Contracting Models for P2P Content Distribution

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Introduction

- A Peer-to-Peer (P2P) network is a social network for pooling resources such as bandwidth, computing, information, and content
- File sharing is probably the most successful and prevalent
- In this paper, we study the contract design of commercial P2P networks

P2P market

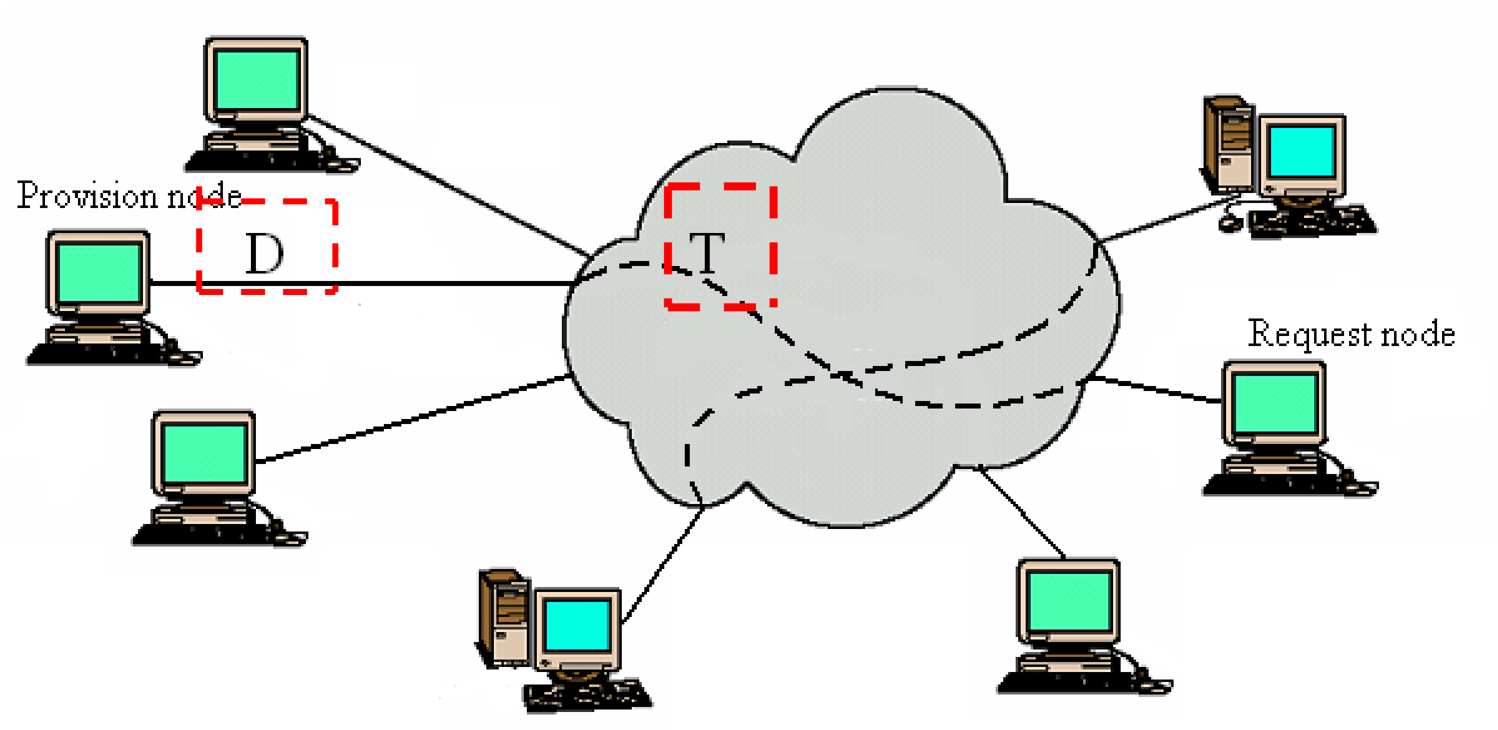
- File sharing services would reach $28 billion by 2012 (Insight Research Corporation, 2008)
- File sharing programs in PC from 51 millions in 2006 to 60.5 million in 2009 (BigCampagne 2009)
- Snocap uses sound fingerprinting to support song trading over a P2P network
- Audio Feast use P2P to deliver digital ratio
- Warner Brothers Home Entertainment use BitTorrent to distribute protected movie and TV program

LimeWire Freenet THE FREE NETWORK FOXY BitTorrent

Realization of Commercial P2P Networks

- Quality measure (file transfer QoS)
- Operating policy (provision nodes recommendation)
- Incentive Mechanism (upload reward and download pricing schemes)

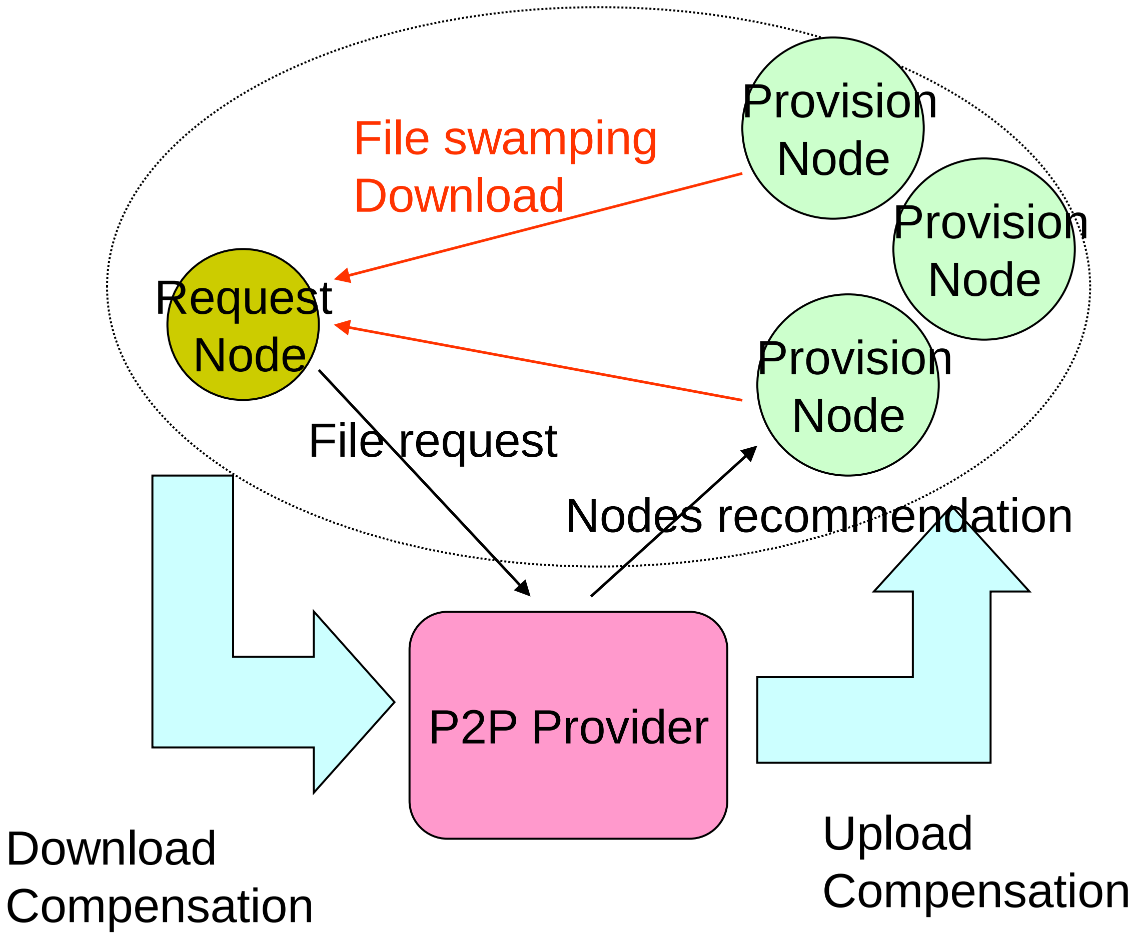
Quality Measure: File Transfer Delay



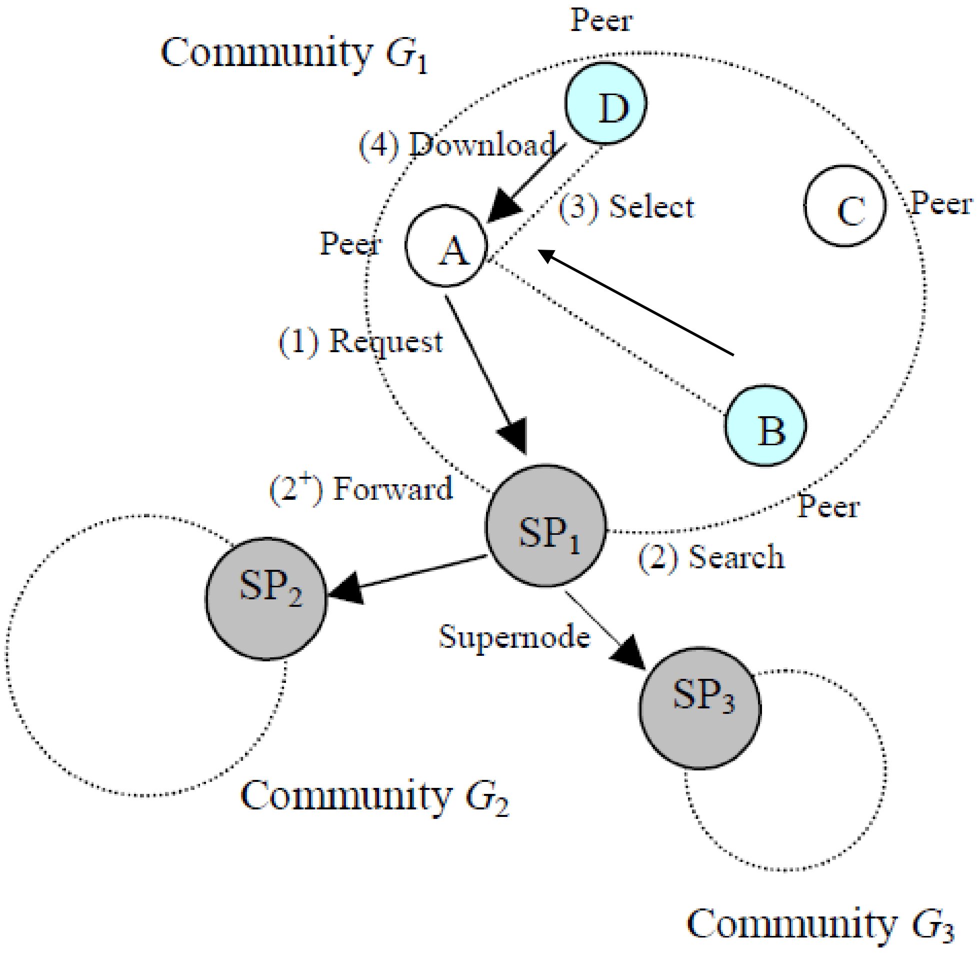
D: **provision delay at peer node**

T: **transmission delay at public network**

Download Service and Monetary Flow

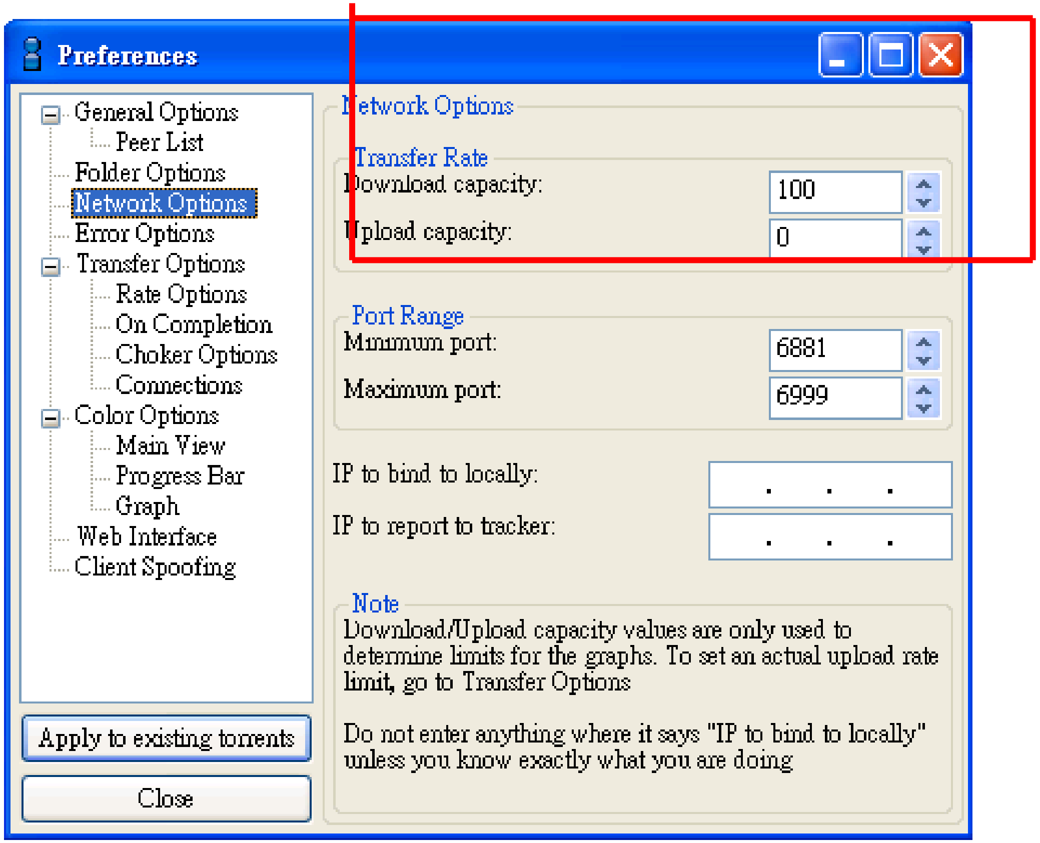


Operating Policy of P2P Download



Optimal effort (upload capacity)

- Example: Kazza



Research Questions

- P2P service quality problems
  - Uncertain public network
  - Hidden actions problems (moral hazard) on upload capacity provision
- Optimal contract design
  - Compensation mechanism
  - Pricing scheme
- Optimal network size
  - QoS maximization
  - Profit maximization
- Competition of P2P providers

The Model

Table 1: Model parameters

Parameter	Description
n	Total number of peer nodes
$\hat{n}_p$	Maximum number of provision nodes allowed to upload
τ	Upper bound of transmission delay
β	Content availability of a peer node
f_0	The size of a typical file
c_b	Cost of bandwidth capacity
D	Provision delay
T	Transmission delay
Q	Transfer delay ($Q = D + T$)
Decision Variables	
w_0	Participation compensation
w_d	Upload compensation
b	Bandwidth capacity
p	Download fee
m	Optimal number of provision nodes

P2P Dynamics

- Content Provision

$$x_{i,m} = \begin{cases} 1, & \text{if node } i \text{ has file } F_m; \\ 0, & \text{otherwise,} \end{cases} \qquad \forall\ i \in \{1, \cdots, n\}$$

$\beta_{i,m} = E(x_{i,m})$: The probability that node i has file F_m

  - n : number of active nodes
  - $x_{i,m}$: Availability of the file F_m stored on node i

P2P Dynamics

- Provision Delay (*D*)
  - The provision delay at peer node j is calculated as $D_j = f_0 / (b_j n_p)$, where $1 \le n_p \le \hat{n}_p$
  - f_0: the size of a file
  - $\hat{n}_p$: the maximum number of peer node allowed to jointly upload the request file
  - b_j: bandwidth capacity

P2P Dynamics

- Transmission Delay (*T*)- delay in the public network
- T_{ij} : The transmission delay between content request node i and provision node j
  - $i.i.d.$ random variable with density function f(.)
  - uniformly distributed on $[0, f_0\, \tau / n_p]$
  - τ : the upper bound of transmission delay per byte

P2P Dynamics

- Transfer Delay (denoted as Q) = Provision delay (denoted as D) + Transmission delay (denoted as T)

P2P Operating Policies

- Provision policy
  - Recommend the "closest" (fastest) provision nodes
  - If more than the maximum allowed nodes, $\hat{n}_p$, $\hat{n}_p$ can provide a file, only the ranked nodes with top-smallest estimated transfer delay will be selected as the provision nodes.
  - The transfer delay between request node i and provision node j is $Q_j = D_j + T_{i,j}$

P2P Operating Policies

- The optimal set of provision nodes

$$\Phi = \left\{ j \mid j \in I_1 \bigcup I_2 \bigcup \cdots \bigcup I_{\min\left(|S_0|, \hat{n}_p\right)} \right\}$$

  - $S_0 = \{Q_j \mid x_{j,m} = 1\}$: the set of transfer delay of all satisfied peer nodes
  - $|S_0|$: the total number of satisfied peer nodes

$$I_k = \{ j \mid Q_j = \inf S_{k-1} \}$$

$$S_{k-1} = S_0 - \{ Q_j \mid j \in I_1 \bigcup I_2 \bigcup \cdots \bigcup I_{k-1} \} \quad \text{for } 2 \le k \le \hat{n}_p$$

Contracting Model

- The principal (the P2P provider) hires many agents (provision nodes) to perform a task (file upload).
- The principal cares only on performance (overall transfer delay $Q=D+T$) and not the effort exerted by agents (upload capacity b or provision delay D).
- As effort is costly to an agent, the principal has to compensate the agents for incurring this cost.

Contracting Model

- Since effort is unobservable, the performance of file transfer is used to evaluate the quality of service.
- Service price and compensation:

w_0 : participation compensation

w_d : upload compensation

p : download price

  - Only the provision node with fastest transfer speed will be chosen to upload the content file, and receives upload compensation!!

Contracting Model

- Stages of the contracting game:
  - (1) The P2P provider makes *take-it-or-leave-it* offers to the peer nodes
  - (2) If they accept the offer, they make the decision of *upload bandwidth capacity*
  - (4) All contracted peer nodes receive a *participation compensation*
  - (5) After the content download is completed, the request node pays the P2P provider content *download service fee*
  - (6) The chosen provision nodes receive *the upload compensation*

Optimal Reward Scheme

- Cost of capacity provision:
  - Assume the cost of bandwidth capacity is c_b per byte/sec, the participating cost of peer node i is formulated as

$$C(D_i) = c_b b_i = \frac{c_b f_0}{\hat{n}_p D_i}$$

- Reward of uploading service:

$$W(D_i) = w_0^* + \text{Prob}\{i \in \Phi \mid D_i \text{ is selected}\} w_d^*$$

Optimal Reward Scheme

- The probability that peer node i will be selected as one of the provision nodes

$$\text{Prob}\left\{i \in \Phi \mid D_i \text{ is selected}\right\} = \beta \cdot \sum_{k=0}^{\hat{n}_p - 1} \binom{n-1}{k} \beta^k (1-\beta)^{n-1-k}$$

$$+ \beta \cdot \sum_{k=\hat{n}_p}^{n-1} \beta^k (1-\beta)^{n-1-k} \sum_{Z \in \Gamma_k} \text{Prob}\left(i \text{ among top-}\hat{n}_p \text{ fastest} \middle| Z\right).$$

Optimal Reward Scheme

- The probability of peer node i being among the top- $\hat{n}_p$ fastest

$$\text{Prob}\left(i \text{ among top-}\hat{n}_p \text{ fastest} \middle| Z, T_{ir}\right)$$

$$= \sum_{u=0}^{\hat{n}_p-1} \sum_{J \in G_u} \prod_{j=1}^{u} \text{Prob}\left\{D_j + T_{jr} < D_i + T_{ir}, j \in J\right\} \prod_{j=u+1}^{k} \text{Prob}\left\{D_j + T_{jr} > D_i + T_{ir}, j \in J\right\}$$

$$= \sum_{u=0}^{\hat{n}_p-1} \sum_{J \in G_u} \prod_{j=1}^{u} F\left(D_i + T_{ir} - D_j\right) \prod_{j=u+1}^{k} \left(1 - F\left(D_i + T_{ir} - D_j\right)\right)$$

Optimal Reward Scheme

- F is the CDF for the transmission delay; therefore, we have:

$$\text{Prob}\left(i \text{ among top-}\hat{n}_p \text{ fastest} \middle| Z\right) = \int_0^{f_0\tau/\hat{n}_p} \text{Prob}\left(i \text{ among top-}\hat{n}_p \text{ fastest} \middle| Z, T_{ir}\right) f(T_{ir})\, dT_{ir}$$

- Thus, the probability of being selected as the provision node is determined by **endogenous provision delays** of all the participating peer nodes and **stochastic transmission delay** incurred in the public network.

Optimal Reward Scheme

- Optimal upload capacity:

$$\max_{D_i} U_i = W(D_i) - C(D_i)$$

- Solving $\partial U_i / \partial D_i = 0$
  - The optimal provision delay of a peer node *i* satisfies

$$\frac{\beta L(n-1,\hat{n}_p)\hat{n}_p w_d^{\ *}}{f_0 \tau} = \frac{c_b f_0}{D_i^{\ 2} \hat{n}_p}, \quad where$$

$$L(n-1,\hat{n}_p) = \sum_{k=\hat{n}_p}^{n-1} \left(\binom{n-1}{k} \beta^k (1-\beta)^{n-1-k} \right)$$

Optimal Reward Scheme

- The best response bandwidth capacity and provision delay of peer node *i* are:

$$b_i^* = \sqrt{\frac{\beta L(n-1,\hat{n}_p)w_d^*}{c_b\tau}}$$

$$D_i^* = \frac{f_0}{\hat{n}_p}\sqrt{\frac{c_b\tau}{\beta L(n-1,n_p)w_d^*}} = \frac{f_0}{\hat{n}_p b_i^*}$$

Optimal Reward Scheme

- Optimal reward scheme
  - Assume that the value of a downloaded content is v.
  - The highest price a peer node is willing to pay is $p = v - \gamma(D+T)$, where γ represents the sensitivity to delay.

Optimal Reward Scheme

- The profit maximization function of the P2P provider

$$\max_{w_0, w_d} \pi_m = Hp - nw_0 - \kappa w_d \;\; s.t. U_i \geq 0,$$

$$H = 1 - (1-\beta)^n, \kappa = \sum_{k=1}^{n} \left(\binom{n}{k} \beta^k \cdot (1-\beta)^{n-k} \cdot \min(k, \hat{n}_p) \right)$$

Solving $\partial \pi / \partial D = 0$ ⇨ $D^*(n) = \sqrt{\dfrac{nc_b f_0}{\gamma H(n) \hat{n}_p}}$

Proposition 1.
Optimal reward scheme and capacity effort

- The optimal reward scheme (participation compensation and upload compensation) and capacity effort are given by:

$$W\left(w_0^{m*}, w_d^{m*}\right) = \left(\sqrt{\frac{c_b \gamma f_0 H(n)}{\hat{n}_p n}} - \frac{\gamma f_0 \tau H(n) \kappa}{n^2 \beta L\left(n-1, \hat{n}_p\right) n_p}, \frac{\gamma f_0 \tau H(n)}{n \beta L\left(n-1, \hat{n}_p\right) n_p}\right)$$

$$b_m^{\ *}\left(n\right) = \sqrt{\frac{\gamma f_0 H(n)}{n c_b \hat{n}_p}}$$

Corollary 1.
The impact of system parameters on the reward scheme and capacity provision

Table 2: Impact of system parameters on reward scheme

	n	$\hat{n}_p$	τ	β	f_0	c_b
$w_d^{m^*}$	−	*	+	−	+	×
b^{m*}	−	−	×	+	+	−

+ increase; – decrease; * non-monotonic; × no effect

- n-network size , $\hat{n}_p$-file swarming, τ-public network, β -content availability, f_0- content size, c_b-bandwidth cost

The impact of File Swamping

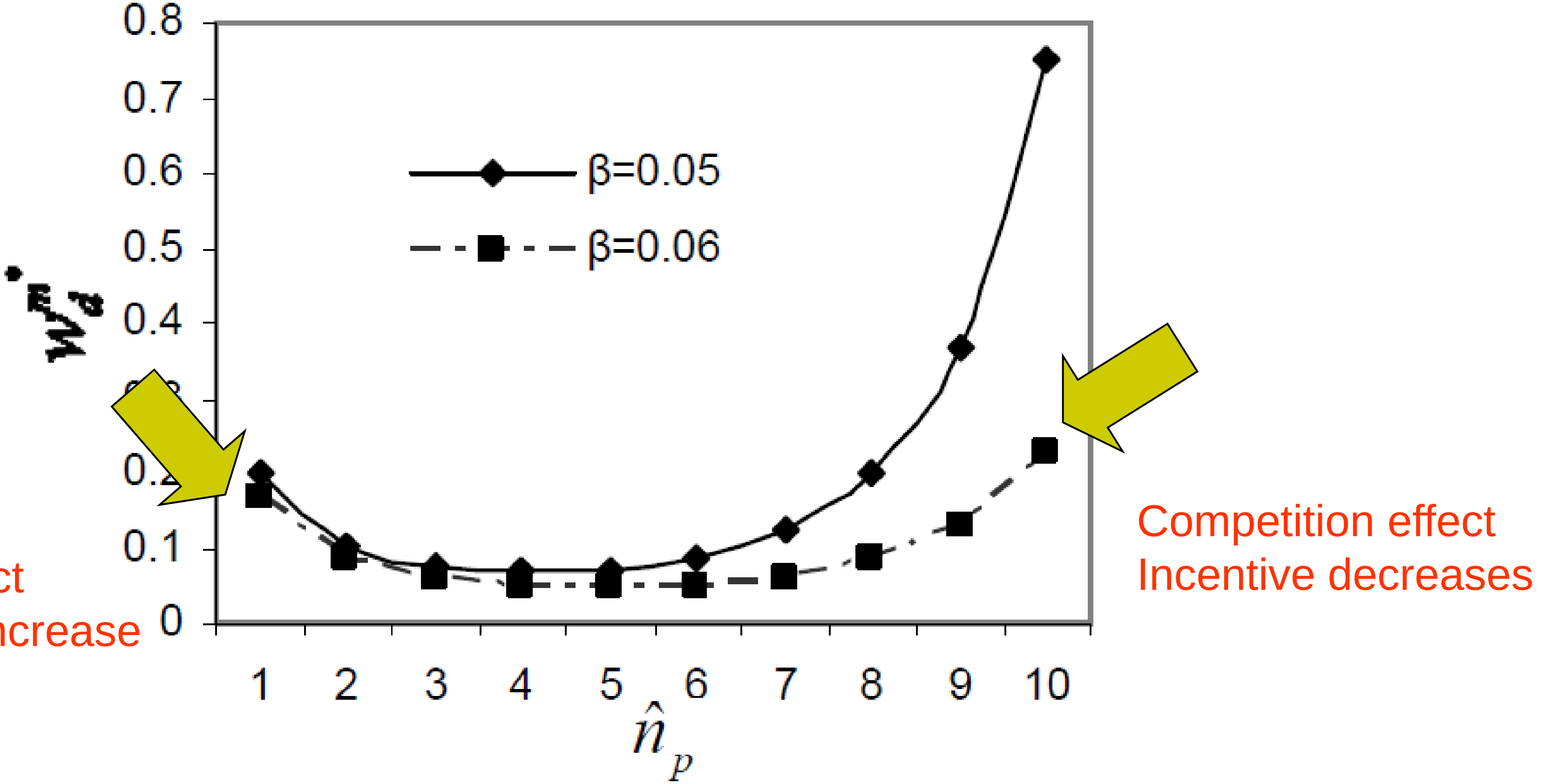


Figure 1: Impact of file swarming on upload compensation

Optimal Pricing Scheme

- Service quality:
  - The expected minimum transmission delay among k nodes is denoted by $T_{min(k)}$.

$$T_{\min(k)} = \frac{k!\int_0^{f_0\tau/\min(k,\hat{n}_p)} T_{ij}\cdot F(T_{ij})^{\min(k,\hat{n}_p)-1}\cdot\left(1-F(T_{ij})\right)^{k-\min(k,\hat{n}_p)}\cdot f(T_{ij})\cdot dT_{ij}}{\left(k-\min\left(k,\hat{n}_p\right)\right)!\left(\min\left(k,\hat{n}_p\right)-1\right)!}$$

- The expected transmission delay for a file in the network with n nodes

$$T(n) = E(T_{\min(k)} \mid \text{requested file is available})$$

$$= \sum_{k=1}^{n} T_{\min(k)} \binom{n}{k} \beta^k (1-\beta)^{n-k} f_0\tau / H(n)$$

Corollary 2.

The impact of network size, file swarming and content availability on QoS

- Provision delay increases with network size, whereas transmission delay decreases with network size .
- Provision delay decreases with the maximum number of simultaneous upload, whereas transmission delay is independent of $\hat{n}_p$
- Both provision and transmission delays decrease with expected content availability at each of the nodes.

Proposition 2.
Optimal pricing scheme

- *The optimal pricing scheme of content download service is given by:*

$$p_m^{\ *} = v - \sqrt{\frac{n c_b \gamma f_0}{H(n)\hat{n}_p}} - \frac{\left(H(n) - n\beta\left(1 - H\left(n\right)\right)\right)\gamma f_0 \tau}{\left(n+1\right)\beta H(n)}$$

Corollary 3.
The impact of system parameters on the price scheme and capacity provision

Table 3: Impact of system parameters on pricing scheme

	n	$\hat{n}_p$	τ	β	f_0	c_b
p^{m*}	*	+	–	+	–	–

+ positive; – negative; * non-monotonic

Optimal Network Size

- The profit function of P2P provider is rewritten as:

$$\pi_m^{\ *} = H(n)v - 2\sqrt{nc_b\gamma f_0 H(n)/\hat{n}_p} - \frac{\left(H(n) - n\beta\left(1 - H(n)\right)\right)\gamma f_0 \tau}{(n+1)\beta}$$

- The P2P quality of service is rewritten as:

$$Q(n) = D(n) + T(n) = \sqrt{\frac{nc_b f_0}{\gamma H(n)\hat{n}_p}} + \frac{\left(H(n) - n\beta\left(1 - H(n)\right)\right) f_0 \tau}{(n+1)\beta H(n)}$$

Corollary 4.

- The optimal network size increases with dispersion degree of peer positions.
- However, the optimal network size decreases with cost of bandwidth capacity. The effect of file size may be positive or negative, depending on cost of bandwidth capacity.

Table 4: Impact of system parameters on optimal network size

	τ	$\hat{n}_p$	f_0	c_b
n^*	+	+	*	–

+ positive; – negative; * non-monotonic

Optimal Network Size

- Denote m as the number of satisfied peer nodes for a given content request.

- We examine the optimal number of provision nodes m who have the requested file and compete for the upload service because the network size can be approximately obtained by calculating $n \approx m / \beta$.

Optimal Network Size

- The profit maximizing function of the P2P provider:

$$\max_{m} \ \pi_m^{*}(m) = v - 2\sqrt{mc_b\gamma f_0 / \hat{n}_p} - \gamma f_0 \tau / (m+1)$$

- The service quality maximizing function:

$$\min_{m} \ \gamma Q(m) \equiv \gamma\left(D(m) + T(m)\right) = \sqrt{mc_b\gamma f_0 / \hat{n}_p} + \gamma f_0 \tau / (m+1)$$

Proposition 3.
Optimal network size

- Optimal network size that maximizes the profit of the P2P provider is smaller than that maximizing service quality. ($m_\pi^* < m_Q^*$)

- When the network size is sufficiently large, approximate optimal numbers of provision nodes are obtained as follows:

$$m_\pi^* \approx \sqrt[3]{\gamma f_0 \tau^2 ? n_p / c_b}, m_Q^* \approx \sqrt[3]{4\gamma f_0 \tau^2 n_p / c_b}$$

Competing P2P Networks

- Two symmetric P2P networks competing for the content distribution service

- Let m is the total number of P2P participants that have the requested file, and m_{π}^{*} the optimal number of satisfied peer nodes in a single P2P network.

Competing P2P Networks

- The case of large population of provision nodes: ($m \geq 2m_{\pi}^{*}$)
  - each P2P provider offers the service reward and price schedule at monopolistic level.
  - The reward scheme is built from the participation constraint

Competing P2P Networks

- The case of small population of provision nodes: ($m < 2m_{\pi}^{*}$)
  - The reward scheme should be built from the incentive constraint as the provider is no longer able extract all the surplus of the participants.

  - In the profit function of a competing P2P provider, we rewrite the objective function as:

$$\max_{D,w_0} \ \pi_c = v - \gamma\left(D+T\right) - c_b f_0{}^2 \tau / \left(\hat{n}_p D^2\right) - m_c w_0$$

Proposition 4. Competing P2P networks

- For a competing P2P networks, the equilibrium reward scheme is:

$$W\left(w_0^{c*}, w_d^{c*}\right) = \begin{cases} \left(\sqrt{\dfrac{c_b \gamma f_0}{\hat{n}_p m_\pi^*}} - \dfrac{\gamma f_0 \tau}{m_\pi^{*2}}, \dfrac{\gamma \tau f_0}{\hat{n}_p m_\pi^*} \right) & \text{if } m \geq 2m_\pi^*; \\ \left(\dfrac{2}{m}\left(v - \left(\sqrt[3]{2} + \sqrt[3]{1/4}\right) \sqrt[3]{\dfrac{c_b \tau \gamma^2 f_0^2}{\hat{n}_p}} - \dfrac{2\gamma f_0 \tau}{m+2} \right), \sqrt[3]{\dfrac{c_b \tau \gamma^2 f_0^2}{4\hat{n}_p^4}} \right) & \text{if } m < 2m_\pi^*. \end{cases}$$

$$b_c^* = \begin{cases} \sqrt{\dfrac{\gamma f_0}{m_\pi^* c_b \hat{n}_p}} & \text{if } m \geq 2m_\pi^*; \\ \sqrt[3]{\dfrac{\gamma f_0}{2 c_b \tau \hat{n}_p^2}} & \text{if } m < 2m_\pi^*, \end{cases}$$

$$p_c^* = \begin{cases} v - \sqrt{\dfrac{m_\pi^* c_b f_0 \gamma}{\hat{n}_p}} - \dfrac{\gamma f_0 \tau}{m_\pi^* + 1} & \text{if } m \geq 2m_\pi^*; \\ v - \sqrt[3]{\dfrac{2 c_b \tau \gamma^2 f_0^2}{\hat{n}_p}} - \dfrac{2\gamma f_0 \tau}{m+2} & \text{if } m < 2m_\pi^*. \end{cases}$$

Corollary 5.

- Upload compensation and capacity provision remain at two constant levels as the population of peer nodes changes.

Conclusion

- Utilizing the tournament model from incentive theory, the paper has presented contract (including reward and pricing) scheme for P2P file-sharing networks.
- We propose a price schedule which is determined based on the performance of P2Pdownload service.

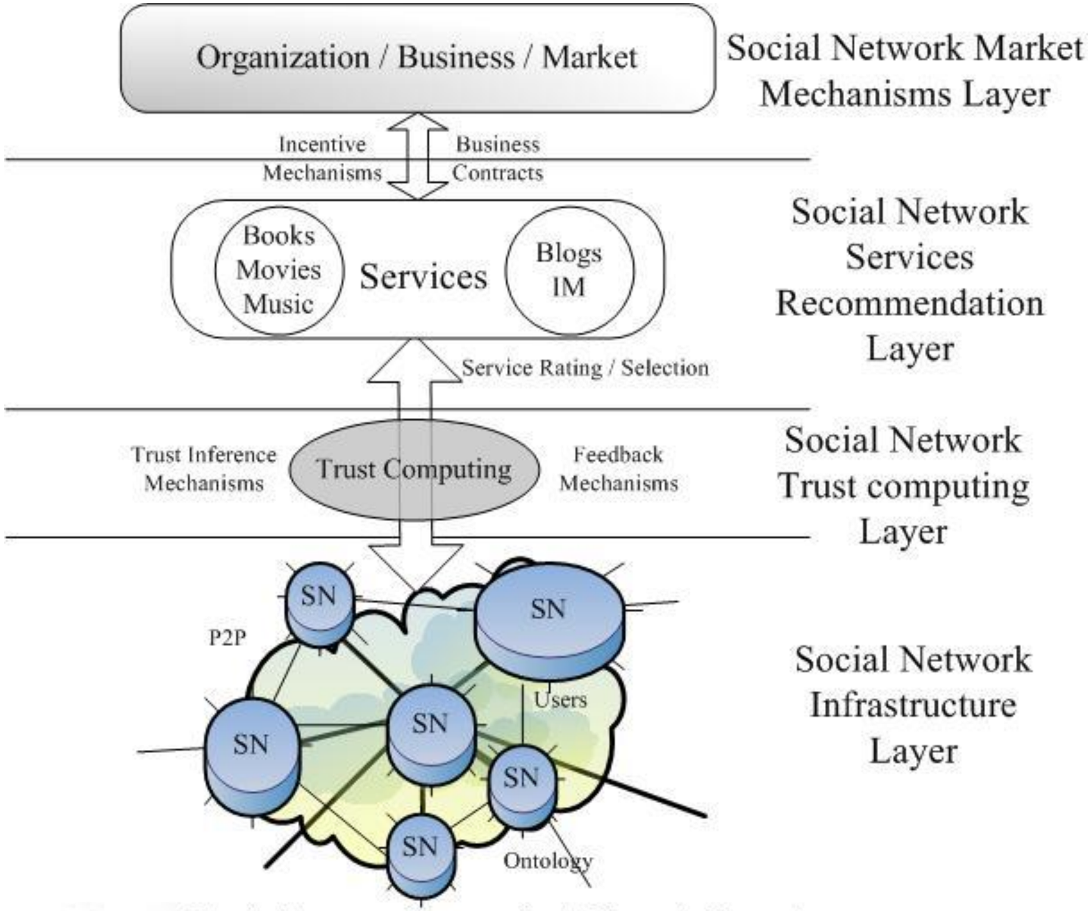
Summary of Findings

- QoS issue
  - larger network size, better transmission delay but worse provision delay
- Optimal Contract
  - Upload compensation increases with uncertainty in public network domain
  - The effect of file swarming technology on upload compensation level is non-monotonic
- Optimal Network Size
  - Network size of profit maximizing is less than network size of QoS maximization
- Competitive Market
  - the results are determined by the population of the peer nodes. Upload compensation and capacity provision keep at two different constant levels

Extended works

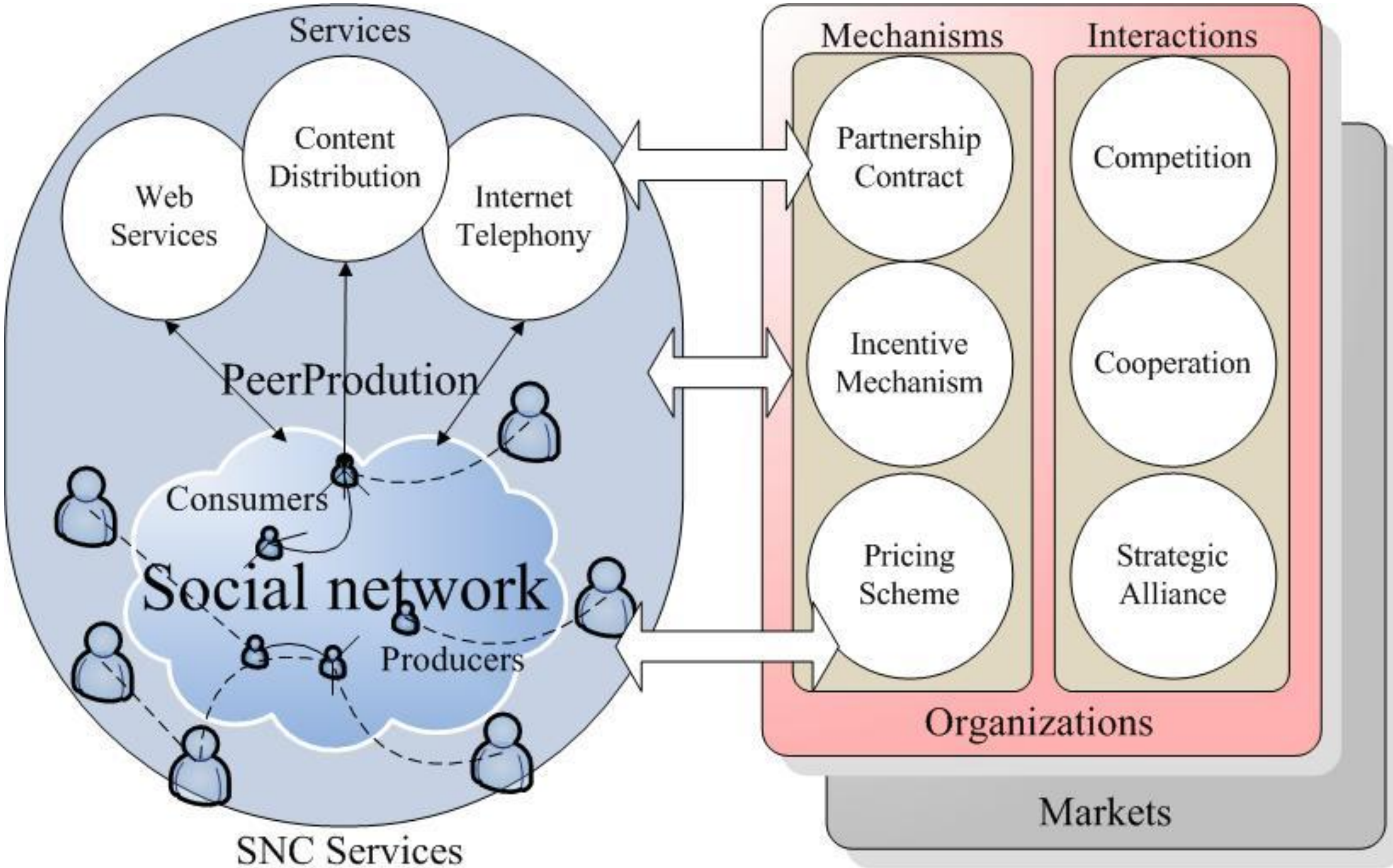
- Heterogeneity of peer nodes
- Asymmetric Information (adverse selection)
- Public networks and P2P topology (transmission delay distribution)
- Comparison of contract formats

Research Issues in IT Economics



The Architecture of Internet Social Network Computing

Research Issues in IT Economics



Market Mechanism of Social Network Computing Services

Current Research: IT Monetization

- Wireless/Mobile Pricing
  - P2P VoIP routing
  - WiFi /MiMax (Hotspot contract, FON)
- Web ads Pricing and recommender system
  - Display Ads / Contextual Ads / Keywords Pricing
  - Social Ads delivery
- Content Pricing
  - DRM pricing
  - Digital movie/music channel
- Peer production Pricing
  - Platform pricing and planning
  - Market mechanism (YouTube)

Q & A