NUS
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On Multi-Resource Procurement in Internet Access Markets:

Optimal Strategies and Market Equilibrium

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Motivation

- Popularity of content delivery services.

NETFLIX YouTube tv+

  - Netflix and YouTube have made up over half of peak-time traffic in North America.

- The Quality of Service (QoS) perceived by users should be among the primary concerns of content providers (CPs).

Long loading time + Low feasible resolution = Less willingness to watch

Low traffic delay + High overall throughput = Better service quality

Motivation

- QoS deteriorates due to network congestion at bottleneck links.
  - CPs have incentives to pay for additional resources that could address the issues.

Premium peering

- Best-effort delivery under public peering commonly suffer from congestion.
- CPs can pay for additional bandwidth capacity dedicated to the peering link.

NETFLIX COMCAST verizon

Cache

- Distributed caches could be deployed to avoid long-distance transmission.
- Shorter response time and relieved traffic pressure on the entire path.

NETFLIX EVCache

- Acquiring bandwidth or cache resource can improve the QoS of content delivery.
  - What about deploying a hybrid of premium peering and cache resources?

Problem

- Access resources available for purchasing from Internet Service Providers (ISPs) in the last-mile access markets.
    - Peering bandwidth, cache, user peers in P2P networks, etc.

More access resources = Better QoS + Additional expenses

- From the perspective of a CP:
    - How much of each type of resources to procure so as to optimize its individual utility?

Individual Utility = Revenue earned from users − Payment to ISP

- From the perspective of the entire market:
    - Regulators concern about the total revenue that can be generated, i.e., social welfare.

Proper pricing = Demand and supply balanced + SW maximized

Problem

- An Internet access market consisting of one access ISP and multiple CPs.
  - CPs determine their purchasing strategies on multiple access resources.

Market equilibrium

- At which demand and supply are balanced.
- It exists, at which optimization for individual utilities and social welfare coincide.
- Market-clearing prices are unique.

Content delivery model

- Characterizes the CPs' throughput.
- At a steady state, the throughput is exactly the desirable throughput of users.
- The steady-state throughput is unique.

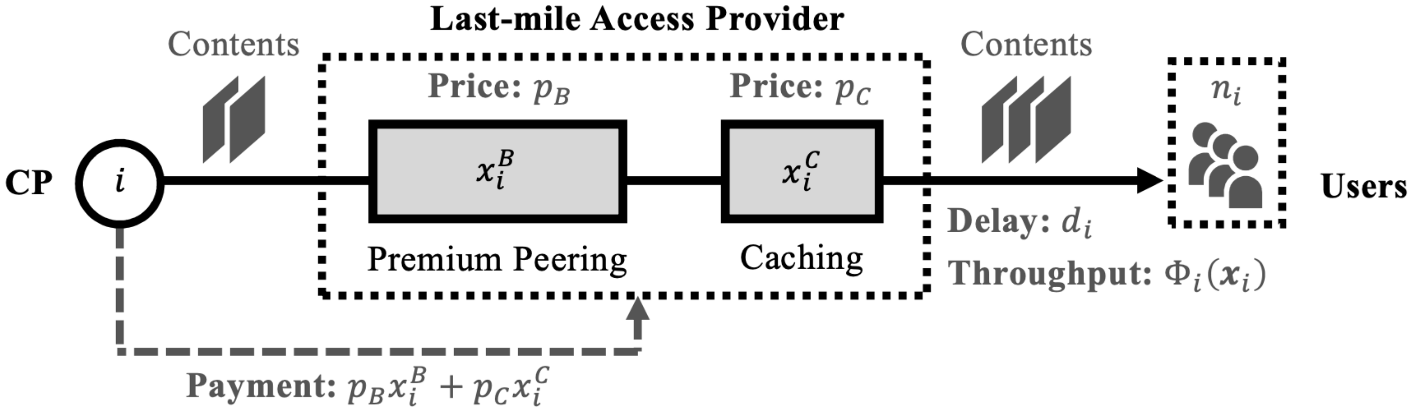
Observation and evaluation

- Relationship and correlation of purchasing strategies.

- CPs may consider purchasing a hybrid of access resources to improve QoS.

Resource Procurement

- Scenario:
  - A last mile access provider (ISP).
  - Multiple CPs denoted by set $\mathcal{N}$.
  - Serving a region of end-users.



Content cached at ISP

Content retrieved from CP i → Delivered using premium peering bandwidth → Better QoS for CP i

- Prices specified by the ISP:
  - Unit prices of premium peering bandwidth and cache are $\boldsymbol{p} = (p_B, p_C)^T > \boldsymbol{0}$.
- Purchasing strategy of CP i:
  - Units of capacity $\boldsymbol{x}_i = (x_i^B, x_i^C)^T > \boldsymbol{0}$. CP i pays the ISP $p^T x_i = p_B x_i^B + p_C x_i^C$.

Resource Procurement

- Utility of CP i:

Revenue $V_i(\boldsymbol{x}_i)$ = Avg. per-unit traffic revenue v_i x Aggregate throughput $\Phi_i(\boldsymbol{x}_i)$

Revenue increases when users request for more contents and generate more traffic.

x_i determines the QoS that could be achieved, which affects users' desire for contents.

Utility $U_i(\boldsymbol{x}_i)$ = Revenue $V_i(\boldsymbol{x}_i)$ - Payment to ISP $\boldsymbol{p}^T\boldsymbol{x}_i$

- Social welfare:
  - An unregulated ISP may focus on maximizing its own revenue.
  - Regulators may concern about the total revenue that could be generated.

Social welfare = Aggregate revenue of CPs $\sum_{i\in\mathcal{N}} V_i(\boldsymbol{x}_i) = \sum_{i\in\mathcal{N}} v_i\Phi_i(\boldsymbol{x}_i)$

Content Delivery

- **Less congestion** and **better QoS** are indeed two sides of a same coin.

Congestion level
Avg. traffic delay d_i

→ Given congestion level, the route accommodates certain throughput

← Larger throughput also influences congestion level with longer delay

Quality of service
Aggregate throughput ϕ_i

- Desirable throughput:
  - Captures users' desire for contents.

User population n_i × **Proportion of active users $\theta_i(d_i)$** × **Desirable throughput of each active user $\lambda_i(d_i)$**

- User population n_i: Users of CP i under its best achievable QoS.
- Proportion of active users $\theta_i(d_i)$: Under **less congestion**, the proportion of users who uses CP i grows.
- Desirable throughput of each active user $\lambda_i(d_i)$: On average, each user also desires more from CP i.

  - **Per-user** desirable throughput $\Lambda_i(d_i) = \theta_i(d_i)\lambda_i(d_i)$.

Content Delivery

- Mutual impact:

Users' desire not fulfilled → CP increases throughput → More severe congestion → Desirable throughput restrained

- Steady state of content delivery:

Actual throughput ϕ_i = Desirable throughput $n_i\Lambda_i(d_i)$

Overall delay d_i is related to ϕ_i

  - The desirable throughput is also dependant on ϕ_i, which is the steady-state throughput.
  - Given purchasing strategies x_i, the steady-state throughput is unique.

Steady-state throughput $\phi_i = \Phi_i(\boldsymbol{x}_i)$

Theorem 2.4 further gives the closed-form steady-state throughput.

Market Equilibrium

- Supply and demand of resources:
  - The ISP has limited capacity of bandwidth and cache X_B and X_C, i.e., supply of resources.
  - CPs respond to varying prices with demand $\mathcal{X}_i(\boldsymbol{p})$, and $\boldsymbol{x}_i = \mathcal{X}_i(\boldsymbol{p})$.

Low price → Unfulfilled demand

High price → Under-utilized resources

  - The market tends to reach an equilibrium at which supply and demand are balanced.

- Market equilibrium:
  - A pair of price and demand $(\boldsymbol{p}; \mathbf{x})$, iff. the demand matrix $\mathbf{x} = (\boldsymbol{x}_1, \ldots, \boldsymbol{x}_N)$ satisfies

$$\boldsymbol{x}_i = \mathcal{X}_i(\boldsymbol{p}), \quad \forall i \in \mathcal{N},$$

$$\sum_{i \in \mathcal{N}} x_i^B = X_B, \ \sum_{i \in \mathcal{N}} x_i^C = X_C.$$

  - $\boldsymbol{p}$ is referred to as the market-clearing prices.

Market Equilibrium

- **Optimality of market equilibrium:**
  - The ISP adjusts the prices to balance supply and demand, while different maximization goals might not be achieved simultaneously.

Perspective of entire market

- To maximize social welfare:

$$\max \sum_{i \in \mathcal{N}} V_i(\boldsymbol{x}_i) = \max \sum_{i \in \mathcal{N}} v_i \Phi_i(\boldsymbol{x}_i),$$

$$s.t. \;\; \sum_{i \in \mathcal{N}} x_i^B \leq X_B, \; \sum_{i \in \mathcal{N}} x_i^C \leq X_C \text{ and } \mathbf{x} \geq \mathbf{0}.$$

Perspective of CP i

- To maximize individual utility:

$$\max U_i(\boldsymbol{x}_i) = \max V_i(\boldsymbol{x}_i) - \boldsymbol{p}^T \boldsymbol{x}_i,$$

$$s.t. \;\; \boldsymbol{x}_i \geq \mathbf{0}.$$

- If any $\Phi_i(x_i)$ is differentiable, strictly increasing and concave, there exists $(p; \mathrm{x})$ at which

x_i maximizes utility $U_i(x_i)$	x maximizes social welfare $\sum_{i \in \mathcal{N}} V_i(x_i)$	Market-clearing prices p is unique	Market equilibrium demand x is unique

Theorem 3.2

If $\Phi_i(x_i)$ is strictly concave

Market Equilibrium

- For more general multi-resource markets:
  - The ISP provides L types of resources.
  - Supply $\boldsymbol{X} = (X_1, \dots, X_L)^T$, price $\boldsymbol{p} = (p_1, \dots, p_L)^T$, purchasing strategies $\mathrm{x} = (\boldsymbol{x}_1, \dots, \boldsymbol{x}_N)$, $\boldsymbol{x}_i = (x_i^1, \dots, x_i^L)^T$.
  - If any $V_i(\boldsymbol{x}_i)$ is differentiable, strictly increasing and concave, there exists $(\boldsymbol{p}; \mathrm{x})$ at which

$\boldsymbol{x}_i$ maximizes utility $U_i(\boldsymbol{x}_i)$	x maximizes social welfare $\sum_{i \in \mathcal{N}} V_i(\boldsymbol{x}_i)$	Market-clearing prices $\boldsymbol{p}$ is unique	Market equilibrium demand x is unique

Theorem 3.6

If $V_i(\boldsymbol{x}_i)$ is strictly concave

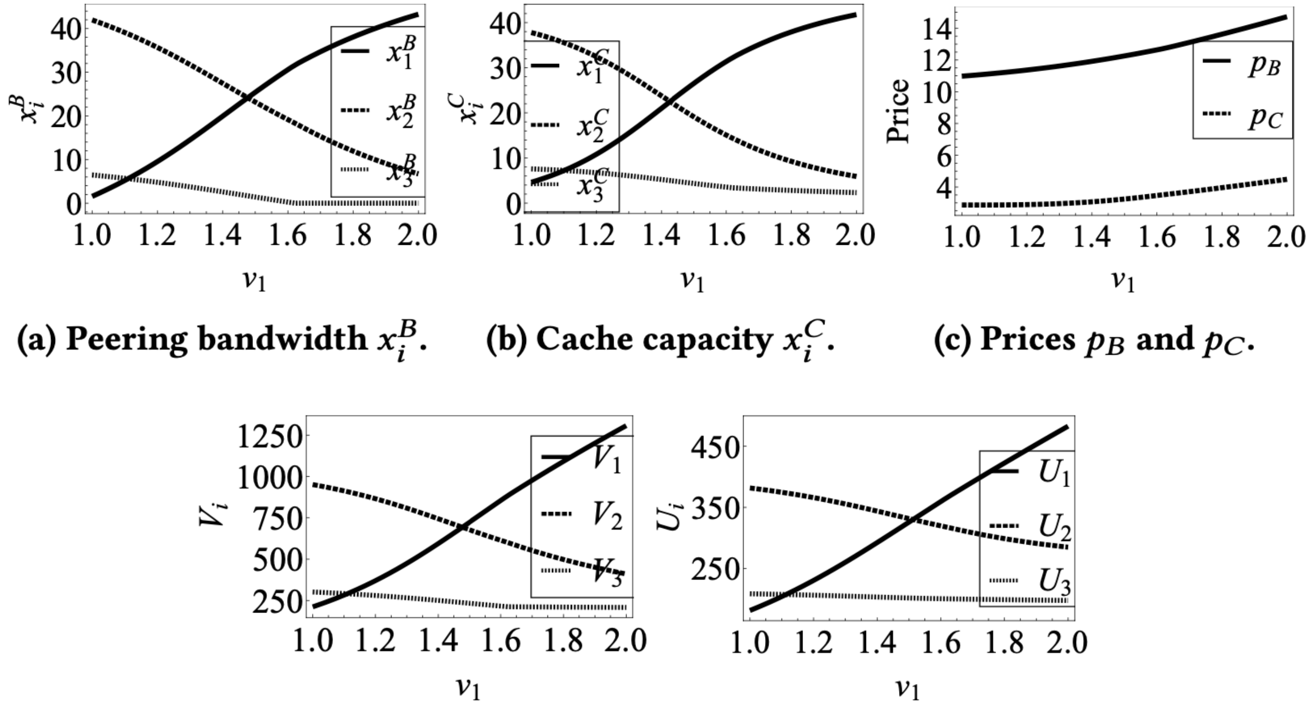
- The market equilibrium achieves various objectives of different market participants:
  - CPs are expected to maximize individual utilities.
  - ISP is expected to fully utilize its supply of resources.
  - Regulators are expected to maximize the social welfare as well.

Numerical Evaluation

- Characteristics of market equilibrium:
  - Relationships among demand.

    Theorem 3.4 and 3.7
  - Response of equilibrium to deviating parameters (sensitivity analysis).

    Theorem 3.8
- Numerical evaluation:
  - Based on the two-resource market.
  - 3 top CPs generating the majority of traffic.
  - Each time one parameter is varied, while others remain their baseline values.
  - To observe the dynamics of market equilibrium.



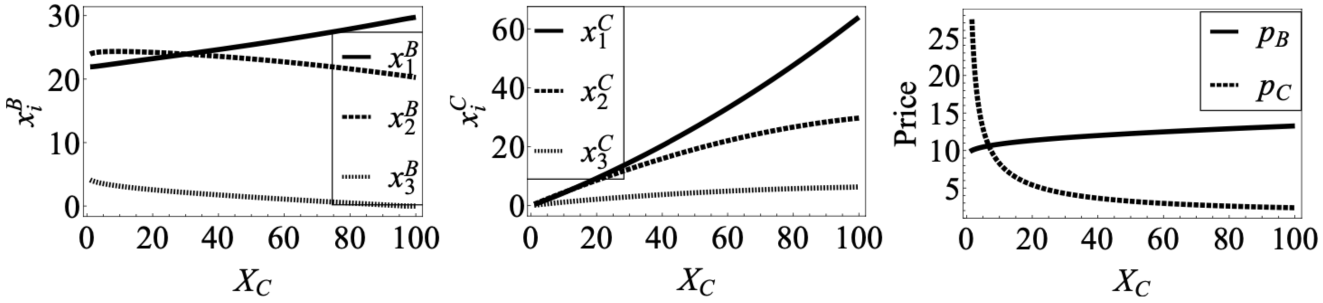
(a) Peering bandwidth x_i^B. (b) Cache capacity x_i^C. (c) Prices p_B and p_C.

(d) Revenue of CP V_i. (e) Utility of CP U_i.

Response of market equilibrium
To CP 1's per-unit traffic revenue v_1

Numerical Evaluation

- Observations from multiple perspectives:
  - CP's per-unit traffic revenue
  - Users' desire for a CP
  - Content popularity of a CP
  - ISP's supply of a resource
- What could be learned:
  - Deeper understanding on how to choose the resource prices and purchasing strategies.
  - Insights on the optimal response of CPs to a dynamically changing market to still reach the market equilibrium.



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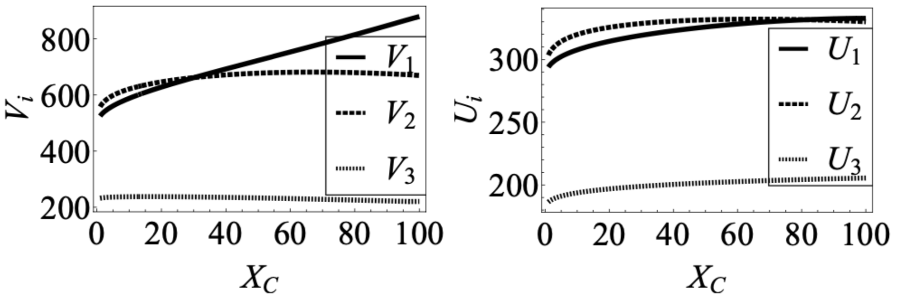

(d) Revenue of CP V_i. (e) Utility of CP U_i.

Response of market equilibrium
To the ISP's supply of cache capacity X_C

THANK YOU