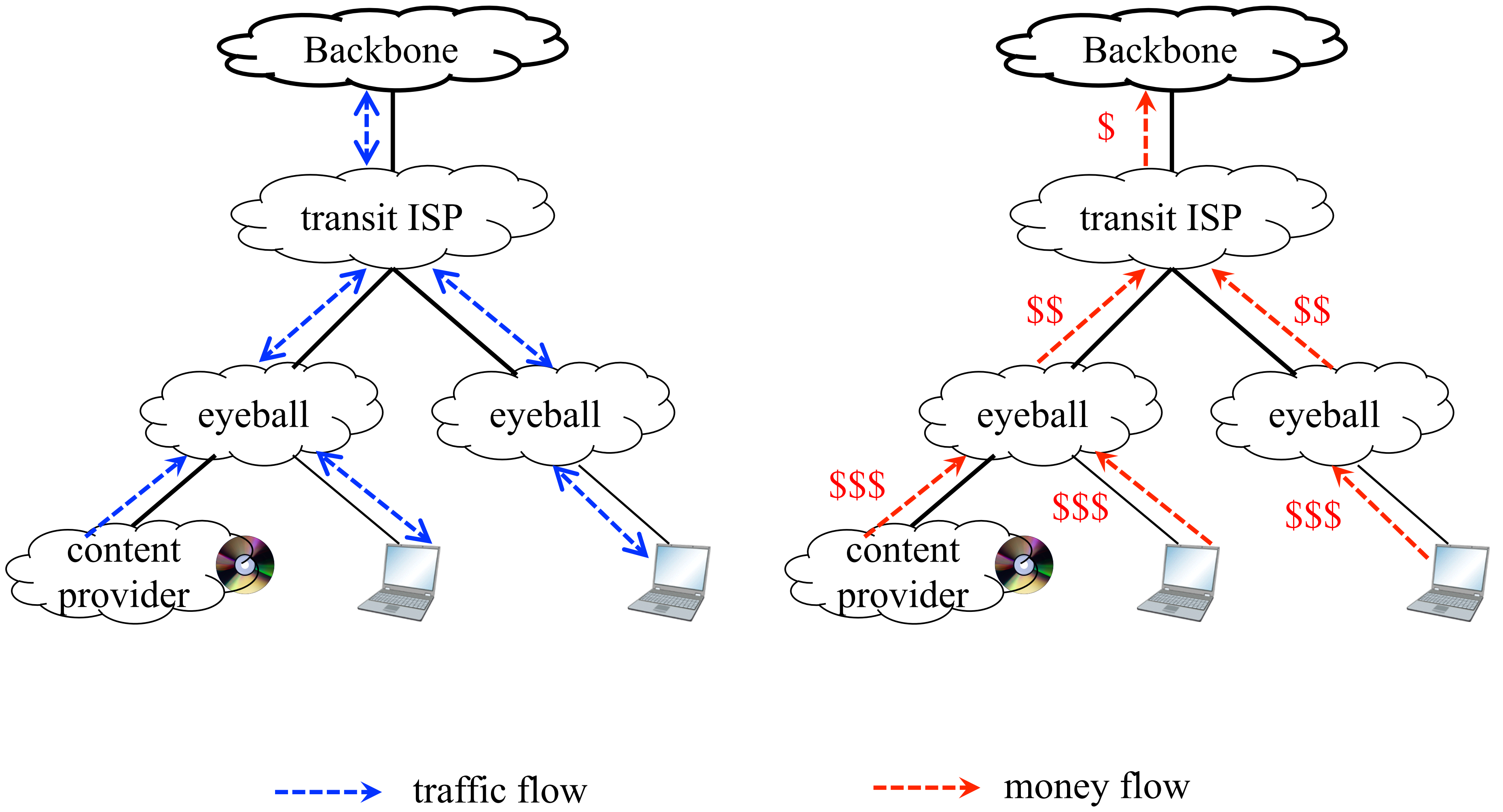
A study on Inter-Domain Cache Sharing Mechanism

Xun Shao, Hitoshi Asaeda
National Institute of Information and Communications Technology (NICT)

2017-05-18

The 8th ICN Workshop

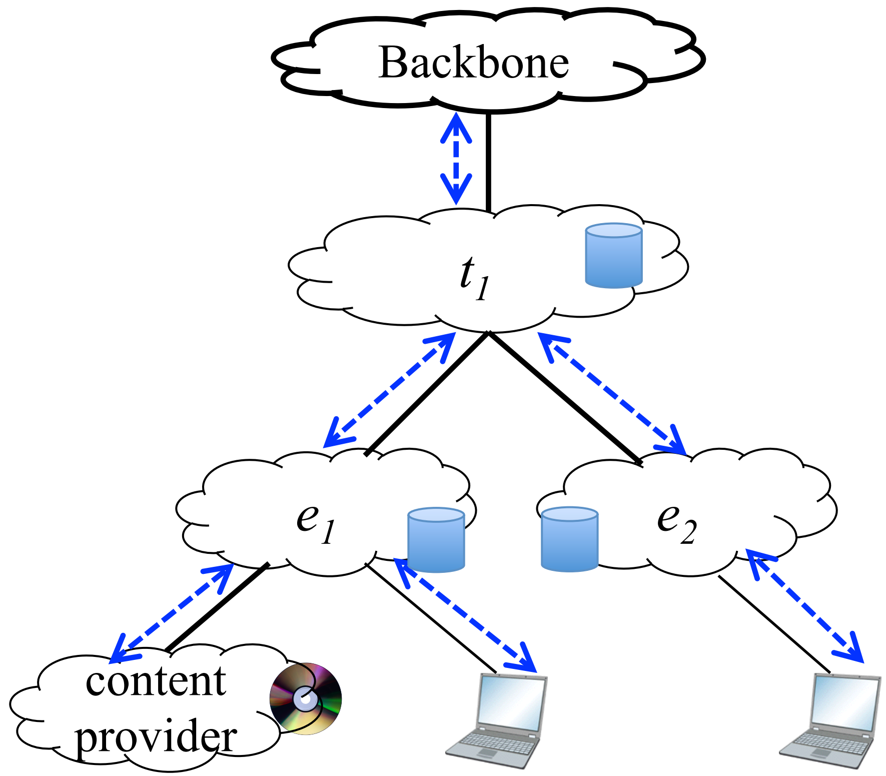
ISP inter-domain routing and pricing



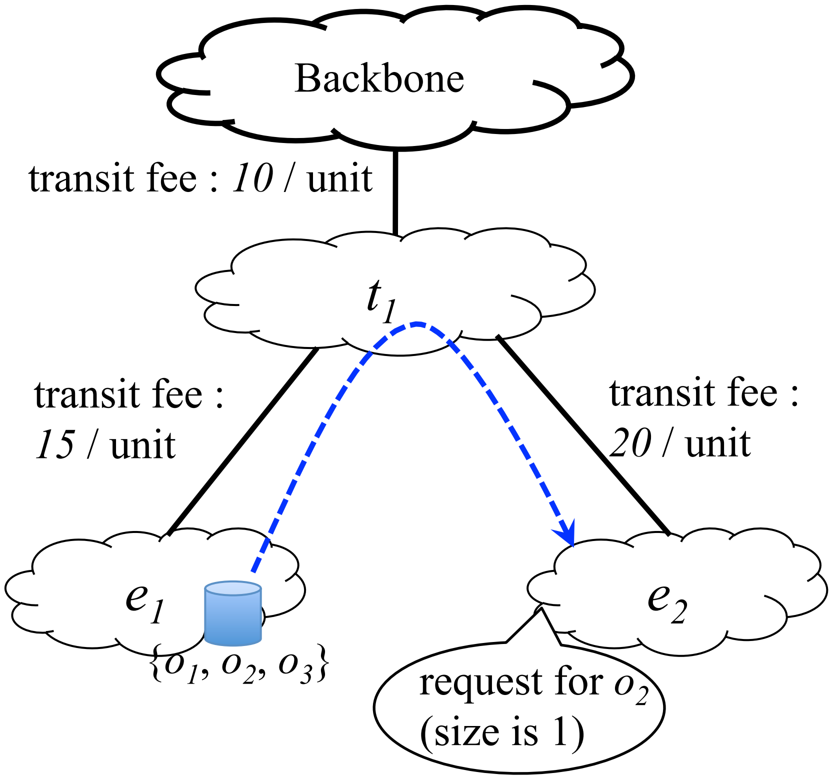
Opportunities for ISPs to reduce cost with in-network cache

- Opportunity to cut transit fee under current business model: In-network cache
  - Transit ISPs save transit fee from backbone ISP
  - Eyeball ISPs save transit fee from transit ISPs

- How to take the advantage of In-network cache further?
  - Increase the cache capacity (cannot be increased infinitely)
  - Cache cooperation between a transit ISP's customer cone (e_1 and e_2)



How to facilitate cache sharing



t : obtains profit $15 + 20 - 10 = 25$

e_1: suffers monetary lose *15*, as well as some operational cost

e_2: makes neither profit nor loss

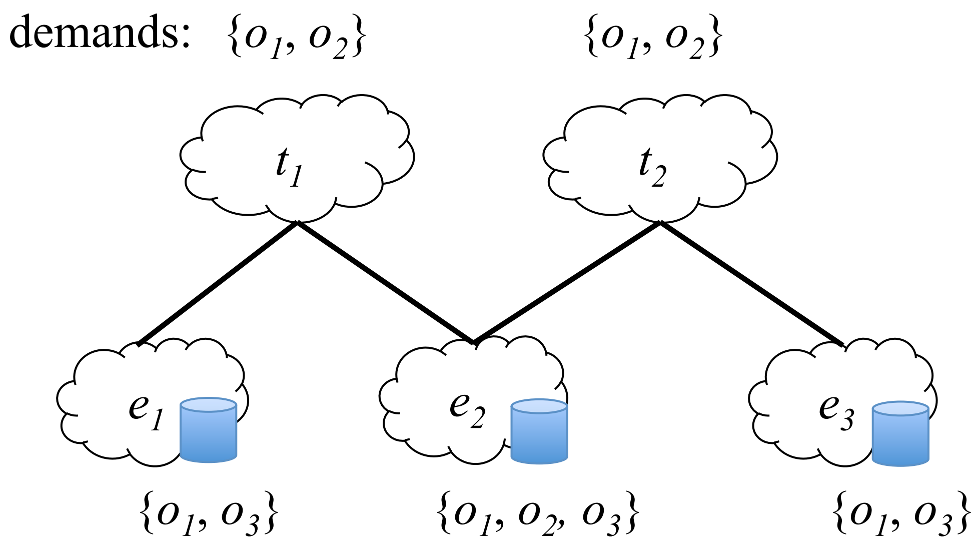
Problem:

e_1 would not make its cache accessible to t (which is obvious)

Our idea:

- t does not charge e_1 for the traffic corresponding to o_2
- t makes a complement p, $0 < p < 10$ to e_1 to motivate the cache sharing

Why difficult in Internet environment?



An inherent double-sided market:

- t_1 and t_2 compete for obtaining o_2 from e_2 by increasing the bidding prices
- e_1 and e_2 (e_2 and e_3) compete for providing o_1 to t_1 (t_2) by lowering the asking prices

Problems:

- An individual ISP does not have enough information of the market to optimize the traffic engineering and pricing decisions

System model

Transit ISP t_i:

- utility of t_i: $u_i(\sum_j x_{ij}) - \sum_j p_{ij}$
- x_{ij} is the cache uploading bandwidth allocated from e_j
- p_{ij} is the money paid to e_j
- $u_i(.)$ is increasing and concave

eyeball ISP:

- utility of e_j: $\sum_i p_{ij} - v_j(\sum_i x_{ij})$
- cost function $v_j(.)$ is increasing and convex

Nash bargaining* solution of our problem

Cache sharing problem (CP):

$$\max \prod_i \left(u_i\left(\sum_j x_{ij}\right) - \sum_j p_{ij} \right)^{K_i} \prod_j \left(\sum_j p_{ij} - v_j\left(\sum_i x_{ij}\right) \right)^{K_j}$$

$s.t.$

$$\underbrace{\sum_j x_{ij}^o \le d_i^o,\ x_{ij} = \sum_o x_{ij}^o}_{x_{ij} \in D} \qquad \ldots \text{ demand constraints}$$

$$\sum_j p_{ij} - u_i\left(\sum_j x_{ij}\right) \le 0 \qquad v_j\left(\sum_i x_{ij}\right) - \sum_i p_{ij} \le 0 \qquad \ldots \text{ individual rational constraints}$$

$$\sum_i x_{ij} \le c_j \qquad \ldots \text{ upload bandwidth constraints}$$

K_i and K_j are bargaining powers of t_i and e_j respectively

* Nash bargaining solution is the unique solution that satisfies the Nash's 4 axioms: Pareto efficiency, Symmetry, invariant to affine transformations, independence of irrelevant alternatives

Decomposition with a constructive method

Cache sharing problem (CP):

$$\max:\quad f_{CP} = \sum_i K_i \log\left(u_i\left(\sum_j x_{ij}\right) - \sum_j p_{ij} \right) + \sum_j K_j \log\left(\sum_j p_{ij} - v_j\left(\sum_i x_{ij}\right) \right)$$

$$s.t.\quad x_{ij} \in D \qquad \sum_j p_{ij} - u_i\left(\sum_j x_{ij}\right) \le 0 \qquad v_j\left(\sum_i x_{ij}\right) - \sum_i p_{ij} \le 0 \qquad \sum_i x_{ij} \le c_j$$

Decomposition: CP to TP + PP

Recovery of the solutions of CP

Traffic engineering problem (TP): $\mathbf{x} = \arg\max \sum_i u_i\left(\sum_j x_{ij}\right) - \sum_j v_j\left(\sum_i x_{ij}\right)$

$$s.t.\quad x_{ij} \in D \qquad \sum_i x_{ij} \le c_j$$

Pricing problem (PP):

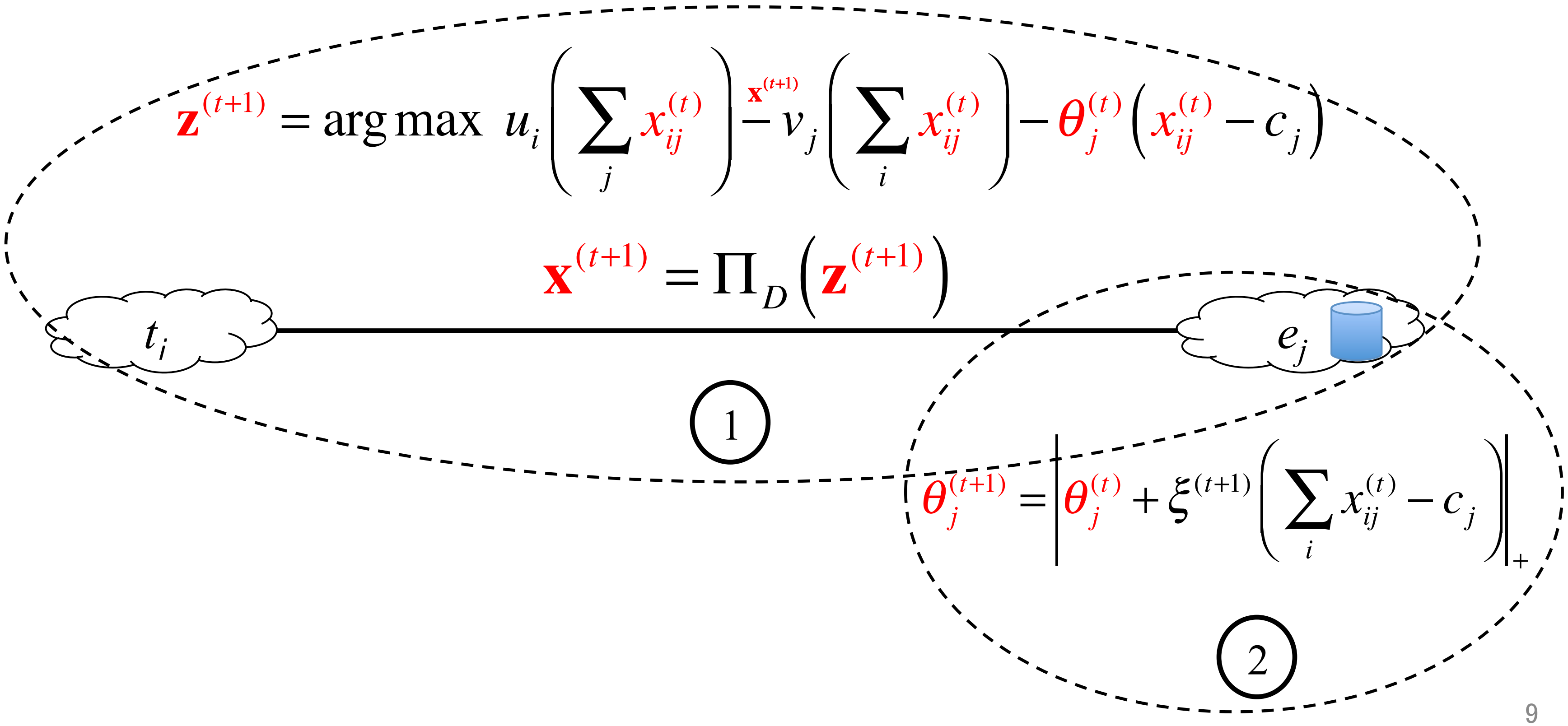
A solution to TP

$$\mathbf{p} = \arg\max \sum_i K_i \log\left(u_i\left(\sum_j x_{ij}^*\right) - \sum_j p_{ij} \right) + \sum_j K_j \log\left(\sum_j p_{ij} - v_j\left(\sum_i x_{ij}^*\right) \right)$$

Solve TP with Primal-Dual decomposition

In step $t+1$ of the iteration:

- t_i and e_j solve the optimal $x^{(t+1)}$ for given $\theta_j^{(t)}$
- e_j updates $\theta_j^{(t+1)}$, the lagrangian multiplier corresponding to the capacity constraint



$$\mathbf{z}^{(t+1)} = \arg\max_{\mathbf{x}^{(t+1)}} \; u_i\left(\sum_j x_{ij}^{(t)}\right) - v_j\left(\sum_i x_{ij}^{(t)}\right) - \theta_j^{(t)}\left(x_{ij}^{(t)} - c_j\right)$$

$$\mathbf{x}^{(t+1)} = \Pi_D\left(\mathbf{z}^{(t+1)}\right)$$

$$\theta_j^{(t+1)} = \left|\theta_j^{(t)} + \xi^{(t+1)}\left(\sum_i x_{ij}^{(t)} - c_j\right)\right|_+$$

Solve PP with primal decomposition

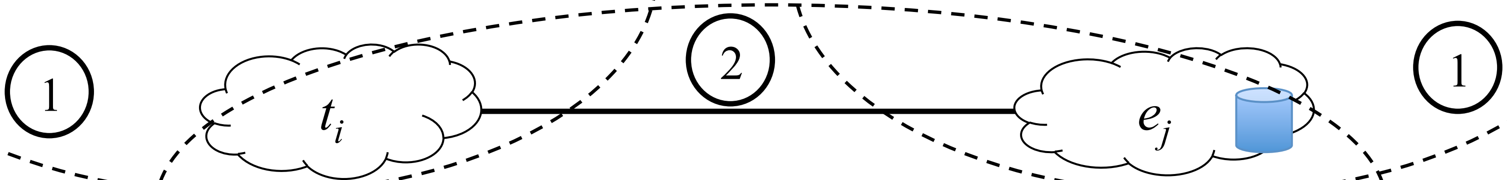
In step $t+1$ of the iteration:
- t_i and e_j solve the derivate w.r.t $p_{ij}^{(t)}$
- $p_{ij}^{(t)}$ is updated with the summation of the derivate

Problem for t_i: max $\mathrm{f}_{PP}^{t_i} = K_i \log\left(u_i\left(\sum_j x_{ij}^*\right) - \sum_j p_{ij} \right)$

Problem for e_j: max $\mathrm{f}_{PP}^{e_j} = K_j \log\left(\sum_i p_{ij} - v_j\left(\sum_i x_{ij}^*\right) \right)$

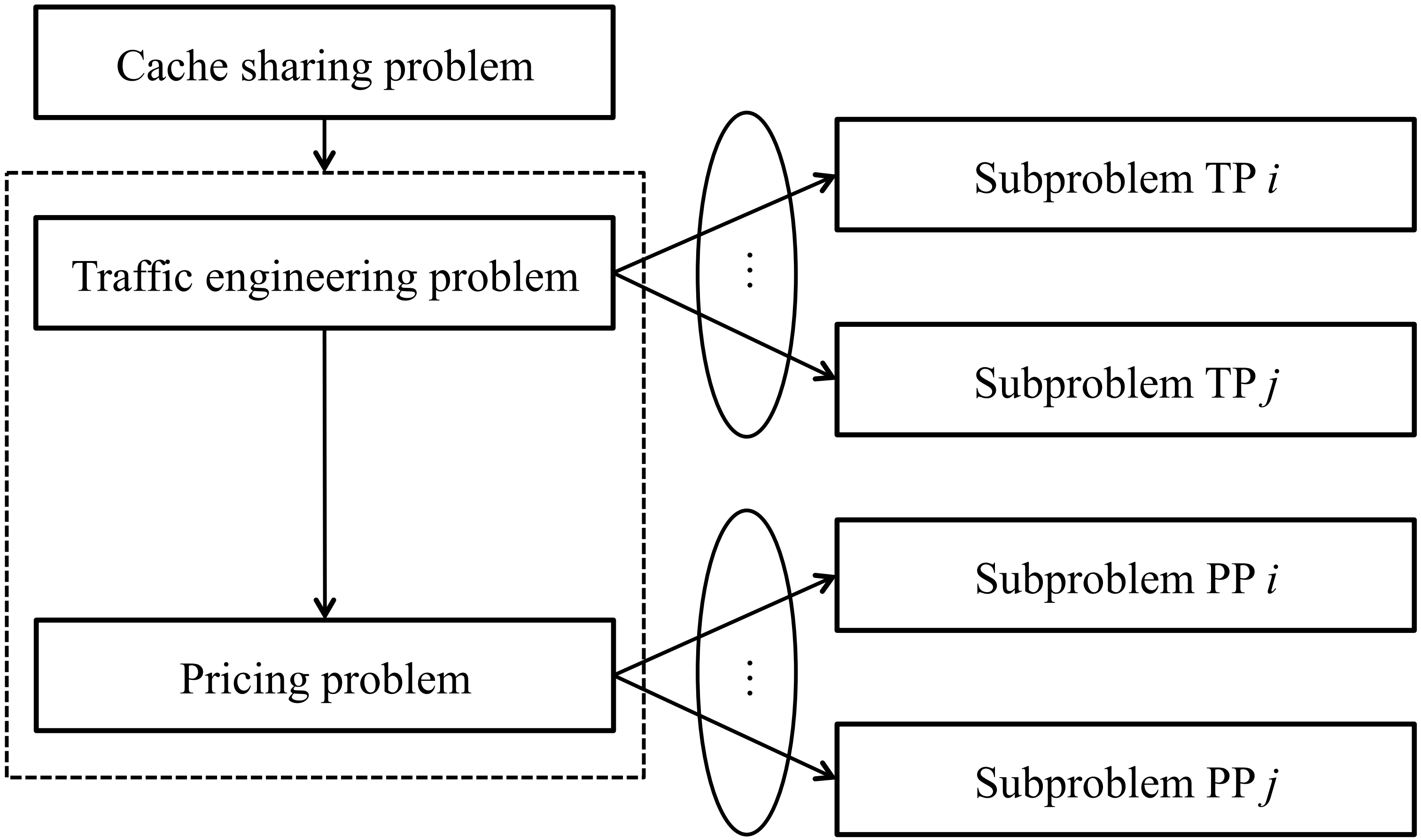
$$\frac{\partial \mathrm{f}_{PP}^{S_i}}{\partial p_{ij}^{(t)}} = K_i \Big/ \left(u_i\left(\sum_j x_{ij}^*\right) - \sum p_{ij}^{(t)} \right)$$

$$\frac{\partial \mathrm{f}_{PP}^{S_j}}{\partial p_{ij}^{(t)}} = K_j \Big/ \left(\sum p_{ij}^{(t)} - v_j\left(\sum_i x_{ij}^*\right) \right)$$



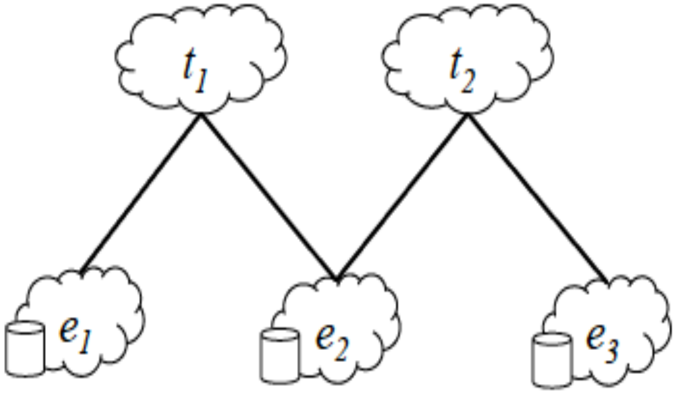
$$p_{ij}^{(t+1)} = p_{ij}^{t} + \tau\left(\frac{\partial \mathrm{f}_{PP}^{S_i}}{\partial p_{ij}^{(t)}} + \frac{\partial \mathrm{f}_{PP}^{S_j}}{\partial p_{ij}^{(t)}} \right)$$

Summarize the algorithm framework



An illustrative example

$u_1 = 40\log(x_{11} + x_{12} + 1)$ $u_2 = 30\log(x_{22} + x_{23} + 1)$



$v_1 = \frac{x_{11}}{20 - x_{11}}$ $v_3 = \frac{x_{23}}{15 - x_{23}}$

$v_2 = \frac{x_{12} + x_{22}}{25 - x_{12} - x_{22}}$

Content set: $\{o_1, o_2, o_3, o_4, o_5\}$

Demand matrix

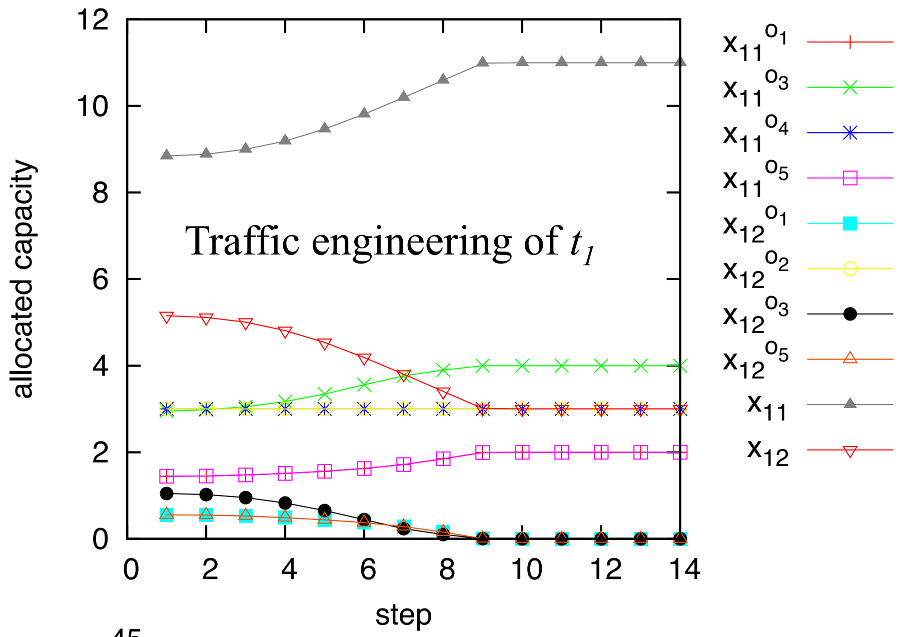
	o_1	o_2	o_3	o_4	o_5
t_1	$d_1^1 = 1$	$d_1^2 = 2$	$d_1^3 = 3$	$d_1^4 = 4$	$d_1^5 = 5$
t_2	$d_2^1 = 2$	$d_2^2 = 0$	$d_2^3 = 2$	$d_2^4 = 3$	$d_2^5 = 4$

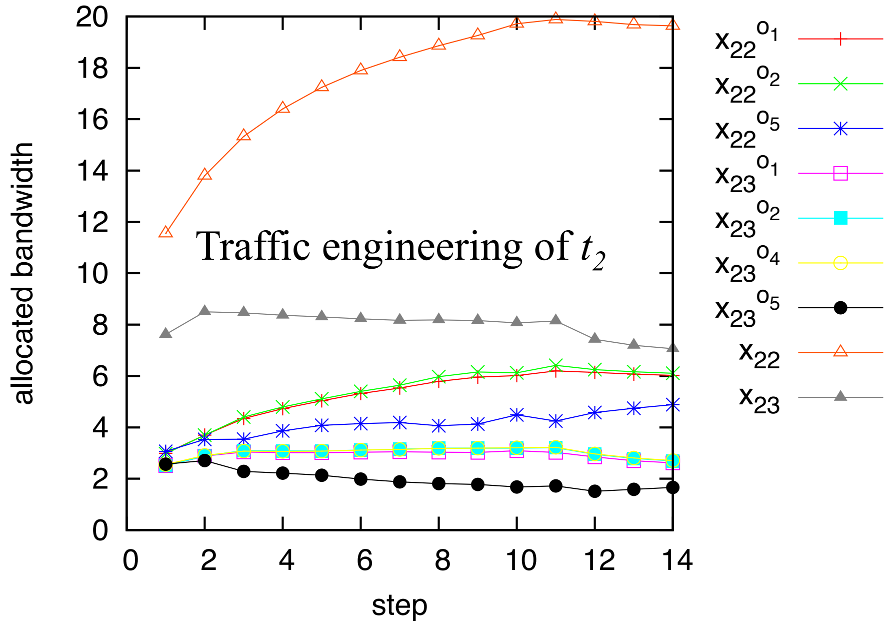
Cache profile

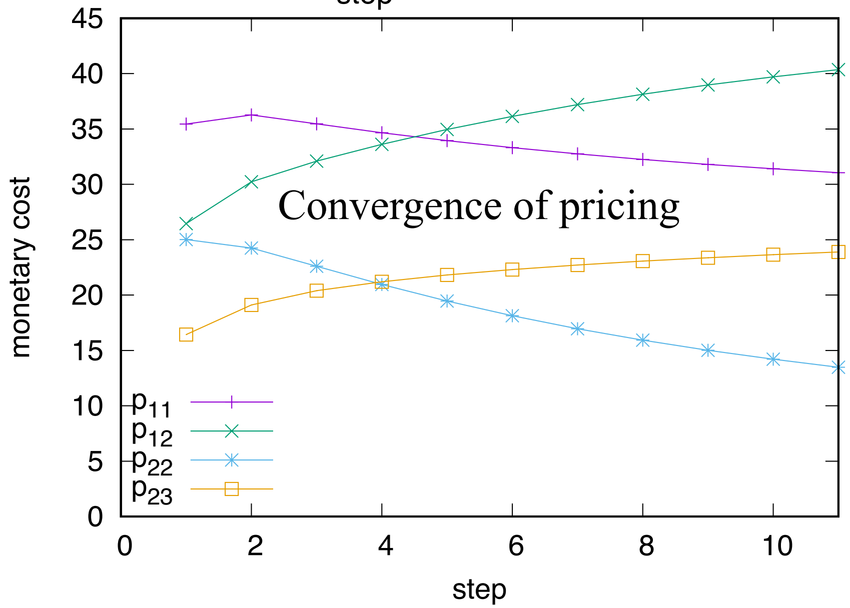
	o_1	o_2	o_3	o_4	o_5
e_1	✓	✗	✓	✓	✓
e_2	✗	✓	✗	✓	✓
e_3	✓	✓	✓	✗	✗

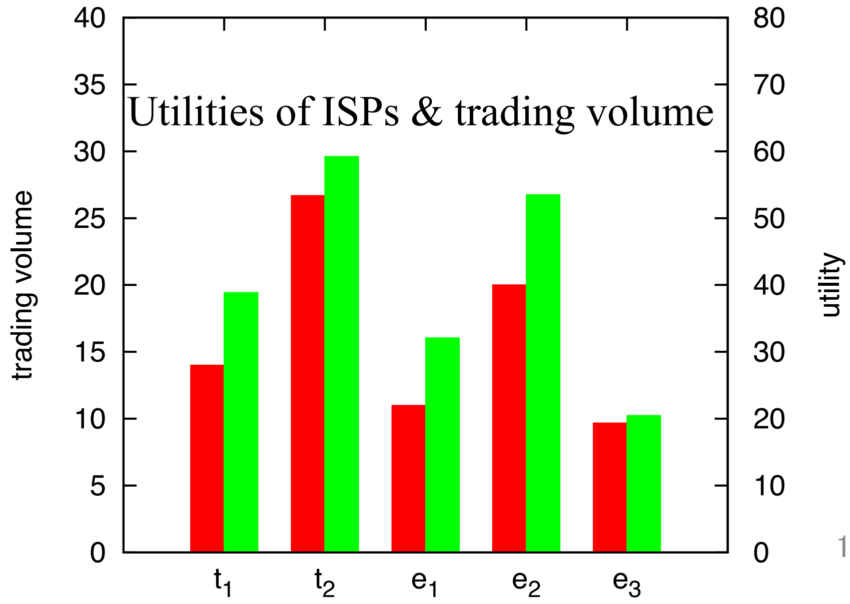
Results

Convergence of traffic engineering









Related research

- Nash bargaining solutions in network formation[1]
  - Extend the original 2-person bargaining to n person, and use the bargaining to a network formation game

- Content peering in CCN[2]
  - ISPs decide which content to cache locally independently
  - Complete selfish behavior will hurt social efficiency
  - Behave cooperatively will improve individual ISP's profit

- Cooperation among Telco-CDNs[3][4]
  - Do not have essential differences from content peering research

- An observation:
  - We have found little literature discussing the cache cooperation between ISPs of different tiers. Most of the literature has a default assumption in common that the participating ISPs do not have provider-customer relationship

[1] K. Avrachenkov, G. Neglia, et al, "Cooperative network design: a Nash bargaining solution approach", Computer Networks, Vol 83, pp: 265-279, June 215
[2] V. Pacifici, et al, Coordinated selfish distributed caching for peering content-centric networks, IEEE trans. Networking, Mar. 2016.
[3] V. Pacifici, et al, Distributed algorithms for content allocation in interconnected content distribution networks, INFOCOM 2015
[4] H. Lee, et al, On the economic impact of Telco CDNs and their alliance on the CDN market, ICC 2014

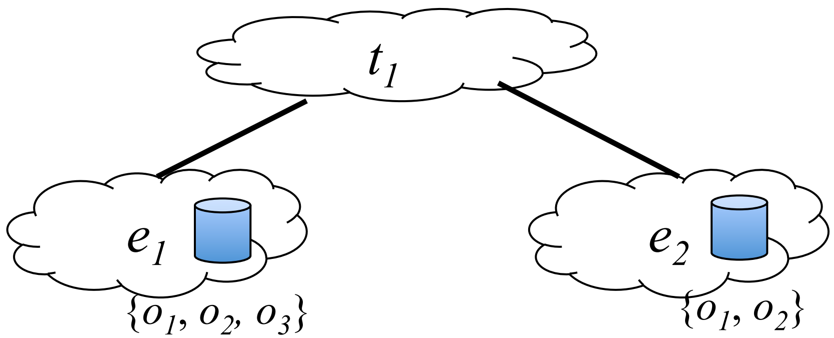
Summary

- We proposed to promote the inter-domain cache sharing for ISP of different tier to reduce transit cost
  - We identified a inherent double sided market
  - We proposed a Nash bargaining based mechanism
  - We decomposed the joint optimization problem (the Nash product) into inter-domain traffic engineering problem and pricing problem, and solve each problem with further decomposition

Appendix: Demand of transit ISPs in content level

demand: <content, intensity>

$\{<o_1, d_1^1>, <o_3, d_1^3>\}$



t_1's "local" decision variables: $(x_{11}^1, x_{11}^3, x_{12}^1)$

satisfy

$$\begin{cases} x_{11}^1 + x_{12}^1 \le d_1^1 \\ x_{11}^3 \le d_1^3 \end{cases}$$

compose

t_1's "global" decision variables : (x_{11}, x_{12})

$$\begin{cases} x_{11} = x_{11}^1 + x_{11}^3 \\ x_{12} = x_{12}^1 \end{cases}$$

The demand of transit ISPs in content level makes fundamentally difference from most of the conventional bandwidth allocation models