Host Model

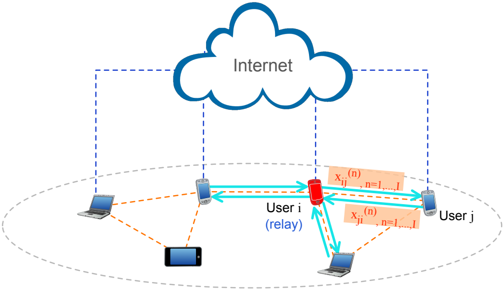
- When user $i \in \mathcal{I}$ is a host (gateway).



  - $y_i^{(j)}$: the data downloaded via host i for a client j;
  - $y_i = \sum_{j \in \mathcal{I}} y_i^{(j)}$: 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: $y_i \leq c_i$.

Relay Model

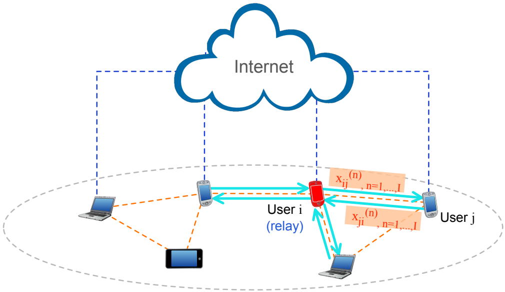
- When user $i \in \mathcal{I}$ is a relay.



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

Relay Model

- When user $i \in \mathcal{I}$ is a relay.



  - $x_{ij,\ n\in\mathcal{I}}^{(n)}$: the data relayed from user i to user j, for client n;
  - $e_{ji}^{r} \cdot \sum_n x_{ji}^{(n)}$: total energy consumption for receiving data from user j;
  - $e_{ij}^{s} \cdot \sum_n x_{ij}^{(n)}$: total energy consumption for sending data to user j.
  - Relay capacity constraints: $\sum_n x_{ij}^{(n)} \leq c_{ij}, \quad \sum_n x_{ji}^{(n)} \leq c_{ji}$
  - Flow balance constraint: $\sum_j x_{ji}^{(n)} + y_i^{(n)} = \sum_j x_{ij}^{(n)}, \ n \in \mathcal{I}$

User Payoff

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

$$J_i(\boldsymbol{x}_i, \boldsymbol{y}_i) = U_i - P_i - E_i$$

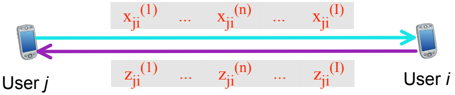
  - $\boldsymbol{y}_i = \{y_i^{(n)}\}_{n \in \mathcal{I}}$: Downloading matrix;
  - $\boldsymbol{x}_i = \{x_{ij}^{(n)}\}_{j,n \in \mathcal{I}}$: Relaying matrix;
  - U_i: Utility of user i (as a client);
  - P_i: Total payment of user i (as a host for internet access);
  - E_i: Total energy consumption of user i (as a host and/or relay);
- To maximize the payoff, each user only wants to be a client, but not as a host or relay.

Our Goal

- Mechanism design to address incentive, efficiency, and fairness issues
  - Encouraging the user participation and cooperation;
  - Achieving an efficient and fair network resource allocation.

Solution: Virtual Currency

- Key idea: User pays certain virtual currency to those who send data to him (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

Modified Payoff with Virtual Currency

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

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

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

- Modified payoff maximization takes care of incentive issues.

Efficiency and Fairness Issues

- How to achieve an efficient and fair network resource allocation?
  - Efficiency: The aggregate payoff of all users is maximised.
  - Fairness: Every user achieves a satisfactory payoff;
- Our Solution: Nash Bargaining

Nash Bargaining Solution

Nash Bargaining Problem (NBP)

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

s.t., (a) $J_i \geq J_i^0$ (J_i^0 : disagreement point)

(b) *Capacity constraints*;

(c) *Flow balance constraint*;

(d) *Virtual currency budget constraint*.

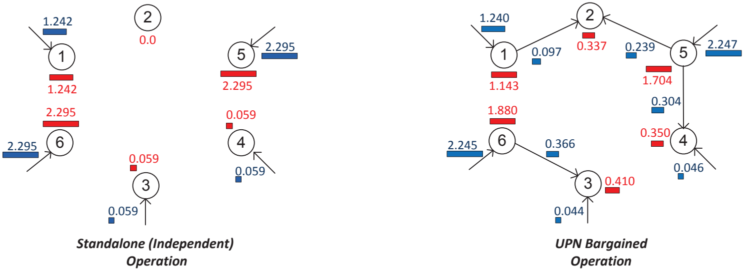
- The NBP problem has a unique optimal solution.

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, and signals to neighbors until convergence.

Simulation

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



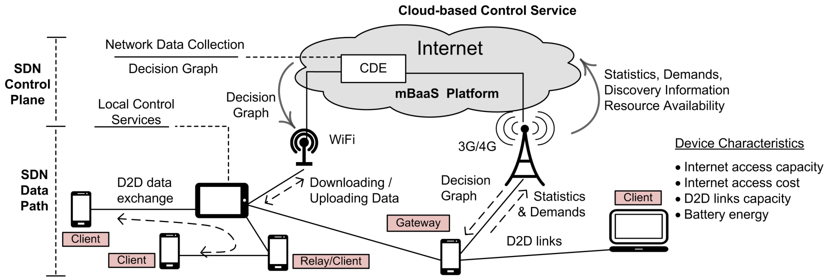
Left: Independent Operation. Right: Crowd-sourced Operation.

Cloud-based SDN-assisted Mobile UPNs

Centralized Implementation

- Goals:
  - Grassroots mesh networks that can adapt to dynamic network environment and fast-changing user needs.
  - Multi-hop service paths and adjustable rate allocation for each client.
  - Account for Internet access prices, effective D2D throughput, etc.
  - Current single-hop application-layer solutions are inadequate.
- Technical Challenges:
  - Provide a flat neighborhood network abstraction, independent of the network interfaces & Internet access technologies.
  - Support fast network reconfigurations.
  - Ensure consistent network reconfigurations across successive time periods and the different nodes.
  - Support seamless transitions of Internet flows as the gateway roles change.

CoNeS: Collaborative Network Sharing System



- Proposed solution overview:
  - SDN-enhanced mobile devices: implement a programmable packet forwarding datapath on each device. Network-layer forwarding.
  - Cloud-based support for UPN monitoring, SDN control, and the "logistics".

D. Syrivelis, G. Iosifidis, D. Delimpasis, K. Chounos, T. Korakis, L. Tassiulas, *Bits & Coins: Supporting Collaborative Consumption of Mobile Internet*, IEEE INFOCOM, 2015.

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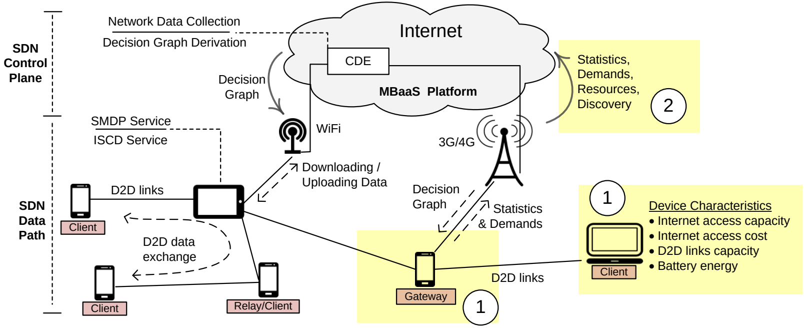
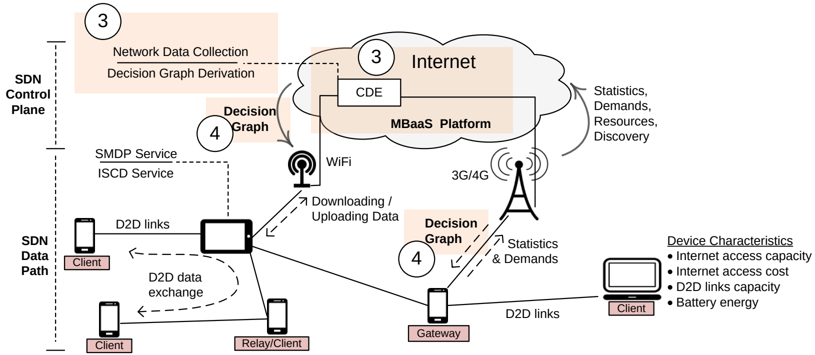


- 1: Each user terminal executes neighbor discovery.
- 2: Each node forwards to the cloud the network information (links capacity), its resource availability (battery, Internet throughput), and its demand (active/no).

CoNeS: Collaborative Network Sharing System



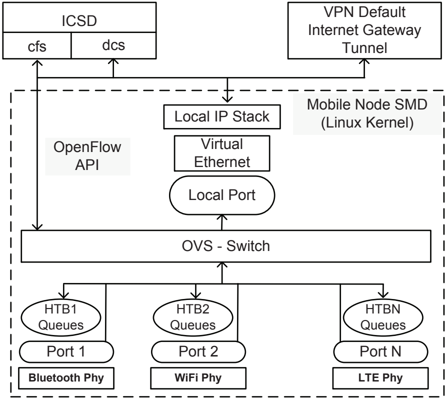
- 3: The mobile Back-end as a Service (mBaaS) platform collects the information; the central decision engine (CDE) derives the servicing policy (role assignment, resource allocation).
- 4: The *decision graph* is communicated to the nodes of the UPN.

The above steps are executed periodically.

CoNeS: Collaborative Network Sharing System

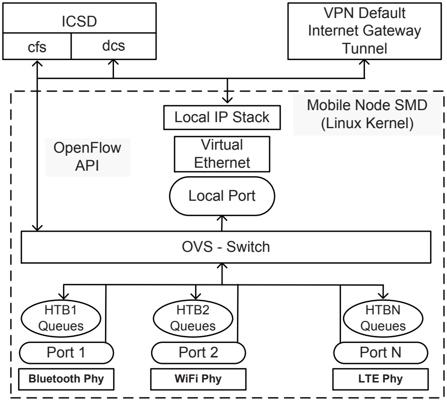
- mBaaS platform details:
  - The Connection Decision Engine (CDE) service runs at the cloud, in proximity with the devices.
  - CDE can provide the interface with mobile operators for pricing, authentication, or even broker services.
  - CDE can implement any policy algorithm.
- The CoNES SDN system is realized as a 3-tier system:
  - CDE uses the so-called "Northbound" API to push the UPN configuration to mobile nodes.
  - Each mobile node "translates" the decision graph to local flow rules.
  - The local rules are pushed to each local datapath via the "southbound" API that it is clean openflow.

Inside the Node



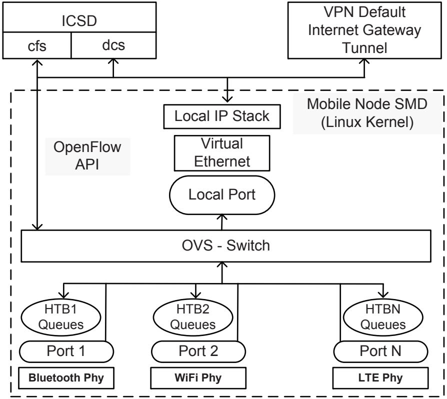
- Overview:
  - All local network interface drivers get under OpenVSwitch control.
  - Ingress traffic is directly delivered to OpenVSwitch
  - Egress traffic is throttled by Hearchical Token Buffer (HTB) queuing.

Inside the Node



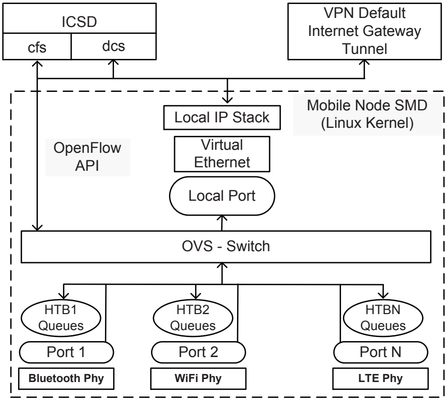
- OpenVswitch datapath:
  - A linux kernel version of an SDN implementation that is used to forward between network interfaces.
  - Can be remotely and dynamically configured to serve any role.
- Virtual Ethernet interface abstraction works independently of the used

Inside the Node



- Internet Connection Sharing Daemon (ICSD):
  - Runs discovery protocol periodically and reports status to CDE.
  - Gets node configuration updates from the CDE periodically, and applies them locally using an appropriate syncing protocol so the neighborhood network does not break.

Inside the Node

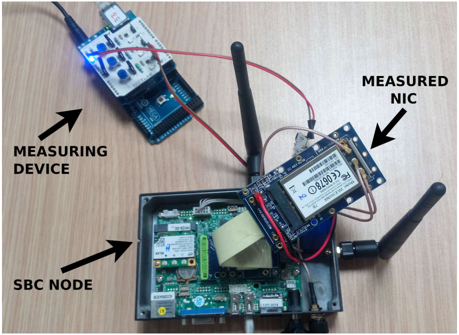


- VPN default internet gateway tunnel:
  - Provides a VPN network for Internet access through the CDE.
  - Local neighborhood Internet gateway changes induce only re-establishments of VPN connections.

Performance Evaluation

- Goals:
  - Implement this new architecture.
  - Quantify overheads and performance limits.
  - Find optimal design choices.
- Specifically, we seek answers:
  - How often should the devices send information to the CDE?
  - How much is the delay, bandwidth and energy consumption overhead?
  - How much does it cost to relays and gateways to serve others?
  - How fast is it possible to reconfigure the network?
  - What are the rates that are achieved in a typical scenario?

Experimental Setup



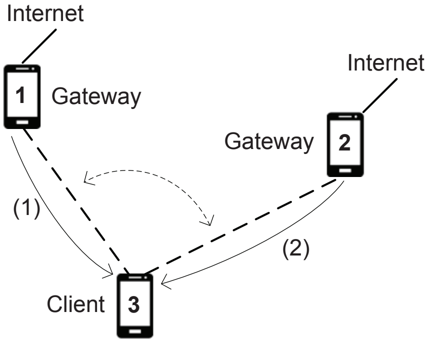
- 3 Embedded Nodes (single-board computers):
  - Intel Atom CPU, 1Gbyte RAM,
  - 802.11n WiFi (ad hoc mode), 100Mbit cable Ethernet interface.
- Real-time power consumption measurement with the NITOS Mobile Monitoring System.
- CDE cloud service deployed on NITOS cluster.

Experimental Setup

- Heartbeat power consumption overhead:
  - The lower the heartbeat period the better the responsiveness to changes; but it can be an overkill.
  - *A period of 3 seconds has been found to be optimal in practice, introducing an additional 2.5% energy consumption per device*.
  - More frequent updates are possible but double (at least) the energy consumption.
  - mBaaS responds are typically within hundreds of msecs; hence hbt msgs do not induce further delay.

- Relaying Overheads:
  - Computation overheads: *the number of active flow rules installed in OVS (look-up/match operations). Negligible for the size of UPNs*.

Experimental Setup



- Network reconfiguration.
  - How fast can the gateway change? What is the impact of this switching on the aggregate energy consumption?
  - 2GB file transfer. Benchmark scenario: no switching.
- *Gateway switching every 20 seconds was found optimal in practice*:
  - Increases the delay from 157 to 197 seconds.
  - Increases the energy consumption 6 to 25% (downloading/uploading).

Experiments Recap

- Extensive experimentation revealed that:
  - The SDN-based design continues to perform similar to the default network stack on embedded nodes; negligible overheads, same throughput, low heartbeat overhead.
  - Network reconfigurations do cost and if they are frequent enough they can eliminate all benefits.
  - Possible Internet delays with the cloud service will affect the reconfiguration process but this is not critical for the system operation and benefits.

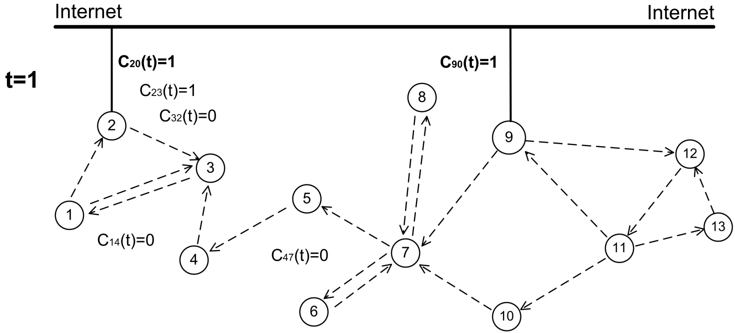
Summary of Technical Contributions

- End-to-end design of a new architecture for cooperative mobile networks.
- Used SDN in an effective and scalable way to implement and orchestrate adhoc UPNs between mobile phones.
- Embedding SDN to mobile devices; extending SDN to the network edge.
- Exploring the design space of such systems, and devising optimal design choices (frequency of reconfigurations, delay requirements, etc).
  - Quantitative approach on evaluating SDN systems operation on mobile phones under real workload.
- The system works automatically from bootstrapping to service end-of-life, with maximum performance.
  - Evaluated the system both in testbeds and with commercial equipments.

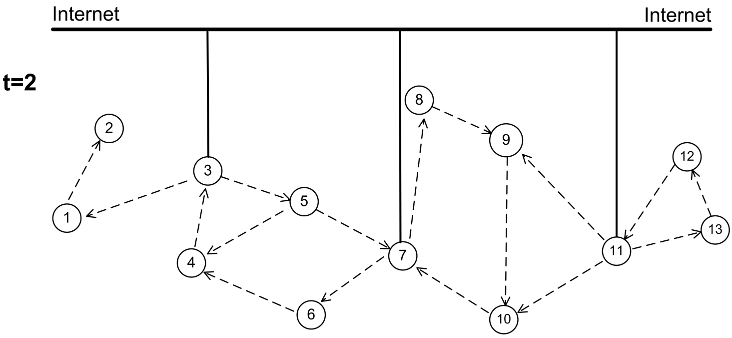
Potential of Cloud

- CoNeS can go beyond device collaboration due to the cloud control:
  - The CDE can act as broker among different operators, apply sophisticated pricing mechanisms, etc.
  - It can be used to alleviate problems of poor coverage (e.g., at the cell edges), exploit end-user devices with high capabilities, etc.
  - It can support direct content exchange among devices through local loops, hence removing burden from core networks.
- The increasing demand for wireless connectivity calls for novel and disruptive solutions:
  - MNOs and innovative start ups are already employing similar architectures/technologies.
  - Novel opportunities for research.

Service Exchange Equilibriums in UPNs



- Directed, time-evolving graph: $\boldsymbol{C}(t) = \left(C_{ij}(t) \in \{0,1\} : i,j \in \mathcal{N}\right)$.
- Infrastructure access configuration: $\boldsymbol{C_0}(t) = \left(C_{i0}(t) \in \{0,1\} : i \in \mathcal{N}\right)$.



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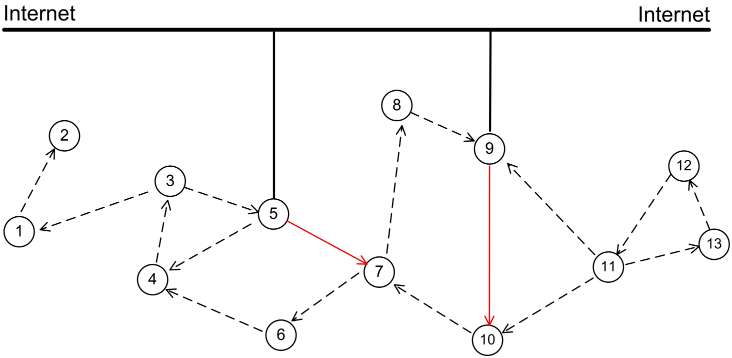


- A connected node relays *one* other node among those *one-hop* away.
  - Instantaneous relay configuration $\boldsymbol{R}(t) = \left(R_{ij}(t) \in \{0, 1\} : i, j \in \mathcal{N}\right)$.
- Goal of the service: connect unconnected nodes.
- Benefit of each node: amount of relay he receives.

- Question 1. Designer's point-of-view:
  - Which is a *sensible* criterion for allocating the relay opportunities?
  - What is the relay allocation policy $\boldsymbol{R}(1), \boldsymbol{R}(2), \ldots$, that achieves this goal?
- Question 2. Node's point-of-view:
  - How should a node allocate his relay opportunities so as to maximize his own future benefit by reciprocation?
- Question 3. Group behavior:
  - Is it beneficial for any subset of nodes to exclude others from relaying?

Are the answers to the above questions related to each other?

L. Georgiadis, G. Iosifidis, L. Tassiulas, *Exchange of Services in Networks: Competition, Cooperation, and Fairness*, ACM Sigmetrics, 2015.

Long Time Average Regime

- The connectivity of nodes with the infrastructure is changing with time.
- The links between nodes are bidirectional and fixed:

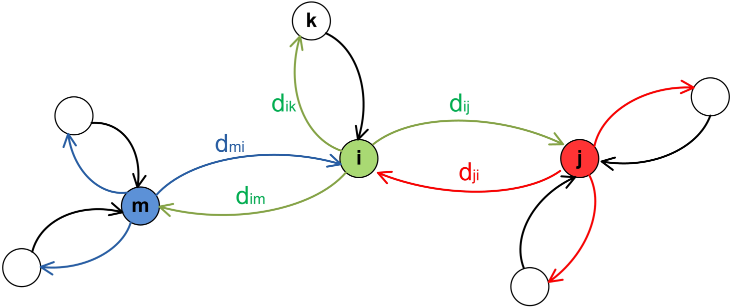
$$C_{ij}(t) = C_{ji}(t) = C_{ij} \in \{0, 1\},\ i, j \in \mathcal{N}$$

- Basic parameters of each node $i \in \mathcal{N}$:
    - D_i: portion of time that i is connected to infrastructure.
    - d_{ij}: portion of time that i relays neighbor j.
    - Utility of node i: $u(\boldsymbol{d}) = \sum_j d_{ji},\ \boldsymbol{d} = \big(d_{ij} : (i, j \in \mathcal{N}\big)$.

Outline

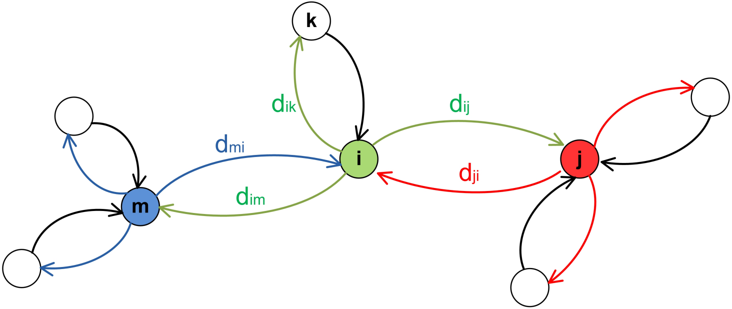
- Model
- Centralized Fair Allocation Policy (Question 1)
- Relation to the Competitive Equilibrium (Question 2)
- Stability of the Solution (Question 3)
- Related Works and Conclusions

Service & Resource Exchange over Networks



- Basic features of the system:
  - Each node has some amount of spare resource.
  - Nodes are complementary in terms of resource types or resource availability.
  - Their cooperation is constrained by a graph. Unsaturated demand.
  - Indifferent in neighbors' resources.

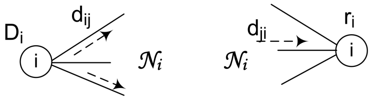
Service & Resource Exchange over Networks



- Various decentralized technological networks (beyond UPNs):
  - Peer-to-peer file sharing overlays.
  - Renewable energy sharing in smart grid.
- Sharing economy platforms:
  - Online bartering: swap.com, neighborgoods.net, etc.
  - Food sharing, favor exchanging, *risk sharing*, etc. More examples: http://www.collaborativeconsumption.com/

Model

- An undirected connected graph $G = (\mathcal{N}, \mathcal{E})$.



- Set of allocations:

$$\mathbb{D} = \{\boldsymbol{d} = (d_{ij})_{(i,j)\in\mathcal{E}} \, : \, d_{ij} \geq 0, \, \sum_{j\in\mathcal{N}_i} d_{ij} = D_i\}$$

- Set of feasible received resource vectors:

$$\mathbb{R} = \{\boldsymbol{r} = (r_i)_{i\in\mathcal{N}} : \; r_i = \sum_{j\in\mathcal{N}_i} d_{ji}, \; i \in \mathcal{N}, \, \boldsymbol{d} \in \mathbb{D}\},$$

- Exchange ratio vector:

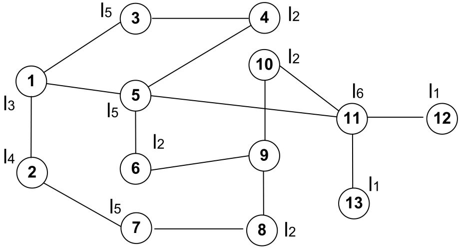
$$\rho_i = \frac{r_i}{D_i}, \quad \boldsymbol{\rho} = (\rho_i, \; i \in \mathcal{N})$$

A Designer's View

- Q1.1: Which is a *sensible* allocation?
  - Ideal allocation: $r_i = D_i, \ \forall\, i \in \mathcal{N}$, i.e., $\rho_i = 1$
  - Else: balance the exchange ratios as much as possible.
- Lexicographically optimal (Max-min fair) vector of exchange ratios $\boldsymbol{\rho}$.
  - If $\boldsymbol{x} \succ \boldsymbol{y}, \ \forall\, \boldsymbol{y}$, then $\boldsymbol{x}^*$ is lex-optimal, where $\boldsymbol{x}, \boldsymbol{y} \in \mathbf{R}^N$.
- There is a unique lex-optimal vector of exchange ratios $\boldsymbol{\rho}^* \succeq \boldsymbol{\rho}$.
  - Set $\mathbb{R}$ of received resource vectors is compact and convex, and $\rho_i = r_i / D_i$.
- Also interested in the allocations $\boldsymbol{d}^*$ that yield $\boldsymbol{\rho}^*$.
  - While $\boldsymbol{\rho}^*$ is unique, there are many allocations $\boldsymbol{d}^*$ (e.g.: 4-node ring graph).
- Q1.2: What are the main properties of $\boldsymbol{\rho}^*$.

Additional Definitions

- For a graph $G = (\mathcal{N}, \mathcal{E})$, endowments $\{D_i\}$, and $\forall\ \boldsymbol{r} \in \mathbb{R}$ define:
  - The different values (*levels*) of the exchange ratios: $l_1 < l_2 < \ldots < l_K$
  - The level index $k(i)$ of each node i: $l_{k(i)} = \rho_i$.
  - The level set $\mathcal{L}_m = \{i \in \mathcal{N} : k(i) = m\}$, $m = 1, \ldots, K$.
  - Node subsets:
    - ★ $\mathcal{Q}_1 = \mathcal{N}$, and $\mathcal{Q}_k = \mathcal{N} - \cup_{m=1}^{k-1}(\mathcal{L}_m \cup \mathcal{L}_{K-m+1})$, $2 \leq k \leq \lceil K/2 \rceil$.
    - ★ Subgraph $G_{\mathcal{Q}_k} = (\mathcal{Q}_k, \mathcal{E}_{\mathcal{Q}_k})$
  - $\mathcal{N}(\mathcal{S})$: neighbors of nodes in set $\mathcal{S}$, which do not belong themselves in $\mathcal{S}$.



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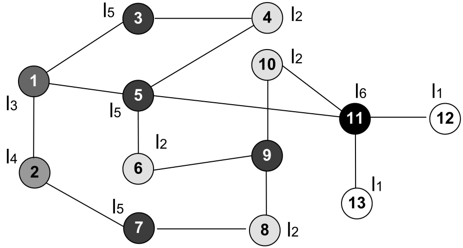

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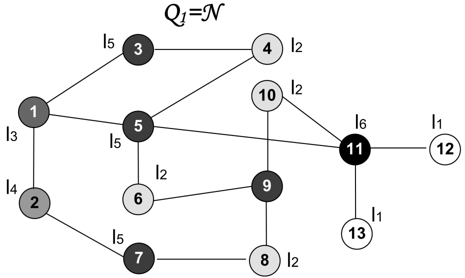

Additional Definitions

- For a graph $G = (\mathcal{N}, \mathcal{E})$, endowments $\{D_i\}$, and $\forall$ $\boldsymbol{r} \in \mathbb{R}$ define:
  - The different values (*levels*) of the exchange ratios: $l_1 < l_2 < \ldots < l_K$
  - The level index $k(i)$ of each node i: $l_{k(i)} = \rho_i$.
  - The level set $\mathcal{L}_m = \{i \in \mathcal{N} : k(i) = m\}$, $m = 1, \ldots, K$.
  - Node subsets:
    - ★ $\mathcal{Q}_1 = \mathcal{N}$, and $\mathcal{Q}_k = \mathcal{N} - \cup_{m=1}^{k-1}(\mathcal{L}_m \cup \mathcal{L}_{K-m+1})$, $2 \leq k \leq \lceil K/2 \rceil$.
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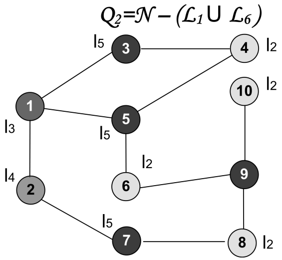

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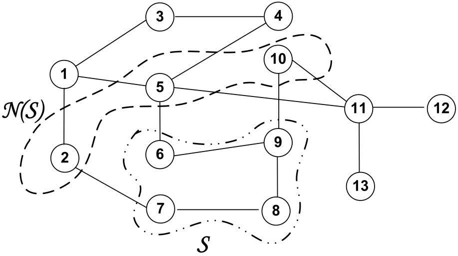


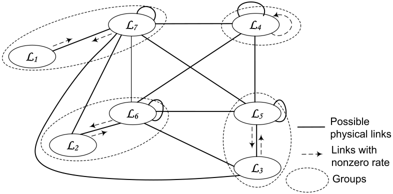
Properties of ρ^*

- **Theorem**: If an allocation $\boldsymbol{d}^*$ is lex-optimal, then the following properties hold:

  1. $\mathcal{L}_k^*$ is an independent set in graph $G_{\mathcal{Q}_k}$, for $k = 1, ..., \lfloor \frac{K}{2} \rfloor$.
     - ★ E.g., nodes in $\mathcal{L}_1^*$ are independent in $G_{\mathcal{Q}_1} = G$, $\mathcal{L}_2^*$ are independent in $G_{\mathcal{Q}_2}$, etc.
  2. $\mathcal{L}_{K-k+1}^* = \mathcal{N}_{\mathcal{Q}_k}(\mathcal{L}_k^*)$, for $k = 1, ..., \lfloor \frac{K}{2} \rfloor$.
     - ★ E.g., (assume $K = 7$) $\mathcal{L}_7^* = \mathcal{N}_{\mathcal{Q}_1}(\mathcal{L}_1^*)$, $\mathcal{L}_6^* = \mathcal{N}_{\mathcal{Q}_2}(\mathcal{L}_2^*)$, etc.
  3. $l_k^* \cdot l_{K-k+1}^* = 1$, for $k = 1, ..., \lfloor K/2 \rfloor$.
     - ★ E.g., $l_1 \cdot l_7 = 1$, $l_2 \cdot l_6 = 1$, etc.
  4. $\sum_{i \in \mathcal{L}_k^*} r_i^* = \sum_{i \in \mathcal{L}_{K-k+1}^*} D_i$, for $k = 1, ..., \lfloor \frac{K}{2} \rfloor$.
     - ★ E.g., $\sum_{i \in \mathcal{L}_1^*} r_i^* = \sum_{i \in \mathcal{L}_7^*} D_i$, $\sum_{i \in \mathcal{L}_2^*} r_i^* = \sum_{i \in \mathcal{L}_6^*} D_i$

Properties of ρ^*

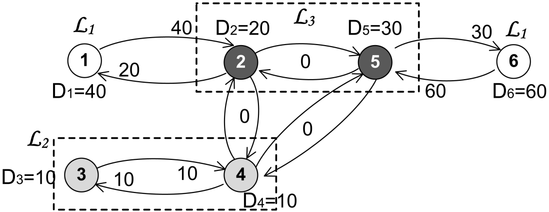
- There is a unique $\boldsymbol{\rho}^*$ and one or more $\boldsymbol{d}^* \in \mathbb{D}$, with properties:



- Nodes are partitioned in distinct exchange ratio sets $\mathcal{L}_1, \mathcal{L}_2, \ldots, \mathcal{L}_7$.
- $K = 7$ depends on $\mathcal{G}$ and $\{D_i\}$.
- $\mathcal{L}_7$ nodes work only with $\mathcal{L}_1$ nodes, and so on.
- It holds: $l_1 \cdot l_7 = l_2 \cdot l_6 = \ldots = 1$.
- Topology: $\mathcal{L}_k$ is independent in graph $G_{\mathcal{Q}_k}$, $k = 1, \ldots, 3$
- Topology: $\mathcal{L}^*_{K-k+1} = \mathcal{N}_{\mathcal{Q}_k}(\mathcal{L}^*_k)$, $k = 1, ..., 3$.

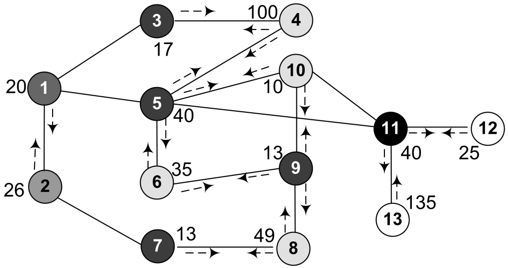
- **Theorem**: If an allocation policy satisfies the above properties, then it is lex-optimal.

Numerical Examples



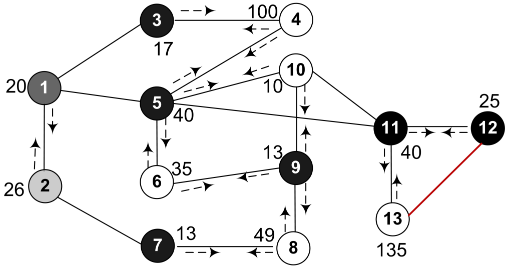
- $N = 6$ nodes, $K = 3$ levels.
- Endowments:
  $D_1 = 40,\ D_2 = 20,\ D_3 = 10,\ D_4 = 10,\ D_5 = 30,\ D_6 = 60.$
- Received resources: $r_1^* = 20,\ r_2^* = 40,\ r_3^* = 10,\ r_4^* = 10,\ r_5^* = 60,$ $r_6^* = 30.$
- Exchange ratios: $\rho_1^* = \rho_6^* = 0.5,\ \rho_3^* = \rho_4^* = 1,\ \rho_2^* = \rho_5^* = 2.$

Numerical Examples



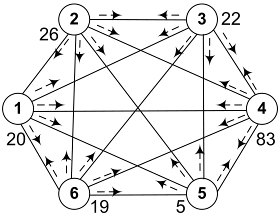
- $r_1^* = 26$, $r_2^* = 20$, $r_3^* = 39.74$, $r_4^* = 42.78$, $r_5^* = 93.49$, $r_6^* = 14.97$, $r_7^* = 30.38$, $r_8^* = 20.96$, $r_9^* = 30.38$, $r_{10}^* = 4.28$, $r_{11}^* = 160$, $r_{12}^* = 6.25$, and $r_{13}^* = 33.75$.
- $K^* = 6$ levels: 0.25, 0.4278, 0.7692, 2.3373, 1.3, 4.
- Level sets: $\mathcal{L}_1^* = \{12, 13\}$, $\mathcal{L}_2^* = \{4, 6, 8, 10\}$, $\mathcal{L}_3^* = \{2\}$, $\mathcal{L}_4^* = \{1\}$, $\mathcal{L}_5^* = \{3, 5, 7, 9\}$, and $\mathcal{L}_6^* = \{11\}$.

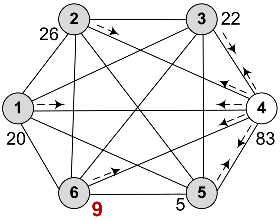
Numerical Examples



- Impact of graph.
- $K^* = 4$ levels: 0.45, 0.77, 1.3, 2.22
- Level sets: $\mathcal{L}_1^* = \{4, 6, 8, 10, 13\}$, $\mathcal{L}_2^* = \{2\}$, $\mathcal{L}_3^* = \{1\}$, $\mathcal{L}_4^* = \{3, 5, 7, 9, 11, 12\}$.
- What has changed?
  - $K = 4$ instead of $K = 6$.
  - Node 12 went from lowest to highest level, while 13 stayed in the lowest!

Numerical Examples





- Impact of endowments.
- Complete graphs of 6 nodes; slightly different endowments.
- Left: $K = 1$, Right: $K = 2$.
- Complete graphs have at most $K = 2$:
  - Whenever the maximum endowment exceeds the sum of the rest.

Stability wrt Trade

- A Competitive Market.
  - Every node $i \in \mathcal{N}$ determines independently his allocation policy $\left(d_{ij}\right)_{j \in \mathcal{N}_i}$
  - The entire endowment is allocated.
  - Objective: maximize $\sum_j d_{ji}$, or, equivalently, the ratio $\rho_i = r_i / D_i$.
  - Ratio ρ_i can be interpreted as the *price* that node i *sells* his resource.
- An allocation $\boldsymbol{d}^*$ is an *exchange equilibrium* iff $\forall i \in \mathcal{N}$:
  - (i) $d_{ji} = d_{ij} \cdot \rho_i, \ \forall j \in \mathcal{N}_i$.
  - (ii) if $d_{ji} > 0$ for some $j \in \mathcal{N}_i$, then $\rho_j = \min_{k \in \mathcal{N}_i} \rho_k$.
- Interpretation:
  - Utility-maximization: exchange resources only with the lowest ratio neighbors.
  - All nodes interacting with i have the same exchange ratio.
  - Neighbors with higher ratio do not interact with i.
- This is a *pricing equilibrium*, or an *equilibrium for price-takers*.

Stability wrt Trade

- Does an exchange equilibrium exist? If yes, is it related to the lex-optimal policy?
- What does the general equilibrium theory tells us?
  - Equilibrium exists under some mild conditions.
- Existence conditions do not apply in the proposed model:
  - (i) Not all nodes are endowed with non-zero quantities.
- Additional differences compared to typical competitive market models:
  - Prices are not given exogenously, instead,...

    ... they are indirectly determined by the nodes' decisions.

Stability wrt Trade

- **Theorem**.
  1. There is a lex-optimal allocation $\boldsymbol{d}^*$ under which every node $i \in \mathcal{N}$ gives resource to its neighbors in proportion to what it gets from them, i.e.,
  $$\frac{d_{ji}^*}{d_{ij}^*} = \frac{r_i^*}{D_i} = \rho_i^*, \ \forall j \in \mathcal{D}_i \,.$$
  2. The neighbors not receiving resource from i have higher ratio ρ_j, i.e.,
  $$\rho_j^* \geq \frac{1}{\rho_i^*}, \ \forall j \in \mathcal{N}_i - \mathcal{D}_i \,.$$
  3. If the allocation satisfies the above conditions, then it is lex-optimal.
- Interpretation:
  - There is a lex-optimal allocation where every node $i \in \mathcal{N}$ serves its neighbors with the same exchange ratio (or, not at all). Any possible exchange equilibrium is also a lex-optimal allocation.

The competitive interactions of users embedded in a graph yield the same allocation point a central designer would have selected.

Dynamic Interactions

- How can the nodes find this equilibrium?
- Dynamic setup:
  - Each node i creates "service token" (e.g., relay opportunity) according to a Poisson process with rate $\lambda_i = D_i$.
  - Every token is allocated to the neighbor with the lowest exchange rate (i.e., larger reciprocation).
  - Decentralized and asynchronous best response under limited information.
- Extensive numerical results show that the system converges to the unique vector of exchange ratios $\boldsymbol{\rho}^*$.
- Previous works showed convergence numerically for similar models, or even proved it under certain conditions.

Stability wrt Coalitions

- Assume that subsets of nodes can jointly decide to exclude others.
- NTU Coalitional Service Exchange game:
  - Played over the graph $G = (\mathcal{N}, \mathcal{E})$, by $\mathcal{N}$ players.
  - Each node i has strategy $d_i = \big(d_{ij} : j \in \mathcal{N}_i, \sum_j d_{ij} = D_i\big)$, and utility $u_i(\boldsymbol{d})$.
- *(Strong) Stability Definition*:
  - An allocation $\boldsymbol{d}$ (and the resource vector $\boldsymbol{r}$) is called *strongly* stable if $\forall \mathcal{S} \subseteq \mathcal{N}$, there is no allocation $\widehat{\boldsymbol{d}}_{\mathcal{S}}$ on the induced subgraph $G_{\mathcal{S}} = (\mathcal{S}, \mathcal{E}_{\mathcal{S}})$, such that $\widehat{r}_i \geq r_i \ \forall i \in \mathcal{S}$, and $\widehat{r}_j > r_j$ for at least one node $j \in \mathcal{S}$.
- **Theorem**: Any max-min fair allocation policy $\boldsymbol{d}^*$ yields a received resource vector $\boldsymbol{r}^*$ that lies in the core of the NTU service exchange game, and it is strongly stable.
  - Hence, the solution of the graph-constrained coalitional game has the above topological and price properties.

Related Works

- The relation between competitive equilibriums and the core is known.
  - A. Mas-Colell, M. Whinston, and J. Green, “Microeconomic Theory”, *Oxford University Press*, 1995.
  - This does not consider the graph; TU coalitional games.
- Graphical competitive economies.
  - S. Kakade, M. Kearns, L. Ortiz, "Graphical Economics", Springer Conf. on Learning, 2004.
  - S. Kakade, et al., "Economic Properties of Social Networks", Advances in NIPS, 2004.
  - Consider explicit pricing signals as in A-D models.
- Similar models in communication networks.
  - C. Aperjis, R. Johari, M. Freedman, "Bilateral and Multilateral Exchanges in Peer-Assisted Content Distribution", IEEE/ACM Trans. on Networking, 19(5), 2011.
  - Not detailed analysis of the equilibrium properties, nodes incur cost for serving others, tatonnement-like convergence.

Conclusions

- A generic model of collaborative consumption with many applications.
  - Technological networks: Internet sharing, renewable energy sharing, peer-to-peer file sharing, etc.
  - Various novel *sharing economy* applications.
  - No explicit price signals, pure bartering.
- **Contributions**:
  1. Characterized the structural properties of the max-min fair vector $\boldsymbol{\rho}^*$.
  2. Proved that it coincides with the solution of (i) the NTU coalitional graph-constrained game, (ii) the competitive resource exchange game.
  3. Provided polynomial-time algorithms for finding $\boldsymbol{\rho}^*$.
- Ongoing work:
  - Directed instead of undirected graphs.
  - Varying resource availability and varying demand.

Part IV: Outlook

3GPP Releases Support UPNs

- Existing functionalities facilitate such services.
  - E.g., ANDSF, D2D communications, dual connectivity.
- Future 3GPP Releases will support even more features.
  - Tighter integration of cellular and Wi-Fi networks, e.g., enhanced-ANDSF.
  - ProSe: proximity services that allow operators to facilitate D2D discovery and communications.
  - LTE unlicensed for carrier-grade D2D communication.
  - Virtualization and cloud-supported network services.

Towards Next Generation 5G Systems

- UPNs are aligned with the design principles for future 5G systems.
- At the Radio Access level:
  - Leverage underutilized or unlicensed spectrum.
  - Exploit multiple connectivity services, and D2D communications.
  - Integrate third-party and user deployments.
  - Automate configuration, optimization and healing; in a bottom-up fashion if possible.
  - Support multi-operator and shared use of infrastructure.
  - Coordinate and cancel interference; in a bottom-up fashion if possible.
- At the Network and Management level:
  - RAT-agnostic core; fixed and mobile convergence.
  - Automation and self-healing, Collaborative management of network resources; Carrier-grade network cloud orchestration.

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More Information

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