Incentivizing Peer-Assisted Services
a Fluid Shapley Value Approach

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Wednesday, June 23th, talk @ Dauphine
Structure of this talk

Motivation

Requirements for incentivizing peer-assistance
A Fluid-Atomic Shapley approach
Applications

Concluding remarks
Peer-to-Peer (P2P) is a double edged sword

P2P is technically beneficial ...

- Self-Scaling, Resilient, Versatile

... but it puts Internet economy under stress

- Content right owners see a shrinking revenue
- Access network providers see increasing traffic

Internet becomes engineering/regulatory battlefields

- Traffic filtering ... will it work?
- Network neutrality ... will it block innovation?
We focus here on **peer-assisted services**

- A service offered by a provider, for a given price
- Some users commit their resources to assist in provision of service

Address P2P via an economic rethink

- Allows to fight illegal content with equal arms (through added features, authentication etc.)
- Focus on fairness and efficiency
Examples of peer-assisted services

The Internet

Content Server

Peer-assistance enabled

Residential Gateways (owned and managed by the ISP)
Examples of peer-assisted services (cont'd)

A principle found in multiple scenarios

- **Content**: broadband, mobile  
  peer-assistance: retrieve content locally

- **Bandwidth**: wireless community, femtocell  
  peer-assistance: make access available

- **CPU**: Crowdsourcing  
  peer-assistance: provide computing power
Incentivizing peer assistance

Incentives have been studied in P2P for several years

- Focus on churn, free-riding, sybil attacks
- Indeed, much of P2P today relies on altruistic users

Incentive is critical for peer-assisted services

- Deployment: users should decide to opt-in
- Stability: users keep control on their own resources (e.g. unplug or throttle their gateway)
- Provider wants to have guaranteed revenue.
Solutions deployed today

One-shot incentive to Opt-in

- receive a gift
  (free upgrade or feature)
- or even make you pay!

Sharing common resource

- Restricted to a zero value economy

Revenue sharing

- Looks more general and promising but how to tune it?
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An incentive mechanism for peer-assistance

1. Stability/Fairness
   - loose: individually rational users do not leave
   - tight: derived from objective fairness axioms

2. Economically efficient
   - loose: sum of incentives matches cost reduction
   - tight: optimality = system leads to minimum cost

3. Manage different scales
   - Interaction of large user population and big players

4. Computationally efficient
Cooperative Game, "Should I stay or should I go?"

Players: \( \mathcal{N} \)

Coalition: \( S \subseteq \mathcal{N} \)
Value: \( \nu(S) \)

Coalitions

Value: \( \nu \)

Coalition: \( T \subseteq \mathcal{N} \)
Value: \( \nu(T) \)
Shapley Value

1. Efficiency

\[ \sum_{i \in S} \phi_i(S, V) = V(S). \]

2. Symmetry

\[ \forall T \subseteq S \setminus \{i, j\}, \quad V(T \cup \{i\}) = V(T \cup \{j\}) \quad \text{then} \quad \phi_i(S, V) = \phi_j(S, V). \]
Shapley Value

1. Efficiency
\[ \sum_{i \in S} \varphi_i(S, V) = V(S). \]

2. Symmetry
\[ \forall T \subseteq S \setminus \{i, j\}, \quad V(T \cup \{i\}) = V(T \cup \{j\}) \]
then \[ \varphi_i(S, V) = \varphi_j(S, V). \]

3. Balanced contribution
\[ \varphi_i(S, V) - \varphi_i(S \setminus \{j\}, V) = \]
\[ \varphi_j(S, V) - \varphi_j(S \setminus \{i\}, V). \]

Shapley value is equal to
\[ \frac{1}{|S|!!} \sum_{\pi \in \Pi} V(S(\pi, i) \cup \{i\}) - V(S(\pi, i)). \]

Exponential Complexity!
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A new multi-class fluid-atomic approach

- 1 atomic player: the provider $P$ (revenue $R$ per user)
- Peers represented by continuous fluid in $m$ classes.

Let $\bar{X} = (\frac{N_1}{N}, \ldots, \frac{N_m}{N})$ denote the fraction of participating peers in each class.

Let $C(\bar{X})$ be the marginal service cost per user.

$V(\{P\}) = R - C(\emptyset)$  
$V(\bar{X}) = 0$  
$V(\{P\} \cup \bar{X}) = R - C(\bar{X})$

(Traditional service)

(Provider is a veto player)

(Peer-assisted service)
Shapley Value

1. Efficiency
\[ \sum_{i \in S} \varphi_i(S, V) = V(S). \]

2. Symmetry
\[ \forall T \subseteq S \setminus \{i, j\}, \quad V(T \cup \{i\}) = V(T \cup \{j\}) \]
then \( \varphi_i(S, V) = \varphi_j(S, V). \)

3. Balanced contribution
\[ \varphi_i(S, V) - \varphi_i(S \setminus \{j\}, V) = \]
\[ \varphi_j(S, V) - \varphi_j(S \setminus \{i\}, V). \]

Shapley value is equal to
\[ \frac{1}{|S|!} \sum_{\pi \in \Pi} V(S(\pi, i) \cup \{i\}) - V(S(\pi, i)). \]

Fluid limit

1. Efficiency
\[ \bar{\varphi}_P(\bar{X}) + \sum_{i=1}^{m} x_i \varphi_i(\bar{X}) = R - C(\bar{X}) \]

2. Symmetry

Users in class \( i \) have \( \varphi_i^N(\bar{X}) \)

3. Balanced contribution
\[ \frac{\partial \varphi_i}{\partial x_j} = \frac{\partial \varphi_j}{\partial x_i}, \quad \text{and} \quad \varphi_i(\bar{X}) = \frac{\partial \bar{\varphi}_P}{\partial x_i} \]

\[ \varphi_i(\bar{X}) = - \int_0^1 s \frac{\partial C}{\partial x_i}(s\bar{X})ds. \]
\[ \bar{\varphi}_P(\bar{X}) = R - \int_0^1 C(s\bar{X})ds \]
An intuitive proof

Shapley value equals $E[V(S(p_i, i) \cup \{i\}) - V(S(p_i, i))]$

- where $S(p_i, i)$ containing predecessors of $i$ in a random "permutation" chosen uniformly
- Let $s$ in $[0; 1]$ be the relative "rank" of a player $i$ in the permutation $p_i$. (essentially it is uniform on $[0; 1]$)

As the system becomes large

- By law of large numbers, $S(p_i, i)$ contains $s\bar{X}$
- If $i$ is not $P$, then $S(p_i, i)$ contains $P$ with probability $s$

$$\varphi_i(\bar{X}) = -\int_0^1 s \frac{\partial C}{\partial x_i} (s\bar{X}) ds.$$
More remarks

The formal proof uses limit axioms
- Simplifies results from Aumann-Shapley74 and Hart73
- Using a limit of balanced contribution Myerson77

The limit axioms offers a flexible methodology
- multiple atomic players
- other scenarios like network neutrality
- cost of peer-assistance incurred by user
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Qualitative properties

General conditions to achieve grand coalition

- Cost saving should compensate cost of sharing

Provider's Shapley value always increases with X

Peer's Shapley Value

- Combination of 2 effects
  1. Cost reduction
  2. Loss of bargaining power

- Characterized by concavity/convexity
Quantitative properties

Linear cost:

- Shapley value independent of $X$

Example: VoD with peer-assistance

- File size $S$; class $i$ upload $S_i$ bits; cost $b$ with $K$

Cost per user becomes

$$C(\bar{X}) = KS - \sum_i X_i KS_i$$

Shapley value:

$$\varphi_i = \frac{KS_i}{2}$$

- "Serve two, get one free" is fair and optimal
Economic rethink of peer-assistance

- Provides strong fairness/efficiency guarantee
- Flexible: interaction of peers and big players, ...
- Computationally simple: closed form expressions

Future works

- Can we apply this model to energy-efficient operation of (distributed) services?
- Can we handle competing providers?
Thank you!

