Traffic Peering Games in Internet Exchange Points

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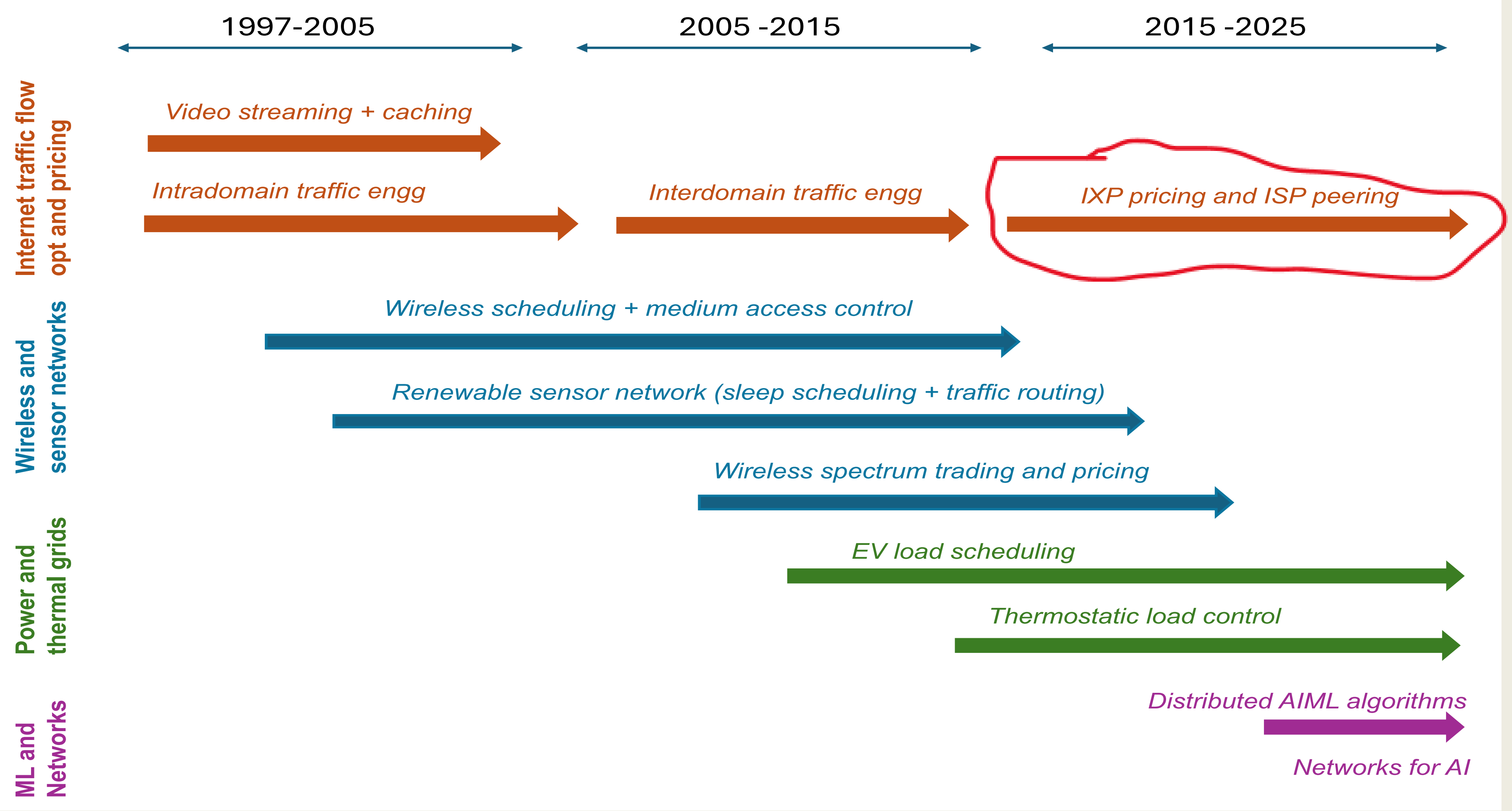
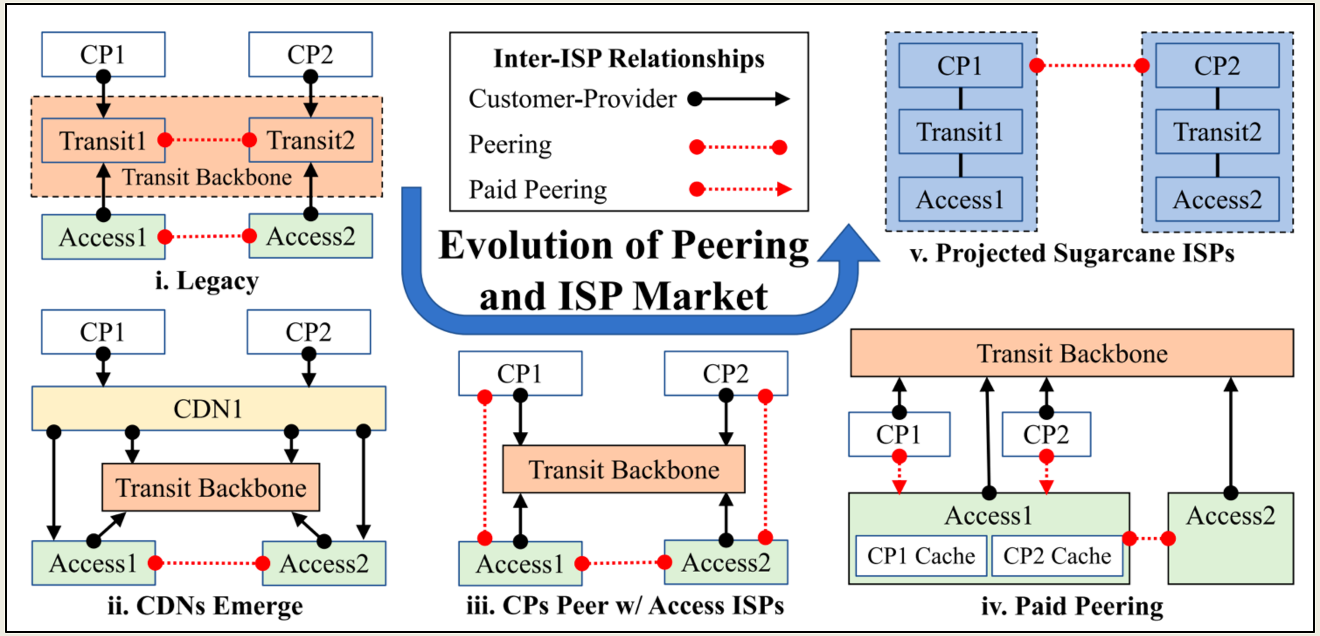
Research Interests and Timeline

- Common theme in my work: Control and optimization of networked systems
- Common tools utilized: non-linear and stochastic optimization, game theory



Background and Motivation

- Internet service providers (**ISPs**) **connect** individuals and companies **to the Internet**.
- **ISPs *peer* at IXP** (data center with network switches) to exchange traffic.
- *Alternatively*, ISPs can **pay transit providers** for global Internet access.
- Recent insurgence of peering between content and access ISPs (flattening of the Internet).

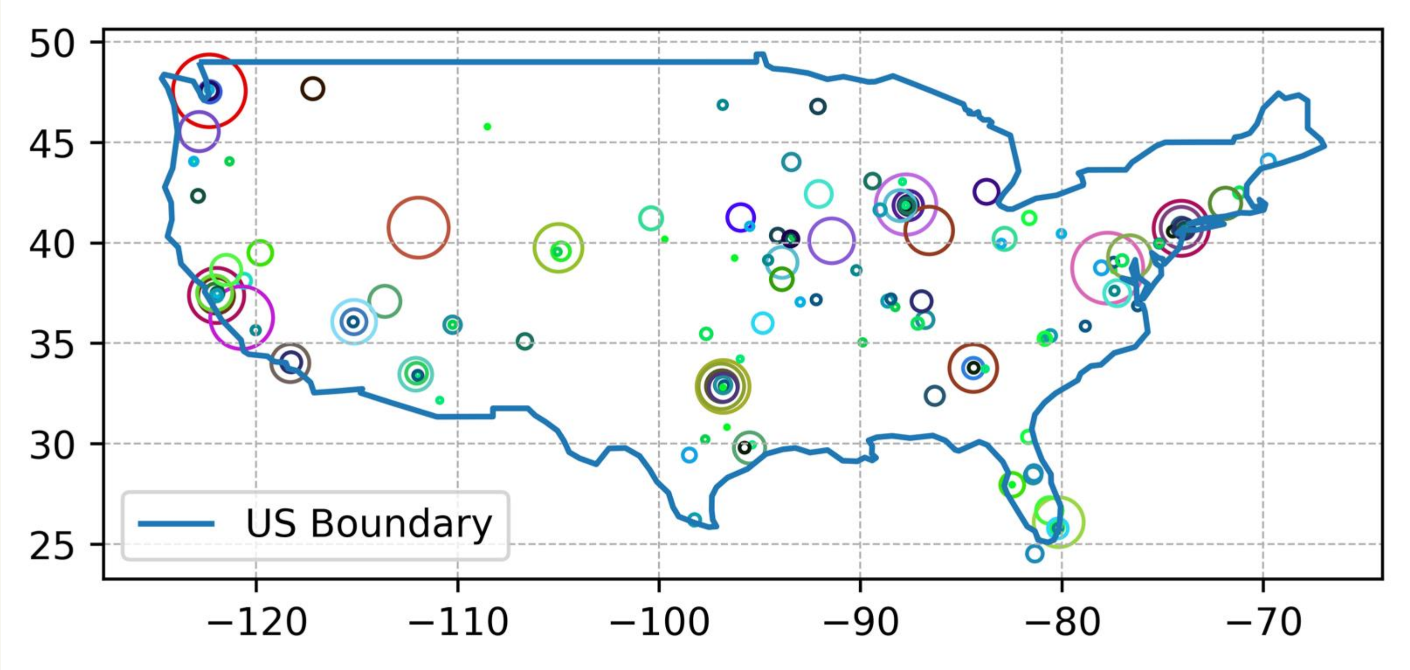


Three Related Topics in this Space

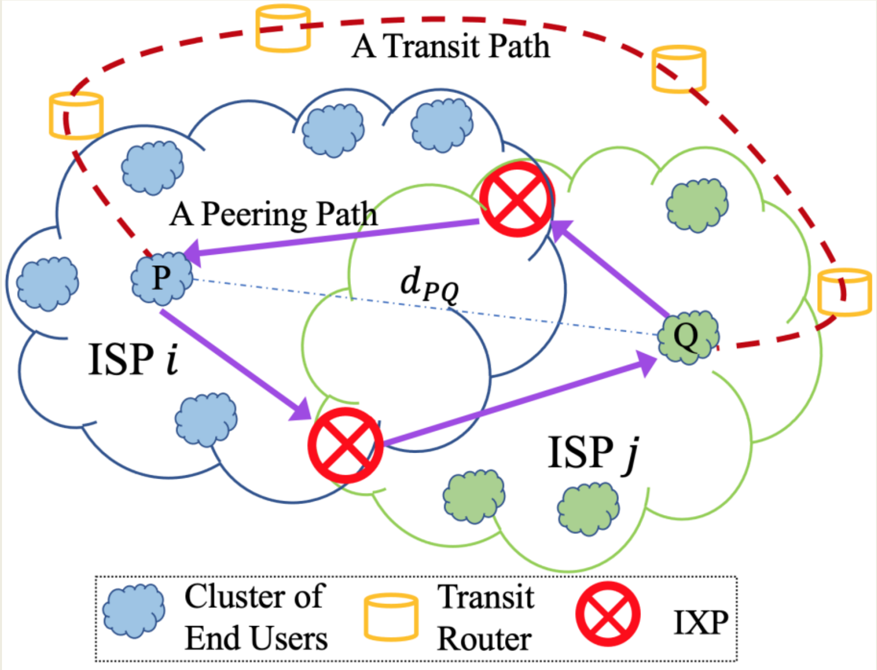
1. Pricing Policy of IXPs
   - **Constant** Pricing
   - **Proportional** Pricing

2. Port Purchase at IXP
   - **No Transit** Available
   - **Transit** Available

3. Peering Choices of ISPs
   - Peering **Partner** Selection
   - Peering **Location** Selection



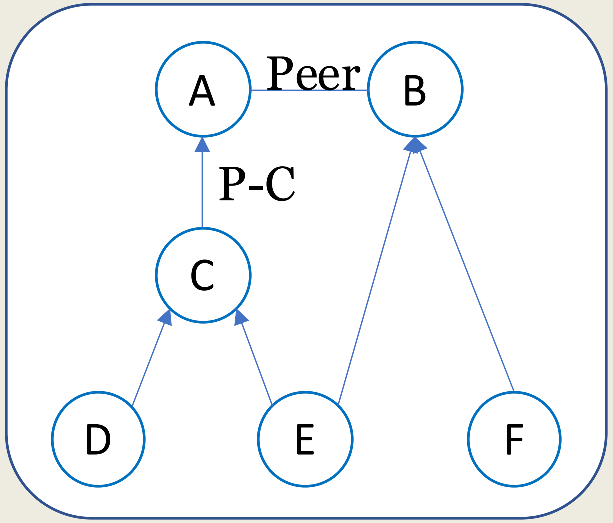
IXPs in the US (Circle size ∝ # of ISPs)

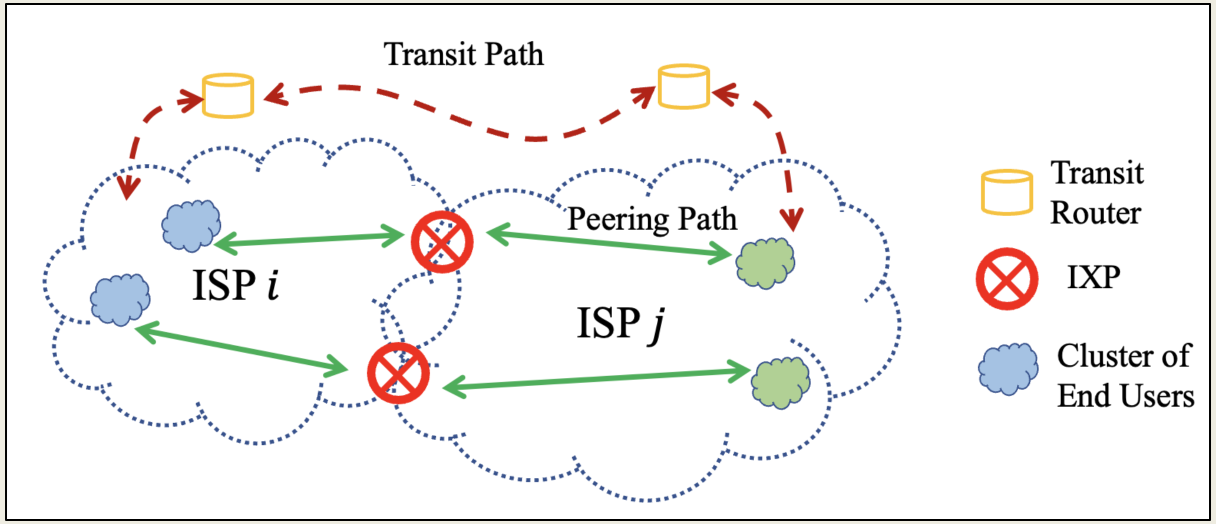


Example of Peering and Transit Path

Background and Motivation

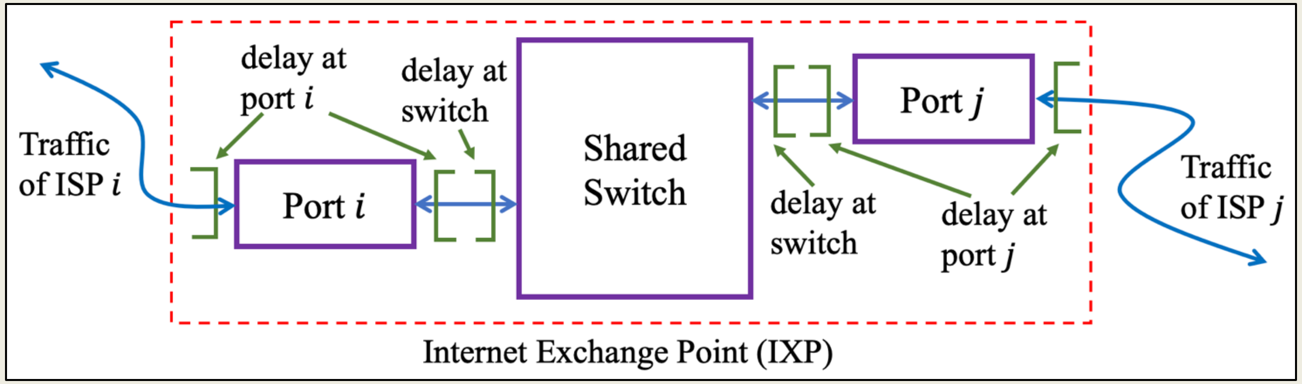
- **Pricing Policy of IXPs**
  - **IXPs** usually **charge a fee** to the ISPs for cost recovery or profit.
  - ISPs' decision to peer at IXP depends on QoS, pricing, transit cost etc.
  - Despite falling transit costs, **peering** between ISPs has been **on the rise**.
  - Careful design of IXP **pricing policy** may **ensure stable** and **efficient peering**.





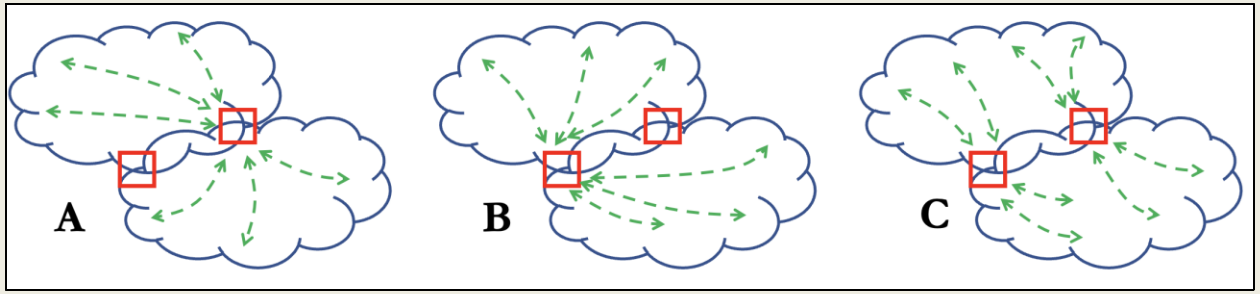
Background and Motivation

- **Port Purchase at IXP**
  - ISPs typically pay the IXPs according to the port capacity purchased by them.



  - The QoS of traffic depends on the port capacities purchased by the ISPs.
  - Making the port-capacity purchasing decisions dependent on other ISPs decision.

- **Peering Decision Process**
  - Peering allows more room for ISP-specific optimizations.



  - Identifying potential peer and locations are crucial for efficient traffic exchange.

Game Theory – Common Terms

- **Agent / Player :** A person or entity that participates in economic activity (ISP and IXP in our study)
- **Utility:** Value / worth / satisfaction of a good / service.
- **Cost:** dissatisfaction / money spent on a service. (Delay in internet traffic)
- **Revenue (Rev):** Income (In our study it is usually IXP's revenue)
- **Social Cost (SC):** *Sum of costs* of all agents / players.
- **Social Welfare (SW): (***Sum of utility* of all agents**)** – **(**Social Cost**)**
- **Equilibrium (Eq.):** A state at which no agents can improve their utility by changing strategy unilaterally.
- $\boldsymbol{PoA}(\mathbf{SW}) : \dfrac{Max\ SW}{SW\ at\ Eq.}$, $\boldsymbol{PoA}(\mathbf{Revenue}) : \dfrac{Max\ Rev}{Rev\ at\ Eq.}$, $\boldsymbol{PoA}(\mathbf{SC}) : \dfrac{SC\ at\ Eq.}{Min\ SC}$

Related Work

- **Selfish routing and congestion games:** many existing work studies Nash equilibrium.
  - Nash Equilibrium **no longer appropriate** when deciding **pairwise peering** decision.
- **Network formation games:** two nodes build links mutually but can sever links individually.
  - Studied for different settings: The models focus on **fixed connection cost**.
- Works on pricing network services and traffic: **Do not consider** an IXP setting.
- **Peering Decision of ISPs:**
  - Only a few works explored solution of **peering decision** on a **global scale**.
  - Peering **location selection** can be computationally difficult.

Topic 1:
Efficient Pricing Policies at IXPs

Our Publications on this Topic:

1. [**ToN 2023**] M. Alam, E Anshelevich, K Kar, M Yuksel. “Pricing for Efficient Traffic Exchange at IXPs”.
2. [**Globecom 2021**] M. Alam, K Kar, E Anshelevich, “Balancing Traffic Flow Efficiency with IXP Revenue in Internet Peering”.
3. [**ITC 2021**] M. Alam, E Anshelevich, K Kar, M Yuksel, “Proportional Pricing for Efficient Traffic Equilibrium at Internet Exchange Points”.

Constant Pricing Policy
Motivation

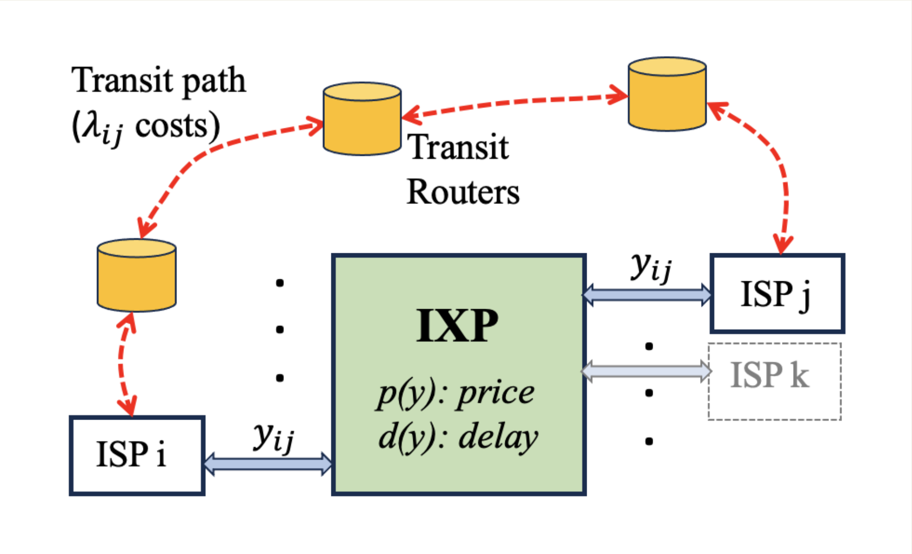
- **ISPs** exchange traffic via IXP to attain **better SW**.
- **IXP** tries to **maximize** its **revenue** with a good pricing policy.
- We aim to choose a pricing policy that attain better SW and Revenue.
- Previous work:
  1. How the operational cost of (non-profit) IXP be shared among ISPs.
  2. Explored conditions to have good SW and revenue (strong smoothness needed)

Constant Pricing Policy

System Model

- Some common notations used in the paper

Term	Description
y_{ij}	Traffic of ISP pair (i,j) sent publicly through the IXP.
y_i	$\sum_j y_{ij}$, total traffic of ISP i going through the IXP.
y	$\frac{1}{2}\sum_i \sum_j y_{ij}$, total traffic flowing through the IXP.
$\overrightarrow{y}$	Total traffic allocation vector (vector of values y_{ij})
λ_{ij}	Per-unit cost incurred by (i,j) for routing traffic externally
$d(y)$	Congestion cost per unit traffic incurred at the IXP
$p(y)$	Price per unit traffic set by the IXP

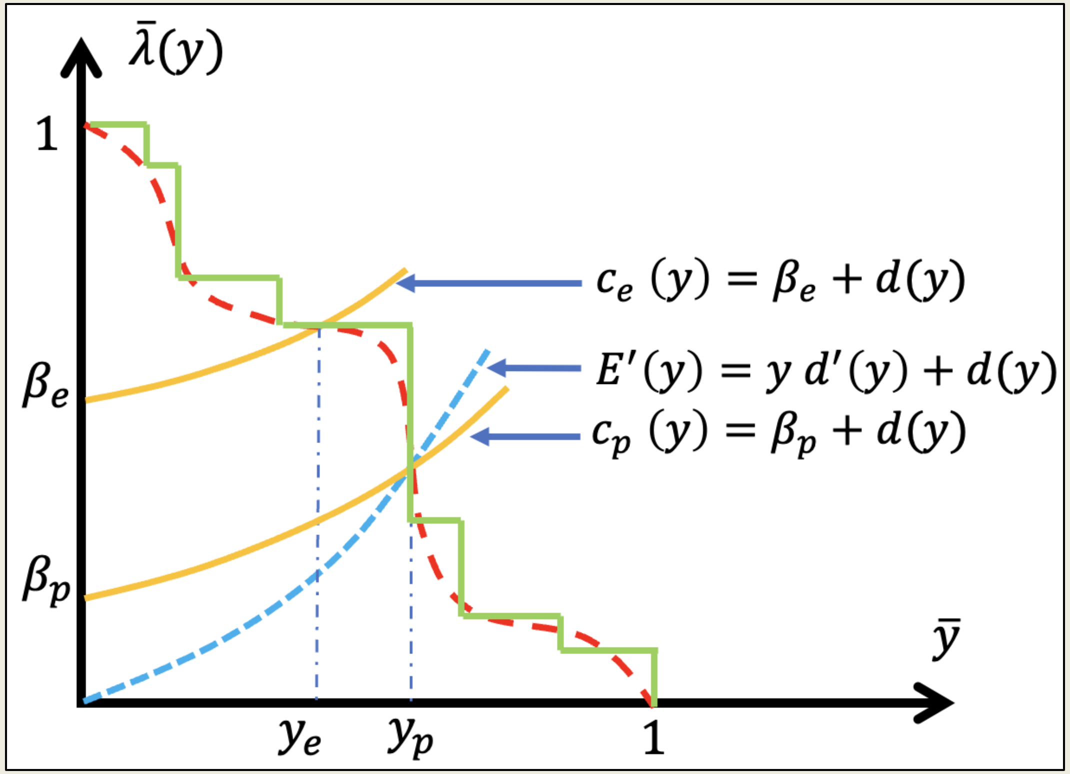


- SW of an ISP *i* is, $\sum_{(ij)\ni i} y_{ij}\lambda_{ij} - \{p(y)\sum_{(ij)\ni i} y_{ij} + d(y)\sum_{(ij)\ni i} y_{ij}\},$
- Or, $SW_i(\vec{y}, c(y)) \;=\; W_i(\vec{y}) - c(y)y_i.$
- SW of al ISPs $SW_{ISP}(\vec{y}, c(y)) \;=\; 2(W(\vec{y})) - c(y)y,$
- Rev of IXP, $\boxed{Rev(\vec{y}, p(y)) = p(y)\sum_i \sum_{(ij)\ni i} y_{ij} = 2p(y)y.}$
- SW (system)

$$\boxed{\begin{aligned} SW(\vec{y}) &= SW_{ISP}(\vec{y}, c(y)) + Rev(\vec{y}, p(y)),\\ &= 2W(\vec{y}) - 2d(y)y = 2W(\vec{y}) - 2E(y), \end{aligned}}$$

Constant Pricing Policy
System Model

- **Definition.** A traffic flow $\overrightarrow{y_e}$ with $y_e = |\overrightarrow{y_e}|$ is said to be an equilibrium flow if and only if all the traffic with $\lambda_{ij} > c_e(y_e)$ is sent and the traffic with $\lambda_{ij} < c_e(y_e)$ is not sent.
- **Theorem.** y_e is an equilibrium traffic flow when $\lambda(y_e^-) \geq c_e(y_e) \geq \lambda(y_e^+)$.
- **Theorem.** At social optimality, all the traffic with $\lambda_{ij} > E'(y_p)$ flows through the IXP and all traffic with $\lambda_{ij} < E'(y_p)$ does not. Also, $\lambda(y_p^-) \geq E'(y_p) \geq \lambda(y_p^+)$.



$\lambda(y)$ curve with $E'(y)$ and $c(y)$.

Constant Pricing Policy

Theoretical Analysis

- An inverse demand curve ($\lambda(y)$) has a **shift factor α_1** if,

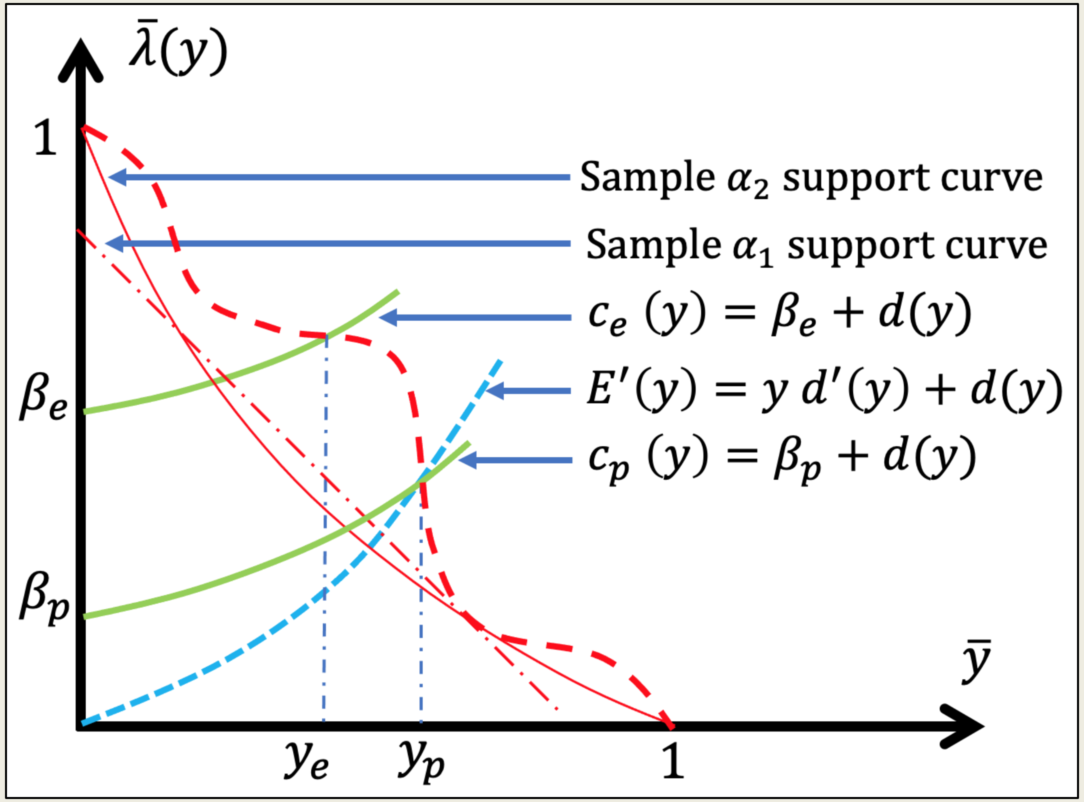
$$\frac{\lambda(y)}{\lambda_{max}} + \frac{y}{y_{max}} \geq \alpha_1, \forall y.$$

- Whereas $\lambda(y)$ has a **stretch factor α_2** if

$$\left(\frac{\lambda(y)}{\lambda_{max}}\right)^{\alpha_2} + \left(\frac{y}{y_{max}}\right)^{\alpha_2} \geq 1, \forall y.$$

- $PoA(SW)$: $\frac{SW \text{ at } OPT}{SW \text{ at Equilibrium}}$

- $PoA(Rev)$: $\frac{\max(Rev)}{Rev \text{ at Equilibrium}}$



Constant Pricing Policy

Theoretical Analysis (contd.)

- The pricing policy to attain good SW and Rev is to charge per unit traffic $p(y) = \beta_b = \max(\beta_e, \beta_p)$,
  - where β_e is dependent on $K, \alpha, d(y)$; e.g. $\beta_e = K\alpha_1 - d(y_e)$, and β_p is dependent on $y, d(y)$.
- **Theorem.** If $\lambda(y)$ has a **shift factor α_1**, then with $p(y) = \beta_b$, we can attain atleast $\left(\frac{1}{\alpha_1\,(1-K)}, \max\left(\frac{1}{\alpha_1\,(1-K)}, \frac{2}{K\alpha_1}\right)\right)$ of the maximum achievable SW and Revenue respectively.
  - With $K = \frac{2}{3}$, the PoA for both SW and Rev is $\frac{3}{\alpha_1}$.
- **Theorem.** If $\lambda(y)$ has a **stretch factor α_2**, then with $p(y) = \beta_b$, we can attain at least $\left(\frac{1}{(1-K)^{1/\alpha_2}}, \max\left(\frac{1}{(1-K)^{1/\alpha_2}}, \frac{2}{K^{1/\alpha_2}}\right)\right)$ of the maximum achievable SW and Revenue respectively.
  - With $K = \frac{2^{\alpha_2}}{1+2^{\alpha_2}}$, the PoA for both SW and Rev is $(1 + 2^{\alpha_2})^{1/\alpha_2}$.

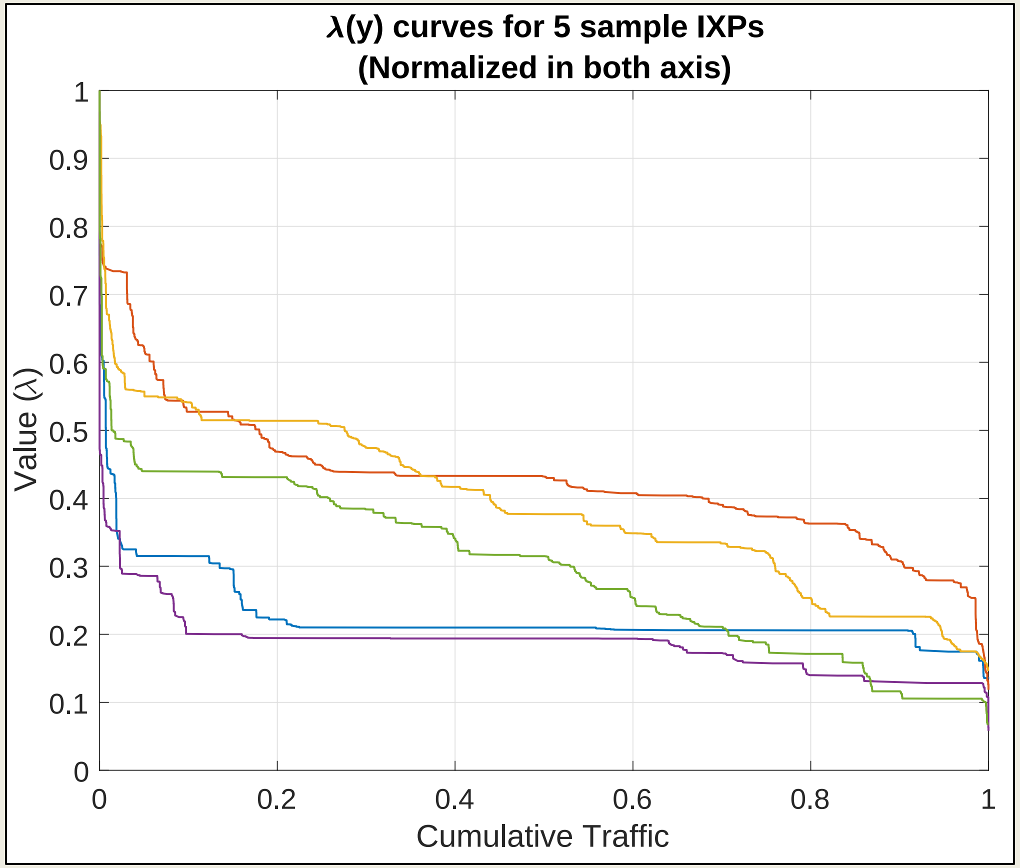
Constant Pricing Policy

Simulations

- Data Collection
  - PeeringDB
  - CAIDA
- Simulation Setup
  - Generating Inverse demand curve (λ(y))
  - Simulations

POA VALUES FOR POLYNOMIAL AND QUEUING DELAY FUNCTIONS.

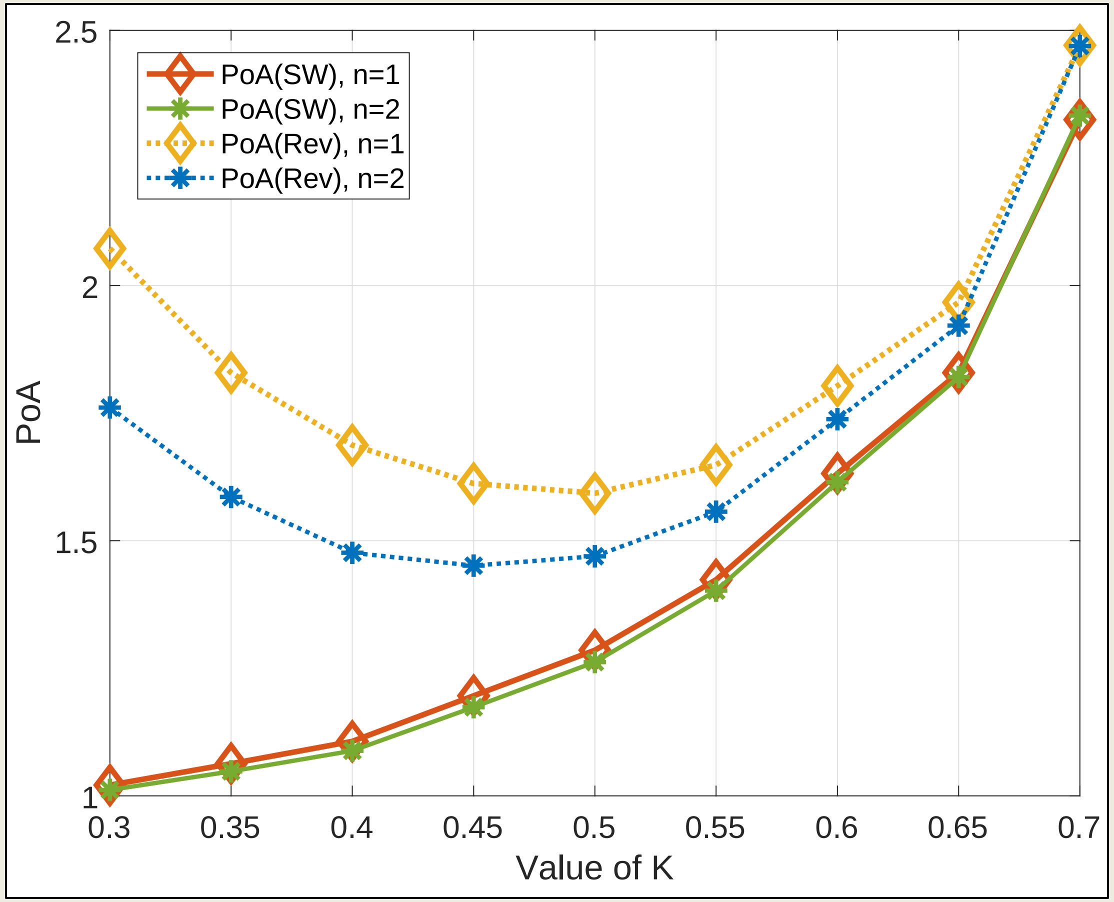
Term	K=0.3	K=0.5	K=0.7
PoA(SW) (polynomial)	3.3851	2.4319	5.8607
PoA(SW) (queuing)	1.9968	2.4902	6.6428
PoA(SW) (Theo)	5.3908	7.5472	12.5786
PoA(Rev) (polynomial)	1.5511	1.8605	5.1399
PoA(Rev) (queuing)	5.5403	1.9556	2.0722
PoA(Rev) (Theo)	25.1572	15.0943	12.5786



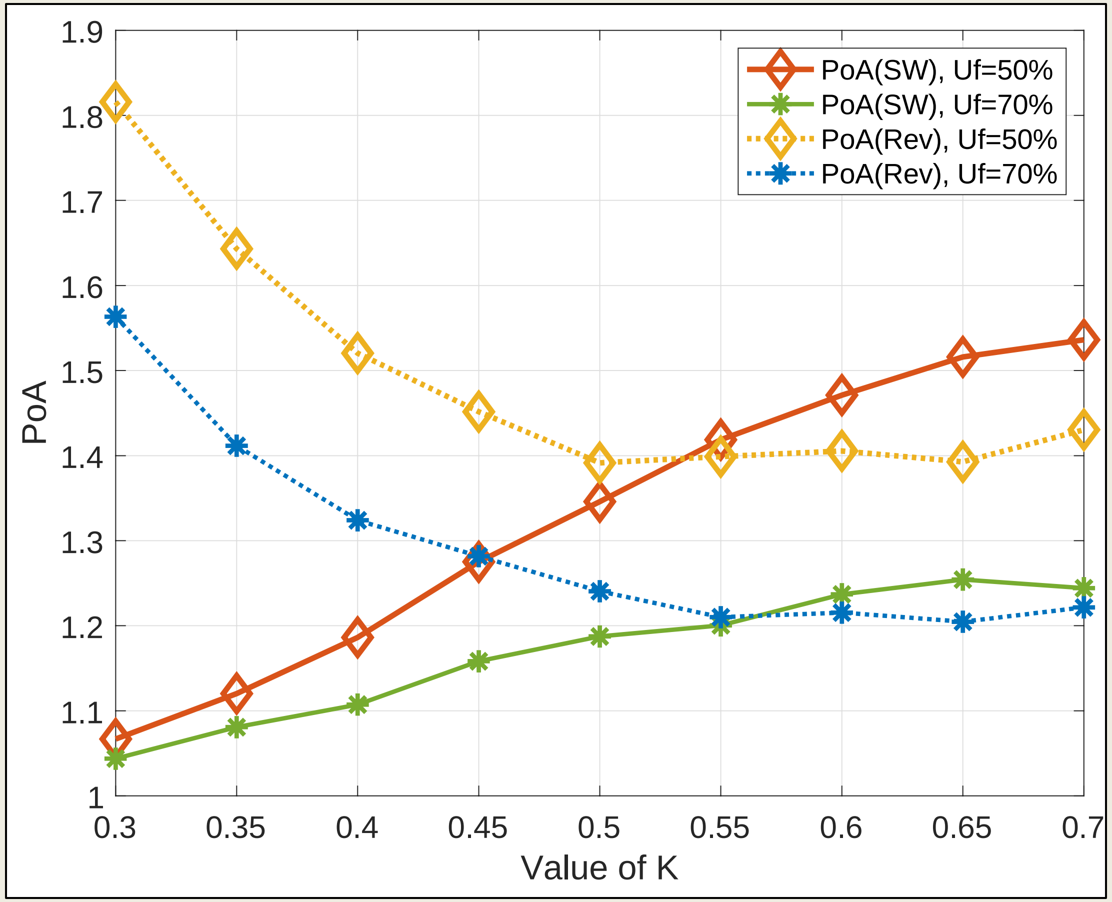
Generated external routing cost (λ(y)) curves

Constant Pricing Policy

Simulations



Avg PoA of SW and Rev - Simulated (polynomial delay function).



Avg PoA of SW and Rev - Simulated (queuing delay function).

Constant Pricing Policy

Conclusion

- **Pricing policy** ensuring **good social welfare** and IXP **Revenue** simultaneously exists.
- The pricing **policy** (and PoA) **depends** on the **sub-linearity measure** of inverse demand curve.

Proportional Pricing Policy

Motivation

- Good ***constant pricing policy*** is heavily **dependent on** the characteristics of **inverse demand curve**.
- ***Proportional pricing policy*** can be used to aid IXPs on the pricing decision policy **without the knowledge of inverse demand curve**.
- Social cost, another performance metric like SW, can be used to bound the performance.
- Show the co-existence of close-to-optimum SC and IXP revenue.

Proportional Pricing Policy

System Model

- Cost of an ISP i is,

$$p(y)\sum_j y_{ij} + d(y)\sum_j y_{ij} + \sum_j (B_{ij} - y_{ij})\lambda_{ij},$$

- Or, $C_i(\vec{y}, c(y)) \;=\; c(y)y_i + L_i(\vec{y}).$

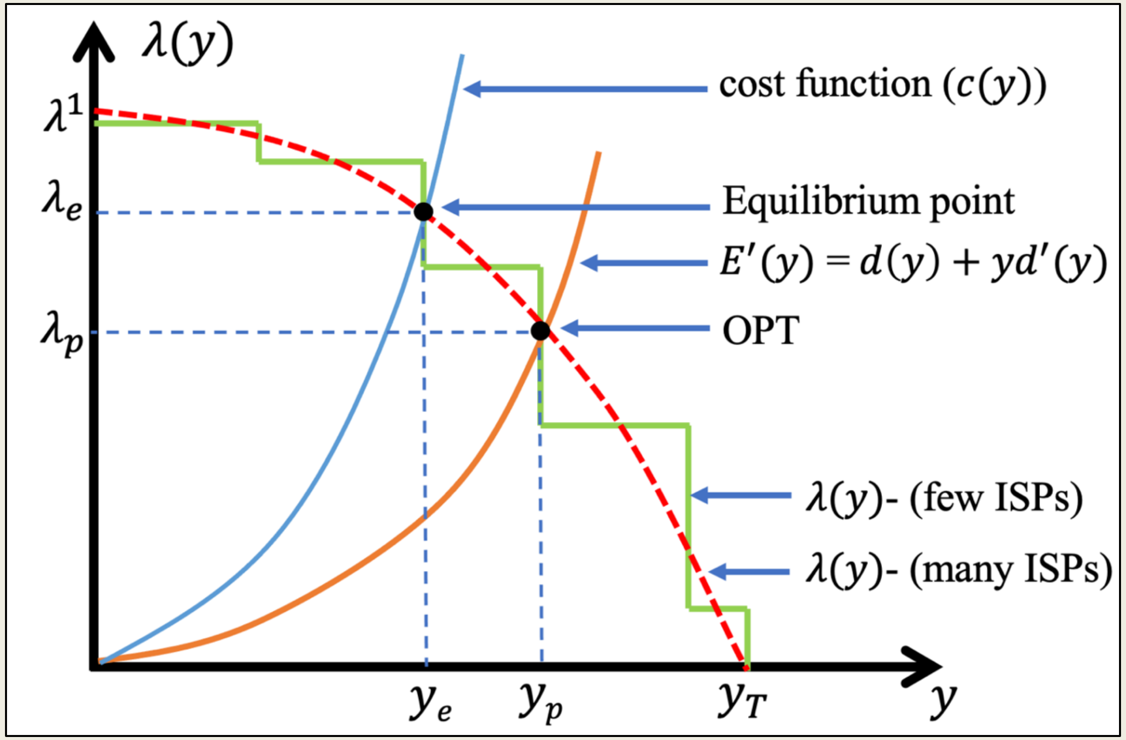
- The total cost of ISPs

$$C(\vec{y}, c(y)) \;=\; 2(c(y)y + L(\vec{y})),$$

- Revenue, $\boxed{p(y)\sum_i \sum_j y_{ij} = 2p(y)y.}$

- Social Cost,

$$\boxed{\begin{aligned} SC(\vec{y}, d(y)) &= C(\vec{y}, c(y)) - Rev(\vec{y}, p(y)), \\ &= 2d(y)y + 2L(\vec{y}) = 2E(y) + 2L(\vec{y}), \end{aligned}}$$



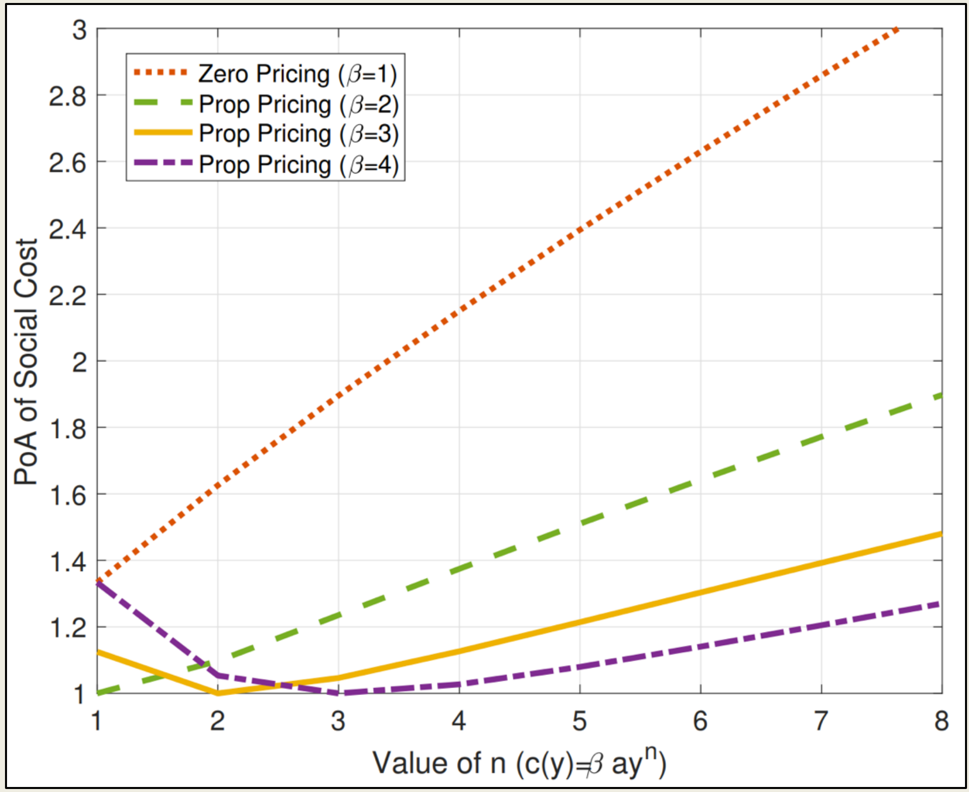
Proportional Pricing Policy

Theoretical Analysis: Social Cost

- $\boldsymbol{PoA(SC)}$: ratio of SC_{eq} to SC_{OPT}
- **Theorem.** $p(y) = y \cdot d'(y)$ attains a $PoA(SC)$ of 1.
  - Can lead to very poor revenue.
- **Definition.** Proportional Pricing with $\beta \geq 1$ means $p(y) = (\beta - 1)\, d(y)$.
- **Theorem.** For Proportional Pricing, if congestion cost (delay) function $d(y) = ay^n$ with $a > 0$, $n \geq 1$, and

i. $\beta \leq n + 1$, then PoA is bounded by $\left[\beta - n\left(\frac{\beta}{n+1}\right)^{\frac{n+1}{n}}\right]^{-1} \leq \frac{n+1}{\beta}$;

ii. $\beta > n + 1$, then PoA is bounded by $\frac{\beta}{n+1}\left[\frac{\beta n}{(\beta-1)(n+1)}\right]^{n} \leq \frac{\beta}{n+1}$



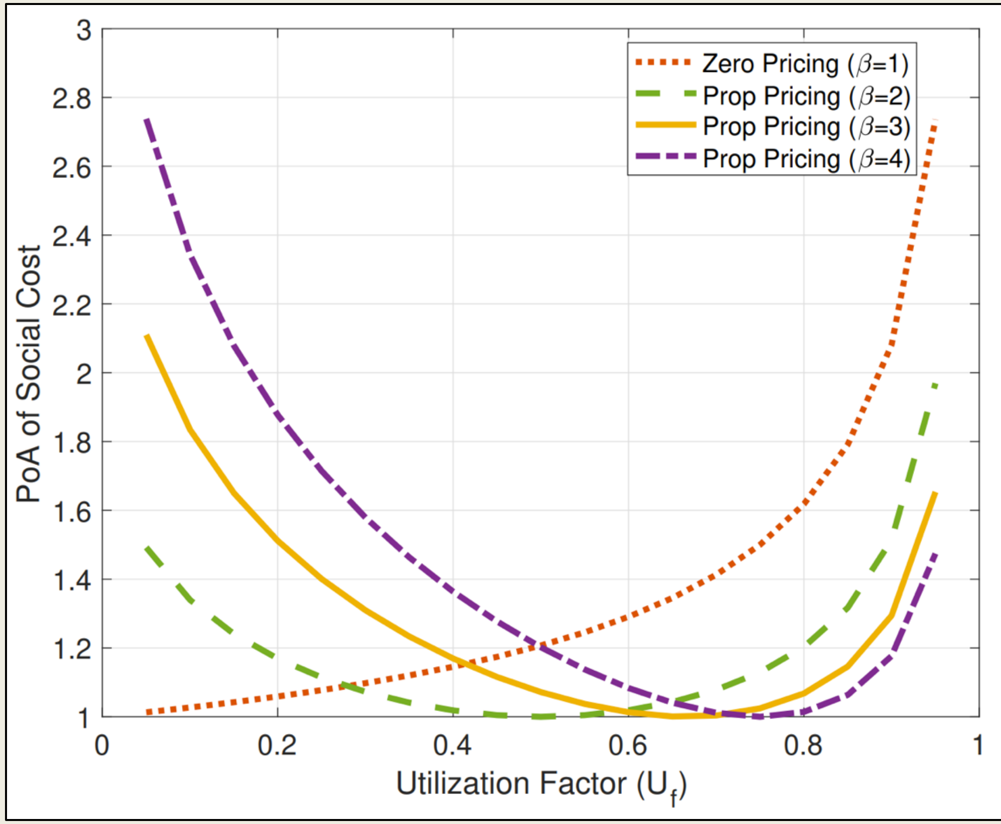
Proportional Pricing Policy

Theoretical Analysis: Social Cost

- **Definition.** Utilization factor, $U_f = \frac{y_e}{\mu}$.
  - y_e the equilibrium traffic
  - μ total capacity
- **Theorem.** For Proportional Pricing (i.e., $c(y) = \beta\, d(y)$) and congestion cost (delay) function $d(y) = \frac{a}{\mu - y}$, the PoA is bounded by

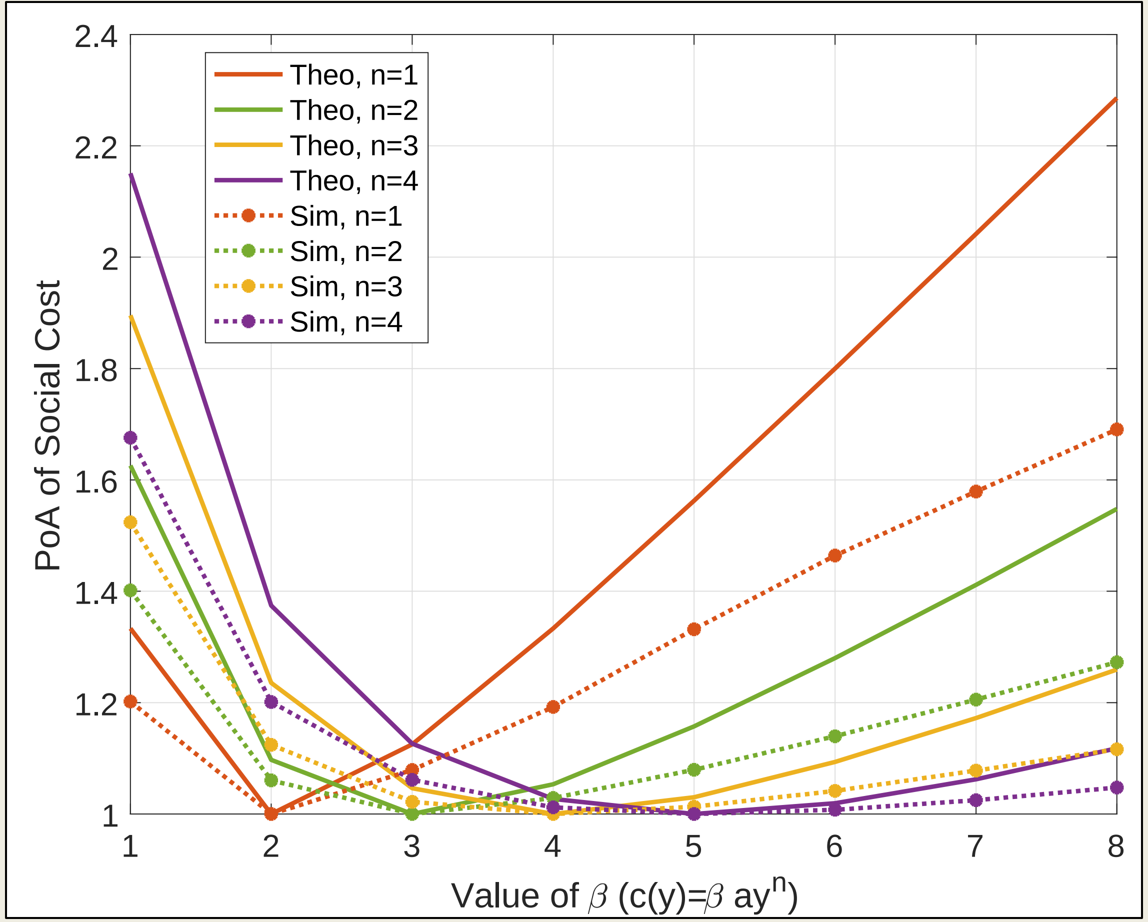
i. $\frac{U_f\sqrt{\frac{1-U_f}{\beta}}}{(1-U_f)\left[2-\sqrt{1-U_f}\left(\frac{1+\beta}{\sqrt{\beta}}\right)\right]}$, when $U_f \geq 1-\frac{1}{\beta}$;

ii. $\frac{\left(\sqrt{\beta}-\sqrt{U_f(\beta-1)}\right)^2}{1-U_f}$, when $U_f < 1-\frac{1}{\beta}$.

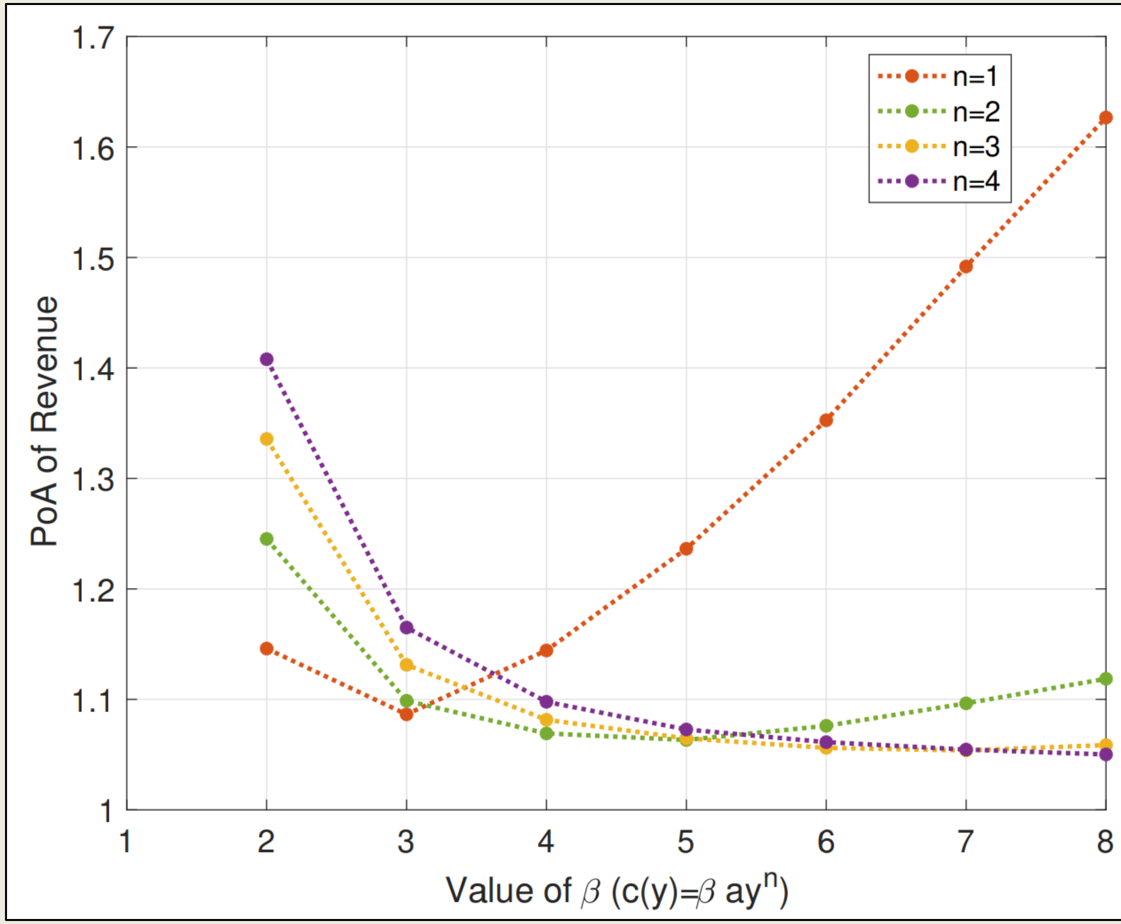


Proportional Pricing Policy

Simulation Results – Polynomial Delay



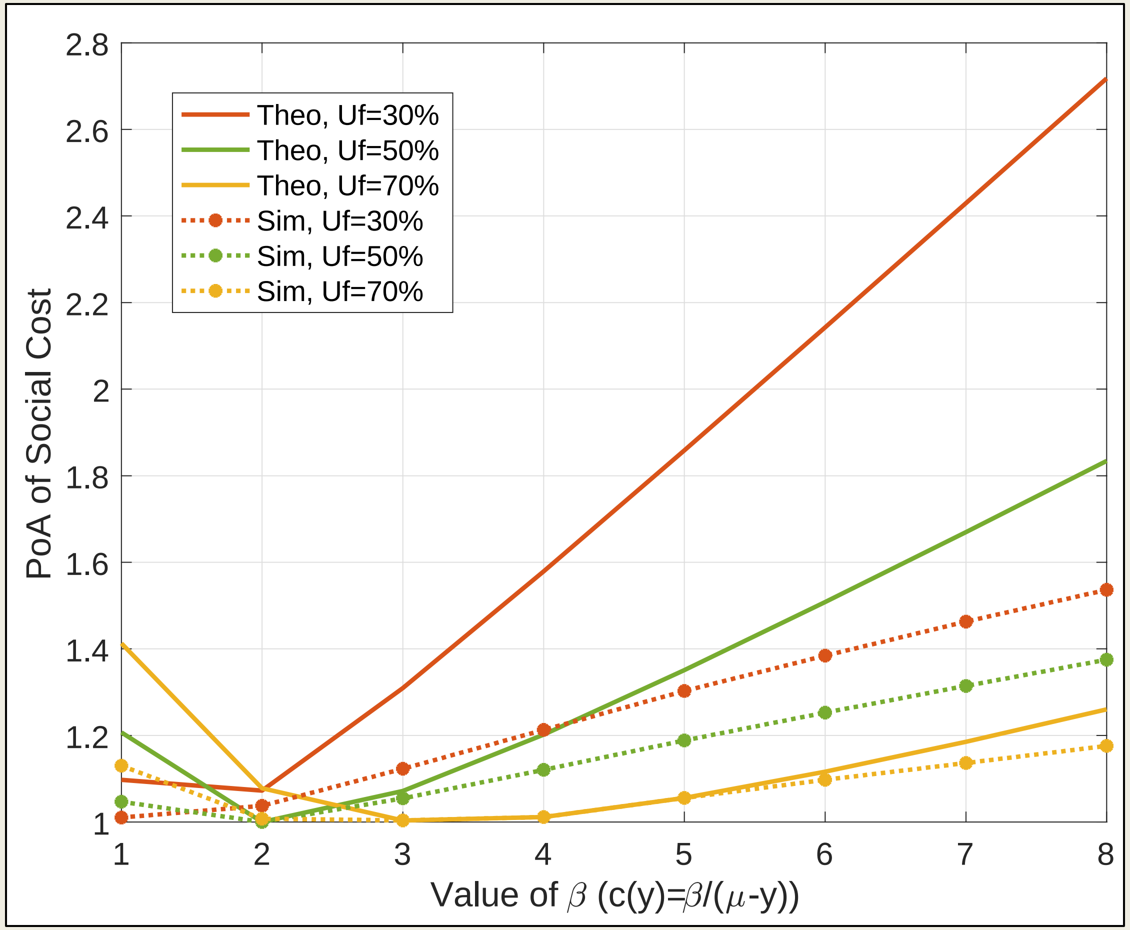
Avg PoA of SC (Sim) with Theoretical bounds



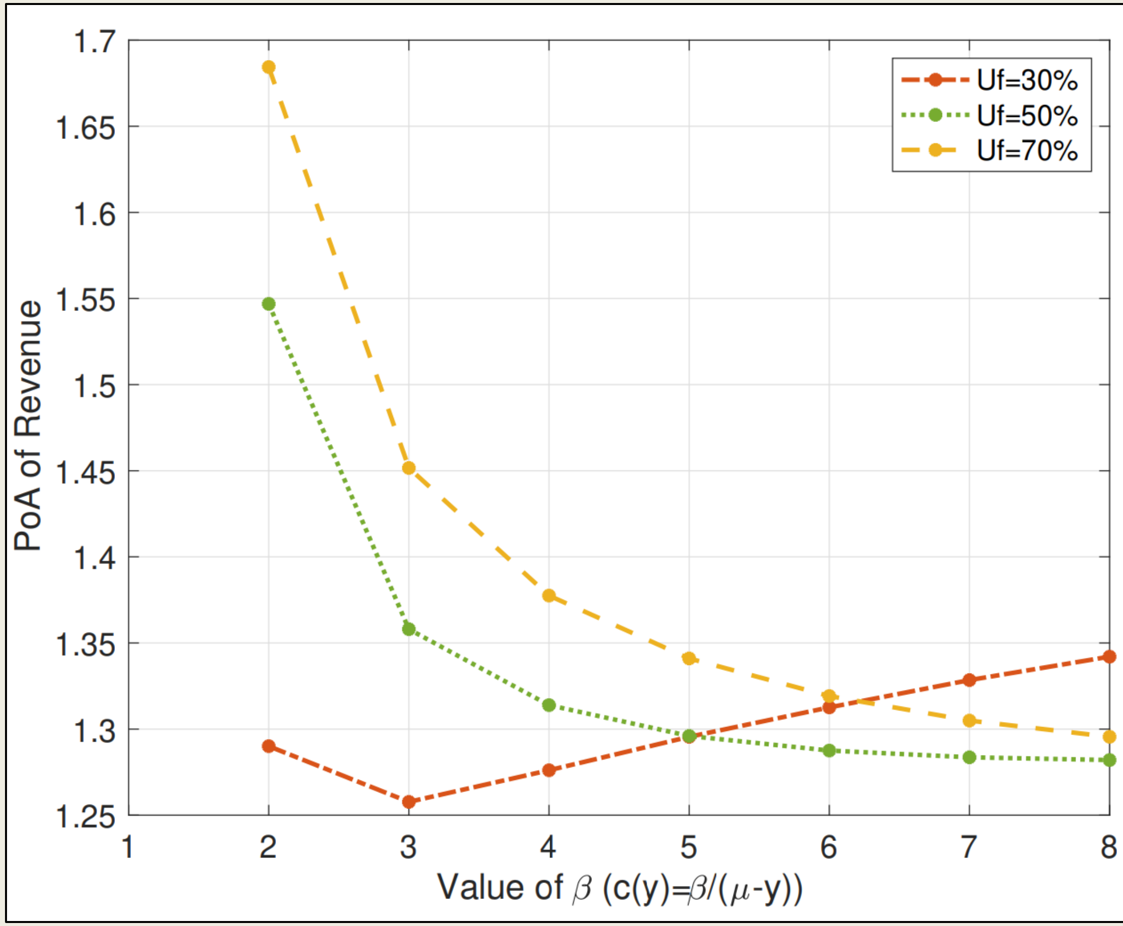
Avg PoA of Revenue - Simulated

Proportional Pricing Policy

Simulation Results – Queuing Delay



Avg PoA of SC (Sim) with Theoretical bounds



Avg PoA of Revenue - Simulated

Proportional Pricing Policy

Conclusion

- Theoretical **PoA (SC)** values **maintained small value** for a wide range of model parameters.
- The **IXP does not need to know the external routing costs** of the participating ISPs.
  - Which is **not possible** with **constant pricing** policy.
- **For appropriate range of** price proportionality factor $(\boldsymbol{\beta - 1})$, the $\boldsymbol{PoA}\ (\boldsymbol{SC})$ and $\boldsymbol{PoA}(\boldsymbol{Rev})$ **are small** for two broad type of delay functions.

Topic 2:
Port Capacity Purchase at IXPs

Our Publications on this Topic:

1. [**GameNets 2021**] M. Alam, E Anshelevich, K Kar, "Port Capacity Leasing Games at Internet Exchange Points".

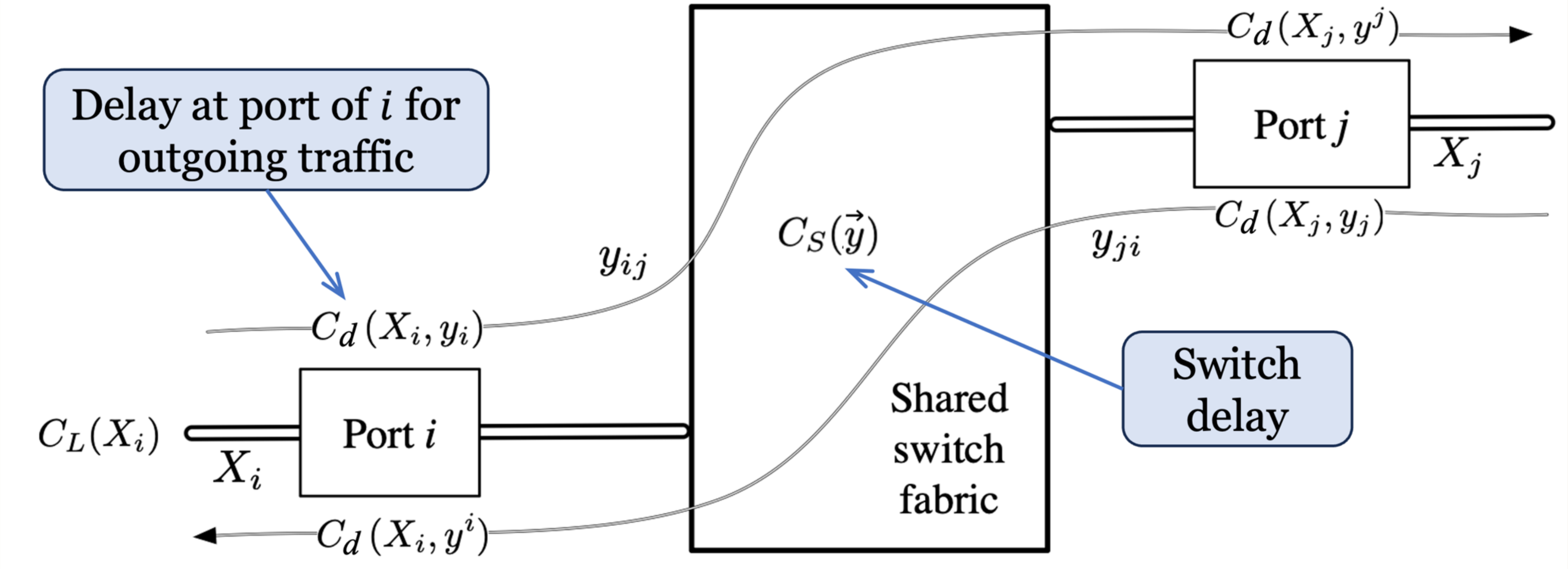
** Under Review in TNSE: "Port Capacity Purchase Games for Public Peering at Internet Exchange Points".

Port Capacity Purchase
Motivation

- ISP decisions at an IXP:
  1. ***unilaterally*** determine the port capacity to purchase at an IXP.
  2. ***bilaterally*** (with the other ISPs) the amount of traffic to exchange.
- **A complex bi-level** coupling between unilateral and bilateral decision
- No prior work on this bi-level problem of Port Purchase at IXP.
- The goal is to ascertain the optimal port capacity to purchase that will
  - minimize the costs,
  - and maximize incentives.

Port Capacity Purchase (PCP)

System model and properties



- Total cost of ISP i, C_i :

$$= \overbrace{\sum_j \left[y_{ij} \cdot C_d(X_i, y_i) + y_{ji} \cdot C_d(X_i, y^i)\right] + \sum_j \left[y_{ij} C_d(X_j, y^j) + y_{ji} C_d(X_j, y_j)\right]}^{\text{Port Delay (Cost), } C_P}$$

$$+ \underbrace{C_L(X_i)}_{\text{Port Lease Cost}} + \underbrace{(y_i + y^i) \cdot C_S(\vec{y})}_{\text{Switch Delay}} + \underbrace{\sum_j \lambda_{ij}(B_{ij} - y_{ij}) + \sum_j \lambda_{ji}(B_{ji} - y_{ji})}_{\text{Transit Cost}}.$$

X_i = Port Capacity of i
y_i = Outgoing traffic of i
y^i = Incoming traffic of i

Port Capacity Purchase

Transit Option Not Available

- **Assumption 1:** $C_i(X_i, X_{-i})$ has a unique minimum in X_i for any given X_{-i}.
- **Proposition:** Under Assumption 1, an equilibrium always exists.
- **Multiple Equilibria:**

$$y_{ij} = y_{ji} = 1; C_P = const.; C_S(X) = \max\left(10 - \left(\sum_i X_i - y\right), 0\right); C_L(X_i) = \log X_i$$

  - Then all values satisfying $X_i + X_j = 12$, is an equilibrium.

Port Capacity Purchase

Transit Option Not Available - Fixed Switch Capacity

- When $C_S(X, y)$ is independent of X, the port purchase game becomes a potential game.
- The potential function is given by,

$$\Phi(X) = \sum_i \left[\left(y_i C_P(X_i, y_i) + y^i C_P(X_i, y^i) \right) + C_L(X_i) + (y_i + y^i) \cdot C_S \right]$$

- **Theorem 1:** Under Assumption 1, if $C_S(X, y)$ is independent of X then:

  i. Each ISP has a dominant strategy; port purchase game has a unique equilibrium.

  ii. $\boldsymbol{PoA = PoS \leq 2.}$

Port Capacity Purchase

Transit Option Not Available - Variable Switch Capacity

- **Well provisioned** IXP switch : $\boxed{\sum_i \left(y_i C_P(X_i, y_i) + y^i\, C_P(X_i, y^i)\right) \geq \sum_i (y_i + y^i)\, C_S(X, y)}$
- Bounding PoA (with Smoothness): if the following condition is true,

$$\sum_i [\lambda \cdot C_i(X^*) + \mu \cdot C_i(X) - C_i(X_i^*, X_{-i})] \geq 0$$

  - Then, $PoA \leq \frac{\lambda}{1-\mu}$
- With $\lambda = 1$, and $\mu = \frac{1}{2}$, PoA of current game can be bounded using Theorem 2.
- **Theorem 2.** If IXP switch is well provisioned, the PCP game has a $\boldsymbol{PoA \leq 2}$.
- **Corollary.** If both C_P and C_S represent $M/M/1$ delay functions, and the switch has a capacity of $\sum_i X_i$, then $\boldsymbol{PoA \leq 2}$.

Port Capacity Purchase

Transit Option Available

- Bilevel game: ISP i chooses port capacity X_i unilaterally, but choose traffic rate y_{ij} through bilateral (pairwise) agreement with ISP j

- Total cost of ISP i :

$$\sum_j \left[y_{ij}C_d(f_i(y_i,y^i),y_i) + y_{ji}C_d(f_i(y_i,y^i),y^i)\right]$$
$$+\sum_j \left[y_{ij}C_d(f_j(y_j,y^j),y^j) + y_{ji}C_d(f_j(y_j,y^j),y_j)\right]$$
$$+C_L(f_i(y_i,y^i)) + (y_i+y^i)\cdot C_S(y) + \sum_j \lambda_{ij}(B_{ij}-y_{ij}) + \sum_j \lambda_{ji}(B_{ji}-y_{ji})$$

$$\equiv \sum_j \left[y_{ij}C_{d_i}(y_i,y^i) + y_{ji}C_{d^i}(y_i,y^i)\right] + \sum_j \left[y_{ij}C_{d^j}(y_j,y^j) + y_{ji}C_{d_j}(y_j,y^j)\right]$$
$$+ C_{L_i}(y_i,y^i) + (y_i+y^i)\cdot C_S(y) + \sum_j \lambda_{ij}(B_{ij}-y_{ij}) + \sum_j \lambda_{ji}(B_{ji}-y_{ji}).$$

- Port cost of ISP i, $\sum_j y_{ij}\left[C_{P_i}(y_i,y^i) + C_{d^j}(y_j,y^j)\right] + \sum_j y_{ji}\left[C_{P^i}(y_i,y^i) + C_{d_j}(y_j,y^j)\right].$

Port Capacity Purchase

Transit Option Available

- **Assumption 2.** For any ISP i, $y_i C_{P_i}(y_i, y^i)$, and $y^i C_{P^i}(y_i, y^i)$ are convex and increasing in y_i and y^i respectively.
- **Assumption 3.** For any ISP i, $y_i C_{d_i}(y_i, y^i)$, and $y^i C_{d^i}(y_i, y^i)$ are convex and increasing in y_i and y^i respectively.

Where

$$C_{d_i}(y_i, y^i) + \frac{y_i}{y_i + y^i} C_{L_i}(y_i, y^i) = C_{P_i}(y_i, y^i)$$

$$C_{d^i}(y_i, y^i) + \frac{y^i}{y_i + y^i} C_{L_i}(y_i, y^i) = C_{P^i}(y_i, y^i)$$

Port Capacity Purchase

Transit Option Available

- **PoA without switch delay:**
  - **Theorem 3.** If switch delay is negligible and Assumption 2 holds, then PCP game with transit option has $\boldsymbol{PoA \leq 4}$.
  - **Theorem 4.** If switch delay is negligible and Assumptions 2 and 3 hold, then PCP game with transit option has $\boldsymbol{PoA \leq 2}$.
- **PoA with switch delay:**
  - **Theorem 5.** If the switch is well-provisioned, then PCP game with transit option has (a) $\boldsymbol{PoA \leq 8}$ if Assumption 2 holds; (b) $\boldsymbol{PoA \leq 4}$ if both Assumptions 2 and 3 hold.

Port Capacity Purchase

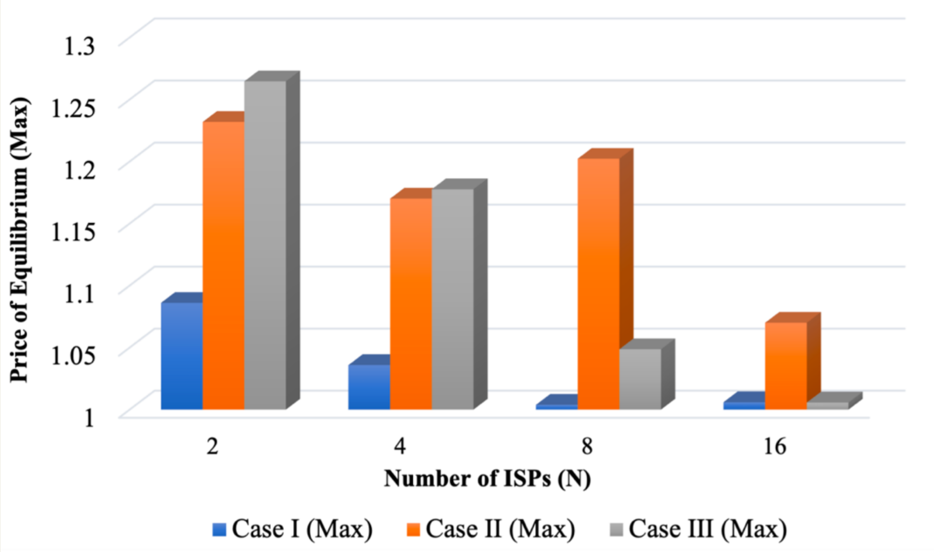
Simulation results

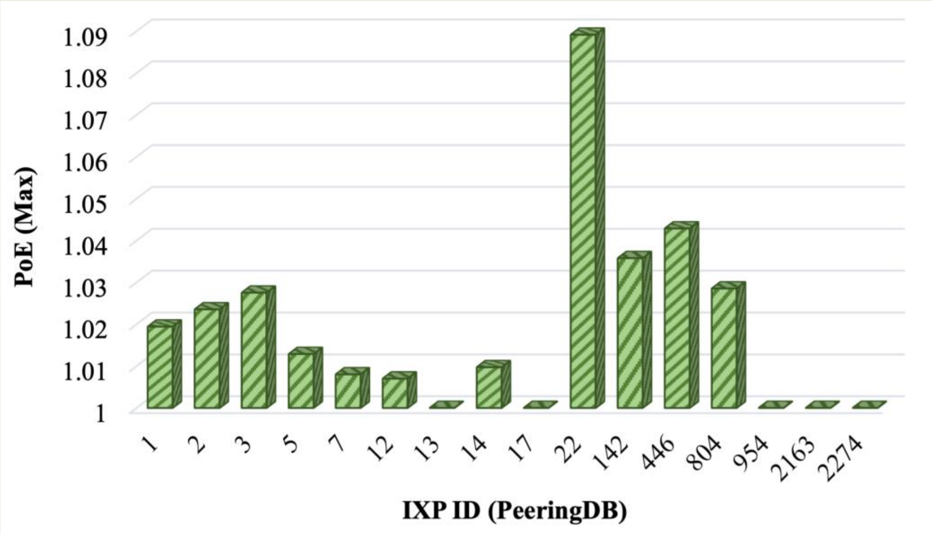
- Price of equilibrium (PoE) = ratio of cost at (any) equilibrium to cost of optimum.
- $\boldsymbol{PoS \leq PoE \leq PoA}$
- **Three cases:** none or some constraints on real traffic data,

  i) No constraint on the B_{ij} values,

  ii) for any ISP pair $(i, j), B_{ij} = B_{ji}$, and

  iii) for any ISP pair $(i, j), 10^{-5} < B_{ij} < 100$.

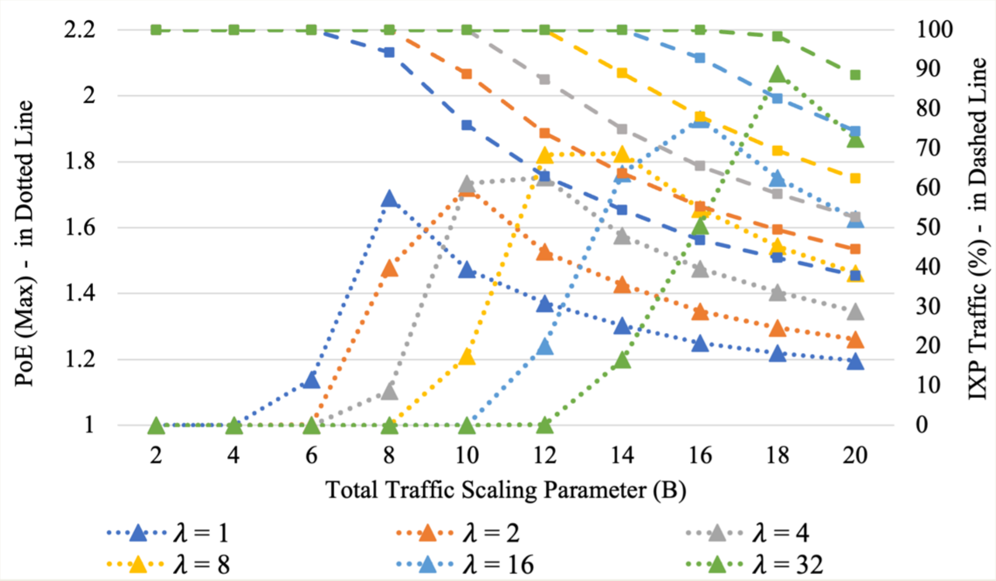




Port Capacity Purchase

Simulation results (contd.)

- For different traffic demands (B), max PoE value is proportional to transit cost (λ values).
- Highest PoE when IXP traffic falls from 100% (dotted and dashed lines of same colors).
- **Worst-case PoE** (PoA): when **ISPs** do not use transit and **exhaust IXP resources** fully.



Effect of transit cost scaling parameter (λ) and total traffic scaling parameter (B)

Port Capacity Purchase
Conclusion

- Port purchase game at IXP is analyzed for two scenarios: **Transit** and **No Transit** option.
- For **No Transit** Scenario:
  - If switch capacity of IXP is fixed, ISPs have a dominant strategy and $PoA \leq 2$.
  - If switch capacity changes but is well provisioned, $PoA \leq 2$.
- For **Transit** Scenario:
  - If switch delay is negligible, $PoA \leq 4$.
  - If switch is well provisioned, $PoA \leq 8$.

Topic 3:
Modeling ISP Peering Decision Process

Our Publications on this Topic:

1. **[ICC 2022]** M. Alam, K Kar, E Anshelevich, "Modeling and Automating ISP Peering Decision Process: Willingness and Stability"
2. [**TNSM 2024**] M. Alam, A Mahmood, K Kar, M Yuksel, "Meta-Peering: Automating ISP Peering Decision Process".

** Under Review in TMLCN: M. Alam, A. Senapati, A Mahmood, K Kar, M Yuksel, "Peering Partner Recommendation for ISPs using Machine Learning".

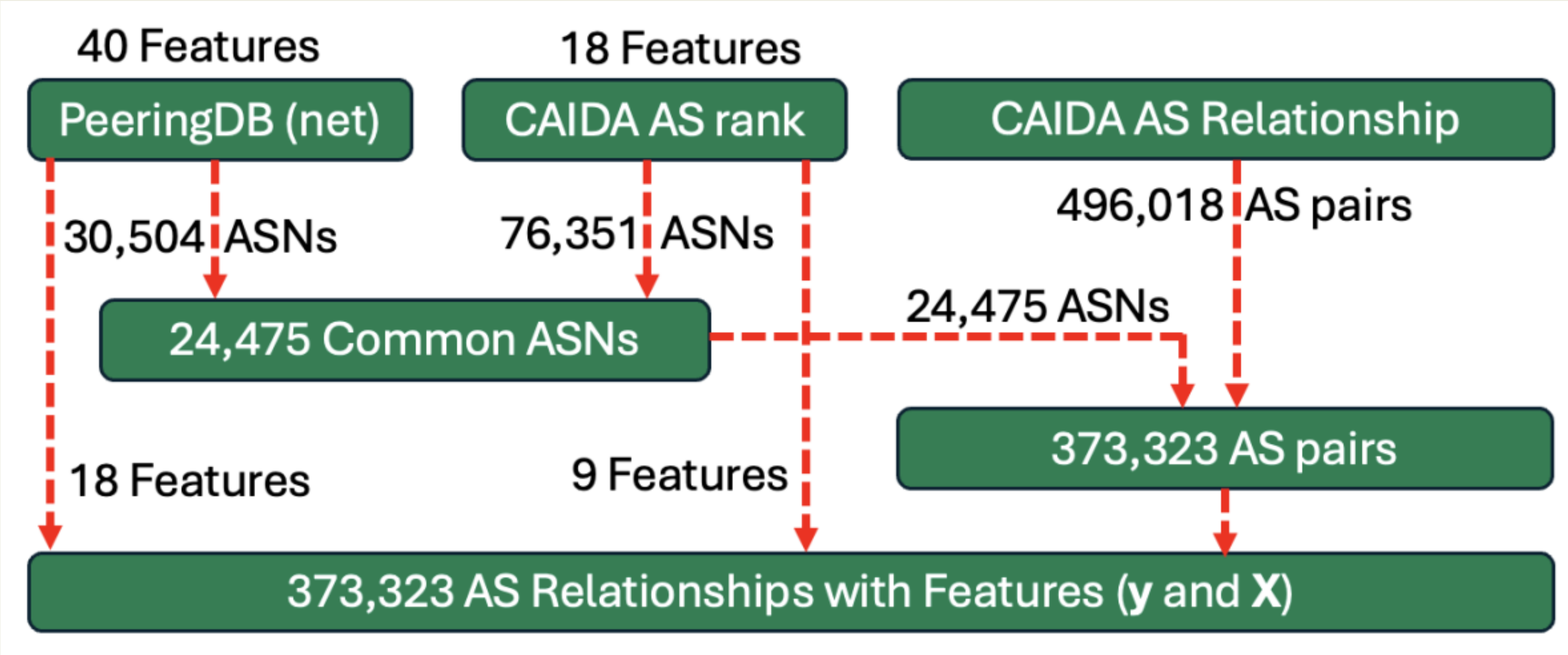
ISP Peering Decisions

Motivation

- **ISPs peer** with **other ISPs** to decrease delay, enhance security etc.
- Finding **suitable peers** is **crucial to survive** the market.
- **Automating** the peering decision process can **save time** and **money**.
- Automation of peering process has only been explored in few recent works.

Peering Partner Prediction
Data Collection

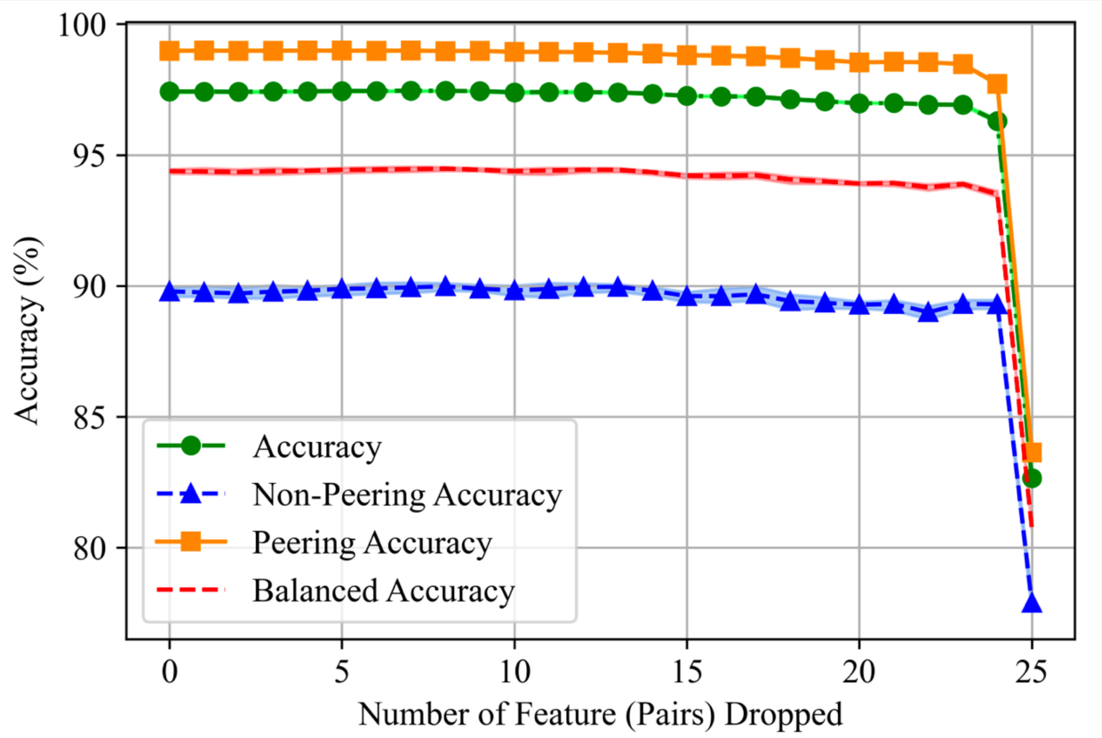
- <u>Data Sources:</u>
  - PeeringDB and CAIDA



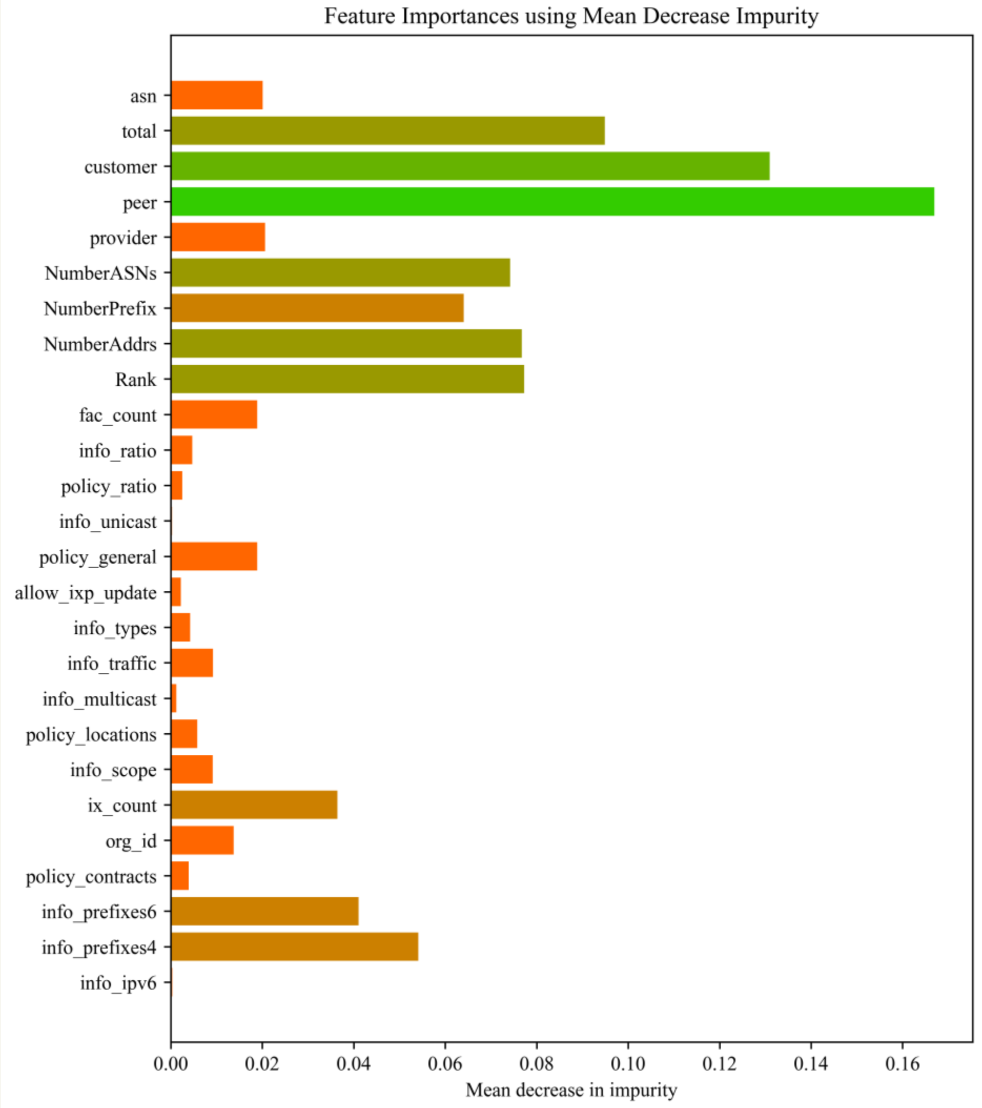
Data extraction and forming feature set of AS pairs

Peering Partner Prediction

Performance (Filtered Dataset)



Accuracy of RF model by sequentially dropping least important feature (pairs)



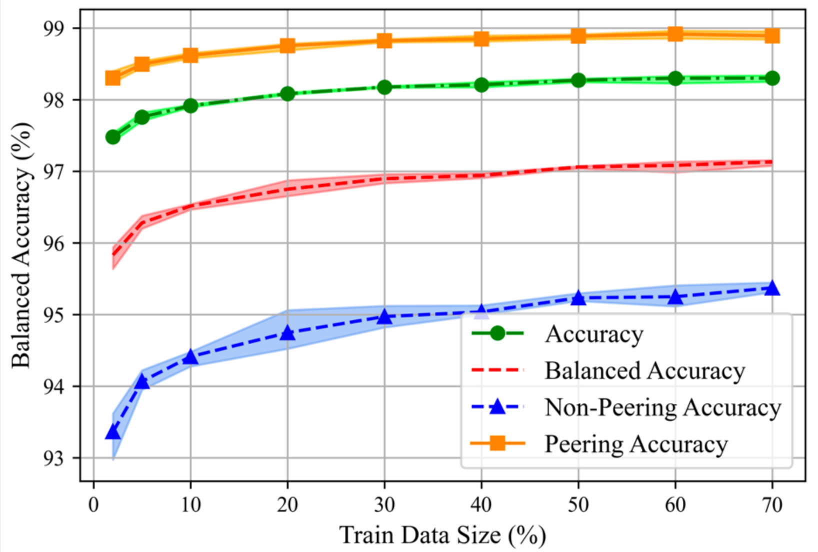
Feature importance

Peering Partner Prediction

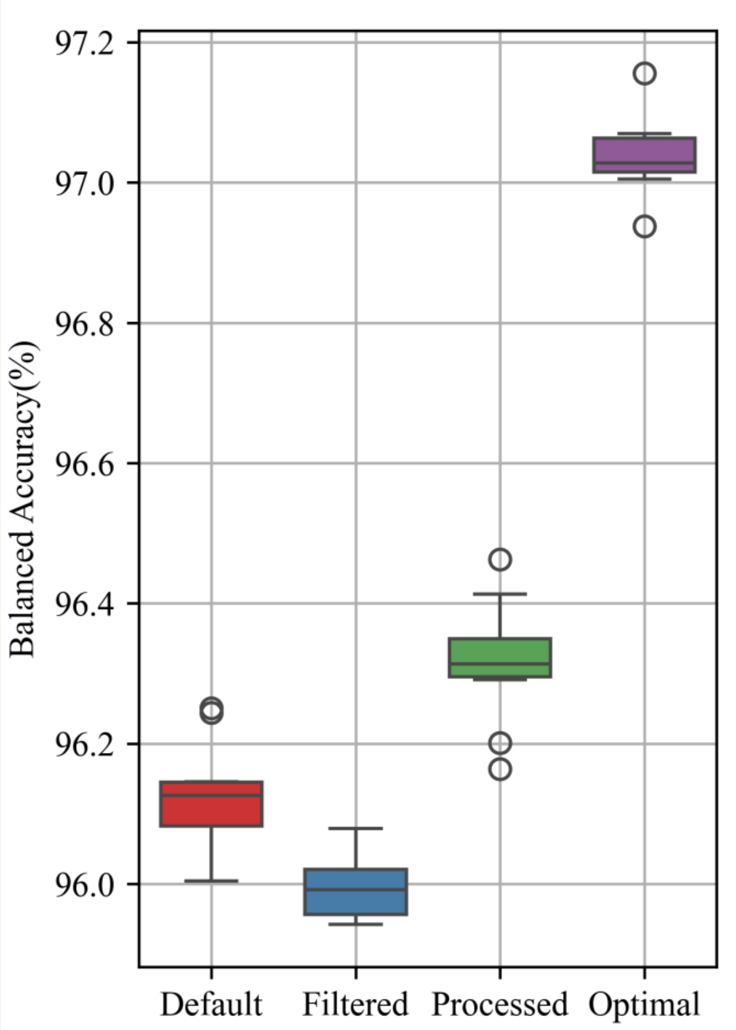
Model and Dataset Selection

Model Name	Overall Accuracy	Balanced Accuracy	Training Time (sec)	Evaluation Time (sec)
BERT	95.80	93.35	5325	10300
DNN	96.01	93.54	14.38	4.19
RF	97.01	95.68	8.29	2.47
SVM	93.65	92.60	20.78	225.9
XGB	97.13	95.70	2.76	0.098

Performance of different ML models



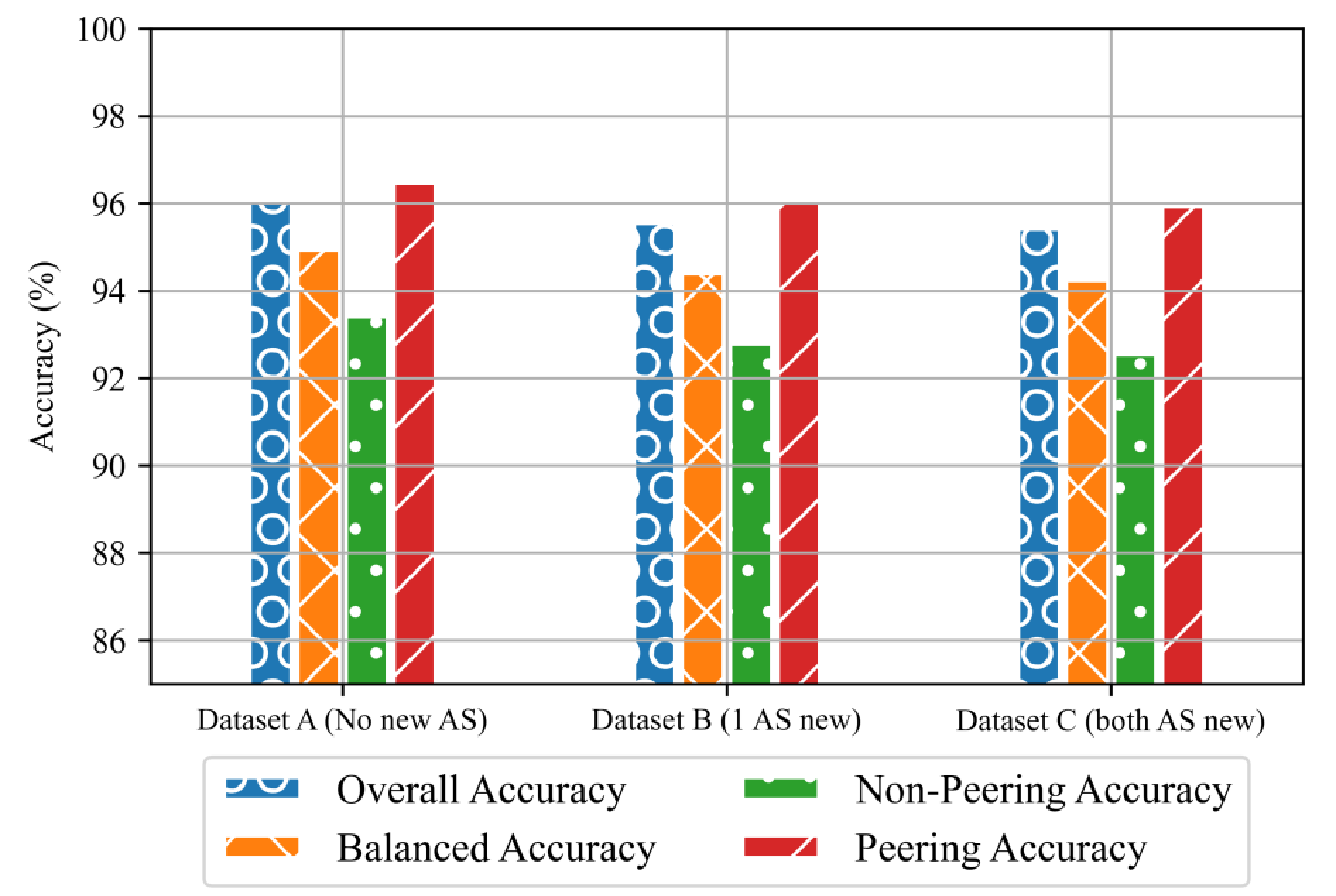
Performance w.r.t. training data size



Performance with default and processed datasets

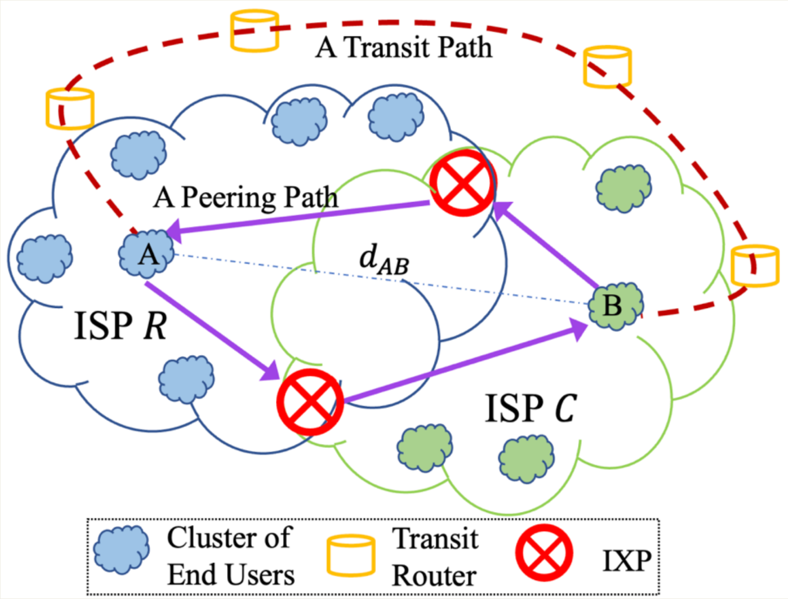
Peering Partner Prediction

Transfer Learning on New Data Over Time



Performance on new AS pairs - Transfer Learning (different timeline)

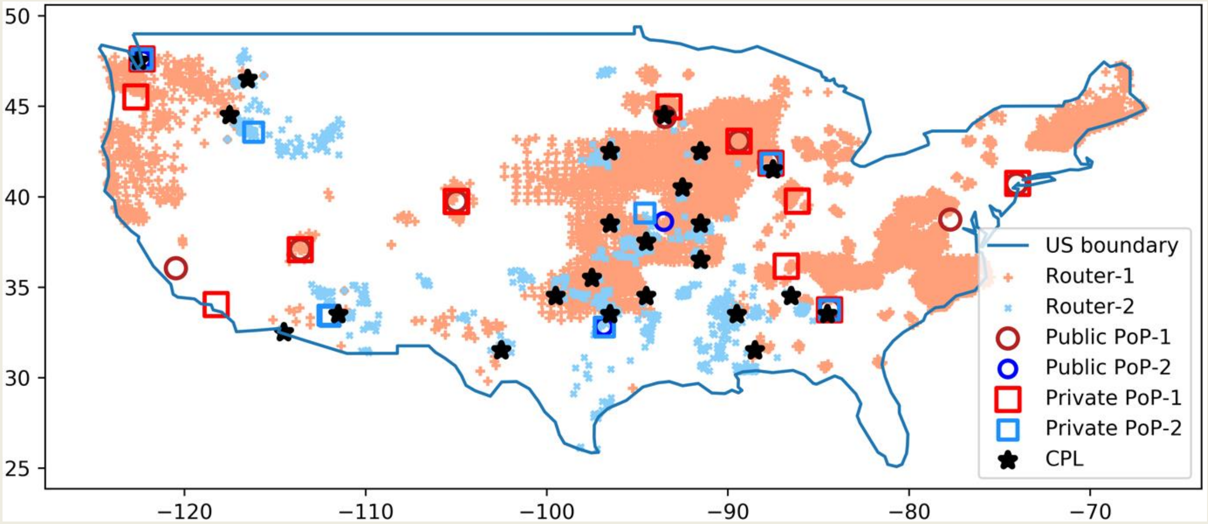
Peering Location Decision
System model and properties



- Possible Peering Points (**PPP**s): where an ISP pair can peer.
- Acceptable Peering Contracts (**APC**s): set of contracts (locations) where ISP pairs have no (policy) issue to peer at.
- Traffic from **ISP R at Location 1** to **ISP C at Location 2**:

$$T_{1,2}^{R\to C} = s_2 * u * \frac{p_2}{d^2} * \frac{R_{C,2}}{\sum_k R_{k,2}},$$

- **Routing Costs**
  - $C_I = a_I \sum_r d_r = a_I \times d_I$
  - $C_T = a_T \times f \times d_{AB}$



Peering Location Decision

Peering Willingness and Stability

- Peering Willingness of ISP R with contact $i \in APC$:

$$W_i^{R\to C} = \frac{\sum_t C_T(t,R,C)}{\sum_t C_I(i,t,R,C)} = \frac{\sum_t a_T * d_{(AB)_t} * f}{\sum_t a_I * d_{I_t}(i)},$$

- Peering willingness between ISPs (R, C) using contract $i \in APC$,

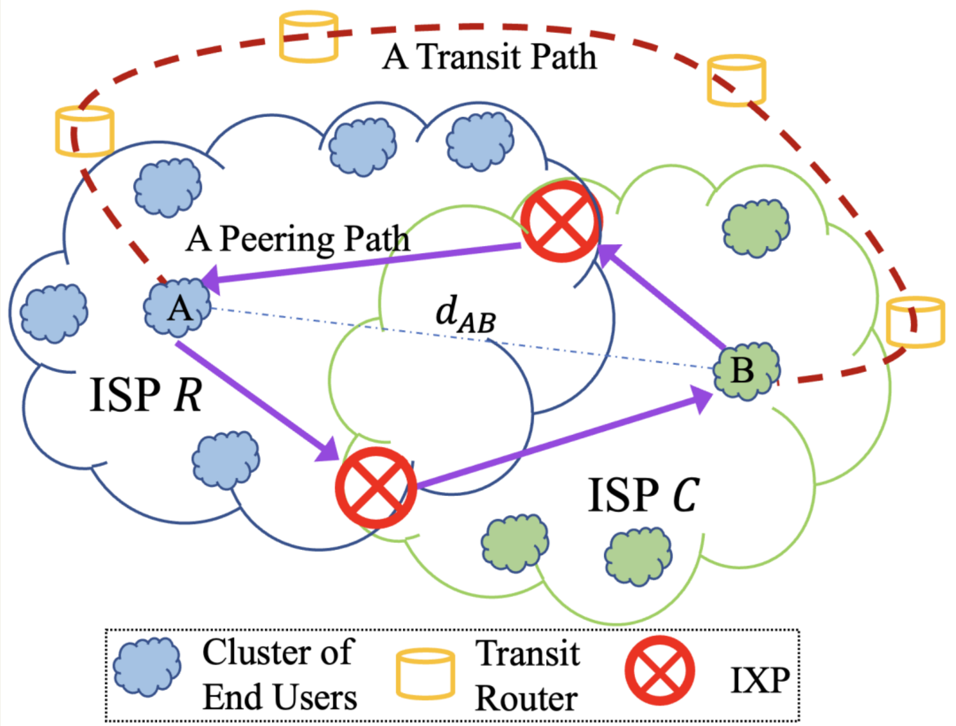
$$W_i^{R,C} = \sqrt{W_i^{R\to C} \times W_i^{C\to R}}$$

- Peering Stability of ISP R with using contact $i \in APC$:

$$S_i^{R\to C} = \frac{\min_{\tilde{i}\in APC} \sum_t C_I(\tilde{i},t,R,C)}{\sum_t C_I(i,t,R,C)}$$

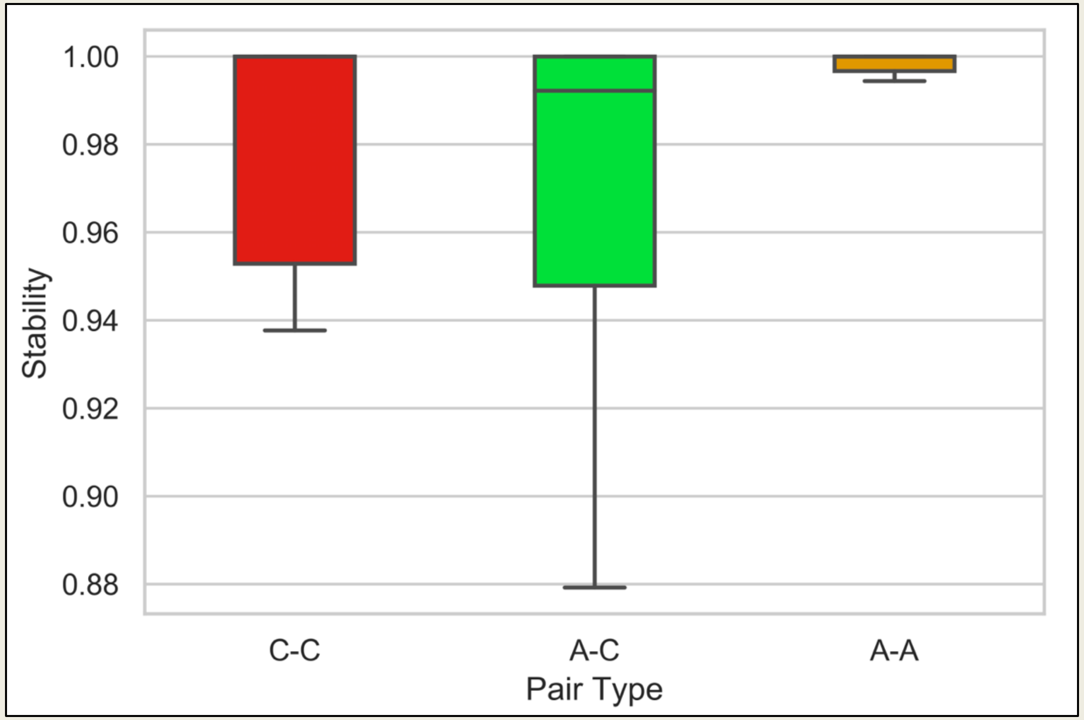
- peering stability for an ISP pair (R, C) using contract $i \in APC$,

$$S_i^{R,C} = \sqrt{S_i^{R\to C} \times S_i^{C\to R}}$$

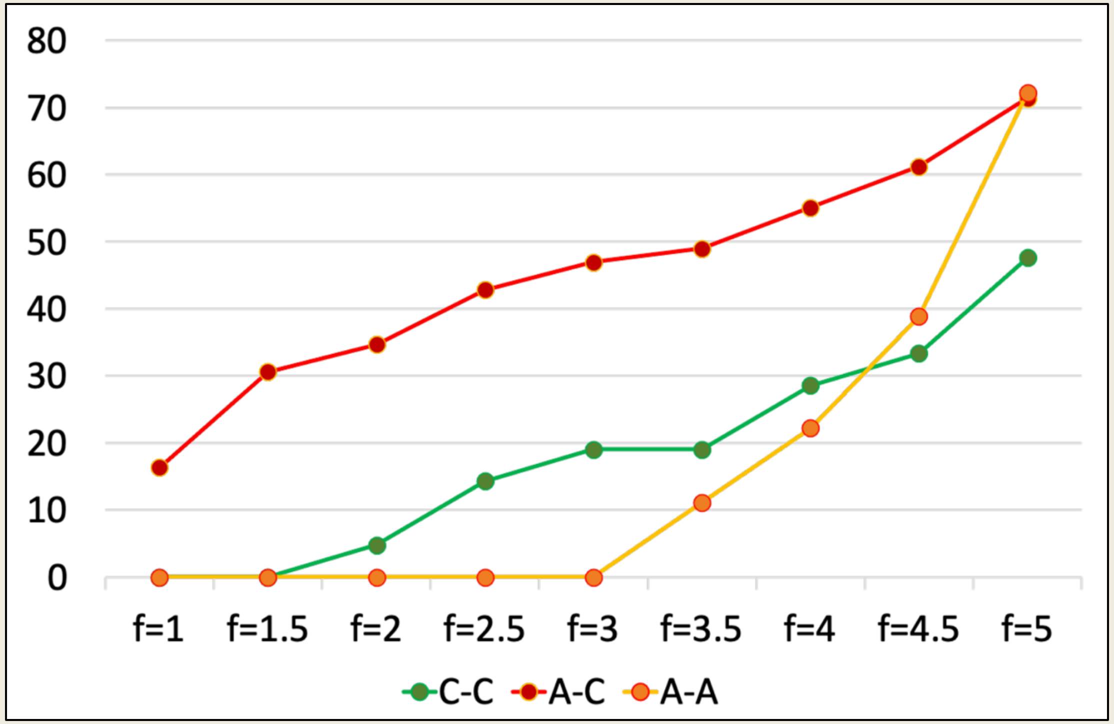


Peering Location Decision

Simulation Results - Single Point Peering



Existence of stable peering location.



Peering willingness with path stretch factor.

ISP Peering Decisions
Conclusion

- Methods that automate the decision of peering and peering locations are developed.

Peering *Partner* Prediction

- AS features are extracted and processed to train machine learning (ML) based models.
- Optimal dataset constructed: contains important features to predict peering partners.
- ML based XGB showed robustness to different scenarios and attained great accuracy (>96%).

Peering *Location* Prediction

- Higher Peering willingness indicates higher motivation to peer.
- There is usually a stable peering location for all ISP pairs.
- The Access-Content ISP pair type showed high PW, PS and low PoS.

Conclusion

Conclusion
Essential Insights

1. **Pricing Policy of IXPs:** Can ensure good Social Cost (or Welfare) and Revenue with
   - **Constant pricing** – when Internet demands are stable.
   - **Proportional pricing** - when Internet demands are dynamic.
2. **Port Capacity Leasing game**
   - The social utility cannot be too bad even with selfish behaviors of ISPs.
3. **ISP Peering Decisions**
   - Machine learning models can **accurately** predict **peering partner** with public data.
   - Peering of an ISP pair depends mainly on the features of the respective ISP pair.
   - ISP peering locations are dependent on the geographic presence of other ISPs.

Practical Implications

- IXP Policy Recommendations
  - For stable internet demand, IXPs can consider constant pricing policy.
  - With appropriately chosen per-unit price, good **social welfare** and **revenue** can be achieved.
  - If Internet demand is more dynamic, IXPs may consider **proportional pricing** policy.
- Recommendation to ISPs
  - ISPs can selfishly take port purchase decisions at IXP and do not hurt the social utility much.
  - The decision of two ISPs to peer does not depend much on the entire system.
  - The peering location decision, however, may depend on the entire system of all ISPs.

Thank you for listening!

Questions?