Incentivizing Peer-Assisted Services
a Fluid Shapley Value Approach

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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?

An alternative to P2P

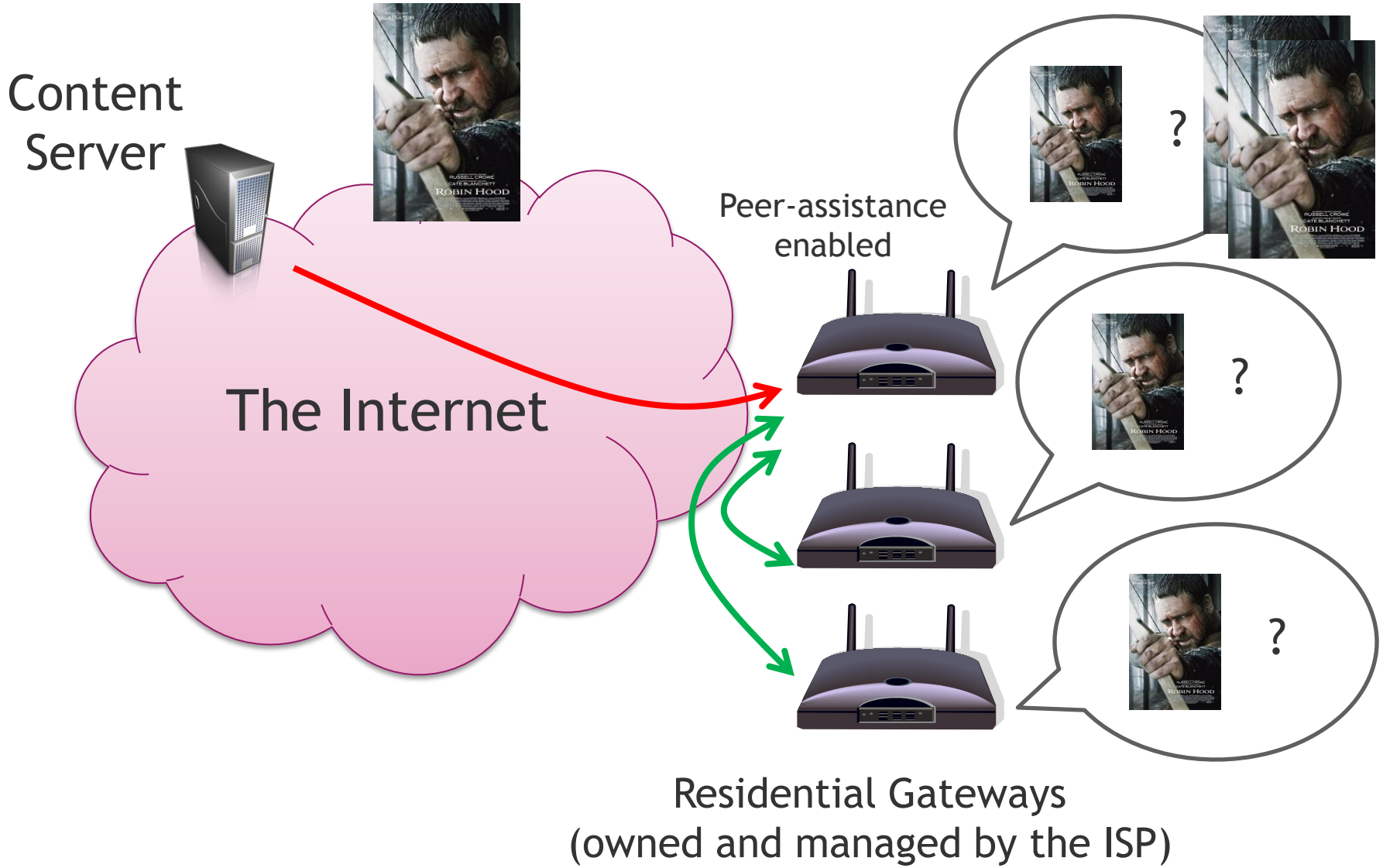
We focus here on peer-assisted services

- 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



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

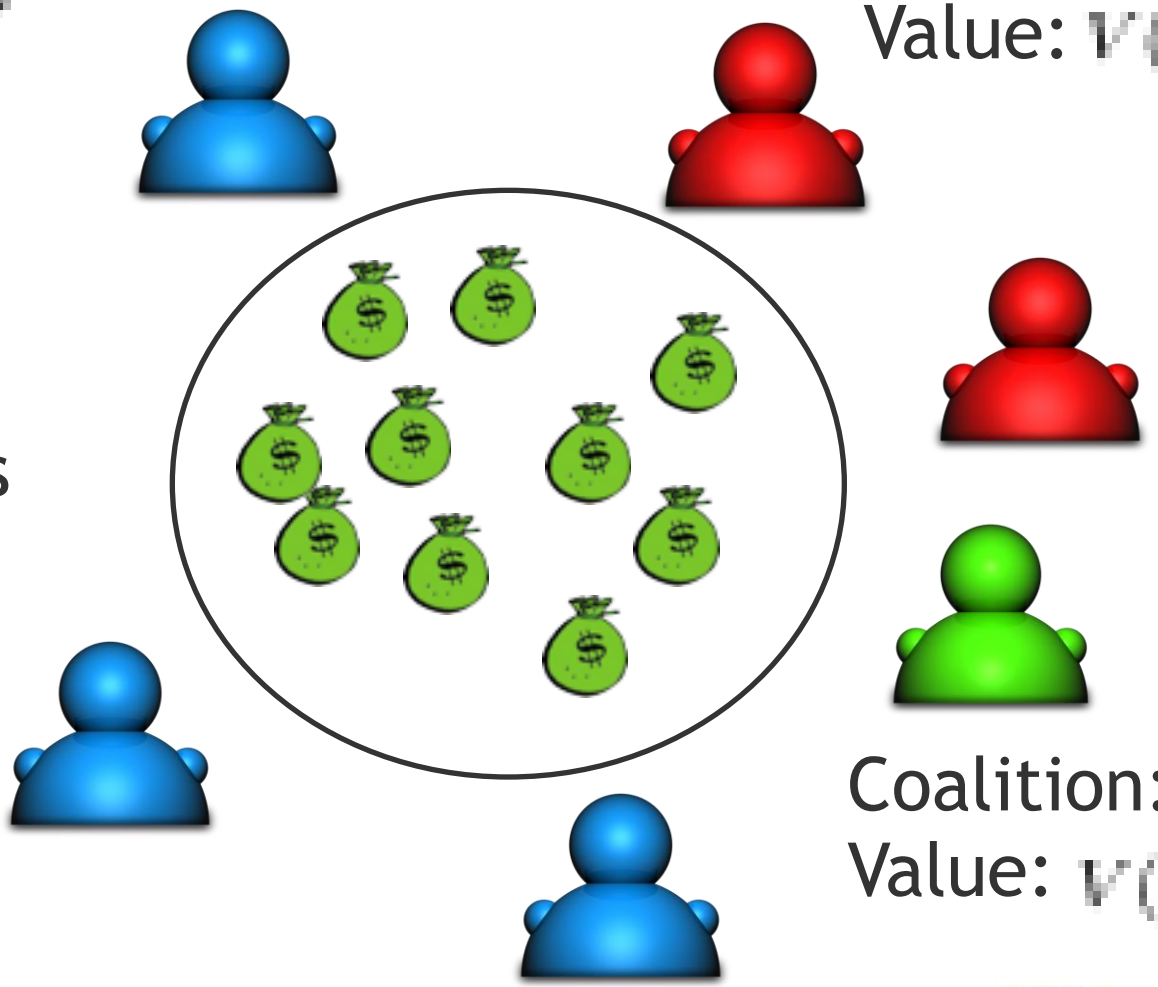
1. Stability/Fairness
   - loose: individually rational users do not leave
   - tight: derived from objective fairness axioms
2. Economically efficient
   - loose: sum of incentives matches cost reduction
   - tight: optimality = system leads to minimum cost
3. Manage different scales
   - Interaction of large user population and big players
4. Computationally efficient

Cooperative Game, "Should I stay or should I go?"

Players: $\mathcal{N}$

Value: V

Coalitions



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

Coalition: $\mathcal{T} \subseteq \mathcal{N}$
Value: $V(\mathcal{T})$

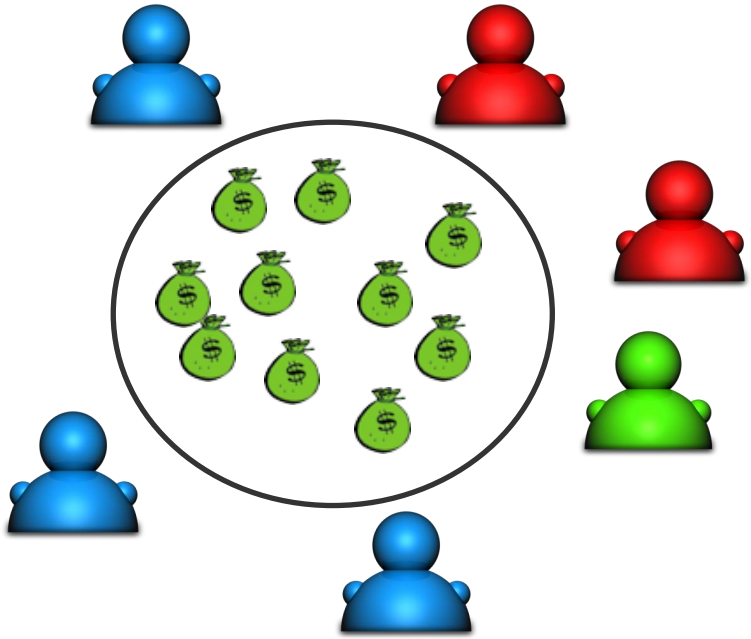
Shapley Value

1. Efficiency

$$\sum_{i \in S} \varphi_i(S, V) = V(S).$$

2. Symmetry

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



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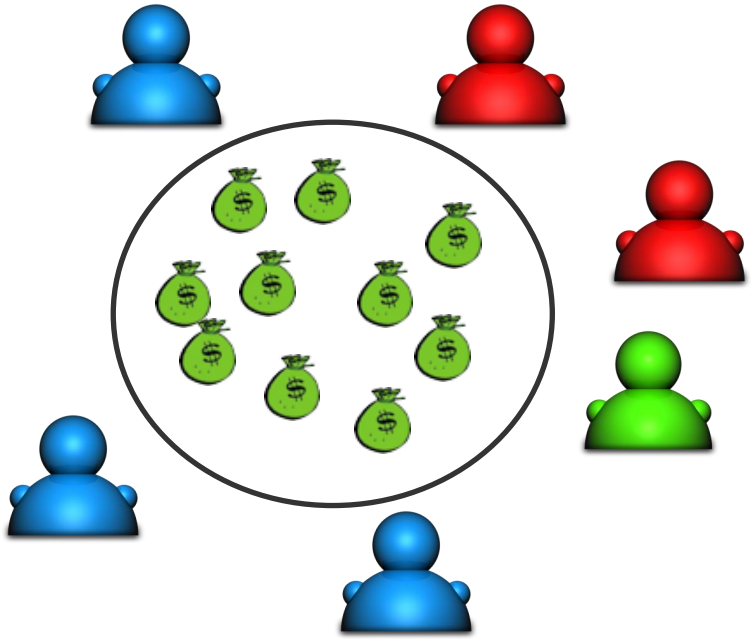
3. Balanced contribution

$$\varphi_i(S, V) - \varphi_i(S \setminus \{j\}, V) = \varphi_j(S, V) - \varphi_j(S \setminus \{i\}, V).$$



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

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

$$V(\{P\}) = R - C(\bar{0})$$ (Traditional service)

$$V(\bar{X}) = 0$$ (Provider is a veto player)

$$V(\{P\} \cup \bar{X}) = R - C(\bar{X})$$ (Peer-assisted service)

Shapley Value

1. Efficiency

$$\sum_{i \in S} \varphi_i(S, V) = V(S).$$

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$$\forall T \subseteq S \setminus \{i, j\}, \quad V(T \cup \{i\}) = V(T \cup \{j\})$$
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Shapley value is equal to

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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(pi,i) U {i}) - V(S(pi,i)]

- where S(pi,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 pi. (essentially it is uniform on [0;1])

As the system becomes large

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

- multiple atomic players
- other scenarios like network neutrality
- cost of peer-assistance incurred by user

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Qualitative properties

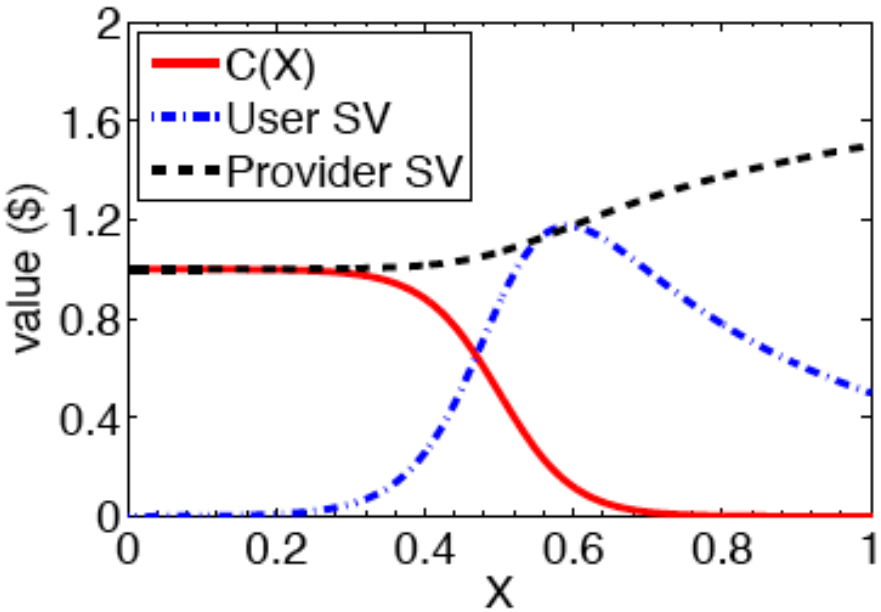
General conditions to achieve grand coalition

- 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 bwidth K

  Cost per user becomes $C(\bar{X}) = KS - \sum_i X_i K S_i$

  Shapley value: $\varphi_i = \frac{KS_i}{2}$

- "Serve two, get one free" is fair and optimal

Conclusion

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!

R. T. B. Ma, D. Chiu, J. C. Lui, V. Misra, and D. Rubenstein. Internet Economics: The use of Shapley value for ISP settlement. *Proc. ACM CoNEXT*, 2007.

R. T. Ma, D. Chiu, J. C. Lui, V. Misra, and D. Rubenstein. On cooperative settlement between content, transit and eyeball internet service providers. In *Proc. of ACM CoNEXT*, 2008.

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